SELENIDE ISOTOPE GENERATOR *for the* GALILEO MISSION

MASTER

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Pictured on the cover is Galileo's drawing of the solar system, which includes the four satellites of Jupiter he discovered in the 1600's. A Renaissance professor, inventor and astronomer, Galileo perfected the telescope with which he made his Jupiter discoveries. The 1982 NASA mission to Jupiter is named in his honor. Like Galileo and his telescope, the NASA mission to the far reaches of outer space will be contributing to Mankind's never ending quest for knowledge.

SELENIDE ISOTOPE GENERATOR

for the GALILEO MISSION

COPPER/WATER AXIALLY-GROOVED HEAT PIPE TOPICAL REPORT

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TES-33009-44

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By:

N. P. Strazza

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COPPER/WATER AXIALLY-GROOVED HEAT PIPE TOPICAL REPORTINTRODUCTION

This report presents a summary of the major accomplishments for the development, fabrication, and testing of axially-grooved copper/water heat pipes for Selenide Isotopic Generator (SIG) applications. The early development consisted of chemical, physical, and analytical studies to define an axially-grooved tube geometry that could be successfully fabricated and provide the desired long term (up to seven years) performance is presented. Heat pipe fabrication procedures, measured performance and accelerated life testing of heat pipes S/Ns AL-5 and LT-57 conducted at B&K Engineering are discussed. S/N AL-5 was the first axially-grooved copper/water heat pipe that was fabricated with the new internal coating process for cupric oxide (CuO) and the cleaning and water preparation methods developed by Battelle Columbus Laboratories. Heat pipe S/N LT-57 was fabricated along with sixty (60) other axially-grooved heat pipes allocated for life testing at Teledyne Energy Systems. As of June 25, 1979, heat pipes S/Ns AL-5 and LT-57 have been accelerated life tested for 13,310 hours and 6,292 hours respectively, at a nominal operating temperature of 225°C without any signs of thermal performance degradation.

Aspects of fabrication, acceptance test data, and test results are presented for the sixty (60) axially-grooved heat pipes life tested at TES. Acceptance test data is also presented for an additional total of twenty (20) heat pipes which were fabricated subsequent to the life test pipes for the Ground Demonstration System (GDS). The failure of three life tested heat pipes, which has been concluded to be due to external contamination, is presented along with results of non-destructive and destructive analysis of several life tested heat pipes. Also, an evaluation of axially-grooved copper tubing and tubing acceptance requirements for the SIG/Galileo Mission are discussed. Corresponding transport capability for this tubing is predicted at operating temperatures of 105°, 125°, and 140°C for 0-g and for

an adverse elevation of 0.127 cm (0.05 inch). Performance predictions for positive heat pipe elevations (condenser above evaporator) corresponding to 45° and 90° orientations are presented. Spin test results for SIG/Galileo prototype heat pipes are shown. These test results include data from spin tests that were conducted to determine the heat pipe's behavior under Galileo Mission spin conditions.

The report is concluded with a discussion of conclusions and recommendations for upgrading the heat pipe fabrication process. All information to date has confirmed that axially-grooved copper/water heat pipes can be successfully fabricated for long term space applications at operating temperature of $\geq 220^{\circ}\text{C}$.

1.0 COPPER/WATER HEAT PIPE DEVELOPMENT

1.1 Background

In June, 1972, Teledyne Energy Systems (TES), at the request of the Department of Energy (DOE), initiated a study program to assess the application of a Space Nuclear Auxiliary Power/SNAP-19 type generator as a backup power supply for the Lincoln Experimental Satellites (LES) 8 and 9 for an earth orbit mission. The LES was eventually launched utilizing a Multi-Hundred Watt (MHW) type power supply. Results of a study by TES showed that by using heat pipes attached to the radiator fins, radioisotopic thermoelectric generators (RTG's) would offer the advantage of a beginning of life (BOL) specific power of 2 watts/pound. In addition, the system could be designed to provide at least 280 watts (e) at the beginning of mission (BOM) and 200 to 230 watts (e) after five years.

Copper/water heat pipes were fabricated as backup for the LES 8/9 program. The heat pipes consisted of a 1/4 inch diameter alloy 122 phosphorus deoxidized copper tube bent to an "L" shape for optimum interfacing with both the generator housing (evaporator) and the radiator fins (condenser). The inner wall of the tube was threaded with approximately 32 circumferential grooves per cm, each approximately 0.127 mm deep. These grooves provide the necessary flow paths from the main wick to the heat transfer surface of the tube. The main wick consisted of a 100-30-100 mesh electrolytic copper (99.9% pure) screen held against the I. D. of the tube wall with a beryllium-copper alloy 25 spring. Water was selected as the working fluid since it has

the best transport characteristics in the temperature range of interest (60° - 175°C). Both the internal surface of the tube and the main wick were chemically treated with an Ebonol-C coating to provide proper wetting of the wick system. These copper heat pipes were then attached to the RTG's housing and radiator with pure tin solder which melts at approximately 230°C.

Teledyne Energy Systems initiated the "High Performance Generator" (HPG) program in November, 1972 and utilized the heat pipe and attachment technology resulting from the LES 8/9 study. Fifty-six (56) heat pipes were fabricated for TES. Forty-eight (48) were attached to a prototype HPG, two (2) were attached to a representative section of an HPG fin and four (4) unattached were subjected to life testing. The remaining two (2) were spares.

Heat pipes S/N 1A12 and S/N 4, which were soldered to a mocked-up HPG fin sections, were life tested in a reflux mode at 155°C and 180°C, respectively. After approximately 8700 hours of life testing, heat pipe S/N 1A12 was removed from test as a result of a perforation in the evaporator section in the vicinity of the solder bond. Heat pipe S/N 4 developed a similar failure after approximately 14,200 hours of life testing. Jet Propulsion Laboratories (JPL) reported that twelve (12) of the heat pipes attached to the prototype HPG under test at JPL had failed to meet the performance requirements after being on life test for approximately 6000 hours. Initial analysis of S/N 4 indicated that a corrosion product within the heat pipe contained copper (Cu), cupric oxide (CuO), cuprous oxide (Cu₂O), heavy traces of sulphate (SO₄⁼) ion and chloride (Cl⁻) ion. Radiography performed on S/N 4 also revealed internal corrosion of the heat pipe wall which was most evident in the evaporator section. The basic chemistry evaluation of the heat pipe failures began by hypothesizing

possible chemical mechanisms that could cause the corrosion problem. Thermodynamically, it could be shown that pure copper and pure water free of oxygen and carbon dioxide are stable and will not react at heat pipe temperatures as high as 250°C. The Ebonol-C process employed to produce a black cupric oxide (CuO) coating on the internal wicking surfaces could have possibly introduced mechanisms for direct chemical attack. The vendor would only reveal that Ebonol-C contains a caustic alkali, sodium hydroxide (NaOH), together with strong oxidizing agents which form the cupric oxide at a nominal temperature of 100°C. Since the vendor did not disclaim chlorides, the presence of chlorites or chlorates (ClO_2^- or ClO_3^-), which are strong oxidizing agents, was postulated.

1.2 Research Activities - Pre-Ground Demonstration System (GDS)

As a result of the heat pipe failures experienced during the LES 8 and 9 backup study, Teledyne Energy Systems initiated a research program to provide information on the following: (1) the cause of pitting failure, (2) the nature of any electrochemical reactions that could occur among the various heat pipe components during operations, (3) the long-term stability of the coating on the wicking surfaces, and (4) future avoidance of similar failures. Results from the study concluded that: (1) chlorides and oxygen must be eliminated from the heat pipe as these substances cause corrosion of copper, (2) beryllium-copper spring material must be eliminated to insure that galvanic effects are not possible (considerable quantities of hydrogen were found in one of the test pipes, and (3) the Ebonol-C coating should be eliminated. Ebonol-C is the source of chloride ion from the reaction which is thought to be:

In order to pursue the requirement for a coating, Teledyne Energy Systems extended its program to investigate various surface treatments on copper ranging from simple abrasion to sophisticated electrochemically-applied oxide (CuO) coatings. Surface treatments which appear to be adequate from a wettability standpoint (contact angle $\leq 30^\circ$) were then investigated electrochemically to determine their stability under working conditions in the heat pipe. A further study investigated the criticality of removing organics and oxygen from the

water prior to sealing the heat pipes.

The contact angle studies clearly showed that, even under carefully controlled conditions, only surfaces which have been chemically or electro-chemically treated to lay down a predominately CuO film gave adequate wettability. Despite high standards of cleanliness during preparation of the copper surfaces by physical or chemical cleaning, including hydrogen cleaning, or by passivating, the desired values of contact angle ($\leq 30^\circ$) were not achieved. The conclusion that only CuO coatings give adequate wettability prompted a study to determine a means to generate the desired coating that would preclude a reactant or a product or species liable to cause degradation of the coating or base metal during heat pipe operation. The findings that only hydrogen peroxide solutions produced the desired coating which satisfied the contact angle requirement and had no detrimental components or residues led to the optimization of an $\text{H}_2\text{O}_2/\text{NaOH}$ treatment. Electrochemical studies on $\text{H}_2\text{O}_2/\text{NaOH}$ -treated surfaces after thorough water rinsing showed that after 20 hours of testing, the CuO coating was quite stable provided that the oxygen concentration in the water working fluid was reduced to sufficiently low levels.

1.3 Axially-Grooved Tubing Development

The development of a copper/water heat pipe for the SIG/Galileo Program required the design of a wick structure and heat pipe geometry that would satisfy mission performance requirements, refer to References 1 and 2. The axially-grooved wick was selected because it offered high, repeatable thermal performance without any unreliable composite effects, refer to Reference 3. In addition, this design with its relatively large open channels would permit a higher degree of reliability for cleaning, coating and configuring (bending to angles of at least 90°) than the conventional screen wicks. The parametric analysis employed to establish the axially-grooved tubing geometry, the thermal performance obtained with prototype heat pipes, and the results of extensive accelerated life testing are described as follows:

1.3.1 Parametric Analysis

A parametric analysis was performed to determine an optimized axially-grooved copper/water heat pipe which would meet SIG/Galileo performance requirements as specified in Table 1-1. The design optimization consisted of determining groove geometries which would give maximum heat transport capability consistent with TES specifications Table 1-1 and which are within the constraints imposed by a cold-forge tubing fabrication process. The basic groove geometry is the divergent form which is shown in Fig. 1-1, along with associated nomenclature. This geometry is the one most widely used with aluminum systems, and has the highest potential for being fabricated in small tube diameters. The draft angle (α) at the root of the land was selected as 35° since this was estimated to be the smallest angle that would permit adequate metal flow to develop the land fully in the cold-forge operation. As this angle gets larger, the liquid flow area gets smaller resulting in a small loss of performance which is a second order effect.

Specific groove geometries were established for each groove width as a function of the various aspect ratios (groove depth/groove width). The range of the groove widths (0.033-0.061 cm) was selected to be consistent with static wicking height of 2.03 cm requirement. Although groove aspect ratios were selected to maximize the theoretical performance, it should be recognized that for the small tube diameters being considered, the maximum groove aspect ratio that can be attained with state-of-the-art cold forging of copper is about 1.5 to 2. Hence, as will be seen, fabrication limits dictate the optimum groove design.

1.3.2 Theoretical Heat Transport

The Groove Analysis Program (GAP) described in Reference 4 was used to predict the maximum heat load ($\dot{Q}$) that can be transported by the various groove geometries as a function of operating temperature. Perfect wetting and sharp land corners were assumed.

TABLE 1-1 - SIG HEAT PIPE*Design and Performance SpecificationsDesignLengths (cm)Evaporator 10Transport Section 2 - 5Condenser 50 - 75Overall 60 - 90Effective Length (max.) 47.5

Diameter Diameter to be consistent with minimum weight and fabrication constraints. Maximum O.D. 0.794-cm. Wall thickness - Must be consistent with minimum weight and must contain the working fluid at a maximum service temperature of 200°C with a safety factor of 1.5.

Performance

Heat applied/removed over 180 degrees of evaporator/condenser circumference

Maximum Heat Load

120 Watts

Heat Transport Requirement (max.)

57 Watt-meter

Operating Temperature Range

Minimum Operating Temperature
(short term ground tests)

20°C with a 60 W heat load

Maximum ΔT across Active Zone

8°C @ 120-W

Maximum Allowable Inactive Zone

4-cm @ 60°C

Heat Pipe Acceptance Test }
Elevation (Evaporator Up) }

0.38 cm (0.15 in.)

Minimum Static Height

2 cm @ 90°C

*The design and performance parameters defined in this Table are original specifications for the SIG system. Current designs are substantially different; a straight configuration with two separate sections and with an overall length of up to 150 cm is specified. The final design is discussed in Section 3.0.

Figure 1-1. Divergent Axially-Grooved Geometry for Small Diameters

The effect of these parameters on thermal performance was taken into account once a nominal design had been selected. The effect of groove width and aspect ratio on the transport capability is shown in Figures 1-2 and 1-3 for 90° and 120°C operation, respectively. There are a number of general trends that can be readily noted:

- (1) For a given groove width, the heat transport maximizes as a function of the aspect ratio. At low aspect ratios, liquid losses are dominant, whereas, vapor losses increase and eventually become dominant as the vapor diameter decreases at high aspect ratios.
- (2) For a smaller groove width, the heat transport capability maximizes at a higher aspect ratio. The maximum transport capability that can be attained tends to increase as the groove width decreases.

Figure 1-4 presents the heat transport as a function of temperature for the various groove widths at a 1.5 aspect ratio. In addition, the data 0.635-cm shows that a 0.635 cm (1/4 in.) O.D. tube cannot meet the transport as specified in Table 1-1. However, all transport requirements are satisfied with each of the groove widths with a 0.794 cm (5/16 in.) O.D. tube. Except for the 0.033 cm (0.013 in.) groove width, the thermal performance for each of the geometries is essentially the same with this diameter. The heat transport increases from approximately 90 W at 90°C to 350-400 W at 150°C. Each of the larger widths is capable of 190-200 W at 90°C, whereas only 150 W can be achieved with the 0.033 cm wide groove. The 0.043 cm (0.017 in.) width and corresponding geometry was selected for the nominal design to allow for loss in static height due to less than perfect wetting (e.g., 0° to 30° contact angle).

Figure 1-3. Transport Capability of Copper/Water Axially-Grooved Heat Pipes at 120°C

Figure 1-4. Heat Transport of Copper/Water Axially-Grooved Heat Pipes vs. Temperature

1.4 Heat Pipe Fabrication Procedure

Copper tubing, alloy CDA 101 per ASTM B-170, which was cold forged to produce an optimized axially-grooved geometry, was fabricated into heat pipes in accordance with procedural requirements. The tubing was cut to specified lengths, identified and degreased by submersion in 1, 1, 1 trichloroethane. The interior surfaces of the tubing were first cleaned by passing a bore brush in and out of the tube followed by an abrasion treatment with a slurry mixture of aluminum oxide. The tubing was then submersed in a sodium cyanide solution, water rinsed and followed by an alcohol rinse. End-fittings chemically cleaned in sodium cyanide were welded to each end of each tube length followed by a vacuum stress relieving of the tube subassemblies. A hydrostatic pressure test was conducted on each tube subassembly to qualify each for pressure containment at the specified temperature requirement for radiator attachment by soldering. Seven-tube-lots of tube subassemblies were installed into a cleaning and coating station (paralleled into a manifold system) where a solution of sodium cyanide followed by water rinse could be flowed through the assemblies for cleaning the interior surfaces. Following cleaning, the tube subassemblies were coated internally with cupric oxide by a sodium hydroxide/hydrogen peroxide solution followed by water rinsing and drying with an inert gas. The subassemblies were removed from the station and the hole in the evaporator-end fittings were TIG seal welded. Each tube subassembly was then bent to the required configuration (90° bend) followed by a helium leak test to verify a leak rate of $\leq 10^{-8}$ std cc He/sec at a pressure of approximately 400 psia. Water charging of each tube subassembly

was charged with water in a charging station. The tube subassemblies were evacuated to $\leq 10^{-6}$ torr, charged with the calculated volume of water which had an electrical resistivity of ≥ 1.5 k ohm-cm, pinched-off at the condenser end-fitting, the pinched-off area cut and TIG seal welded, and the water charge verified gravimetrically.

1.4.1 Measured Heat Pipe Performance

The initial run for the production of axially-grooved copper tubing was performed in accordance with the design presented in Figure 1-5. This design corresponds to the nominal dimensions previously discussed for the 0.794 cm O.D. tubing. The larger diameter tubing which has the same internal geometry but a 0.2 cm wall thickness was also fabricated for use at high temperatures, e.g., up to 225°C for accelerated life tests. Actual groove dimensions were determined from cross-section of samples removed from each tube. Measurements were made from shadowgraphs magnified approximately 25 times. The average groove width measured was approximately 0.044 cm (0.0175 in.) with an average aspect ratio of 1.4. The theoretical performance of this tubing is approximately 10% less than the theoretical associated with the nominal design, Figure 1-5. This is directly attributed to the smaller groove area associated with its 1.4 aspect ratio versus the nominal 1.5. Figure 1-6 presents a comparison of measured heat transport data for heat pipe S/N AL-5 with theoretical predictions. This heat pipe was one of the first axially-grooved heat pipes fabricated under this program in August of 1976. It has a heavy wall for high temperature life tests. The transport data includes initial test measurement (pre-life test) and test measurements obtained during the course of life tests and at shutdown. All performance tests to obtain transport data were conducted at $90 \pm 10^\circ\text{C}$. As previously noted, this heat pipe has been operating at $200 \pm 10^\circ\text{C}$ for 13,310 hours.

The measured transport data shows that there are no significant differences between the least square extrapolation for the initial measurements and measured data obtained throughout the life tests. After 13,310 hours on life test, the measured data shows a 0-g transport of about 2800 W-inches which is approximately 10% lower than theoretical. The extrapolated static height is 0.94 inch which is approximately 8% lower than predicted. The lower measured value in heat transport is probably due to inaccuracies in the shadowgraph

Figure 1-5. SIG Axially-Grooved Copper Tubing

Figure 1-6. Heat Transport Performance of AL-5 ($90 \pm 5^\circ\text{C}$)

measurements which were made to obtain the groove characteristics used in predicting the theoretical transport capability. However, all of the data is within experimental error. The close agreement between the measured/extrapolated value and the predicted static wicking height indicates that a near perfect wetting is being attained.

1.5 Accelerated Life Testing at B&K Engineering, Inc.

Accelerated life testing of axially-grooved, copper/water heat pipes was initiated on November 12, 1976 with heat pipe S/N AL-5. On February 20, 1978, heat pipe S/N LT-57 was also placed on test. The test program consisted of operating the heat pipes continuously at $220 \pm 10^\circ\text{C}$ except when discontinued for periodic thermal performance and non-condensable gas testing. Performance tests were conducted at $90 \pm 10^\circ\text{C}$ to determine any degradation in the heat pipe's transport capability. Non-condensable gas tests were performed at low temperatures to determine if any non-condensable gas was being generated as a by-product of system incompatibility.

During the accelerated life tests, the heat pipes were operated with a 120 W throughput in a slight reflux mode with the condenser end raised approximately one inch above the evaporator end. The purpose of operation at 220°C was to accelerate any potential degradation mechanisms (e.g., corrosion). Thus, accelerated life test data could then be used to predict long term operation (up to seven years) at nominal SIG conditions (e.g., 125°C).

1.5.1 Low Temperature Gas Test Data

The low temperature test was conducted by cooling the heat pipe over the last 6 inches of its condenser end employing a saddle cooled by ice water at $5 \pm 3^\circ\text{C}$. A nominal 25 W heat load was applied to a saddle attached to the evaporator end which was oriented approximately one inch below the condenser end (positive tilt). The apparent non-condensable gas accumulation is presented in Figure 1-7 for S/N AL-5 and also LT-57. S/N LT-57 was one of sixty heat pipes that was fabricated under the Life Test Phase of the SIG Program (refer to Section 2.0). A total of 13,310 hours of operation at 220°C has been obtained for S/N AL-5 and 6,292 hours for S/N LT-57 through June 25, 1979.

The amount of non-condensable gas (n) present in the heat pipe was determined assuming "Sharp Front" Theory from the following equation:

$$n = \frac{(p_v - p_{v,s}) V}{R T_s} \quad (\text{kg - mole})$$

Figure 1-7. Accelerated Life Test Results (AL-5 & LT-57)

- where
- p_v = Saturated vapor pressure at the heat pipe vapor temperature (N/m^2)
 - $p_{v,s}$ = Saturated vapor pressure at the sink temperature T_s (N/m^2)
 - R = Gas Constant = 8310 ($\text{J/kg} - \text{mole} - ^\circ\text{K}$)
 - T_s = Sink temperature (inactive zone) ($^\circ\text{K}$)
 - V = Volume occupied by non-condensable gas (m^3)
 - $V = \frac{\pi}{4} D_v^2 L_{ic}$
 - D_v = Vapor core diameter $D_v = 0.564$ cm.
 - L_{ic} = Inactive condenser length which was estimated to be 13.3 cm.

There is an initial amount of non-condensable gas which is present in each pipe. The higher amount in AL-5 is probably due to improper evacuation of this pipe prior to charging. The amount of apparent gas tends to level off in each pipe after 250-500 hours of operation. This initial build-up has been attributed to adsorbed and absorbed air/argon, air being attributable to inadequate evacuation prior to water charging. The argon was used to deoxygenate the water prior to charging.

It should be noted that some initial quantity of gas in the heat pipes has been a normal occurrence and is attributed to the fabrication process.

The apparent non-condensable gas accumulation for AL-5 has varied between 2 and 3 $\times 10^{-8}$ lbm-mole over its entire life test period. At various times, the apparent amount of gas tends to increase. In all cases though, the measured amount of gas decreases after refurbishment of the low temperature saddle/heat pipe interface and reinstrumentation of thermocouples. Initially, evaporator and condenser saddles were clamped on with thermal grease applied at their interface. This interface tended to degrade with time and high temperature ($220 \pm 10^\circ\text{C}$). After approximately 9700 hours of life testing, brass saddles were soldered to

the heat pipes to negate interface degradation. However, as a result of different coefficients of expansion between the copper pipe and brass saddles, a fracture occurred at the interfaces which in turn showed an apparent increase in gas accumulation, refer to Figure 1-7. Initial data acquired in June 1979 for heat pipe S/N AL-5 showed that the apparent gas accumulation was back down to 2×10^{-8} lbm-mole after a copper saddle was soldered onto the pipe.

The data for S/N LT-57 however, showed an increasing trend in non-condensable gas accumulation even with a copper saddle attached. A comparison of the temperature profiles for the two pipes indicates that there is more gas in LT-57 than in AL-5. It has been judged that the apparent increase in gas content is due to a poor solder bond. This assumption is based upon visual inspection of the interface and problems incurred during soldering. It is also possible that additional outgassing took place due to over-temperaturing during the soldering cycle. A continuation of accelerated life testing for both pipes would establish that no gas was being generated as a result of corrosion.

1.5.2 Accelerated Life Test Data Summary

Table 1-2 presents a summary of all data obtained, including transport and thermal conductance data which is compared, where applicable, to theoretical predictions. Zero-elevation (0-g) heat transport and static wicking height values are based upon an extrapolation of the average of all data obtained. It should be noted that measured conductances, and film coefficients and gas blockage (non-condensable gas accumulation) values are highly sensitive to an interface degradation when being tested as previously discussed. On the basis of the data obtained for heat pipes S/Ns AL-5 and LT-57 throughout the accelerated life testing time frame, the following is concluded:

- (a) No apparent degradation in heat transport or static wicking height was noted.
- (b) Measured heat pipe conductances tend to be in good agreement with theory.

TABLE 1-2
ACCELERATED LIFE TEST PERFORMANCE SUMMARY

	Symbol	Units	LT-57		AL-5	
			Theor.	Meas.	Theor.	Meas.
Maximum 0-g Heat Transport @ 90°C	$(QL)_{\max}$	watt-in.	2521	2322	3143	2750
Static Wicking Height	h_s	in.	1.21	.84	1.05	.98
Total Heat Pipe Conductance	$Q/\Delta T$	watt/°C	23.8	27.4	23.8	21.0
Evaporator Conductance	$(Q/\Delta T)_E$	watt/°C	25.4	27.4	25.4	21.0
Condenser Conductance	$(Q/\Delta T)_c$	watt/°C	370.0	---	370.0	---
Evaporator Film Coefficient	h_E	BTU/HR-FT ² -°F	2170	2340	2170	1800
Condenser Film Coefficient	h_c	BTU/HR-FT ² -°F	6200	---	6200	---
Gas Blockage Volume @ 125°C	V	X10 ⁻⁴ liter	---	12.79	---	8.76
Inactive Condenser Length @ $T_v = 125^\circ\text{C}$	L_{CI}	X10 ⁻² M	---	5.18	---	3.55
Average Inactive Zone Temperature @ $T_v = 125^\circ\text{C}$	$\bar{T}_g$	°C	---	120°C	---	120°C
Accumulated lifetime @ 220 ± 10°C		Hrs.		6292		13310

- (c) Degradation of the saddle/heat pipe interface significantly affects the measured amount of non-condensable gas.
- (d) Based upon the amount of gas measured for LT-57, an inactive length of approximately 2 inches would exist with an average temperature in the inactive zone of 120°C. This applies for a condition where the heat pipe vapor temperature is at 125°C. As a result, an overall loss in the SIG/Galileo radiator's heat rejection capability would be less than 0.5%. This in turn would result in the cold junction temperature running approximately 1°C higher.

2.0 GROUND DEMONSTRATION SYSTEM (GDS)/HEAT PIPE LIFE TEST PROGRAM AT TES

2.1 Background

On January 1, 1976, Teledyne Energy Systems (TES), was contracted by the Department of Energy (DOE) to conduct a technology program to develop a high performance Radioisotopic Thermoelectric Generator (RTG). The objective of this program was to develop essential hardware components required to support the design and fabrication of a nominally 100-watt electrically heated thermoelectric generator. This Ground Demonstration System (GDS) required the use of a selenide thermopile to be furnished by the 3M Company under a separate DOE contract. This GDS design was to be representative of a flight design which was projected for delivery in the 1980 and 1981 time frame to meet with the requirements of the Galileo Mission, a Jupiter Orbiter/Probe spacecraft.

One of the components to be developed to meet the design requirements was a copper/water axially-grooved heat pipe heat-transfer system, to enhance the overall heat rejection capability of the radiative fins of the generator. Analysis had confirmed that the use of heat pipes for this system offered significant weight savings due to the reduction in the required radiative fin area and thermally conductive structure. The crucial problem to be resolved in the development of a copper/water heat pipe was long term (a minimum of seven year life) compatibility. Previous experience had shown that long term materials compatibility was a problem particularly when temperatures exceeded 150°C. Therefore, research and development activities were instituted which included the development of axially-grooved copper tubing and the continuation

of corrosion experiments to ascertain the fabrication requirements and techniques to achieve copper/water heat pipes having long term chemical compatibility and high temperature (up to 225° C) capability.

2.2 Fabrication of Life Test Heat Pipes

A total of sixty (60) axially-grooved heat pipes were fabricated for evaluation under the Life Test Program. All heat pipes were fabricated in accordance with the following documents:

LCP 10022, "Heat Pipe Fabrication Processing Requirements"

LCP 10023, "Heat Pipe Assembly Axially-Grooved Internally, Life Test"

Fifty (50) of these pipes were light wall LCP 10023-009 assemblies and the remaining ten (10) were heavy wall assemblies LCP 10023-019. All pipes were tested to demonstrate performance as specified in LCP 10021, "Heat Pipe Assembly, Axially-Grooved Performance Requirements."

With the exception of different diameters and wall thickness, both assemblies have identical L-shaped (90°) configurations. Each have a single evaporator and condenser section which is 3.5 inches and 28.37 inches long respectively. The effective length for each assembly is 17.51 inches. Quality assurance data and test results are presented in the following B&K Engineering reports submitted to TES:

BK033-1016 "Quality Assurance Data and Performance Test Results for SIG Life Test, -019 Heavy Wall Heat Pipe Assemblies"

BK033-1017 "Quality Assurance Data and Performance Results for SIG Life Test, -009 Light Wall Heat Pipe Assemblies"

Quality data for both assemblies includes shadowgraph measurements, check-off sheets, hydrostatic pressure test data, and fluid charge weight measurements. The tubing fabrication Run Nos. and the corresponding heat pipe Serial Nos. are listed in Table 2-1.

TABLE 2-1TUBING IDENTIFICATION FOR LIFE TEST HEAT PIPE ASSEMBLIES

<u>Tubing Run No.</u>	<u>Heat Pipe Serial No.</u>
<u>-009</u> 12-0-1	LT1, LT2
12-4-2	LT3
22-3-1	LT4
22-4-1	LT5
12-2-1	LT6
22-1-1	LT10, LT11, LT12, LT13
12-3-1	LT17, LT19
22-1-3	LT28, LT29, LT30
12-0-2	LT31, LT32, LT33, LT34
13-0-1	LT35, LT36, LT37
22-2-1	LT39, LT40, LT41, LT42
12-1-4	LT43, LT44, LT45
12-5-2	LT48
12-5-1	LT50, LT41, LT52, LT53A
Item 22 - Run 34	LT53B, LT55, LT46
Item 28 - Run 35	LT74
22-1-2	LT76, LT77, LT78
22-2-2	LT79, LT80, LT81, LT82
12-6-1	LT83, LT84, LT85
<u>-019</u> 22-2-3	LT61, LT62, LT64
22-0-3	LT65, LT66, LT67
22-0-1	LT68, LT69, LT70, LT71

2.2.1 LCP 10023-009 Life Test Heat Pipe Acceptance Test Data

A summary of the thermal performance which was demonstrated by acceptance testing is presented in Table 2-2 for the -009 assemblies. The maximum heat load that each pipe can transport was determined at 60° and 90°C. Heat pipe temperature drops were also measured at 120°C with a 120-watt heat load applied.

The maximum heat load at 90°C for most -009 assemblies was in the range of 100 to 130 watts which corresponds to an average heat transport capability of 2014 W-inches. This transport capability will increase by 25% and 49% at operating temperatures of 105°C and 120°C, respectively. The maximum heat load measured at three elevations is shown in Figure 2-1 for Serial No. LT83. This data extrapolates to a 1.1 in. static height for the 90°C operating temperature and indicates near perfect wetting (i.e., 0° contact angle). Static wicking height data for a total of sixteen (16) heat pipes is also listed in Table 2-2. Values range from 1.0 inch to 1.3 inches.

TABLE 2-2. PERFORMANCE DATA SUMMARY FOR LCP 10023-009 LIFE TEST HEAT PIPES

LT	AREA (in ²)	60°C				90°C				120°C	h (in)
		Q _{TH} (watts)	Q _{TEST} (watts)	% Q _{TH}	ΔT _a @60W (°C)	Q _{TH} (watts)	Q _{TEST} (watts)	% Q _{TH}	ΔT _a @60W (°C)	ΔT _a @120W (°C)	
1	.0103	98	75-85	85-97	3.5	169	140-155	83-92	2.7	7.2	1.21
2	.0108	88	75-85	85-97	4.9	169	130-140	77-83	2.0	9.0	
3	.0098	86	75-85	87-99	3.5	163	130-135	81-84	2.0	7.2	
4	.0110	82	75-85	97-104	2.7	161	130-140	81-87	3.2	7.3	
5	.0116	97	75-85	86-98	2.2	174	140-150	80-86	1.2	3.6	
6	.0104	99	75-85	84-96	3.7	163	130-140	77-83	2.5	7.1	1.02
10	.0110	73	75-85	96-109	3.9	154	140-145	91-94	2.0	8.5	
11	.0110	78	70-75	90-96	5.2	154	120-130	78-84	3.4	8.4	
12	.0110	78	75-85	96-109	4.3	154	135-140	83-91	2.7	8.2	
13	.0110	78	75-85	96-109	4.5	154	130-140	84-91	1.6	7.1	
17	.0105	90	60-70	67-78	3.2	171	100-110	59-64	2.9	9.2	1.00
19	.0105	90	60-70	67-78	4.6	171	100-110	59-64	3.0		
22	.0099	65	75-85	115-130	4.4	126	130-135	103-107	2.0	7.4	
23	.0099	65	75-85	115-130	6.2	126	130-135	103-107	3.8	9.5	
35	.0106	95	65-75	65-79	3.2	180	135-145	75-81	1.5	6.8	
36	.0106	95	75-80	79-84	4.6	180	135-140	75-78	2.0	7.9	1.14
37	.0106	95	70-75	74-79	5.1	180	130-135	72-75	1.8	6.4	
40	.00926	66	40-50	61-76	D/O	127	100-110	78-87	2.9	10.8	
45	.0101	85	75-85	83-100	3.9	161	130-140	81-87	2.8	7.3	
43	.0086	64	70-75	109-117	4.4	120	110-120	92-100	3.0	8.2	
52	.0084	63	60-65	95-103	6.8	118	100-110	85-93	3.7	12.5	1.22
53A	.0084	63	40-50	63-79	D/O	118	80-100	63-85	2.4	10.0	
53B	.0107	49	60-65	125-135	6.1	102	100-110	98-108	2.0	11.2	
55	.0107	48	30-40	62-83	D/O	102	70-80	69-78	7.0		
56	.0107	48	50-60	104-125	D/O	102	85-100	83-93	4.8	12.6	
74	.0082	51	50-60	98-118	D/O	96	80-100	83-104	3.1	13.3	1.1
76	.0103	75	75-85	100-113	4.4	145	120-130	83-90	2.6	7.6	
77	.0103	75	70-75	93-100	3.4	145	130-140	90-97	1.2	6.9	
78	.0103	75	70-75	93-100	3.1	145	130-140	90-97	0.9	7.1	
79	.0093	68	70-75	103-110	6.5	130	110-120	85-92	3.2	11.2	
80	.0093	68	60-70	88-103	4.5	130	110-120	85-92	2.2	9.1	1.1
81	.0093	68	60-70	88-103	5.9	130	110-120	85-92	3.5	10.1	
82	.0093	68	60-70	88-103	5.8	130	110-120	85-92	3.5	11.1	
83	.0091	66	70-75	106-114	4.0	127	120-130	94-102	3.4	9.4	
84	.0091	66	70-75	106-114	4.7	127	120-130	94-102	2.4	9.7	
85	.0091	66	80-90	121-136	3.6	127	130-140	102-110	2.1	7.4	

TABLE 2-2. PERFORMANCE DATA SUMMARY FOR LCP 10023-009 LIFE TEST HEAT PIPES (Continued)

SN #	AREA (in ²)	60°C				90°C				120°C	h (in.)
		Q _{TH} (watts)	Q _{TEST} (watts)	% Q _{TH}	ΔT_a @ 60W (°C)	Q _{TH} (watts)	Q _{TEST} (watts)	% Q _{TH}	ΔT_a @ 60W (°C)	ΔT_a @ 120W (°C)	
28	.0095	71	65-75	92-106	4.0 ⁺	134	110-120	82-90	3.0 ⁺⁺	7.1	1.15
29	.0095	71	60-75	85-106	7.5	134	110-120	82-90	2.9	9.4	1.11
30	.0095	71	60-75	85-106	3.8	134	120-130	90-97	2.9	8.4	1.18
31	.0089	73	65-75	89-103	4.3 ⁺	135	100-110	74-81	2.6 ⁺⁺	7.9	1.08
32	.0089	73	60-75	82-103	4.7	135	100-110	74-81	3.5	10.6	1.30
33	.0089	73	60-65	82-89	4.7	135	105-110	77-81	3.1	9.4	1.11
34	.0089	73	75-85	103-116	4.3	135	100-110	74-81	3.6	8.6	1.29
39	.00926	66	65-75	95-114	4.9 ⁺	127	100-110	79-87	3.9 ⁺⁺	8.8	1.16
41	.00926	66	65-75	98-114	5.4 ⁺	127	105-110	83-87	5.0 ⁺⁺	10.5	1.24
42	.00926	66	60-70	91-106	5.8	127	100-110	79-87	2.0	11.0	
43	.0101	85	80-85	94-100	3.7 ⁺	161	130-140	81-87	2.2 ⁺⁺	1.2	1.18
44	.0101	85	75-80	88-94	3.5	161	120-130	75-81	1.9	7.5	
50	.0084	63	60-70	95-111	6.1	118	100-110	85-93	5.0	14.3	
51	.0084	63	60-70	95-111	5.4	118	100-110	85-93	4.4	13.3	

* Heat loads (Q_{TEST}) were applied with the evaporator 0.156-in. above the condenser end.

These Heat Pipes were provided for attachment to the Life Test Radiator Fin.

Q_{TH} is the maximum theoretical heat load that the pipe can transport at the 0.156-in. evaporator elevation.

D-O = Heat pipe "dry-out", ΔT_a = Temperature drop across the active portion of the heat pipe.

+ ΔT_a @ 65W

++ ΔT_a @ 70W

Figure 2-1. Maximum Heat Load Versus Evaporator Elevation

2.2.2 LCP 10023-019 Life Test Heat Pipe Acceptance Test Data

A summary of the thermal performance which was demonstrated by acceptance testing is presented in Table 2-3 for the -019 assemblies. The maximum heat load that each pipe can transport was determined at 60° and 90°C. Heat pipe temperature drops were also measured at 230°C with a 120-watt heat load applied. Again, the maximum heat load at 90°C was in the range of 100-130 watts. The temperature drop at 230°C was between 5.1° and 8.2°C with the 120-W heat load input.

TABLE 2-3. ACCEPTANCE TEST DATA SUMMARY FOR LCP 10023-019 HEAT PIPES*

SN	AREA (in ²)	90°C				60°C				230°C
		Q _{TH} (watts)	Q _{TEST} (watts)	% Q _{TH}	ΔT_a @ 60-W (°C)	Q _{TH} (watts)	Q _{TEST} (watts)	% Q _{TH}	ΔT_a @ 60-W (°C)	ΔT_a @ 120-W (°C)
61	.009	128	110-120	86-94	1.5	67	70-75	89-96	2.0	5.6
62	.009	128	100-120	78-94	2.7	67	60-70	96-111	2.3	5.8
64	.009	128	110-120	86-94	2.3	67	70-75	89-96	2.0	6.4
65	.0088	112	120-130	107-116	2.1	60	75-80	125-133	2.6	5.1
66	.0088	112	110-120	98-107	2.5	60	60-70	100-116	4.2	6.8
67	.0088	112	110-110	89-98	2.1	60	60-70	100-116	5.1	8.0
68	.0087	112	120-130	107-116	3.0	60	60-65	100-108	3.9	5.6
69	.0087	112	105-115	94-103	3.1	60	65-75	108-125	6.6	7.4
70	.0087	112	100-110	89-98	2.6	60	60-70	100-117	3.8	8.2
71	.0087	112	120-130	107-116	2.6	60	50-60	83-100	DO	7.3

* Heat Loads (Q_{TEST}) were applied with the evaporator 0.156-in. above the condenser end.

Q_{TH} is the maximum theoretical heat load that the pipe can transport at the 0.156-in. evaporator elevation

DO = Heat pipe "dry-out", ΔT_a = Temperature drop across the active portion of the heat pipe.

2.2.3 Axially-Grooved Heat Pipe (LCP 10023) Life Test Data Summary

This section presents the results determined from an analysis of the thermal data obtained for the axially-grooved heat pipes which were placed on life test. A total of forty-nine (49) -009 assemblies and eight (8) -019 assemblies were tested. Life test conditions and the allocation of the heat pipes are defined in Table 2-4. All thermal tests were conducted in accordance with LCP 10069, "Heat Pipe Life Test Procedure ". The variation of the evaporator (ΔT_E) and total heat pipe temperature drop ($\Delta T_{max.}$) were measured as a function of the operating time. Also, low temperature gas tests were performed and the results were analyzed to predict any non-condensable gas accumulation in the heat pipes. Both sets of data give information related to the possible degradation in the heat transfer characteristics of the pipes. It should be noted that interface degradation between the saddles and the heat pipes utilizing thermal grease was also observed for these tests and the data is questionable. There was also insufficient test data to evaluate the behavior of the heat pipes' transport capability with time. Refer to Reference 5 for results of accelerated life testing at TES.

2.2.4 Axially-Grooved Heat Pipe Life Test Temperature Drop

An analysis for the heat transfer data obtained for the axially-grooved heat pipe assemblies which were placed on life test is presented in References 6 and 7. The heat transfer data was obtained by measuring the evaporator temperature drop, ΔT_E (T/C 1 - T/C 5) and the overall heat pipe temperature drop ΔT_{max} (T/C 1 - T/C 8) versus the operating time. All heat pipes were operated with a nominal 120 watts applied and with the condenser end approximately one-inch above the evaporator end. The operational times varied from one to seven thousand hours depending on when the pipes were placed on test. Figure 2-2 presents an example of ΔT_E and ΔT_{max} versus time for 66% of the 57 heat pipes on life test. The increase in ΔT_E and ΔT_{max} tends to be linear and in a range from 1° to 8°F (average 3.2°F) from their initial values. The remainder of the pipes showed a

TABLE 2-4. AXIALLY-GROOVED HEAT PIPE LIFE TEST CONDITIONS

<u>Fixture No.</u>	<u>Heat Pipe Assembly</u>	<u>Test Temp. (°C)</u>	<u>Heat Pipe Serial Nos. * LT-</u>	<u>Total Pipes</u>
1	-009	125	79, 45, 12, 77, 53B, 48, 80, 17, 84, 40, 35, 55	12
**2	-009	165	3, 4, 78, 11, 82, 37, 83, 5, 23, 81, 10/(50), 85	13
**3	-009	185	52, 74, 19/(1), 2, 76/(22), 36, 56, 53A, 6, 13	12
4	-019	225	65, 71, 70, 69, 68, 67, 66, 64	8
5	-009	125	29, 31, 33, 28, 39, 43, 34, 32, 42, 41, 44, 30	12

*Heat Pipe Serial Numbers are listed in the order of their fixture location. LT-79 is at location no. 1 and LT-48 is at location no. 6 for example.

** Heat Pipe Serial Numbers in parenthesis, i. e., (50), (1), and (22) replace S/Ns 10, 19 and 76 respectively.

Figure 2-2. Heat Pipe Temperature Drops Versus Operating Time

temperature drop which either decreased with time or remained nearly constant. The decrease in ΔT_E and ΔT_{max} cannot be explained at this time due to a lack of sufficient data. The rise in temperature is generally due to an increase in the evaporator temperature, T_E (T/C 1) and implies a deterioration of the internal film coefficient in the evaporator section. Destructive tests of some of the heat pipes did show an accumulation of particulate matter in the evaporator end. This material was analyzed and identified as CuO and Cu_xO_y . Therefore, it is possible that this accumulation of oxides could be causing the reduction in the film coefficient.

It should be pointed out that three of the -009 assemblies, Serial Numbers LT11, LT19 and LT23 were determined to have failed after several hundred hours on life test. The failures were concluded to have been due to externally induced penetrations of the evaporator walls. Refer to Section 2.3 and the "Heat Pipe Failure Evaluation Report", (Reference 8).

2.2.5 Low Temperature Life Test Data Analysis

The predicted amount of non-condensable gas accumulation is plotted versus time for 53 of the 57 axially grooved heat pipes that are on life test at TES in Figures 2-3 through 2-7. The amount of gas (n) present in the heat pipe has been determined assuming "Sharp Front" Theory from the following equation:

$$n = \frac{(p_v - p_{v,s}) V}{R T_s} \quad (\text{kg-mole})$$

where

- p_v = saturated vapor pressure at the heat pipe vapor temperature (N/m^2)
- $p_{v,s}$ = saturated vapor pressure at the sink temperature T_s (N/m^2)
- R = Gas Constant = $8310 \text{ (J/kg-mole-}^\circ\text{K)}$
- T_s = Sink temperature (inactive zone) ($^\circ\text{K}$)
- V = Volume occupied by non-condensable gas (m^3)
- $V = \frac{\pi}{4} D_v^2 L_{ic}$
- D_v = Vapor core diameter $D_v = 0.564 \text{ cm.}$
- L_{ic} = Inactive condenser length which was estimated to be 13.3 cm

Also shown in the Figures 2-3 through 2-7 is the molar gas content calculated by the TES computer program. B&K's calculations which are based upon the same temperature measurements obtained by TES are in general, 10-15% less than the apparent gas content determined by TES. These differences are not significant and are due primarily to the different methods used to calculate the saturated vapor pressure.

125°C LIFE TEST TEMPERATURE

Figure 2-3. Accelerated Life Test Results of Heat Pipes on Fixture #1

Figure 2-4. Accelerated Life Test Results of Heat Pipes on Fixture #2

Figure 2-5. Accelerated Life Test Results of Heat Pipes on Fixture #3

Figure 2-6. Accelerated Life Test Results of Heat Pipes on Fixture #4

Figure 2-7. Accelerated Life Test Results of Heat Pipes on Fixture #5

The amount of non-condensable gas accumulation in the life test heat pipes is in the range of 1 to 3×10^{-8} lbm-moles. This is in good agreement with results presented in Figure 1-7 for the accelerated life tests that have been conducted by B&K Engineering. In particular, Serial No. AL-5 has only shown a non-condensable gas accumulation of approximately 2.0×10^{-8} lbm-mole after more than 13,000 hours at 225°C. Also, S/N LT-57 which was fabricated along with the life test heat pipes showed non-condensable gas accumulation of approximately 3×10^{-8} lbm-moles after more than 6,200 hours at 225°C. Although there are relatively few data points for the TES life test heat pipes, it can be concluded that the amount of gas accumulation tends to level off after one to two thousand hours of life testing. The results presented for AL-5 and LT-57 show a leveling off after the first 500 hours. This initial gas buildup has been attributed to outgassing of non-condensable gases from the internals of the heat pipe.

The life test conditions consisted of operation at four different temperatures (125°, 165°, 185° and 225°C) to determine the effect of elevated temperature on the long term (up to seven (7) years) performance of the heat pipes. A comparison of the results presented in Figures 2-3 through 2-7 shows that the non-condensable gas accumulation is generally lower for heat pipes operating at 125°C and is approximately 2 to 3×10^{-8} lbm-moles after 4000 hours of operation. This gas buildup appears to level off after approximately 1800 hours of operation at 125°C. It has been judged that a longer time period is required for outgassing due to operation at a lower life test temperature (125°C) versus the 225°C operating temperature for AL-5 and LT-57 that were accelerated life tested at B&K Engineering.

The amount of non-condensable gas accumulation for the 165° and 185°C life test temperatures is slightly higher and is approximately 3×10^{-8} lbm-moles for most pipes. The data at these temperatures is more limited but the non-condensable gas accumulation tends to level off between 1000 and 2000 hours of operation.

Results in Figure 2-6 show that the non-condensable gas accumulation is greater for the -019 assemblies which were operated at 225°C. It is impossible to determine whether the non-condensable gas accumulation has ceased since there are only two data points to be evaluated. Five of the seven -019 assemblies do however, show a gas accumulation which is greater than 3.5×10^{-8} lbm-mole. This is higher than the amounts observed in LT57 and AL-5. The data for these life test pipes is also too limited to make any absolute judgements and it is therefore important to obtain additional data points to establish their long term behavior. In addition, the test fixture interface must be either refurbished or redesigned to secure reliable data. An improvement in the thermal performance of both heat pipes S/Ns AL-5 and LT-57 was observed at B&K Engineering after the test fixtures were refurbished. The final conclusion is that these heat pipes have the same transport capability and thermal conductance today as when they were first placed on accelerated life test.

2.3 Heat Pipe Failure Analyses

2.3.1 Background

During the period of October 30 through November 18, 1978, three (3) TES/B&K heat pipes failed during life testing. The first heat pipe to fail, LT-23, was exhibiting poor thermal performance during life testing at 328°F on October 30. A burnout test on this heat pipe indicated that it could only transport 30 watts at a positive 0.75 inch elevation. As the pipe was removed from Fixture #2 for examination, a hissing sound was detected coming from the evaporator end of the pipe. A perforation of the heat pipe wall was obvious upon closer examination.

Because of the failure of LT-23, all the remaining heat pipes were removed from test on November 6 for radiography. During a Quality Control visual inspection of these pipes, water was found to be leaking out of pipe LT-19. A closer examination revealed a perforation of the pipe wall in the evaporator end similar to that found in pipe LT-23. There had been no indication of performance degradation in pipe LT-19 during the period preceding its removal from test.

The results from the heat pipe radiographs indicated a problem with pipe LT-11. A closer examination of LT-11 revealed a perforation of the pipe wall again in the evaporator end. This perforation was not detected during the Quality Control visual examination that preceded the radiography. Recent life testing data on LT-11 did indicate a slight increase in the quantity of non-condensable gas, however, the pipe still appeared to be performing.

All three (3) heat pipe failures have been characterized by perforation(s) of the pipe wall in the evaporator section in the vicinity of the aluminum heater block/thermal grease/heat pipe interface. Initial investigations into the background of these pipes revealed that all three (3) heat pipes were from a lot of pipes which had been accidentally contaminated during the fabrication process and had been reworked. The heat pipe contamination is believed

to have occurred during the charging operation when the high vacuum atmosphere of the charge manifold was exposed directly to the low pressure of a mechanical vacuum pump. Backstreaming of the oil from the mechanical pump into the charge manifold resulted and the heat pipes on the charging manifold at that time were exposed to the pump oil. The mechanical vacuum pump had previously been used with Dowtherm A (diphenyl and diphenyl oxide) and the pungent odor associated with it was detected in the charge station. These heat pipes were ultimately reworked to eliminate the contamination problem. The following heat pipes were contaminated, reworked and delivered to TES:

LT-2	} Lot No. 16	LT-17	} Lot No. 17	LT-1	} Lot No. 18
LT-9		LT-18		LT-3	
LT-5		LT-19		LT-10	
LT-6		LT-20		LT-12	
LT-11			LT-22		
LT-13			LT-23		

2.3.2 Failure Analysis Plan

A failure analysis plan for the B&K heat pipes was initiated outlining a systematic plan for the determination of the origin and cause. The plan included parallel analytical efforts by Packer Engineering Associates, Inc., Structure Probe, Inc., and in-house TES evaluations. On November 9, 1978, failed heat pipe LT-19 was forwarded to Structure Probe, Inc., located in Metuchen, New Jersey, for analysis of the interior and exterior surfaces of the pipe and an examination of the corrosion mode utilizing Scanning Electron Microscopy (SEM) and Energy-Dispersive Electron Probe Microanalysis (EDX) techniques.

On November 15, ten (10) B&K heat pipes (including failed heat pipes LT-11 and LT-23) were forwarded to Packer Engineering Associates, Inc., located in Naperville, Illinois, for failure analysis. Of the group of ten heat pipes to be analyzed: two (2) were failed, LT-11 and LT-23; two (2) were contaminated/reworked/life tested, LT-5 and LT-10; three (3) were contaminated/reworked/not life tested, LT-18, LT-14 and LT-21; and three (3) were non-contaminated/life tested, LT-45, LT-76 and LT-78. Packer Engineering was to

perform a complete failure analysis on both failed pipes and a thorough analysis (including gas analysis and water analysis) on the other eight (8) heat pipes. Under the direction of Dr. John Slater, formerly of Battelle Columbus Laboratories, Packer Engineering was to identify the cause of failure in LT-11 and LT-23 and to determine whether incipient failure may be present in the other pipes.

On November 15, TES began its own in-house evaluation of the heat pipe problem with emphasis placed on determining the operational status of the remaining heat pipes. Several B&K heat pipes were retested to determine if a performance degradation trend could be detected. Also three (3) heat pipes LT-17, LT-77 and LT-82 were cut open to examine the condition of the interior of the heat pipes.

2.3.3 TES Failure Evaluation

The in-house TES investigations centered on determining the mechanism for corrosion of the heat pipe wall from the outside in. Quality Control visual examinations of the life tested heat pipes revealed a consistent trend in the condition of the exterior of the heat pipes in the evaporator section. Pitting of the exterior of the heat pipe was observed for almost every heat pipe examined. The pitting was most prominent in the evaporator section with the deeper pits located just adjacent to the weld zone of the end cap/tube weld. In several cases, round crystalline beads were found embedded into the exterior of the pipe. Many of the pits could be characterized as rounded-bottom indentations (or craters) which were probably caused by the crystalline beads. Investigations revealed that the crystalline beads were present in the rock wool type insulation (Johns Manville Cera-Form Type CF-13186) used to insulate the heat pipe test fixtures. These beads, which are readily dislodged from insulation itself, have been found universally throughout the heat pipe testing area. It is believed that the crystalline beads (most likely silica) become mixed in with the Dow Corning Thermal Grease (Compound No. 342) and are then spread on with the grease into the saddle areas of the heat pipe fixtures. When the heat pipe is mounted into the saddles and clamped firmly into place with the keeper bars, the beads are embedded into the wall of the copper heat pipe. Microhardness tests of

the exterior of the heat pipes indicates that the copper tubing is in the full-annealed condition. With only a modest amount of clamping force, the hard crystalline beads could very easily be embedded into the pipe surface. Measurements of random crystalline bead sizes show that beads exist in the insulation of a diameter equal to and greater than the present heat pipe wall thickness. Although the majority of the beads in the insulation are oval, there are also large sharp-pointed crystalline fragments present. If some large beads were to be trapped between the 6061-T6 aluminum alloy heater saddle and the copper heat pipe, the clamping force would be sufficient to cause very deep penetrations into the heat pipe wall. The heat affected weld zone is considered extremely vulnerable to such a penetration. Even if the bead did not penetrate the wall completely, the locally reduced wall could have been unable to withstand the vapor pressure of the operating heat pipe. Discussions with the insulation manufacturer and the thermal grease manufacturer did not reveal any ingredients which would be corrosive to the copper heat pipe. Therefore, crevice corrosion initiated in the bead indentations must be ruled out as a corrosion mechanism.

Another phase of the TES in-house investigation involved the metallographic examination of three (3) life tested heat pipes. Heat pipe LT-17 (contaminated and reworked), and heat pipes LT-77 and LT-82 (both non-contaminated) were destructively examined. Special emphasis was placed on comparing the condition of the cupric oxide existing in each pipe. In the evaporator of each pipe, the oxide coating was found to be changing from the velvety black condition to a rough textured red oxide condition. The structure of the red oxide can best be characterized as clumps of red flowers growing out of the land portion of the heat pipe groove geometry. Very little of the red oxide was found growing in the bottom of the heat pipe grooves. The black oxide coating was nearly completely gone in the condenser section of all three pipes. Aside from the change in the condition of the oxide coating, no evidence was found of internal corrosion.

2.3.4 Structure Probe Failure Evaluation

On December 19, 1978, the written report summarizing the results of the failure analysis conducted by Structure Probe, Inc., was received. Technical Report W0043, Metallurgical Failure Analysis of Heat Pipe LT-19; discusses the findings and conclusions reached as the result of examinations of the interior and exterior of the heat pipe and metallographic sections through the failure region. The following conclusions are drawn from the report:

- The failure mechanism was not identified.
- Chemical analysis of areas surrounding the corrosion site (s) was purely qualitative in nature without being able to identify specific chemical compounds. The finding of elements such as Fe, Cu, Zn and Al in and around the corrosion site(s) does not confirm either an internal or external corrosion reaction mechanism.
- The metallurgical presentation of a transverse section through one (1) of the four (4) perforations in the evaporator region suggests internal corrosion but does not eliminate the possibility of a contaminant being introduced from external sources via one of the other three (3) perforations.
- The opinion expressed by Dr. Stephen Duerr, Technical Director of Structure Probe, Inc., was that the corrosion was initiated internally. However, he made no attempt to suggest a potential chemical reaction to cause corrosion of copper based on his qualitative chemical findings.
- A qualitative chemical analysis of the Dow Corning Heat Transfer Compound #342 revealed the presence of Si, Zn, Fe, Ni and Cu, none of which confirm a reaction mechanism to corrode copper. Many crystalline bead type particles were observed in the thermal grease which is consistent with the TES findings.

2.3.5 Packer Engineering Failure Evaluation

On December 28, 1978, a summary of the findings of the failure analysis on heat pipes LT-11, LT-23, LT-5, LT-10, LT-18, LT-14, LT-21, LT-45, LT-76 and LT-78 were received by TES. The results of the analysis are divided into three (3) categories:

1. Corrosion observations
2. Coating observations
3. Contaminant observations.

The only heat pipes which showed any evidence of corrosion were the failed pipes LT-11 and LT-23. Both of these showed significant internal corrosion and LT-23 had a chloride-rich corrosion product on the inside and outside surfaces. Careful inspection of all other heat pipes revealed no other corrosion problems.

The examination of LT-11 and LT-23 showed extensive corrosion of the internal surface at the evaporator end. For LT-11, this was associated with a build-up of oxide at this location, while for LT-23, a chloride-containing compound was present on the interior and exterior surface. Both pipes showed perforation to the outside surface in the form of pitting at this location.

While it is tempting to state categorically that penetration was "outside-in" or "inside-out", the available data do not allow a definitive conclusion to be reached in this point. Thus, while extensive corrosion occurred on the inside of LT-11 and LT-23, this could have transpired following penetration from the outside (inlet of oxygen, moisture, grease and other contaminants). The micrographs obtained do not shed light on this situation either, because although the pitting leading to penetration is clear, the direction of penetration cannot be ascertained.

It is instructive to consider factors possibly affecting corrosion from the exterior. Chloride will corrode copper when present in substantial amounts. Such amounts were present

on the inside and outside of LT-23, but, not on LT-11. Contact with other materials, such as aluminum, generally protects copper from corrosion because of galvanic effects. Impurities in the heat transfer grease may cause corrosion. However, it is to be noted that no signs of exterior corrosion were noted on any heat pipes other than LT-23 and LT-11. Should corrosion have been "outside-in", it is probable that such signs would have been evident. Differences in treatment etc., may give such effects (e.g., inadequate rinsing after cleaning, breakdown of traces of Cl-containing hydrocarbons, etc.), but the statistical likelihood is against such observations.

The levels of Cl^- in charge-water found in the present study give some cause for concern as to the adequacy of water preparation and/or rinsing techniques following coating. However, they would not be expected to create problems as far as corrosion per se is concerned. Of course, an unknown exists here as to the effect of the evaporative process on concentrating chloride, but a 10:1 concentration ratio in the absence of oxygen, at the pH levels of the water as analyzed, would not be expected to be potentially corrosive. Should levels of oxygen in the pipe have been high, then some pitting could have occurred initially before the oxygen was used up. However, this again should be self-limiting.

It is again noticeable that no corrosion on the internal surface was evident on any pipes but LT-11 and LT-23. If the chloride level was a factor, corrosion may have been expected to have initiated in other pipes but to have self-limited. No such observation was noted.

This discussion leads to the conclusion that there is insufficient evidence to identify the mechanism of corrosion precisely. To obviate potential corrosion in future pipes on life test, and indeed on space missions, care needs to be taken to reduce Cl^- levels to the lowest possible levels by reconsidering water purification, chemical selection and post-coating rinsing techniques. Oxygen level in the charge water should also be measured.

The CuO coating was intact on all pies which had not been life-tested (LT-14, LT-21, and LT-18). At the other end of the scale, pipes LT-76 and LT-78 showed an apparent destruction of the oxide over the majority of the inside surface of the heat pipe. LT-5, LT-10 and LT-45 showed a purpling of the originally black oxide with some apparent destruction at either the condenser and/or the evaporator ends. For the failed pipes LT-11 and LT-23, visual appearance gave a matte black oxide, but severe crystallinity was observed. X-ray diffraction analysis on the heat-pipe coating originally identified only CuO. A check analysis on LT-11 and LT-10 using a diffractometer technique showed CuO and Cu₂O.

The CuO coating laid down on the internal surface of the heat pipe is present to aid in wetting. The known instability of this coating at elevated temperatures was considered in a contract at BCL by TES. Briefly, this program showed that in the absence of Cl⁻ and at low oxygen levels, the coating was relatively stable, but that some degradation occurred even so. The degradation, however, did not appear to be detrimental to wetting; in view of this, the coating was specified but was laid down in a manner so as to obviate the presence of chloride in the heat pipe from reaction products of the coating process.

The degradation process appears to result from the following reaction between the CuO and the base Cu:

Based on previous work, the driving potentials for this reaction are:

at 25°C: 0.198V

at 100°C: 0.201V

at 200°C: 0.240V.

Thus, the thermodynamic driving force increases somewhat with increasing temperature; however, the reaction kinetics probably overwhelm this effect.

This degradation thus results in the consumption of some copper and all the CuO to form Cu₂O. It is unlikely that the Cu₂O would have the same morphology and therefore, wetting characteristics as the CuO; it is also possible that the "finishing" action of the water in the heat pipe may lead to an accumulation of the Cu₂O close to the evaporator end.

The degradation phenomenon will be hastened by higher temperatures due to kinetic effects, and the presence of chloride in the water will increase the conductivity and thereby increase the reaction velocity (since ion transport through the water is necessary for the reaction to take place). In high concentrations of chloride, a further reaction becomes possible:

or in total : $\text{Cu} + \text{CuO} + 2\text{H}^+ + 4\text{Cl}^- = 2\text{CuCl}_2^- + \text{H}_2\text{O}$.

This reaction is pH-dependent, and will occur readily only in acid solutions containing relatively large quantities of chloride. In any case, the reaction will again be self-limiting due to the limited availability of chloride ion.

Some comment has been made as to the possible presence of iron in the heat pipe and its effect on the possible corrosion process. Iron is unstable in water, forming oxides which are quite insoluble particularly in the presence of oxygen.

In the opinion of Dr. John Slater, if elemental iron did get into the heat pipe and remained elemental until it reached the Cu surface, then reduction of CuO to Cu could occur. No corrosion of the copper would occur, however. The presence of Fe₂O₃ in the heat pipe would not give any reaction with the copper because of its generally low solubility in neutral water. Refer to Reference 9.

In summary, degradation of the coating is a known factor and was considered previously, It will be accelerated by the presence of Cl⁻ and high temperatures. Nevertheless, no significant corrosion of the heat pipe envelope is expected as a result of this degradation process.

Gas analysis from the intact heat pipes showed that very little, if any, hydrogen was present. The major constituent (aside from water) of the gas analyzed was CO_2 . The water analysis showed significant quantities of chloride, reaching more than 300 ppm in one instance (LT-5). Little iron was noted. The pH was exceptionally high (>11) in LT-45. EDAX analysis of the interior and exterior surfaces of all heat pipes which had not failed showed:

- a) Only Cu, Al (possibly from trace Al_2O_3) and Si was observed on any internal surface (except for LT-23).
- b) On external surfaces, Cl^- was observed on LT-23, LT-21, and LT-10 (latter two in trace amounts only) with Si being seen on most other pipes (probably from the heat-transfer grease) and occasionally Zn (from the same source).

2.4 Non-destructive and Destructive Analysis of TES/B&K Life Test Heat Pipes

X-ray examination of all heat pipes to be subjected to destructive analysis revealed no evidence of internal or external corrosion. Two of the sixty (60) as-fabricated heat pipes S/N's LT-51 and LT-62 underwent destructive testing to analyze the residual gas, the charge water, the as-deposited internal coating, and the tube material used in each assembly. The results of the gas analysis by mass spectrometric techniques showed that the amounts of non-condensable gas in the heat pipes were in the micro-millimole range. Table 2-5 summarizes this data. Analysis of the charge water extracted from each heat pipe is given in Table 2-6. The chloride level for heat pipe S/N LT-51 was not determined due to loss of sample volume. Analysis of water from the charging system showed a chloride level higher than the water from heat pipe, S/N LT-62. This water was not analyzed at the same time as the charge water extracted from heat pipes, S/N's LT-51 and LT-62. The same amperometric equipment was employed in both analyses but reasons for the differences are speculative. Results of this water analysis are also shown in Table 2-6. The cupric oxide (CuO) coated surface structure as viewed by the scanning electron microscope (SEM), showed a very fine needle-like structure. An Electron Dispersion X-ray (EDAX) scan of the coating showed peaks of copper (K_{α} and K_{β}) only. X-ray diffraction showed that the coating consisted of Cu_2O and CuO. Metallographic

Table 2-5. Analysis of Gas Extracted from Heat Pipes

Heat Pipe Serial No. (S/N)	Millimoles of Gas in Heat Pipes ($\times 10^6$)					
	<u>H₂</u>	<u>N₂</u>	<u>O₂</u>	<u>CO₂</u>	<u>A</u>	<u>CH₄</u>
LT-51-1*	3	24	7	3	4	---
LT-51-2*	11	74	17	8	5	<1
LT-62-1	68	29	5	1370	<3	3
LT-62-2	14	76	33	21	2	1
LT-45-1	65	310	110	66	9	15
LT-45-2	0.37	1.8	0.65	0.38	0.05	0.08
LT-76-1	< 5.1	260	170	600	5.1	< 5.1
LT-76-2	< 5.1	125	78	450	5.1	< 5.1
LT-78-1	< 3.5	96	46	450	< 3.5	< 3.1
LT-78-2	< 5.1	48	16	88	10	< 5.1

*A-1 and -2 denotes first and second gas samples extracted.

Table 2-6. Analysis of Charge Water Extracted from Heat Pipes

Heat Pipe Serial No. (S/N)	ppm						
	<u>pH</u>	<u>K⁺</u>	<u>Cl⁻</u>	<u>Mn²⁺</u>	<u>Cu²⁺</u>	<u>Total Cu*</u>	<u>Total Fe**</u>
LT-51	~ 8	0.93	N/D	0.003	1.04	N/D	N/D
LT-62	7.09	0.54	9.0	0.07	1.03	N/D	N/D
LT-45	11.01	N/D	95	< 0.001	N/D	5	1.2
LT-76	8.65	N/D	132	< 0.001	N/D	5	1.4
LT-78	7.21	N/D	179	< 0.001	N/D	5	1.25
Charge Water Sample	7.45	N/D	54	N/D	N/D	2	N/D

N/D = Not determined

*Total Cu = Cu¹⁺ and Cu²⁺

** Total Fe = Fe₂O₃ and FeO

examination of transverse and longitudinal sections of the axially-grooved tubing showed relatively equiaxed grains ranging in size from ASTM 5 to 6. Microhardness readings ranged from a Rockwell R_B 6.5 to R_B 69; lower values were recorded in the weld area of the end-fittings and the higher values were in the area of the fins where a higher degree of cold working was evident. Since the heat pipes had to be soldered at temperatures up to 220°C, recrystallization in the heat affected zone was of some concern because of pressure containment. However, tubes with minimum wall thicknesses of 0.016 inch did survive hydrostatic pressure testing at 555 psia. The criteria for acceptance was that a permanent deformation would not exceed 0.32% of the tube's initial diameter at three measured locations, two of which were in vicinity of the weld area and one at the midpoint of the tube.

Three heat pipes, S/N's LT-45 life tested at 125°C for 2338 hours, LT-78 life tested at 165°C for 2680 hours, and LT-76 life tested at 185°C for 1422 hours also underwent destructive analysis. Amounts of non-condensable gas in the life tested heat pipes was also relatively low, the highest value being 1.60×10^{-3} millimoles. Analysis of gas extractions are presented in Table 2-5. Charge water samples extracted from these heat pipes were analyzed and the analyses are presented in Table 2-6. In general, the chloride levels in these samples were higher than those determined for the as-fabricated heat pipes. The level of chloride contamination causes some concern because of its potentially corrosive nature. High levels of chloride and low acid pH's could lead to corrosion in the absence of oxygen. A theoretical study conducted at Battelle Columbus Laboratories, Reference 9, compiled potential vs. pH (Pourbaix diagrams) at various temperatures and chloride ion (Cl^-) concentrations to establish the thermodynamics of Cl^- corrosion of copper. As an example, at 200°C, the

pH of the charge water would have to be below 3 in the presence of 355 ppm Cl^- (10^{-2}M) to corrode copper. Considering the pH and Cl^- concentration values presented in Table 2 for extracted charge water and the fact that pH does shift to lower pH values due to changes in the dissociation constant of water and the activity of the hydronium ion at elevated temperatures, a critical combination of Cl^- /pH/temperature is unlikely. However, fabrication techniques have been upgraded as a precautionary measure and these will be discussed in the conclusion section. Metallographic examination of the tubing showed essentially the same results as for the as-fabricated heat pipes. S/N-76 grain size was slightly larger, ASTM 4, but micro-hardness values were also higher, R_B 48 to $R_B > 67$. S/N-78, which was life tested at a temperature of 20°C less than S/N 76 but was on test for 1258 more hours, had lower microhardness values, in the range of $R_B < 2$ to R_B 69. The most significant find was that the cupric oxide (CuO) coating laid down on the internal surfaces of the heat pipe to enhance the wetting angle to $< 30^\circ$ is apparently thermodynamically unstable in contact with water. The instability is probably a result of the following reactions:

Examination of the internal surfaces of heat pipes S/N's LT-76 and LT-78 revealed bare copper surfaces over most of their length with an accumulation of oxides (Cu_xO_y) at the evaporator end. The feasibility of the chloride ion to hasten this phenomenon was studied by Packer Engineering Associates Inc. Packer Engineering postulated that the presence of the chloride ion increases the conductivity of the water and could increase the current flow, therefore the $\text{Cu}^0 + \text{CuO} \rightarrow \text{Cu}_x\text{O}_y$ reaction rate

can be increased as the temperature and chloride ion levels increase in the charge water. Although this coating reaction occurs, heat pipe thermal performance did not degrade on any heat pipe life tested when compared to initial data. It is therefore concluded that the loss of coating and/or transformation to Cu_xO_y has left an internal surface with wetting characteristics which could not be achieved by prior cleaning and other coating techniques.

2.5 GDS Heat Pipes

A total of twenty (20) heat pipes were fabricated for the Selenide Isotope Generator (SIG) Ground Demonstration System (GDS). These heat pipes were fabricated per LCP10022, which was also used to process the Life Test heat pipes. Their configuration is defined by SIG30042, "Heat Pipe Assembly - Axially-Grooved Internally, GDS." These heat pipe assemblies are of a configuration with an 80° bend and having a single evaporator section 3.17 inches long. The condenser section is 10.2 inches long and the corresponding effective condenser length is 8.07 inches long. Serial Nos. of the heat pipes that were fabricated for the GDS application are listed in Table 2-6. Shadowgraph measurements of tube samples removed from each of these assemblies prior to fabrication were reported by B&K Engineering in BK046-1003, "Shadowgraph Measurements for GDS-1 Heat Pipes." These measurements were made per LCP10077, "Acceptance Specification, Axially-Grooved Tubing, Life Test and GDS-1 Heat Pipes," and include details of the groove geometry, water charge data and calculated performance parameters.

TABLE 2-6. GDS HEAT PIPE ASSEMBLIES*

1GDS-1	1GDS-10	1GDS-17
1GDS-2	1GDS-11	1GDS-18
1GDS-3	1GDS-12	1GDS-19
1GDS-4	1GDS-13	1GDS-20
1GDS-6	1GDS-14	1GDS-22
1GDS-7	1GDS-15	1GDS-23
1GDS-9	1GDS-16	

* 1GDS denotes the first GDS unit, a total of two were planned.

Fabrication data for the individual assemblies were reported by B&K Engineering in BK046-1002, "GDS-1 Heat Pipe Fabrication Data." The data consists of a Fabrication Log, Water Charge and Weight Data, and Hydrostatic Pressure test results.

Thermal performance data for all assemblies except 1GDS-20 were reported by B&K Engineering in BK046-1004, "Test Report for GDS-1 Heat Pipes." Serial No. 1GDS-20 was not charged with the water working fluid but hydrostatically pressure tested without failure to 3000 psia. The heat pipe tube did, however, yield indicating tube and weld integrity to more than a factor of 6.5 times the maximum pressure that the pipe would experience when being attached to GDS generator hardware by soldering at 225°C. The remaining nineteen (19) heat pipes were tested in accordance with B&K Engineering Documentation BK046-1001, "GDS Heat Pipe Thermal Performance Test Procedure" to demonstrate performance requirements as specified by SIG30041, "Heat Pipe Assembly, Axially-Grooved, Performance Requirement." Test results are presented in Table 2-7. All of the pipes satisfied the 0.80-inch static wicking height requirement. Serial Nos. 1, 3, 6, 10, 11, 12 and 22 exceeded the maximum temperature drop criterion of 6°C with a 120-watt heat load and $90 \pm 10^\circ\text{C}$. The maximum measured temperature drop (heat pipe ΔT_{max}) decreased to less than 8.3°C in all of these pipes when the operating temperature was increased to approximately 120°C. At this temperature Serial Nos. 3 and 12 were within the 6°C specification.

Actual test data for the individual heat pipes are recorded in B&K Engineering Documentation, BK046-1004, "Test Report for GDS-1 Heat Pipes." A review of this data shows that the evaporator temperature drop ($T_1 - T_3$) is the largest fraction of the total heat pipe ΔT , especially as the heat load approaches or exceeds the 120-watt level. In those cases, when the 6°C criterion was exceeded at 90°C, the total temperature drop was less when the pipes were retested at 120°C. Since the transport capability is approximately 25% greater

TABLE 2-7GDS COPPER/WATER HEAT PIPE PERFORMANCE DATA SUMMARY

<u>Serial No.</u>	<u>ΔT_{M1} (°C)</u>	<u>ΔT_{M2} (°C)</u>	<u>Q_{M1} (W)</u>	<u>h_s (in.)</u>
GDS-1 1	13.0	8.3	110	1.11
2	3.6		187	1.02
3	6.1	4.6	145	1.14
4	2.9		187	1.02
6	8.9	7.5	155	0.88
7	5.7		130	0.81
9	4.0		145	1.24
10	8.5	7.7	150	0.80
11	8.4	7.2	135	0.81
12	6.9	3.9	129	0.82
13	5.0		165	1.05
14	2.7		144	1.01
15	1.9		144	1.01
16	5.6	4.0	127	1.13
17	3.0		160	0.99
18	5.6	2.7	126	9.98
19	3.2		160	1.05
22	10.7	8.1	160	1.34
23	5.6		160	0.94

$\Delta T_{M1} = \Delta T_{MAX}$ @ 120 watts and $90 \pm 10^\circ \text{C}$

$\Delta T_{M2} = \Delta T_{MAX}$ @ 120 watts and $120 \pm 5^\circ \text{C}$

$Q_{M1} = \text{Maximum 0-g heat load @ } 90^\circ \text{C (Extrapolated)}$

$h_s = \text{Static height @ } 90^\circ \text{C}$

at the 120°C condition, the reduction in temperature drop is due to the fact that a "partial dry-out" of these heat pipes was occurring at the 90°C condition with 120-watts applied.

The reduced transport that was obtained with the GDS heat pipes is associated with the relatively poor tubing that was used. The best tubing was used to fabricate Life Test heat pipes (LCP10023) since their performance requirements are approximately two times greater. In any case, the performance provided by the GDS heat pipes will be more than adequate for the system requirements which are nominally 75-watts at 95°C. Serial Nos. 1, 10 and 22 were retained as spares since they have the lowest performance. The remaining sixteen (16) pipes were soldered to the GDS radiator fin.

3.0 SIG/GALILEO HEAT PIPES

3.1 General Description

The requirements for SIG/Galileo heat pipes are defined by SIG 110040, "Heat Pipe Assembly" and SIG 110041, "Heat Pipe Assembly, Axially-Grooved, Performance Requirements." Ten each of two separate heat pipe assemblies (-009 and -019) are required for each generator in this application. The overall geometry of each assembly is shown schematically in Figure 3-1. Both types of heat pipes are straight and each has the same dual evaporator section. An extended reservoir is utilized to accommodate excess liquid that will be driven into the evaporator end during the various spinning modes associated with the Galileo mission (Reference 10). The reservoir is shorter for the -019 pipe and is a result of the shorter condenser length required for this assembly.

The following sections present the results of an evaluation of the axially-grooved tubing that was fabricated at Noranda Metal Industries under Purchase Order No. 81143. Also included are the results of gas and hydrostatic pressure tests that were conducted with representative weld samples to determine pressure containment capability and weld integrity. Finally, the results from static and spin tests which were performed with prototype heat pipes whose configuration is similar to the SIG 110040-009 assemblies are presented.

DIM.	DESCRIPTION	ASSEMBLY *	
		-009	-019
A	—	.390 $\begin{smallmatrix} +.000 \\ -.100 \end{smallmatrix}$	.390 $\begin{smallmatrix} +.000 \\ -.100 \end{smallmatrix}$
B	RESERVIOR EXTENSION	4.50	1.50
C	EVAPORATOR SECTION	3	3
D	—	3.12	3.12
E	EVAPORATOR SECTION	3	3
F	—	7.0	0.0
G	CONDENSER SECTION	25.442	4.955
H	—	.625 $\begin{smallmatrix} +.000 \\ -.100 \end{smallmatrix}$	.625 $\begin{smallmatrix} +.000 \\ -.100 \end{smallmatrix}$
J	TOTAL LENGTH	47.08	16.59

* DIMENSIONS IN INCHES

Figure 3-1. SIG/Galileo Heat Pipe Assemblies

3.2. SIG/Galileo Heat Pipe Tubing Evaluation

A total of 141 axially-grooved copper tubes were fabricated at Noranda Metal Industries per SIG 110044, "Tubing-Axially Grooved, Internally" for use as heat pipes in the SIG/Galileo Program. Each of these tubes was visually inspected for any damage to the walls and shadowgraphs of samples obtained from one end of each undamaged tube were made per SIG 110043 Revision A, "Heat Pipe Tubing Selection and Charge Requirements," and SIG 110045, "Heat Pipe Fabrication and Processing Requirements."

Shadowgraph measurements were performed in accordance with SIG 110043, Revision A. An example of a typical shadowgraph from tube Sample No. 006B is presented in Figure 3-2. The corresponding data sheet with measurements of various groove characteristics and calculated heat pipe parameters is presented in Figure 3-3. This figure is a duplicate of Table 1.0 from SIG 110043. Tubing acceptability for fabrication as SIG 110040-009 or -019 heat pipe assemblies was determined in accordance with criteria specified in SIG 110043 as follows in Table 3-1:

Table 3-1. SIG Heat Pipe Tubing Acceptance Criteria*

	<u>-009 Assembly</u>	<u>-019 Assembly</u>
Wall thickness (t_w')	0.008 inch	0.008 inch
Groove Depth (δ')	≥ 0.027 inch	≥ 0.024 inch
$NN_g G_v$	$\geq 1.55 \times 10^{-5} \text{ in}^3$	$\geq 0.441 \times 10^{-5} \text{ in}^3$

*Refer to Figure 3-3 and SIG 110043, Revision A.

Figure 3-2. Tube Shadowgraph

Fig. 3-3. Data Sheet for shadowgraph analysis

Geometric CharacteristicsTube Sample No. 006 B N Grooves 24 Date 12/2/78 Weight 207.7 gms

Position	O.D.	D_o	D_v	F_m	F_m^2
1	<u>.3068</u>	<u>7.81</u>	<u>5.42</u>	$(F_m = \frac{D_o \text{ Avg.}}{O.D. \text{ Avg.}})$	
2	<u>.3063</u>	<u>7.74</u>	<u>5.43</u>		
3	<u>.3064</u>	<u>7.66</u>	<u>5.40</u>		
4	<u>.3063</u>	<u>7.73</u>	<u>5.33</u>		
Avg.	<u>.30645</u>	<u>7.7350</u>	<u>5.3950</u>	<u>25.2407</u>	<u>637.0909</u>

$F_m = \text{MAGNIFICATION FACTOR}$

$D_v' = \frac{D_v \text{ Avg.}}{F_m} = .2137$

Hydrostatic Deflection Data

Position	WP	W	l_w^+	l_{wA}	δ	D_1	D_2	Deflection
1	<u>1.86</u>	<u>.43</u>	<u>.48</u>	<u>.0190</u>	<u>.72</u>	1	1	1
2	<u>1.83</u>	<u>.45</u>	<u>.40</u>	<u>.0158</u>	<u>.68</u>	2	2	2
3	<u>1.90</u>	<u>.48</u>	<u>.37</u>	<u>.0147</u>	<u>.74</u>			
4	<u>2.07</u>	<u>.48</u>	<u>.35</u>	<u>.0139</u>	<u>.79</u>			
5	<u>1.99</u>	<u>.44</u>	<u>.36</u>	<u>.0143</u>	<u>.76</u>			
6	<u>1.97</u>	<u>.45</u>	<u>.41</u>	<u>.0162</u>	<u>.75</u>			
7	<u>1.97</u>	<u>.46</u>	<u>.45</u>	<u>.0178</u>	<u>.76</u>			
8	<u>1.90</u>	<u>.43</u>	<u>.48</u>	<u>.0190</u>	<u>.74</u>			
Avg.	<u>1.9363</u>	<u>.4525</u>	<u>.4125</u>	<u>.0163</u>	<u>.7425</u>			

Avg $\div F_m$ $WP = .0767$ $W = .0179$ $l_w = .0163$ $\delta = .0294$

Reading	A_g	$\frac{\delta'}{W} = 1.6409 = \alpha$ (aspect ratio)
1	<u>8.86</u>	
2	<u>8.78</u>	
3	<u>8.85</u>	

 $0.5 D_v' + \delta' = .1363$ R_i (internal radius)

Avg. $A_g = 8.83$ $A_g' = \frac{A_g A_v}{F_m^2} = .0139$ $A_g = \frac{A_g'}{N} = 5.775 \times 10^{-4}$

Fluid Charge (gms/unit length) - See Figure 3 (S16110043)

Min. .1922 Max. .2021

Performance Parameters - Refer to Para. 4.4.3

$NN_g (\text{in.}^3) = 4.087 \times 10^{-5}$ $f_{lv} = .01316$ $f_v = .00713$

$G_v = .4232$

$NN_g G_v (\text{in.}^3) = 1.7296 \times 10^{-5}$

Locations ①, ② through ⑧ are the locations for the wall thickness measurements

The tubing acceptance requirements are substantially lower for the -019 assemblies. This is due to their shorter lengths and correspondingly lower heat load and heat transport requirements. With a few exceptions, tubing which did not satisfy the -009 criteria was acceptable for -019 assemblies. A total of ninety-two (92) tubes are available for fabrication as -009 assemblies and thirty-one (31) tubes for -019 assemblies as listed in Table 3-2. The balance of eighteen (18) tubes which were rejected are listed in Table 3-3 with the reason for their rejection. Thirteen (13) of the tubes were rejected because their wall was either damaged or too thin. The other five (5) had grooves whose depth was not fully developed and did not exceed the 0.024 inch criterion. A summary of significant data obtained from the shadowgraph measurements, including groove depth, groove area, $NN_g G_v$ and fluid charge is given in Table 5.0 of Reference 11.

After the determination for acceptable tubing had been completed, an analysis was performed to predict each tube's transport capability at operating temperatures of 105°, 125° and 140°C. Predictions were made for 1-g operation with the evaporator end elevated 0.05 inch above the condenser end and also for 0-g operation. Performance predictions for positive elevations (condenser above evaporator) of 45° and 90° were also obtained. The analysis was made for the groove characteristics obtained from the aforementioned shadowgraph measurements. The predictions are based on grooves with sharp corners and are limited to laminar vapor flow. For the SIG tubing, the diameter of the vapor core (D_v) is approximately 0.22 inch and laminar conditions will prevail as long as the heat load is less than 250 watts which is well above the level specified for the Galileo application (Refer to SIG 110041).

TABLE 3-2. ACCEPTABLE TUBING*

<u>SIG 110040-009*</u>						<u>SIG 110040-019*</u>	
003	042	061	080	108	129	009	043
004	044	062	081	110	130	012	053
005	045	063	082	111	132	019	088
006	046	064	083	112	136	021	095
007	047	065	084	113	139	022	098
008	048	066	085	114	140	023	099
015	049	067	086	115	141	025	100
016	050	068	087	116		026	101
017	051	069	089	118		027	102
018	052	071	091	121		029	103
020	054	072	092	122		033	106
024	055	073	093	123		034	109
028	056	074	094	124		035	117
030	057	075	096	125		036	131
031	058	077	097	126		038	
032	059	078	105	127		039	
040	060	079	107	128		041	

Total No. of Tubes Acceptable for SIG 110040-009 Assemblies = 92

Total No. of Tubes Acceptable for SIG 110040-019 Assemblies = 31

Yield for -009 Assemblies = 65%, Yield for -009 and -019 Assemblies = 87%

TABLE 3-3. REJECTED TUBING*

<u>Damaged Wall</u>	<u>Wall Thickness (t_w)</u> <u>< 0.008 Inch</u>	<u>Groove Depth (δ')</u> <u>< .024 Inch</u>
070	001	010
090	002	011
104	076	013
133	119	014
134	120	037
135	137	
	138	

Total No. of Tubes Rejected from 141 Produced = 18

*Refer to SIG 110043, Revision A and BK058-1001 per P. O. No. B-81202

The transport capability in 0-g and at an adverse elevation of 0.05 inch is summarized in Table 3-4 for operation at 105°, 125°, and 140°C. Figure 3-4 shows the distribution of the theoretical transport capability at 105°C with an adverse elevation of 0.05 inch for all of the acceptable tubing. The average transport capability for all the tubing is 4937 W-in. at 105°C and at the 0.05 inch elevation. This average transport capability increases to 7206 W-in. at 140°C. The transport capability is approximately 5% higher in 0-g.

Table 3-4. Summary of SIG Tubing Performance

<u>Elevation</u>	<u>T (°C)</u>	<u>Heat Transport (W-in.)</u>		
		<u>Minimum</u>	<u>Maximum</u>	<u>Average*</u>
0-g	105	3,333	6,452	5,175
	125	4,346	8,407	6,674
	140	4,993	9,653	7,613
-.05 in.	105	3,162	6,159	4,937
	125	4,111	8,003	6,350
	140	4,711	9,169	7,236

*Average of 123 tubes.

Figure 3-4. Transport Capability at .05 Inch Adverse Elevation and 105°C

For the Galileo Mission, the SIG generator would have been oriented whereby, the heat pipe's condenser would be above the evaporator during various modes of 1-g operation. This was done to insure that the heat pipes would always be operative. When the condenser is above the evaporator the liquid return is assisted by gravity and the transport capability of a heat pipe is increased substantially. The analysis presented in Reference 12 determined that the transport capability at positive orientations of 45° and 90° (condenser above evaporator) is more than an order of magnitude greater than the transport requirement associated with the SIG heat loads. As a result, excess liquid would have accumulated in the evaporator end. The amount of evaporator blockage that would have resulted is important to know so that the associated higher evaporator temperature drops can be estimated.

The amount of liquid blockage that results at 45° and 90° positive orientations when the heat pipes are operated at their nominal heat loads is listed in Table 3-5 for operating temperatures of 105°, 125° and 140°C. The analysis presented in Reference 13 was used to obtain these results. Because the transport capability is so much higher than the actual requirement, the amount of blockage approaches the asymptotic limit and it is independent of the differences that exist among the groove geometries of the individual tubes. The -009 and -019 SIG heat pipe assemblies have a 4.5 and 1.5 inch reservoir respectively, to accommodate the liquid blockage. However, as indicated in Table 3-5, the blocked length exceeds the reservoir lengths of both assemblies. The blocked length is 0.10 to 0.30 inch greater for the 90° orientation. There is a 0.20 to 0.40 inch increase in the amount of blockage as the temperature increases from 105° to 140°C. This is due primarily to the liquid expansion.

TABLE 3-5. BLOCKED LENGTH OF SIG HEAT PIPES AT 45° AND 90° POSITIVE ORIENTATIONS

		L_b (in.)			L_{be} (in.)			% L_u		
		105°C	125°C	140°C	105°C	125°C	140°C	105°C	125°C	140°C
-009 Assy.	45°	6.3	6.5	6.7	1.8	2.0	2.2	70	67	63
	90°	6.4	6.6	6.8	1.9	2.1	2.3	68	65	62
-019 Assy.	45°	2.1	2.2	2.3	0.6	0.7	0.8	90	88	87
	90°	2.2	2.3	2.6	0.7	0.8	1.1	88	87	82

L_b = Total blocked length including reservoir and part of first evaporator

L_{be} = Blocked length of first evaporator

% L_u = Percentage of total evaporator which is unblocked

As illustrated in Figure 3-1, the -009 and -019 assemblies have dual evaporator sections which are each three (3) inches long and are separated by a 3.12 inch long transport section. This blockage occurs only in the first evaporator section and varies from 0.6 to 1.1 inches for the -019 assembly and from 1.8 to 2.3 inches for the -009 assembly. The percentage of total evaporator section that is unblocked ($\%L_u$) is presented in Table 3-5. The increase in the total evaporator temperature drop is inversely proportional to this value ($\%L_u$). The -009 assemblies are predicted to experience up to 60% increase ($1/\%L_u$) in the evaporator temperature drop, depending on the operating condition (temperature and orientation) during 1-g testing.

3.3 SIG/Galileo End Cap Weld Integrity and Tubing Pressure Containment Evaluation

Two (2) tubes with minimum wall thicknesses of .0089 inch (Tube No. 059) and .00128 inch (Tube No. 054) were selected to evaluate their pressure containment capability and the weld integrity of end cap welds. Shadowgraph measurements of samples taken from one end of each tube are summarized in Table 3-6. Each tube was marked as to orientation, serialized and cut into nine (9) samples, as shown in Figure 3-5. The center section of each tube (Sample E) was to be tensile tested. The Stop Work order concluded further activity. The remaining sections from each tube were fitted with end caps, welded, and pressure tested.

Sixteen (16) sets of closure end fittings were machined and fabricated in accordance to SIG 110040-029 and -005. The weld sample tubes were degreased, slurry cleaned, chemically cleaned, rinsed and dried per LCP 10022 para. 3.1.3.2. The closure end fittings were cleaned and welded to the sample tubes per LCP 10022 para. 3.1.3.3. Closure of the evaporator end fittings was performed in accordance with LCP 10022 para. 3.1.3.7.1 through 3.1.3.7.4. All welding was performed without filler wire.

Each weld sample was radiographed along its entire length at the 0° and 90° index (Figure 3-5) to ascertain 100% weld penetration in accordance with SIG 110040. The weld samples were then helium leak tested per PS 1100011 to a sensitivity of 10^{-9} std. cc He/sec. Weld penetration of all sixteen (16) weld samples was determined to be in compliance with the criterion for 100% penetration of the wall. Leaks, however, were detected in three (3) of the sixteen (16) samples. Those were rewelded, without filler wire. Radiographic inspections and helium leak tests were repeated. The repair of these three samples was determined to be satisfactory.

TABLE 3-6. WELD EVALUATION SAMPLES SHADOWGRAPH MEASUREMENTS

Sample No.	Average Outside Diameter (in.)	Minimum Wall Thickness (in.)	Maximum Wall Thickness (in.)	Average Wall Thickness (in.)
054 End Sample	.3064	.0128	.0192	.0154
054 A	.3070	.0128	.0192	.0158
054 B	.3071	.0119	.0175	.0154
054 C	.3070	.0144	.0176	.0160
054 D	.3090	.0127	.0183	.0155
054 F	.3070	.0144	.0168	.0157
054 G	.3075	.0137	.0177	.0157
054 H	.3068	.0132	.0172	.0155
054 I	.3074	.0131	.0174	.0153
059 End Sample	.3065	.0089	.0206	.0153
059 A	.3070	.0136	.0168	.0156
059 B	.3085	.0132	.0177	.0155
059 C	.3091	.0135	.0162	.0150
059 D	.3070	.0140	.0171	.0154
059 F	.3070	.0143	.0174	.0160
059 G	.3084	.0111	.0191	.0157
059 H	.3072	.0120	.0168	.0151
059 I	.3077	.0115	.0191	.0161

Figure 3-5 Weld Sample Tube Marking and Identification

3.4 Room Temperature Gas Pressure Testing

Eight (8) of the weld samples consisting of Serial Nos. 054A, C, F, and H and Serial Nos. 059A, C, F and H were subjected to room temperature gas pressure cycling as defined in Table 3-7. Components of the test set-up are defined schematically in Figure 3-6.

Diameter measurements obtained prior to and during gas pressure testing are reported in Appendix A of Reference 11. Diameter measurement changes after each pressure cycle are presented in Tables 3-8 and 3-9. All diameter changes are given with respect to the initial (pre-gas pressure cycling) measurements. Throughout the gas pressure test, repeatability of diameter measurements were determined to be sensitive with respect to the location of the points measured. This was especially true for those samples whose ends became oval due to welding and subsequent handling. A repeatability error of approximately $\pm .0005$ inch was therefore included in the evaluation of the data. As a result, a 0.5% yield (.001 to .002 inch) was observed with all the samples tested at the 850 psia pressure cycle. In all cases, yield was most severe near the condenser end fitting (swaged end).

The yielding at the condenser end was probably due to the fact that the condenser end fitting is heavier, therefore requiring more heat during the welding operation. This additional heat resulted in a higher degree of annealing. With respect to wall thickness, no distinction in the yield point could be made between the heavier walled samples (Tube No. 054) and the lighter walled samples (Tube No. 059). This is probably due to the repeatability error of diameter measurements, the fact that measurements were only obtained after discrete pressure increase steps and the fact that the minimum wall thickness varied from sample to sample.

TABLE 3-7
ROOM TEMPERATURE GAS PRESSURE
TEST SEQUENCE

1. Measure and record the diameter of the weld sample tubes at three (3) locations; two (2) of which shall be one-half inch from each end fitting weld and the third shall be at the mid-point of the weld sample tube. Obtain two (2) sets of readings 90° apart corresponding to the markings defined in Fig. 5-6.
2. Pressurize samples to 390 psig and hold for 1/2 hour.
3. Remove pressure and repeat diameter measurements as defined in Step #1.
4. Pressurize samples to 480 psig and hold for 4 - 5 minutes. Increase pressure to 590 psig and hold for 1/2 hour.
5. Remove pressure and repeat diameter measurements as defined in Step #1.
6. Pressurize samples to 710 psig and hold for 4 - 5 minutes. Increase pressure to 850 psig and hold for 1/2 hour.
7. Remove pressure and repeat diameter measurements as defined in Step #1.
8. Pressurize samples to 1015 psig and hold for 1/2 hour.
9. Remove pressure and repeat diameter measurements as defined in Step #1.
10. Pressurize samples to 1115 psig and hold for 45 sec. Increase pressure in steps of 100 psig at 45 sec. intervals until burst or until the 2500 psig test fixture limit has been achieved, whichever occurs first.

Figure 3-6. Room Temperature Gas Pressure Test Schematic

TABLE 3-8. ROOM TEMPERATURE GAS PRESSURE TEST

Tube No. 054: .0128" min., .0192" max., .0154" Avg.

Measured Wall Thickness*

Diameter Change: in. x 10³

Sample No.	Pressure Cycle	Swaged End		Middle		Closed End	
	PSIA	0°	90°	0°	90°	0°	90°
054 A	390	+0.4	+0.7	0	0	-2.2	-0.7
054 C		+0.3	+0.3	0	+0.2	-0.5	+0.1
054 F		-0.3	+0.2	-0.7	-0.1	-0.6	0
054 H		+0.2	-0.7	-0.3	-0.2	0	-0.4
054 A	590	+0.8	+1.0	+0.2	-0.1	-3.3	-0.8
054 C		+0.1	+0.5	-0.3	-0.1	+0.4	+0.8
054 F		+0.8	+0.8	-0.5	-0.1	-1.0	+0.4
054 H		+0.1	+0.3	-0.3	-0.2	-0.1	-0.1
054 A	850	+2.3	+2.4	+0.1	-0.1	-1.3	-0.1
054 C		+1.1	+1.3	-0.2	+1.1	-0.6	+0.1
054 F		+2.7	+2.7	-0.7	-0.1	+0.3	+1.8
054 H		+3.2	+1.5	-0.2	0	+0.4	+1.2
054 A	1015	+3.8	+3.9	-0.1	+0.3	-2.3	+0.3
054 C		+2.3	+2.5	+0.2	0	+0.8	+1.5
054 F		+4.5	+4.3	-0.4	-0.1	+0.9	+2.9
054 H		+4.7	+3.8	-0.4	-0.3	+1.0	+2.2

BURST PRESSURE CYCLE

054 A	No Burst at 2500 psia
054 C	No Burst at 2500 psia
054 F	No Burst at 2500 psia
054 H	Burst at 2375 psia after 0 sec.

*Wall Thickness Measurements Closest to 054 H Section

Tube No. 059: .0089" min., .0206" max., .0153" Avg.
Measured Wall Thickness*

Sample No.	Pressure Cycle PSIA	DIAMETER CHANGE					
		Swaged End		Middle		Closed End	
		0°	90°	0°	90°	0°	90°
059 A	390	0	+0.1	-0.2	-0.2	0	+0.1
059 C		+0.2	+0.3	0	-0.1	0	-0.1
059 F		0	-0.1	0	-0.5	+1.8	+0.1
059 H		+0.2	0	-0.3	-0.4	-1.8	+0.2
059 A	590	0	+0.2	-0.1	-0.1	+0.4	+1.3
059 C		+0.4	+0.7	-0.1	0	+0.5	+0.3
059 F		+0.7	+2.0	-0.2	-0.1	-0.6	+1.4
059 H		+0.3	+0.5	+0.1	+0.1	-0.5	+0.2
059 A	850	+1.0	+1.9	+0.1	-0.1	+2.5	+3.0
059 C		+1.9	+2.7	-0.1	0	+2.5	+2.2
059 F		+2.6	+4.1	+0.5	-0.3	-2.1	+4.7
059 H		+1.9	+1.4	+0.1	+0.2	-0.2	+2.3
059 A	1015	+2.8	+3.8	+0.2	-0.1	+3.5	+5.2
059 C		+2.3	+4.3	+0.3	+0.5	+5.7	+3.1
059 F		+4.7	+6.0	-0.3	-0.6	-0.9	+6.0
059 H		+3.9	+2.5	-0.3	-0.2	+0.7	+3.1
BURST PRESSURE							
059 A	Burst at 2495 psia after 0 sec.						
059 C	Burst at 2500 psia after 15 sec.						
059 F	No Burst at 2500 psia						
059 H	Burst at 2415 psia after 15 sec.						

*Wall Thickness Measurement Closest to 059 H Section

Figures 3-7 and 3-8 show the samples after gas pressure testing. As can be seen, only one of the four samples from Tube No. 054 burst at or below 2500 psia, whereas, three of the four Tube No. 059 samples burst at or below 2500 psia. This is consistent with the lighter wall thickness measurements for Tube No. 059. In addition, burst in all cases occurred at the condenser end fitting (swaged end).

3.5 Temperature Cycle Pressure Testing

(8) of the weld samples consisting of Serial Nos. 054B, D, G and I, and Serial Nos. 059B, D, G, and I were charged with distilled water per LCP 10022 para. 2.2.3. The amount of charge was determined on the basis of SIG 110043 para. 7.1. The net charge for each sample as determined by weighing is presented in Table 3-10. Each sample was subjected to temperature cycles as defined in Table 3-11. Each sample was instrumented with a thermocouple to monitor the temperature during cycling.

Diameter measurements taken throughout the temperature cycling tests are reported in Appendix B of Reference 14. Diameter measurement changes after each temperature cycle are presented in Tables 3-12 and 3-13. All diameter changes are given with respect to the initial (pre-temperature cycling) measurements. Results for the magnitude of these diameter changes are essentially the same for the temperature cycling tests and the room temperature gas pressure tests. The exact yield point could not be established because diameter measurements could not be obtained during temperature cycling. Yield occurred at lower pressures for the temperature cycling test than for the room temperature gas pressure test. This was due to loss of material strength at elevated temperatures. As noted for the room temperature gas pressure test, a higher degree of yielding occurred near the condenser end fitting for samples from Tube No. 054. The degree of yielding was approximately the same at both tube ends for samples from Tube No. 059.

GAS/PRESSURE TESTING

AXIALLY-GROOVED OFHC COPPER TUBING (SIG110044)

S/N LT-054

MIN. WALL THK. : .0128" - AVG. WALL THK. : .0154" - MAX. WALL THK. : .0192"

SHADOWGRAPH MEASUREMENTS TAKEN FROM ONE END OF TUBING (H).

GAS/PRESSURE TESTING
AXIALLY-GROOVED OFHC COPPER TUBING (SIG110044)
S/N LT-059

* MIN. WALL THK.: .0089" - AVG. WALL THK.: .0153" - MAX. WALL THK.: .0206"

TABLE 3-10. WELD SAMPLE CHARGE SUMMARY
FOR TEMPERATURE CYCLE TEST

<u>SAMPLE NO.</u>	<u>GROOVE AREA (in.²)</u>	<u>MINIMUM REQ'D CHARGE⁽¹⁾ gm</u>	<u>NET CHARGE⁽²⁾ gm</u>
054 B	.0136	1.10	1.20
054 D	.0136	1.10	1.25
054 G	.0136	1.10	1.25
054 I	.0136	1.10	1.25
059 B	.0139	1.13	1.30
059 D	.0139	1.13	1.40
059 G	.0139	1.13	1.30
059 I	.0139	1.13	1.25

(1) Per SIG 110043 para. 7.1

(2) Gravimetric measurement

TABLE 3-11.TEMPERATURE CYCLE TEST SEQUENCE

1. Measure and record the diameter of the weld sample tubes at three (3) locations; two (2) of which shall be one-half inch from each end fitting weld and the third shall be at the mid-point of the weld sample tube. Obtain two (2) sets of readings 90° apart corresponding to the markings defined in Fig. 3-5.
2. Heat samples to 420°F and hold for 1/2 hour.
3. Cool samples and repeat diameter measurements as defined in Step #1.
4. Heat samples to 440°F and hold for 4 - 5 minutes. Increase temperature to 460°F and hold for 1/2 hour.
5. Cool samples and repeat diameter measurements as defined in Step #1.
6. Heat samples to 480°F and hold for 4 - 5 minutes. Increase temperature to 500°F and hold for 1/2 hour.
7. Cool samples and repeat diameter measurements as defined in Step #1.
8. Heat samples to 520°F and hold for 1/2 hour.
9. Cool samples and repeat diameter measurements as defined in Step #1.
10. Heat samples until burst or working fluid leakage is detected.

Tube No. 054: .0128" min., .0192" max., .0154" Avg.
Measured Wall Thickness

Sample No.	Temperature Cycle (°F)	Diameter Change: in. x 10 ³					
		Swaged End		Middle		Closed End	
		0°	90°	0°	90°	0°	90°
054 B	420	+0.4	+0.5	0	-0.5	-0.2	-0.5
054 D	(308.8 PSIA)	-0.4	-0.4	-0.5	-0.8	+2.0	+0.7
054 G		-0.2	+1.0	+0.5	+0.5	-0.2	-0.3
054 I		0	0	-0.4	+0.3	+0.2	-0.3
054 B	460	+0.5	+0.7	-0.1	-0.8	+0.5	-0.7
054 D	(466.9 PSIA)	0	-0.5	-0.6	-0.7	+3.8	0
054 G		-0.1	+0.4	+0.4	-0.1	-0.2	+0.3
054 I		-0.3	0	0	-0.9	-0.9	-0.4
054 B	500	+2.2	+2.8	-0.4	-0.5	+1.0	+1.7
054 D	(680.8 PSIA)	+0.3	+1.4	-0.5	-0.5	+2.3	-0.2
054 G		+1.8	+2.2	+0.1	-0.3	+1.0	+2.1
054 I		+0.8	+2.1	+0.1	-0.6	-0.1	+1.3
054 B	520	+3.9	+4.3	-0.2	0	+2.2	+3.5
054 D	(812.4 PSIA)	+1.6	+4.9	-0.4	-0.6	+0.6	+0.7
054 G		+3.3	+3.8	0	0	+2.4	+4.3
054 I		+3.0	+4.4	+0.1	-0.5	+1.6	+2.9
BURST TEMPERATURE CYCLE							
054 B	Burst @ 575°F (1278 psia)						
054 D	Burst @ 583°F (1358 psia)						
054 G	Developed a leak** @ 568°F (1210 psia)						
054 I	Developed a leak** @ 586°F (1390 psia)						

* Wall Thickness Measurements Closest to Section 054 H

** A leak was indicated by a drop in sample temperature caused by the sudden venting (evaporation) of the charge water.

TABLE 3-13. TEMPERATURE CYCLE TEST

Tube No. 059: .0089" min., .0206" max., .0153" Avg.
Measured Wall Thickness*

Sample No.	Temperature Cycle (°F)	Diameter Change: in. x 10 ³					
		Swaged End		Middle		Closed End	
		0°	90°	0°	90°	0°	90°
059 B	420	0	-0.5	-0.1	+0.3	+0.3	-0.2
059 D	(308.8 PSIA)	-0.8	-0.2	-0.3	+0.2	+0.1	-0.5
059 G		-0.1	0	+0.2	+0.5	-0.3	+1.7
059 I		+0.4	+0.9	+0.4	-0.5	-0.1	0
059 B	460	+0.3	+0.1	-0.2	-0.2	+0.2	-0.9
059 D	(466.9 PSIA)	+0.7	+0.6	+0.3	+0.4	+1.0	+0.2
059 G		0	+0.1	+0.3	-0.1	-0.4	+1.2
059 I		+1.0	+0.3	+0.5	-0.3	-1.9	-1.2
059 B	500	+3.2	+2.2	-0.1	-0.1	+2.8	0
059 D	(680.8 PSIA)	+2.5	+2.6	0	0	+2.8	+0.8
059 G		+1.7	+2.6	-0.1	+0.5	+1.4	+3.2
059 I		+2.6	+2.2	-0.2	+0.5	+0.9	+0.3
059 B	520	+4.3	+4.2	-0.4	+0.5	+5.0	+1.8
059 D	(812.4 PSIA)	+3.6	+4.3	-0.1	+0.8	+4.8	+3.3
059 G		+3.5	+4.5	-0.1	+0.5	+3.0	+6.0
059 I		+4.3	+4.8	-0.2	+0.6	+3.6	+4.2
BURST TEMPERATURE CYCLE							
059 B	Developed a leak** at 584°F (1369 psia)						
059 D	Developed a leak** at 585°F (1380 psia)						
059 G	Burst at 577°F (1297 psia)						
059 I	Burst at 580°F (1326 psia)						

* Wall Thickness Measurements Closest to Section 059 H

** A leak was indicated by a drop in sample temperature caused by the sudden venting (evaporation) of the charge water.

The tube samples after temperature cycling to failure are shown in Figures 3-9 and 3-10. All samples from Tube No. 054 failed at the condenser end which is consistent with results from the room temperature tests. All failed samples from Tube No. 059 occurred at the evaporator end which was due to lighter wall thicknesses (as determined by subsequent wall thickness measurements). Failures of the temperature cycle test samples occurred at lower pressures (1210 psia to 1390 psia) as compared to room temperature gas pressure test (2375 psia to 2500 psia), refer to Tables 3-8, 3-9, 3-12 and 3-13. As noted before, this is due to loss of material strength at elevated temperatures.

All pressure tests results show that for the SIG/Galileo application, the safety factor for pressure containment is approximately three (3) times the requirement for the maximum pressure condition. This condition would occur for the solder attachment of heat pipes to generator/radiator hardware at a soldering temperature of 220°C (428°F). In addition, the safety factor would provide more than a 100°F temperature margin for soldering.

TEMPERATURE/PRESSURE TESTING

AXIALLY-GROOVED OFHC COPPER TUBING (SIG110044)

S/N LT-054

* MIN. WALL THK. : .0128" - AVG. WALL THK. : .0154" - MAX. WALL THK. : .0192"

B

D

G

I

CONDENSER
ENDS →

FAILED @
575°F (~1240 PSIA)

FAILED @
583°F (~1250 PSIA)

FAILED @
568°F (~1225 PSIA)
LEAKED SIDE-WALL
CONDENSER END

FAILED @
586°F (~1400 PSIA)
LEAKED SIDE-WALL
CONDENSER &
EVAPORATOR END

* SHADOWGRAPH MEASUREMENTS TAKEN FROM ONE END OF TUBING (I).
NOTE : TUBES SECTIONED FOR HELIUM LEAK TESTING.

TEMPERATURE/PRESSURE TESTING

AXIALLY-GROOVED OFHC COPPER TUBING (SIG110044)

S/N LT-059

* MIN. WALL THK.: .0089" - AVG. WALL THK.: .0153" - MAX. WALL THK.: .0206"

B

D

G

I

CONDENSER
ENDS →

FAILED @
584°F (~1400PSIA)
LEAKED SIDE WALL
EVAPORATOR END

FAILED @
585°F (~1400PSIA)
LEAKED SIDE WALL
EVAPORATOR END

FAILED @
577°F (~1240PSIA)

FAILED @
580°F (~1245PSIA)

* SHADOWGRAPH MEASUREMENTS TAKEN FROM ONE END OF TUBING (I).
NOTE: TUBES SECTIONED FOR HELIUM LEAK TESTING.

3.6 SIG/Galileo Heat Pipe Spin Testing

A total of three (3) axially-grooved heat pipes were fabricated and tested at the Naval Surface Weapons Laboratory in White Oak, MD., to determine their performance in a spinning environment. The heat pipe configuration is similar to the SIG 110040-009 assemblies. They are straight and have a dual evaporator section and a 32 inch long condenser section. The evaporator section was extended 4.5 inches to accommodate excess liquid which is driven toward the evaporator and when the heat pipes are in a spinning mode. The overall configuration is consistent with the (SIG) system that had been evaluated for the SIG/Galileo Mission. Heat pipe serial numbers SP12 and SP13 contained a nominal fluid inventory. Heat pipe serial number SP14 was overcharged with an excess inventory of 2.8 gms to completely block the extended reservoir.

Three (3) series of tests were conducted with the heat pipes. The first series consisted of determining the transport capability of the heat pipes under static conditions. In the second series, all three heat pipes were tested under spin conditions which were representative of the SIG/Galileo Mission requirements (Reference 10). Only SP 12 was tested in the third series of tests which consisted of cooling the reservoir to determine its ability to act as a condenser section. Spin test conditions are summarized in Table 3-14. Spin tests were conducted in accordance with B&K Engineering Documentation, BK050-1003, "Thermal Performance Test Procedure for SIG Heat Pipe Spin Tests."

TABLE 3-14. SIG HEAT PIPE SPIN TEST CONDITIONS

SERIAL NO.	SPIN RADIUS		EVAPORATOR* ELEVATION (in.)	TEST SPIN RATE (rpm)						
	r ₁ (in.)	r ₂ (in.)		0	5-10	24	31	5-10	70	0
SP 12	70	124	-.12	X	X	-	X	X	X	X
	70	124	+.18	X	X	-	X	X	X	X
	51	73	+.16	X	-	X	-	X	-	X
	51	73	-.10	X	-	X	-	-	X	X
SP 13	70	124	-.09	X	X	-	X	X	X	X
SP 14	51	73	-.07	X	-	X	-	-	-	X
	70	124	-.06	X	X	-	X	X	X	X

*Negative sign indicates evaporator end above condenser

3.6.1 Test Set-Up

Schematics of the test set-up and heat pipe orientations for the stowed and deployed conditions are presented in Figures 3-11 and 3-12, respectively. The test fixture consists of an aluminum mounting plate with attachment points for the heat pipe's evaporator and condenser blocks. The aluminum evaporator block interfaces with 50% of the circumference of the heat pipes and consists of a dual heat input section as shown in Figure 3-13. Individual cartridge heaters are used in each evaporator section to apply the heat load.

Forced air cooling and a trim heater were used to provide temperature control of the condenser block which includes an aluminum saddle that also interfaces with only 50% of the heat pipe's circumference. The heat pipes were instrumented with a total of thirteen (13) chromel/alumel thermocouples, refer to Figure 3-13. The fixture which is shown in Figure 3-11 and when mounted to the centrifuge arm is level to within 1/16 inch. Tests were conducted at two (2) spin radii, as defined by Table 3-14. The 123 inch radius is representative of the Radioisotopic Thermoelectric Generator (RTG) in the deployed position. The smaller radius, to be discussed in the next section, represents a test simulation of the conditions when the RTG is in the stowed position.

Figure 3-12.

Figure 3-13. SIG Spin Pipes With Instrumentation

3.6.2 Heat Pipe Orientation Relative to Spin Arm

The position of the heat pipes relative to the spin axis for their application in the SIG/Galileo Mission is shown in Figure 3-14. The angles between the heat pipe and the plane parallel to the spin axis are 72° and 3.5° , respectively, for the deployed and stowed positions.

Figure 3-14. Heat Pipe Orientation for SIG/Galileo Mission

The deployed position was essentially duplicated during testing. The only exception being that the maximum spin radius that could be accommodated at the spin facility was 123 inches versus the 135.2 inch length which had been specified for the SIG/Galileo Mission. However, the orientation of the generator in the stowed position is such that an exact simulation of the spin forces would require that the heat pipe be tested in a vertical orientation with the evaporator at the top. The heat pipe could not operate under these conditions except at spin rates above 16 rpm. In addition, an adverse 1-g effect would not permit meaningful

0-g simulation. Simulation of the stowed condition was accomplished by orienting the heat pipes in a horizontal position and adjusting the spin rate so that the total force across the heat pipe was the same as what was predicted for the 0-g condition. As a result, the 24 rpm test spin rate did simulate the 70 rpm rate as specified for the SIG/Galileo Mission. However, tests were conducted at 70 rpm to determine what effect high acceleration forces would have on the heat pipes' thermal performance. The 73.5° orientation of the heat pipe in the stowed simulation tests (Refer to Figure 3-11) is such that the point of tangency is outside of the condenser end and therefore all excess liquid not required for transport would be driven toward the evaporator. This is also the case for the intended flight condition.

3.6.3 Spin Test Results

A summary of static test results obtained by B&K Engineering are presented in Table 3-15. Data sheets for these tests are included in Appendix A of Reference 15. Heat pipe SP12 gave the highest measured transport capability value which extrapolates to slightly more than 3850 watt-inches for the 0-g condition. The corresponding heat load is 132 watts. This performance is 15% higher than theoretical. The measured performance of heat pipes SP13 and SP14 is about 10% below that of SP12 but their transport capability is 30% above theoretical prediction. Sharp corners on the grooves would give a 15% improvement over the 0.003-in. radius used in the prediction. A review of the shadowgraphs for the tubing employed does show that the corners are sharp. There is no explanation for the additional 15% that was realized with SP13. The excess charge in SP14 could be responsible for its higher performance. The large condenser temperature drop (ΔT_c) listed for SP14 in Table 3-15 indicates the liquid blockage that exists due to the 2.8 gms overcharge.

The primary objective of the spin tests was to determine the effect of liquid blockage on the temperature distribution in the reservoir and evaporator sections under spin conditions representative of the SIG/Galileo Mission requirements. Typical axial temperature profiles are presented in Figures 3-15 and 3-16. The significant temperature drops are: $T_3 - T_1$, $T_3 - T_9$, and $T_7 - T_9$. The temperature difference between the first evaporator and the reservoir end ($T_3 - T_1$) is a measure of the ability of the extended tubing to act as a condenser section. A large temperature drop in the first evaporator ($T_3 - T_9$) is indicative of blockage into this region. Similarly, a large value for ($T_7 - T_9$) is indicative of liquid blockage into the second evaporator.

TABLE 3-15. STATIC TEST PERFORMANCE SUMMARY

SERIAL NO.	ELEVATION (in.)	Q _T (W)	(QL _{eff}) _T (W-in.)	(QL _{eff}) _{TH} * (W-in.)	% QL) _{TH} (W-in.)	ΔT _e @ 70-W (°C)	ΔT _c @ 70-W (°C)
SP 12	.0625	125	3642	3155	115	10.8	1.2
	.156	115	3351	2907	115	10.5	1.1
SP 13	.0625	115	3351	2617	128	5.6	0.7
	.156	105	3060	2389	129	6.3	0.8
SP 14	.0625	115	3351	2578	130	4.5	7.0
	.156	105	3060	2353	130	4.9	8.8

* The predicted performance is based on a .003" tip radius

$$L_{eff} = \frac{1}{4} L_{e1} + \frac{1}{2} L_a + \frac{3}{4} L_{e2} + L_t + \frac{1}{2} L_c$$

$$= \frac{2.81}{4} + \frac{2.94}{2} + \frac{3}{4} \times 2.81 + 9.86 + \frac{30}{2} = 29.14 \text{ in}$$

ΔT_e = Evaporator (1) temperature drop (T₃ - T₉)

ΔT_c = Condenser (active) temperature drop (T₉ - T₁₂)

(QL_{eff})_T = Test Values

(QL_{eff})_{TH} = Theoretical Values

Case 1 = 42% of applied heat load is dissipated at the reservoir

Case 2 = 21% of applied heat load is dissipated at the reservoir

Figure 3-15. Axial Temperature Profiles From Spin Tests With SP12

Case 1 = 42% of applied heat load is dissipated at the reservoir

Case 2 = 21% of applied heat load is dissipated at the reservoir

Figure 3-16. Axial Temperature Profiles From Spin Tests With SP12

The spin test results presented in Tables 3-16, 3-17 and 3-18 and in Figures 3-15 and 3-16 can be summarized as follows:

1. The results in Table 3-16 are for heat pipe S/N SP12 without any cooling of the reservoir. The following conclusions can be made:
 - (a) The amount of blockage in the first evaporator and its temperature drop ($T_3 - T_9$) are both strongly dependent on the spin rate. In the case of the stowed position there was a 6° to 7°C temperature drop at the first evaporator for the 24 rpm test condition which corresponds to the 70 rpm flight condition. Increasing the power from 70 to 100-W resulted in approximately a 1°C increase in the first evaporator for the stowed case. Blockage extends into the second evaporator only at the 70 rpm test rate. The first evaporator's temperature drop for the deployed test condition increases more significantly with spin rate due to the increased blockage that results from the longer spin radius. At 30 rpm, the first evaporator appears to be almost completely blocked. Because of the additional blockage, an increase in the heat load has a more pronounced effect on the temperature drop.
 - (b) Tests were repeated at a positive elevation to determine whether liquid could have been running back out of the reservoir when the evaporator end was oriented above the condenser. The results showed that this was a negligible effect. There was a 0.5°C increase in $T_3 - T_9$ when the evaporator was down for the deployed case. The stowed conditions exhibited a 0.5°C decrease for this evaporator orientation.

TABLE 3-16. SPIN TEST PERFORMANCE SUMMARY FOR
SP 12 -- NO RESERVOIR COOLING

DATE	SPIN RADIUS (in.)	ELEVA- TION (in.)	SPIN RATE (rpm)	HEAT LOAD (watt)	ΔT 3-1	ΔT 3-9	ΔT 7-9
7/6	70	-.12	0	70	5.6	6	3.3
				90	D.O.	D.O.	3.9
			10	70	5*	5*	2.8
				100	6.7*	6.7*	3.3
			31	70	6.7*	8.9*	3.3
				100	8.9*	11.7*	3.9
			7-8	70	7.2*	8.3*	2.2
				100	8.9*	10.6*	3.9
			71	70	14.4	7.8	0 ⁺
				100	14.4	12.2	3.3 ⁺
7/7	70	+.18	0	70	3.3	3.3	2.8
				90	6.1	6.1	3.3
			9	70	6.1*	5*	2.2
				100	7.2*	7.2*	3.9
			31	70	7.8*	9.4*	3.9
				100	9.4*	12.2*	5.6
			9	70	7.2*	8.9*	2.8
				100	8.3*	11.1*	3.9
			72	70	12.8	14.4*	5.5 ⁺
				100	12.8	15*	6.1 ⁺
7/10	51	+.16	0	70	3.9	3.3	3.3
				90	5	5	3.9

* T/C 3 oscillates

⁺ T/C 7 oscillates

D.O. = "Dry Out"

Table 3-16. - Continued

DATE	SPIN RADIUS (in.)	ELEVA- TION (in.)	SPIN RATE (rpm)	HEAT LOAD (watt)	ΔT 3-1	ΔT 3-9	ΔT 7-9	
7/11	51	+.16	24	70	6.1*	5.6*	3.3	
				100	6.7*	6.7*	4.4	
			- .10	9	70	6.7*	6.7	2.8
				0	70	3.9	3.9	3.3
					90	7.2	7.2	3.9
		24	70		5.6*	6.1*	2.8	
			100	6.7*	7.2*	3.9		
			70	70	10*	11.7*	4.4 ⁺	
				100	12.2*	11.1*	6.7 ⁺	

* T/C 3 oscillates

⁺ T/C 7 oscillates

TABLE 3-17. THERMAL PERFORMANCE SUMMARY
(SP 12 -- RESERVOIR COOLED)

DATE	CASE NO.	SPIN RADIUS (in.)	ELEVATION (in.)	SPIN RATE (rpm)	HEAT LOAD (watt)	ΔT 3-1	ΔT 3-9	ΔT 7-9
7/20	1	70	-.04	0	70	2.8	3.3	1.1
	1				90	5	5.6	1.7
	1			5	70	3.9*	4.4*	1.1
	2			5	70	2.2*	5.6*	1.1
7/21	1	70	-.04	5-6	70	4.4*	6.1*	0.6
	1				100	8.9*	7.2*	0.6
	1			72	100	18.3*	12.2*	4.4 ⁺
	1			5-6	100	9.4*	7.8*	1.1
	1	51	-.025	0	70	2.2	2.8	1.1
	1				100	3.3	3.9	1.1
	1			5	100	3.9	2.2	1.7
	1			70	100	14.4*	11.7*	3.9 ⁺
	1			5-6	100	4.4	2.2	2.2
	1				70	2.2	1.1	1.1
	2				70	1.1	1.6	1.1

* T/C 3 oscillates

⁺ T/C 7 oscillates

Case 1 = 42% of applied heat load is dissipated at the reservoir

Case 2 = 21% of applied heat load is dissipated at the reservoir

TABLE 3-18. THERMAL PERFORMANCE SUMMARY
(SP 13 & SP 14 -- NO RESERVOIR COOLING)

DATE	SPIN RADIUS (in.)	ELEVA- TION (in.)	SPIN RATE (rpm)	HEAT LOAD (watt)	ΔT 3-1	ΔT 3-9	ΔT 7-9
7/12	51	-.07	0	70	1.7	1.7	1.7
SP 14				90	2.2	2.2	1.7
			24	70	4.4*	6.1*	2.2
				100	7.2*	7.8*	2.8
			9	70	7.2*	7.8*	1.1
7/14	70	-.06	0	70	1.7	1.7	1.7
SP 14				90	2.8	2.8	2.2
			9	70	6.1*	6.7*	1.7
				100	7.2*	8.3*	2.8
			31	70	8.3*	10*	5 ⁺
				100	10.6*	13.9*	8.3 ⁺
			9	70	7.2*	9.4*	1.1
				100	8.9*	12.2*	1.7
			72	70	11.7	10	5.6 ⁺
				100	13.3*	13.3*	7.2 ⁺
7/18	70	-.09	0	70	3.9	3.9	3.9
SP 13				90	D.0	D.0	5
			9	70	6.7*	4.4*	3.9
			31	70	8.9*	7.8*	4.4*
			9	70	8.3*	7.8*	3.9
			72	70	15*	12.8*	5 ⁺

* T/C 3 oscillates

⁺ T/C 7 oscillates

2. The results that were obtained with the reservoir end cooled to simulate radiation from the RTG housing are presented in Table 3-17. Case 1 corresponds to having the cooling adjusted so that 42% of the applied heat load is dissipated at the reservoir end. Case 2 corresponds to 21% being rejected at this end. The purpose of this test was to determine if a heat piping action could be established into the reservoir end even though liquid blockage would exist. The results showed that the temperature drop in both evaporators was reduced by approximately 1° to 2°C. Heat was obviously being dissipated by the reservoir end, but as the gradients as shown in Figures 3-15 and 3-16 indicate, it appears to be a conduction mode of heat transport rather than a heat piping action. There was no adverse effect due to potential condensation in the reservoir. This is probably due to very limited condensation that occurs because of the liquid blockage that already exists.
3. The results presented in Table 3-18 indicate that the performance of heat pipe S/N SP13 without reservoir cooling is essentially the same as with heat pipe S/N SP12 for the same conditions. A comparison of the data for heat pipe S/N SP14 which was overcharged with 2.8 grams of water, indicates that this does result in any additional blockage. The evaporator temperature drops are increased anywhere from 2° to 5°C depending on the spin condition. The higher ΔT s will occur at higher spin rates and for the deployed case.

4.0 CONCLUSIONS AND RECOMMENDATIONS FOR UPGRADING THE HEAT PIPE FABRICATION PROCESS

Experience to date confirms that the internal corrosion of copper-water heat pipes is primarily a result of oxygen and the chloride ion. To illustrate the potential basic mechanism for the corrosion of copper in the presence of oxygen, the following overall reaction is presented:

After oxygen is depleted, no further oxygen reduction occurs.

Copper in the presence of chloride ions, for example at a concentration of 10^{-2}M (355 ppm Cl^{-}) and at a temperature as high as 200°C , cannot undergo a direct chemical attack if the pH is greater than approximately 3. At acid pHs < 3 , a chemical attack can occur and evolve hydrogen as illustrated by the following reaction:

The potential of the chloride ion to enter into direct chemical changes of the cupric oxide coating is presented by:

In light of the above, the procedural techniques in the fabrication of heat pipes must be optimized to assure freedom from potential contaminants that changes the thermal characteristics of copper-water heat pipes. The most significant steps to be undertaken are as follows:

- All chemicals employed in the cleaning and coating of copper must be completely removed in the process.
- Processing and charge water should have an electrical resistivity ≥ 2.0 meg ohm-cm and be free of organics to achieve a wetting angle $< 30^\circ$.
- Deaeration of the water is required to minimize corrosion by oxygen and maximize electrical resistivity by removal of carbon dioxide (air contains 0.030 volume percent CO_2 and can lower the pH of pure water to 5.7).
- A closed system is required for final cleaning and coating of heat pipe tube subassemblies to maintain purity levels. Water rinsing to maximum levels of electrical resistivity can be monitored by sensing devices.
- Water charging should be undertaken only with a well-designed system which can introduce the working fluid into the heat pipe without introducing any organic or ionic species, especially non-condensable gases such as oxygen or carbon dioxide, and with a minimum volume of non-condensable inert gases.

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