SELENIDE ISOTOPE GENERATOR
for the
GALILEO MISSION

TELEDYNE ENERGY SYSTEMS

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Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
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

MONTHLY TECHNICAL PROGRESS REPORT
OCTOBER 1978
TES-2865-23

W. E. OSMEYER
PROGRAM MANAGER

Prepared for the U.S. Department of Energy
under Contract ET—78—C—01—2865

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SELENIUM ISOTOPE GENERATOR
FOR THE
GALILEO MISSION

SUMMARY SCHEDULE
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*Demonstration Milestones

** COMPLETED
1. The bulk of the TES GDS diagnostic tests were completed during this report period. The unit will be readied for shipment to 3M in November. Test plans for module diagnostic tests - to be performed after the 3M GDS investigations - were documented by JPL, GA and TES and forwarded to the DOE San Francisco program office for approval. The results of the TES GDS diagnostic verify the necessity for the new cold end hardware design and a sublimation wrap in order to achieve an acceptable operating lifetime for the unit. The observed N element cracking was not anticipated and an immediate plan for eliminating this particular problem is not yet available, but is being formulated by the 3M Company.

2. The TES/3M interface drawings were signed off on October 31, 1978.

3. A JPL interface meeting was conducted at TES on October 5, 1978 to resolve the mechanical structures and mounting requirements for the SIG system.

4. An Improved Heat Source Meeting was held at TES on October 19, 1978 to discuss the upcoming safety tests.

5. The regular TES/3M Interface Meeting was conducted at TES on October 18, 1978.

6. TES attended an informal SIG thermoelectric review meeting at DOE on October 25, 1978. Early results of the GDS diagnostic tests were presented by TES. The 3M Company reviewed the problems currently affecting the production of modules incorporating new hardware and the schedule for S/N-1.

7. TES attended a Reliability Meeting at DOE on October 31, 1978 to review the failure mode and effects plan and the single point failure analysis. Action items and results of this meeting will be reflected in the Design Review to be held in November.

8. Continued preparation for the November 28, 29 and 30 Design Review No. 1 at DOE, Germantown.


10. All hardware and capital equipment on schedule as of this month.
B. Planned Next Period

1. Submit Design Review No. 1 Agenda to DOE Headquarters for approval.


3. Attend the JPL Quarterly Review on November 14, 1978 and prepare viewgraphs for DOE/San Francisco presentation at the review.


5. Publish letter to DOE/San Francisco, listing five major problems confronting the SIG/Galileo program.


7. Work with 3M on their revised schedule for delivery of module hardware and the S/N-1, S/N-2 generator deliveries.

8. Complete machining on S/N-1 housing, solder cooling tubes, leak check, etc., for delivery of unit to 3M on December 1, 1978.

9. Prepare for potential reviews with NASA Headquarters, Congressional Committees, second SIG Managers' Meeting and first SIG DOE Quarterly Review.

10. Continue to provide technical liaison personnel to 3M to assist where possible.

11. Review re-issue of the 3M GDS diagnostic test plan.

C. Problems

1. The SIG thermoelectric power and reliability performance goals have not been demonstrated as yet. The schedule for S/N-1 and S/N-2 may slip at the 3M Company from six to eight weeks. Demonstration module tests are late. In view of these problems TES will be requesting DOE/San Francisco approve a comparison study effort at TES which will provide data to assess the feasibility, penalties, advantages, etc., of using the MHW RTG's for the Galileo Mission in comparison to the SIG RTG's.

2. Three heat pipes which have been on accelerated test temperatures at TES have failed. Preliminary investigations into the processing of these pipes at B & K Engineering have shown the pipes did not receive an appropriate cleaning prior to assembly. X-ray investigation of all the test heat pipes did not show any other corrosion in process. (Since this event happened early in November the details of the diagnostic test plans, results, analysis, etc., will not be available until next month's report.)
D. SIG/Galileo Power-Weight-Size Statement

There is no change in this month's statement. Blast overpressure results for the improved aeroshell were excellent, thus the dual performance table remains as stated below.

<table>
<thead>
<tr>
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<th>Standard Heat Source</th>
<th>Improved Heat Source</th>
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<td>Power, BOL</td>
<td>228 W(e) nominal,</td>
<td>230 W(e) nominal,</td>
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<td></td>
<td>218 W(e) @ 95%</td>
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<td>Power, EOM</td>
<td>199 W(e) nominal,</td>
<td>201 W(e) nominal,</td>
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<td>189 W(e) @ 95%</td>
<td>191 W(e) @ 95%</td>
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<tr>
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<td>reliability</td>
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<tr>
<td>Weight</td>
<td>104.7 pounds without</td>
<td>13.2 pounds is allocated for spacecraft integration and orientation requirements</td>
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<td>attachments, of which</td>
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<td></td>
<td>13.2 pounds is allocated for spacecraft integration and orientation requirements</td>
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<tr>
<td>Envelope</td>
<td>24.3-inch diameter, 50-inch length.</td>
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TASK 2.0 - 3M COMPANY LIAISON AND INTERFACE

A. Accomplishments

1. The October TES/3M/DOE interface meeting was held at TES on October 18, 1978. Agenda items and results of the meeting are documented in the meeting minutes. A majority of the meeting activity was devoted to finalizing the interface drawing (SIG116001).

2. The TES/3M interface drawing (SIG116001) was signed off by 3M and DOE on October 31, 1978. The drawing was placed in the release system by TES.

3. TES personnel were at the 3M Company October 25 through October 27, to review existing problem areas, discuss GDS disassembly and review processes where TES background could be of use to 3M.

4. TES supported and attended a SIG thermoelectric status review meeting held at DOE Headquarters on October 25, 1978.

B. Planned Next Period

1. Conduct monthly interface meeting to be held at 3M Company on November 15, 1978.

2. Organize and conduct a meeting to resolve the issues pertaining to selenide theory (meeting to be held at the 3M Company on November 16 and 17).

3. Continue liaison with 3M in support of the diagnostic evaluation of 3M modules M-7, M-15 or any other modules subjected to diagnostic disassembly.

C. Problems

S/N-1 thermoelectric module design and performance data are not available for system evaluation prior to the RTG Design Review No. 1.
A. **Accomplishments**

1. DOE (ASMP, AL, SAN and DAO) comments on the DOE-TES-MRC Heat Source Interface Agreement draft were received and are being incorporated into the final agreement which will be transmitted to the designees for signature.

2. The scheduled ASMP Heat Source Program Review Meeting at the Mound facility was rescheduled for November 8, 1978. Visual aids were updated for the new meeting.

3. Telecons were held with C. Collins at DOE/AL concerning Galileo Mission requirements for Safety/Safeguards/Transportation during qualification and acceptance testing at the Naval Surface Weapons Center (NSWC).

4. A preliminary draft of an IHS/RTG flow chart from receipt at TES through fueling, testing and delivery was completed. Nine separate procedures for handling and safety were identified. Effort was initiated on a draft of the IHS Receiving, Storage and Monitoring Procedure.

B. **Planned Next Period**

1. Complete revisions to the DOE-TES-MRC Heat Source Interface Agreement.

2. Presentation at ASMP Heat Source Program Review Meeting at MRC.

3. Continue effort on heat source handling procedures.


C. **Problems**

None.
TASK 4.0 - JPL LIAISON AND INTERFACE

A. Accomplishments

1. A major JPL/TES/DOE technical interface meeting was held at TES on October 5 and 6. The purpose of the meeting was to discuss and resolve mechanical, thermal, electrical and specification questions. Results of the meeting are documented in SIG-WRM-1572 (Attachment 1).

2. Numerous technical interface questions were discussed on a daily basis throughout the report period. These included finalization of mounting interfaces, fin clearance requirements, cooling line interface finalization, venting mechanism review, dynamics analysis, boom deployment loads, RTD requirements and the RTG/spacecraft thermal interface.

3. A partial review was made on JPL Interface Specification ES512282.

B. Planned Next Period

1. Complete review of Interface Specification ES512282 and submit comments to DOE.

2. Review the October versions of JPL specifications ES512280 and ES512281 and submit comments to DOE.

3. Resolve the interface uncertainty for the RTG vent device.

4. Complete TES response to JPL request for RTG structural dynamics data.

C. Problems

None.
A. Accomplishments

1. Generator Design

a. The following drawings were released:
   - Clip and Spacer, Tube Support, SIG110024
   - Power Section Housing Assembly, SIG110050
   - Housing Leak Check Procedure, SIG110021
   - Fin Welding Procedure, SIG110054

b. The following drawings were submitted to checking:
   - Welded Assembly, Transition Fitting and Electrical Receptacle, SIG110017
   - Electrical Receptacle, SIG110026
   - Transition Fitting, Bimetal, Electrical Receptacle, SIG110062
   - Electrical Heat Source Transfer Container, SIG113001

c. The following drawings are in final review/signoff:
   - Bimetal Seal Ring, GVS, SIG120004
   - Bimetal Ring/Diaphragm Assembly, SIG120008

d. Design effort was continued on the generator power section handling and assembly tooling.

e. Work began on the drawing defining the TES/GE Electrical Heat Source Interface, SIG116002.

f. Final design layouts were started on the radiator, power section end covers and CBCF/Min-K insulation details.

g. MRC liaison - outgassing support.
   - Two outgassing runs were completed during this reporting period as follows: (1) 3 DCC test specimens, and (2) Min-K 1400 support discs for use in heat source support vibration development tests.
h. ORNL liaison
   * Three nominal 22" diameter by 1.87" thick CBCF-3 billets were received from ORNL on October 27. These billets comprise the reproducibility test series.
   * Revision of the ORNL QA program for CBCF-3 insulation fabrication and test procedures was completed. These documents are being processed thru the ORNL sign-off loop.

i. Final NDT inspection of the first of two clad plates (i.e., 1.1" 6061-T651/0.035" silver/1" 304L for weld transition joints) was observed and acceptance per specification was concurred.

j. Molybdenum/selenium compatibility tests.
   * The first TECO molybdenum multifoil washer stack was integrated by 3M into a single TPM couple assembly which was placed on test on approximately October 16.

k. System Effluents Review and Assessment.
   * An advance copy of a forthcoming LASL topical report on CO/\(\text{PuO}_2\) interactions in an MHW GIS assembly was requested from D. Peterson/LASL.

2. Generator Analysis
   a. Structural analysis of the flight system housing was completed. This effort included definition of the attachment lugs and lug support integral with the housing.
   b. Released moments of inertia and cross sectional area profiles as a function of length or station for the flight housing and radiator, SIG-FAS-1587 (Attachment 2).
   c. Completed numerous studies pertaining to the random vibration response for both electrical and isotopic heat sources.
   d. The in-air temperature calculation reported in the September 1978 Technical Monthly were documented. These showed a 25°C drop in SIG radiator temperatures in 70°F air (open environment) if the heat pipes are oriented such that they are functioning.
   e. Calculations of SIG weights were continued. Details of the multifoil weights were completed along with a weight summary. An effort was initiated on a probabilistic interpretation of dimensional tolerances upon the system weight.
f. Radiator analyses were continued. Modifications were initiated on the detailed TAP-3 model to account for fin extensions and heat pipe blockage (at the evaporator end). A study was documented on two suggested improvements to the radiator design, SIG-JDS-1556 (Attachment 3).

g. A summary of SIG heat losses and power was published, SIG-TEH-1578 (Attachment 4). BOL power for the improved heat source is 230.0 W(e) and 227.5 W(e) for the existing heat source.

h. A summary of SIG insulation thermal conductivity test requirements was published, SIG-TEH-1589 (Attachment 5). Details of materials and gas environments were considered.

i. A flow chart and memo were prepared outlining the TES SIG power prediction technique. Inputs required from 3M are specified. The objective of the procedure is to predict EOM SIG power and its distribution using 3M module test results.

j. Efforts were continued on the detailed system thermal model. Numerous design changes were incorporated to update the model and the necessary modifications were being made to include a gas fill.

k. Evaluation of SIG temperatures while stowed was continued. As a result of a JPL/TES interface meeting, changes are planned to the TES stowed radiator model. JPL will forward additional spacecraft details and temperatures to enable more realistic determination of stowed SIG temperatures. Details of concerns over temperatures during uncontrolled IUS coast can be found in SIG-VS-1586 (Attachment 6).

l. Analysis of heat pipe failure due to meteoroid puncture was continued. Results indicated the need to orient the heat pipes, in their saddles, such that the exposed portion of their circumference is thicker than 0.015 inches. This gives a reliability of 99.99% at 50% confidence that three or fewer heat pipes will fail over the mission. The radiator system is sized to handle a failure of three heat pipes.

3. Heat Pipes

- Under subcontract P.O. No B-81172, Battelle Columbus Laboratories electroplated copper and 60 Sn-40 Pb solder on Generator Housing S/N-2 per SIG110051, Rev. Level A.

- The following documents were released:

  Auxiliary Cooling Tube Installation, SIG110015

  Heat Pipe Tubing Selection and Charge Requirements, SIG110043
A statement of work has been prepared for B&K Engineering to conduct a heat pipe fabrication program and provide related software and technical assistance for the SIG/Galileo flight program.

An evaluation has been completed to ascertain the required dimensional tolerances of the critical mandrel dimensions per SIG111001-001 to increase the mandrel safety factor.

B&K Engineering/TES have revised SIG30041, Heat Pipe Performance Requirements, to meet the requirements of the SIG/Galileo flight program under SIG110041.

The report dealing with the effects of the Jovian environment on heat pipes has been released as SIG-DCA-1540 (Attachment 7).

4. Facility Design

a. Continued Brew liaison. Approved design for graphite load rack.

b. No positive responses were received from the air bakeout furnace RFQ concerning a new furnace. Alternate plans have been formulated.

c. Preparation of RFQ's for an optical pyrometer and residual gas analyzer system was initiated.

B. Planned Next Period

1. Generator Design

a. Begin drawings for radiator section, power section end covers, insulation details, and handling/assembly tools.

b. Release the following drawings:

   Bimetal Seal Ring - GVS, SIG120004
   Bimetal Ring/Diaphragm Assembly - GVS, SIG120008
   Welded Assembly - Transition Fitting and Electrical Receptacle, SIG110017
   Transition Fitting, Bimetal, Electrical Receptacle, SIG110062
   Electrical Receptacle, SIG110026
   TES/GE Electrical Heat Source Interface, SIG116002
c. Begin design layouts required for generator support stand, cover removal tool (3M shipping container), end cover leak check tools and radiator ring frames.

d. Continue ORNL and MRC liaison.

e. Continue review of system effluents and assessment of their effects and plausible method of control.

f. Initiate optimization study of bakeout/outgassing parameters for Varglass sleeving.

g. Receive and initiate evaluation of test sample of ceramic fiber yarn tie material produced by Santa Fe Textiles, Inc.

2. Generator Analysis

a. Continuation of the structural analysis of the housing covers and radiator.

b. Initiation of a computerized solution for the thermal stresses developed in the solder at the heat pipe - saddle interface.

c. Additional structural analysis support as required.

d. Complete documentation of the TES power prediction procedure.

e. Document meteoroid analyses.

f. Continue stowed and deployed radiator analyses.

g. Continue weight studies.

h. Continue modification of the TAP-3 system thermal model to include a gas fill.

i. Perform outgassing conductance studies.

j. Update convective generator thermal analysis.

3. Heat Pipes

A purchase order will be written to place B&K Engineering under subcontract to fabricate heat pipes and assist TES to meet with the SIG/Galileo program requirements.
The following documents will be released:

- Heat Pipe Performance Requirements, SIG110041
- Copper Plating, Electrodeposition on Aluminum and Aluminum Alloys, PS0300037
- Tin-Lead Plating, Electrodeposition on Copper and Copper Alloys, PS0300038

B&K Engineering/TES Quality shall perform weight measurements and obtain outer diameter (OD) measurements on centerless ground axially-ground copper tubing fabricated at Noranda during July 1978 under subcontract P.O. No. B-81143. In addition, the tubing shall be sampled for shadowgraph analysis and radiographed to ascertain degree of spiraling eccentricity, if any.

B&K shall perform a weld evaluation on axially-grooved tubing of the minimum wall thickness of .008 inches. This evaluation shall include a helium leak check, radiography for weld penetration and weld quality and a hydrostatic pressure test to confirm pressure containment during solder attachment.

TES/B&K shall revise LCP10022, Heat Pipe Fabrication and Processing Requirements and issue it as SIG110045.

4. Facility Design

a. Continue Brew liaison.

b. Follow-up on RFQ response for both new and refurbished air bake-out furnace facility. Pursue contingency plans as required.

c. Complete and review response for RFQ's for an optical pyrometer and residual gas analyzer systems (i.e., for use with outgassing furnaces).

d. Screen available low vapor pressure grease lubricants and select preferred grease for use within glove box/submarine" inert atmosphere assembly chambers.

C. Problems

None.
TASK 6.0 - SYSTEM TESTING AND RTG FUELING

A. Accomplishments

1. ETG/RTG test planning activities continued this month between NSWC and TES personnel. Emphasis has been placed on defining the appropriate test facility for the pyrotechnic shock environment. NSWC (and most other) electrodynamic vibration shakers are unable to attain the 7000 Hz frequency peak required by the pyrotechnic shock response spectrum.

2. A draft of the mass properties test procedure (SIG114003) has been initiated.

3. A conceptual design of the ETG/RTG shock and vibration test fixture has been initiated.

4. A conceptual design of the engineering mass model has been initiated. The mass model is intended to serve as a tool for test fixture checkout, dynamic test spectrum shaping and for fueling training sessions.

5. The flight system outgassing station consists of three basic divisions:
   a. A turbomolecular pumping system and plumbing to the generator.
   b. A gas management system for filling the generator with a desired gas.
   c. A calibration and measurement system for measuring outgas constituents.

Drawing SIG111019 was released describing the turbomolecular pumping system and associated plumbing to the generator.

Drawing SIG111020 was released showing the gas management system and the calibration and gas measuring system. A new outgassing station schematic was completed.

6. All components of the outgassing station have been defined and requisitions written for the turbomolecular pumping system, the gas management system and the calibration and measurement system. There have been delays in obtaining approval to purchase the above equipment.

7. During outgassing of GDS-1, a problem was recognized that the connection between the outgassing tube and the pumping station did not consistently achieve an ultra high vacuum seal. The GDS seal consisted of brass Swagelok ferrules on an aluminum outgas tube. A new outgassing tube being investigated for the generator is a bimetallic, explosively bonded tube with a Conflat seal flange. The tubes undergoing test have responded well to machining and thermal cycles between room temperature and 450°F. Of the four tubes tested, none have shown any detectable helium leaks.
8. The laboratory test power supply for the GE-supplied GFE graphite heaters has been designed and most parts have been ordered.

9. The load bank has been designed and all parts ordered. The open circuit voltage timing circuit is being investigated to determine if less components are needed to do the same job. Hopefully, smaller and improved circuitry will result from the investigation.

10. The SIG-GDS-1 outgassing station was disassembled and components are being stored for use in the flight system outgassing station. The new station incorporates a different plumbing arrangement from GDS. Part of the change is due to the increased size of the flight generator and part to planned improvements. (See Monthly Progress Report TES-2865-7, August 1978.)

B. Planned Next Period

1. Coordination of ETG/RTG test activities at NSWC with emphasis on defining the test fixtures required for vibration, shock, mass properties and magnetics testing.

2. Initiate the design of the ETG/RTG test fixture for magnetic properties testing.

3. Completion of the ETG Acceptance Test Plan (CDRL product definition item #4) covering testing of SIG ETG's at TES and NSWC.

4. Complete design of an engineering mass model.

5. Perform tests which correlate leak rate measurements made with a VEECO leak detector and the Q200 Leybold Heraeus residual gas analyzer.

6. Construct a test setup which verifies performance of a modified outgassing station heat rejection system employing water as the working fluid.

C. Problems

1. Approval for purchase of mass properties testing system. Further delay in placing order jeopardizes the receipt of the system in time for the scheduled engineering mass model testing in April 1979.

2. Approval for purchase of outgassing station components. Of particular importance are the components needed to modify the GDS station into the flight system configuration.
A. Accomplishments

1. At the User Interface meeting held at the TES facility on October 5 and 6, points of discussion were: (a) TES/JPL interface connectors, (b) types of electrical insulations for generator power output and instrumentation cables for flight hardware, and (c) temperature measurement ranges for generator temperature sensors. The latter item is used by TES to determine the design for the basic input range of the temperature measurement instrumentation section of the generator readout console. This console is also called a PMP (Portable Monitor Package) in subsequent paragraphs.

2. Liaison with JPL personnel was maintained during this reporting period to finalize the selection of the TES/JPL interface connectors. There will be two types of interface connectors. The model selected for the generator power output and internal generator ground is a NB-OE-18-8 SNC. This unit is a narrow square flange receptacle, size 18 shell (aluminum) with eight #12 AWG sockets.

The connector model chosen for generator temperature instrumentation signal lines is a NB-OE-14-19 NBC. This unit is also a narrow square flange receptacle, size 14 shell (aluminum) with nineteen #20 AWG pins.

The respective mating plugs of the spacecraft system interface cables and/or of the TES PMP interface cables are a NB-6E-18-8 PN-S-18 connector for the generator power output and internal ground, and a NB-6E-19SN-S-14 connector for the generator temperature instrumentation. All interface connector units selected are approved for space applications per NASA MSFC specifications 40M39569.

3. A 3-foot long generator radiator cable which interfaces with the hermetically sealed receptacle located on the generator end cover, carries generator output power and internal ground to the TES/JPL interface receptacle NB-OE-18-8 SNC. This cable runs along the inside of the cylindrical radiator body. The interface receptacle is mounted at the end of the boom-mount end of the radiator.

A second interface cable for the four generator RTD's (Resistance Temperature Detector) carries eight signal lines from these sensors to the TES/JPL interface receptacle NB-OE-14-19 PNC. The RTD's are mounted around the perimeter of the generator housing and their interface cable runs along the outside of the radiator body to the aforementioned interface receptacle. This receptacle is also mounted at the end of the boom-mount end of the radiator.
Since both cables will be exposed to impinging space radiation particles, Kapton was selected as insulation material for the wires of both interface cables. This is also the insulation material JPL will use for wiring of the spacecraft interface cables. Efforts were completed to locate a JPL-approved supply source for these Kapton-insulated wires. The vendor is Teledyne Thermatics, Elm City, N.C.

4. The outside surfaces of the generator power output and instrumentation cables must be provided with an electrically conductive finish according to JPL spacecraft wiring specifications. Efforts were initiated to determine a suitable material with respect to electrical conductivity and weight penalty to serve as shielding material for these cables runs. Each shielding sleeve is then single-ended grounded to generator ground. The functional purpose of the shielding is to prevent a buildup of an electrostatic charge along the cable runs during the space mission.

5. Efforts were started to size the temperature/resistance input range for the temperature instrumentation section of the generator PMP unit. The primary generator temperature sensor will be an RTD type with a high-purity nickel wire element. Since the resistance input range of the temperature sensor signal conditioning unit of the spacecraft telemetry extends from 292.8 ohm to 646.4 ohms (a measurement span of 353.6 ohms), design efforts were initiated to optimize this available span for significant temperature data about generator status (engineering measurements) throughout the Galileo mission. A number of computer runs were conducted to evaluate theoretical RTD calibration curves.

6. The design of drawing SIG113001, EHS (Electrical Heat Source). Shipping Container, was completed. The functional purpose of this unit is to protect the GFE-furnished EHS assembly during transportation and storage against shock and vibration and against any exposure to the ambient air atmosphere. The EHS shipping container is a hermetically sealed metal container with internal shock mounts for the EHS assembly.

7. Meetings with suppliers of hardware components for GSE applications were continued during this reporting period.

8. A number of connectors (receptacles and mating plugs) for GSE interface cabling and consoles were received from the Deutsch Company, Banning, California.

9. A. P.R. 58142 was placed for TES/JPL interface receptacles and mating plugs. TES Procurement transmitted RFQ's for these connectors to various manufacturers.

10. Responses to RFQ's for instrumentation and other GSE components were received and evaluated.
11. TES Procurement placed additional P.O.'s for long-lead delivery GSE hardware items.

B. Planned Next Period

1. TES Procurement will place a P.O. for Kapton-insulated #12 AWG and #24 AWG wire with Teledyne Thermatics, Elm City, North Carolina. The materials will be purchased per JPL specification ST-11932. These items will be long-lead delivery items.

2. Design drawing SIG113001, EHS Shipping Container will be released.

3. Efforts to define the temperature/resistance range of the nickel element RTD will be continued and finalized in order to transmit RFQ's to potential vendors of RTD readout instrumentation.

4. TES Procurement will continue to place P.O.'s for long-lead delivery GSE items.

5. Efforts of RFQ writeups, RFQ response evaluations and vendor liaison will be continued.

6. Liaison with cognizant JPL personnel will be continued to finalize cable shielding configurations, RTD operational temperature ranges and other pertinent items.

7. Design layouts of drawings SIG111013 (test cable) and SIG111014 (test stand) will be continued.

8. Design efforts for drawing SIG113009, Generator Handling Sling, will be initiated.

C. Problems

None.
TASK 8.0 - MANUFACTURING

A. Accomplishments

1. The following generator details and tooling were fabricated during this period.
   - Heated Bonding Tool for Auxiliary Cooling Tubes
   - Housing/Fin Welding Fixture
   - Housing Leak Check Fixture with Internal Housing Wall Support Details
   - Dummy Generator Development Housing (for weld and coating development studies)
   - Dummy Housing Fin Details
   - End Cover Weld Development Details
   - Cooling Tube Extension Details

2. Manufacturing welded fins on the dummy generator development housing to verify welding procedures and tooling.

3. Manufacturing completed the fabrication of test specimens in support of Task 12.0.

B. Planned Next Period

1. Complete fabrication of the ETG S/N-1 generator housing for shipment to 3M on December 1, 1978. Operations will include:
   - complete machining of housing
   - installation (soldering) of auxiliary cooling tubes
   - welding of fins
   - final leak check
   - packaging for shipment

2. Continue support of SIG/Galileo Program as required.

C. Problems

None.
TASK 9.0 - QUALITY ENGINEERING AND CONTROL

A. Accomplishments

1. Quality Engineering was present at Battelle Columbus Labs during the masking and plating operations performed for the "backup housing" (S/N-1) SIG110051. Aside from minor surface roughness and edge effects the plating (both copper and tin-lead) appeared satisfactory for usage. Details of the on-site inspection are reported in RS Tag 13625.

2. Further review of proposed changes to the SIG Quality Assurance Program Plan (TES-2865-13) were held at DOE, Germantown, Maryland on October 5. At the conclusion of the discussions with the DOE Quality representative, there was concurrence among the parties involved that all changes necessary were completed and upon adoption of these changes a final issue of the plan could be released.

3. The audit of PS0300036, "Protection and Cleaning of Aluminum and Aluminum Alloys," has been successfully completed and the auditors did not uncover any deficiencies or needed revisions to the specification. An audit is still in progress for Q.D. 3.5, "Handling of Scrap and Salvage Hardware."

4. Completed data package for the Disassembly of Generator Body Assembly Part No. SIG30001-009 Serial No. GDS-1 (copy to 3M Company with shipment of GDS-1; also Sandia's M. Zapach has copy of data package).

B. Planned Next Period

An internal Quality Audit has been initiated for PS0300038, "Tin-Lead Plating, Electrodeposition on Copper and Copper Alloys." The audit is scheduled for completion on November 30, 1978.

C. Problems

None.
TASK 10.0 - RELIABILITY

A. Accomplishments

1. A single point failure analysis (SPFA) for the SIG-RTG power section enclosure seals was completed. Approximately twenty SPF locations were identified, none of which easily lend themselves to elimination from the design. An allowable leak rate criteria for the enclosure of $1.0 \times 10^{-8}$ sec He/sec-atm was established for the RTG configuration for assessment purposes. (Refer to SIG-LLR-1551, Attachment 8.)

2. An updated SIG Reliability Program Plan was reviewed at a DOE/TES meeting on October 20. Action items generated at that meeting were incorporated and the plan re-submitted to DOE for final approval as a CDRL No. A-11 document.

3. Resolution of the variability associated with the thermal performance data generated from the ongoing heat pipe life tests, reported last month, is progressing. An identification of the cause(s) for the variation in data and a proposed revision in the method by which the data are analyzed are covered in Task 16.0. As part of Task 10.0 activities, a method for predicting and assessing the thermal performance of the heat pipe at end of mission was completed. The method uses the Arrhenius rate model as a basis. (Refer to SIG-GWB-1576, Attachment 9.)

4. An update of the analysis of non-condensable gas produced by the axially-grooved (B & K Engineering) and sintered metal wick (Hughes Aircraft) heat pipes was completed covering ~4,000 hours of operation. The gas generation rate for the axially-grooved heat pipe (selected for the flight generators) is less than the backup sintered metal wick pipe. Trend analysis, using curve fitting functions, was deferred due to insufficient test time. Refer to SIG-GWB-1581 and SIG-GWB-1585 for the axially-grooved and sintered metal wick analyses, respectively, (Attachments 10 and 11).

5. The first reliability program review, conducted in accordance with the program plan requirements, was held October 31 at DOE, Germantown. The review summarized the failure modes, effects and criticality analysis for the TES responsible portions of the SIG-RTG and identified the single point failures. The contents for the reliability portion of the Preliminary Design Review was also identified at this review.
B. Planned Next Period

1. Distribute DOE approved SIG Reliability Program Plan, TES-2865-06.

2. Prepare detail single point failure analysis for electrical circuit.

3. Review component test program and establish applicability of test data to the reliability data base.

C. Problems

None.
TASK 11.0 - SAFETY ASSESSMENTS

A. Accomplishments

1. In response to a request from MRC, the advisability of eliminating the PICS outer surface sandblasting from the fabrication process is being examined. This was originally suggested by Fairchild Industries as a means for increasing the PICS temperature on impact in the event of an accident and thus enhancing the ability of the PICS to survive impact. However, the elevated nominal temperature prior to impact could have a detrimental effect. Given an accident which left the heat source in earth orbit for an extended period of time, the elevated PICS temperature, resulting from no sandblasting, could appreciably accelerate the "aging" effects which degrade the impact capability (grain growth, migration of impurities). The detriments associated with aging could more than offset the benefits of higher temperature at impact. A study is in progress which will determine the impact temperature distributions and examine the effects of the impact and orbit residual steady state temperature for the sandblast versus the non-sandblast cases.

2. Plasma arc tests on various forms of graphite (POCO, AXF-5Q, GE 3DCC, Avco FWPF, Graphonol and Pyrocarb 406) were observed in the Air Force Flight Dynamics Laboratory's 50 megawatt Re-entry Nose Tip (RENT) Test Facility at Wright-Patterson Air Force Base on October 24 and 25. This heat source test program is reported more fully in Task 12.0.

B. Planned Next Period

1. Complete the above described study.

2. Review fragment environment and response models (for PSAR analysis).

3. Observe overpressure tests at LASL (tests tentatively scheduled for week beginning November 13).

C. Problems

None.
TASK 12.0 - IMPROVED MHW HEAT SOURCE DESIGN

A. Accomplishments

1. All plasma arc testing was completed at the AFFDL 50 megawatt test facility at Wright-Patterson Air Force Base. Two high pressure environments were applied to two groups of seven test models per group. The models included GE/3DCC, AVCO/FWPF, POCO AXF-5Q, Graphmol and a combination of Pyrocarb 406 and POCO, the latter models simulating the existing MHW aeroshell plus ablation sleeve.

2. The 3DCC aeroshell details in support of the system blast overpressure tests were fabricated and shipped to Mound Facility for vacuum outgassing. These components will then be shipped to LASL and assembled at LASL by Mound personnel. The test program is tentatively scheduled to begin during the week of November 13.

3. Numerous additional testing has been initiated during the past reporting period including chemistry, outgassing experiments, flyer plate, gas gun and oxidation.

4. The complete matrix of test coupons of GE/3DCC, AVCO/FWPF and POCO have been forwarded to the test laboratories with exception to the NASA/Ames plasma arc model assemblies. The arc models have been fabricated, outgassed and weighed and the model holder-model assemblies will be completed early in the next reporting period.

B. Planned Next Period

1. Receipt of all 3DCC specifications and associated material to fully define the billets procured and tested.

2. Completion of numerous tests including oxidation, flyer plate, system overpressure and chemistry.

3. Evaluation of completed tests with an emphasis on the AFFDL plasma arc tests.

4. Shipment of sixteen model assemblies to NASA/Ames for plasma arc testing.

C. Problems

None.
TASK 13.0 - (RESERVED)
TASK 14.0 - ADVANCED CONCEPTS AND MISSION APPLICATIONS

A. Accomplishments

No activity during this reporting period.

B. Planned Next Period

No activity anticipated.

C. Problems

None.
**TASK 15.0 – FIELD AND LAUNCH SUPPORT**

A. **Accomplishments**
   
   No activity during this reporting period.

B. **Planned Next Period**
   
   No activity anticipated.

C. **Problems**
   
   None.
TASK 16.0 - COMPONENT DEVELOPMENT, RELIABILITY AND LIFE TESTING

A. Accomplishments

1. GDS Testing

   a. GDS-1 was cooled to room temperature in preparation for diagnostic disassembly. During the cool-down the thermoelectric module resistance exhibited erratic behavior, varying from 1.6 ohms to more than 1000 ohms. The insulation resistance was consistently less than ten ohms with the short being localized in the region of T/C's #15 and #16.

   b. A hot leak test of GDS-1 was performed with the hot junction at 230°C. Because of the large helium background, the leak rate could only be determined to be less than $5 \times 10^{-6}$ scc He/sec. When the housing was cooled to room temperature the leak rate increased to $5 \times 10^{-5}$ scc He/sec. This leak rate was associated almost completely with the swagelok fitting at the top of the generator which had originally shown a leak rate of $3.6 \times 10^{-7}$ scc He/sec during the initial generator heat-up and operation at temperature.

   c. Three gas samples taken from GDS-1 were analyzed. Two samples which had been taken at 850/150°C were analyzed by Gollob Analytical Service and Monsanto Research Corporation (MRC). The third sample was taken at 700/150°C and was analyzed by Battelle Columbus Laboratory (BCL). Results of the three analysis are:

<table>
<thead>
<tr>
<th></th>
<th>Gollob</th>
<th>MRC</th>
<th>BCL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_2$</td>
<td>&lt;4 ppm</td>
<td>&lt;20 ppm</td>
<td>&lt;20 ppm</td>
</tr>
<tr>
<td>$O_2$</td>
<td>&lt;4</td>
<td>&lt;20</td>
<td>&lt;20</td>
</tr>
<tr>
<td>$H_2O$</td>
<td>-</td>
<td>&lt;20</td>
<td>&lt;100</td>
</tr>
<tr>
<td>$CO_2$</td>
<td>&lt;100</td>
<td>&lt;60</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Ar</td>
<td>14</td>
<td>&lt;20</td>
<td>-</td>
</tr>
<tr>
<td>$H_2$</td>
<td>11</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>He</td>
<td>72+%</td>
<td>74.8%</td>
<td>-</td>
</tr>
<tr>
<td>Xe</td>
<td>27.6%</td>
<td>25.2%</td>
<td>-</td>
</tr>
</tbody>
</table>
The analyses indicate low quantities of the critical trace gases O₂, H₂O, CO₂, and H₂. The results confirm the fact that earlier analyses of the generator gas were in error in that they indicated large quantities of N₂, O₂, or H₂O.

d. GDS-1 was disassembled according to a prepared procedure. The end covers and IHF were removed by machining. The T/E module resistance and insulation resistance were continuously monitored during machining and disassembly steps. The heater and insulation components showed little physical change since assembly. There were slight stains on various insulation details and some loose foreign particulates. Numerous samples were taken which will be analyzed, and photographs were made of the disassembly and visual observations. Insulation was removed from the T/E legs on each end of the module. The following is a listing of observations made of the elements and cold end hardware:

- Black coating on all copper cold end hardware
- Large amounts of black crystalline deposits on copper cold straps
- Cracks in all n-legs
- Orange ring around all n-legs
- Bullet nosing of hot ends of both p-leg segments
- Large amount of misalignment of legs with hot and cold shoes
- Some n-legs tilted badly
- Hot p-leg segment larger in diameter than cold segment
- Crystalline deposits on many p-legs which sometimes results in bridging of partition
- Dark deposits on BeO insulation disc bridging cold strap and follower
- Copper extrusion between cold end of p-legs and copper cold shoe, sometimes extreme, resulting in distortion of p-leg material

The ends of the GDS housing have been cut off and the inner step machined away so that the module can be removed by 3M without having to retract the cold end segments any great distance.
e. As a prelude to GDS disassembly, the initial stage of the diagnostic disassembly of Module M-7 was observed at the 3M Company, St. Paul, Minnesota on October 5 and 6, 1978. Pertinent observations are summarized in SIG-WJB-1580 (Attachment 12).

2. Heat Pipe Testing and Development

a. A flight configuration heat pipe was tested in a vertical refluxing mode with various reservoir lengths. The results are presented in SIG-JPC-1559 (Attachment 13).

b. The problems associated with the heat pipe data collection and analysis are explained in SIG-JPC-1565 (Attachment 14). The re-evaluation of the heat pipe test effort and data collection is presented in SIG-JPC-1564 (Attachment 15).

c. A subcontract, placed with Battelle Columbus Laboratories to conduct the Heat Pipe Soldered Joint Evaluation, has been held up pending a BCL/TES review and technical critique of work scope adjustments suggested by DOE (refer to FSEC-ESD-217 78/147 from H. Kling to F. Dieringer and letter 1412 from R. Harnar to F. Dieringer).

d. Brass condenser blocks were soldered to heat pipes S/N AL-5, S/N 4D and S/N LT-57 with 95 Sn - 5 Sb solder (melting range of 232° - 240°C).

e. A statement of work has been written for B & K Engineering to continue accelerated life testing of heat pipes S/N AL-5, S/N 4D and S/N LT-57 at 225°C and for technical assistance in the area of non-destructive and destructive analysis of heat pipes being life tested at TES.

f. A subcontract was initiated with Packer Engineering to conduct a failure analysis of failed Hughes heat pipes S/N 15A and S/N 9A.

3. Generator Vent System Tests

a. Drawings for diaphragm, lance and diaphragm pierce test fixture were completed and released. Details for test are being prepared by Manufacturing.

b. Follow-up was made on the request to General Electric for diaphragm forming information.

c. Preparation of SIG125019, Generator Vent System Test Procedure, was initiated.
4. Thermal Insulation Properties

a. Multifoil vibration test fixture was run at NSWC to determine spectral response.

b. Vibration test sample was received and modified for bolting to fixture. One tab was pulled loose and is being repaired.

c. Multifoil Edge Effect Tests were delayed by vacuum system problems at TECO. These have been corrected and tests are proceeding. They should be completed by the end of November.

d. The test program on multifoil performance is being modified to include the effect of gases on performance. He, Xe, and Ar will be used.

e. The purchase order to TECO has been amended to allow the use of 0.0004" Mofoil in place of 0.0003" Mo in the center section of ETG S/N-1 only. This is because of schedule problems with the thinner foil. TECO indicates that the effect on Q will be negligible. All other parts will use 0.0003" Mofoil.

f. Thermocouples will be added to the hot and cold getters and the outer foil on the first generators to check the heat flux in situ.

g. A program to measure gas effects in the fibrous insulations is being developed. Xe, He, and Ar are being investigated to aid in prediction of submarine and launch pad environment operation.

h. Two room temperature load relaxation tests were run on Min-K 1400 at 50 psi. Neither sample showed any load relaxation at 900 hours. One was removed and found to have taken no permanent set. The other sample will be removed next month.

i. The two 800/150°C load relaxation tests outgassed on Min-K 1400 are continuing.

j. The 1000/650°C CBCF-3 load relaxation test is continuing.

k. The 1000/650°C CBCF-5 load relaxation test was terminated at 350 hours. The sample had relaxed to 18% of its initial value. CBCF-5 will not be used in the flight system because of its relatively high thermal conductivity previously reported.
5. Weld Attachments
   a. Fin/housing weld trials – Manufacture of the dummy housing, fins and fin weld tool was completed. Fin welding was completed and dimensional inspection was initiated.
   b. Based on initial results from an ongoing evaluation of weld joint parameters for the fueling end cover/housing weldment, a weld joint geometry was recommended for incorporation into the housing design.

6. Cold End ΔT Test
   The Sn plated cold end ΔT sample was tested in vacuum and argon. The average results were comparable to the foil tests, but the individual T/C's showed wider variation.

7. Emissive Coatings
   a. Z-93 emittance tests at TRW were completed. The emittance data, as discussed in memorandum SIC-MEH-1573 (Attachment 16), was somewhat lower than expected -- typically 0.90 versus 0.93. Additional emittance tests are being planned at both Boeing and Aerojet.
   b. Initiated preparation of the Boeing emittance test samples.
   c. A PR and DOE approval package were prepared for an optical-electrical property degradation (simulated space environment) measurement study to be conducted by Boeing, Seattle, Washington.
   d. Discussions regarding a detailed test plan for the electrostatic charging/UV exposure test program were continued with NASA/Lewis personnel.
   e. Completed Z-93 coating resistivity tests at NASA/Goddard. Letter report of test data was received. Values are well within JPL requirements.
   f. Continued long-term thermal aging of adherence test coupons. Aging time now exceeds 3,000 hours. Preparation of additional adherence test coupons (i.e., representative of the current and improved operator skills) was initiated.
   g. Z-93 coating application scale-up studies (i.e., operator technique development) were initiated. This on-going effort will be directed toward progressively larger and more complex hardware shapes and will culminate with the coating of the dummy housing assembly.
h. Responses to RFQ for eddy current type thickness gauge were evaluated. The Sigma ED Eddy Current Coating Thickness Tester was selected and preparation of a procurement package for DOE approval was initiated.

8. Electrical Receptacles

a. The Deutsch Steel Shell Receptacle Test Plan was completed. The test plan defines a total of 19 test samples for thermal margin rating, elevated temperature life and thermal cycling types of tests.

b. The Deutsch Company, Banning, California (the supplier of the hermetically sealed receptacles) completed the firing and room temperature leak tests of 60 hermetically sealed receptacles, Model 78033-16-26PN. Teledyne Energy Systems received these 60 receptacle units on October 31.

c. A document SIG110027, Quality Control Acceptance Test Procedure, Electrical Receptacle, was drafted for TES Quality acceptance test operations for the new Deutsch receptacle units.

d. The updating of document LCP10032, Electrical Receptacle Life and Cycle Test Procedure, was started to incorporate the scope of the revised receptacle test plan.

e. Two (2) receptacle/bimetal transition ring assemblies reached 4,444 hours of continuous life performance testing at 400°F by the end of this reporting period. Their previous test history and latest leak rate measurements are presented in Table 1. The life performance test comprises aging for 8,000 cumulative hours at 400°F with periodic leak rate checks during this test period.

f. Seven (7) dummy receptacle/bimetal transition ring assemblies reached 3,000 hours of cumulative life performance (thermal aging) testing to date. Their previous test history and latest leak rate measurements are shown in Tables 2 and 3. The life performance tests consist of aging for 10,000 cumulative hours at elevated temperatures with periodic leak rate tests during this test span.

g. A number of receptacle test stations of the TES test loop installation were prepared and checked out for the operation of additional receptacle test specimens from the new Deutsch receptacle batches.
### TABLE 1

**RECEPTACLE/BIMETAL RING LIFE TEST RESULTS**

Test History: 2 receptacle/bimetal ring assemblies.  
2 thermal cycles, 300°F to 150°F to 300°F.  
36 thermal cycles, 400°F to 150°F to 400°F.  
4000 hours aging at 400°F to date.

<table>
<thead>
<tr>
<th>Receptacle</th>
<th>Previous Leak Rate</th>
<th>Latest Leak Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>S/N-323</td>
<td>$1.1 \times 10^{-9}$ scc He/sec-atm</td>
<td>$1.45 \times 10^{-9}$ scc He/sec-atm</td>
</tr>
<tr>
<td>S/N-370</td>
<td>$1.4 \times 10^{-9}$</td>
<td>$1.48 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

### TABLE 2

**DUMMY RECEPTACLE/BIMETAL RING LIFE TEST RESULTS**

Test History: 3 test specimens.  
2 thermal cycles, 475°F to 100°F to 475°F.  
30 thermal cycles, 400°F to 100°F to 400°F.  
3000 hours aging at 400°F to date.

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Previous Leak Rate</th>
<th>Latest Leak Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>S/N-B0701</td>
<td>$6.2 \times 10^{-10}$ scc He/sec-atm</td>
<td>$1.1 \times 10^{-9}$ scc He/sec-atm</td>
</tr>
<tr>
<td>S/N-B0702</td>
<td>$4.5 \times 10^{-10}$</td>
<td>$9.2 \times 10^{-10}$</td>
</tr>
<tr>
<td>S/N-B0703</td>
<td>$4.0 \times 10^{-10}$</td>
<td>$7.4 \times 10^{-10}$</td>
</tr>
</tbody>
</table>
### TABLE 3

**DUMMY RECEPTACLE/BIMETAL RING LIFE TEST RESULTS**

Test History: 4 test specimens.
- 2 thermal cycles, 475°F to 100°F to 475°F.
- 30 thermal cycles, 300°F to 100°F to 300°F.
- 3000 hours aging at 300°F to date.

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Previous Leak Rate</th>
<th>Latest Leak Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>S/N-B0704</td>
<td>$4.0 \times 10^{-10}$ scc He/sec-atm</td>
<td>$9.0 \times 10^{-10}$ scc He/sec-atm</td>
</tr>
<tr>
<td>S/N-B0706</td>
<td>$6.4 \times 10^{-10}$</td>
<td>$8.9 \times 10^{-10}$</td>
</tr>
<tr>
<td>S/N-B0801</td>
<td>$5.0 \times 10^{-10}$</td>
<td>$9.5 \times 10^{-10}$</td>
</tr>
<tr>
<td>S/N-A1205</td>
<td>$3.8 \times 10^{-10}$</td>
<td>$7.9 \times 10^{-10}$</td>
</tr>
</tbody>
</table>
9. Characteristics of the Flight System Auxiliary Cooling Loop

Test specimen preparation activities included:

a. Mycalex heater ring supports have been deleted in favor of three set screws for location of heater rings concentrically within generator housing.

b. Hypodermic needle pitot design was generated in order to monitor flow rates of water in each cooling loop. Inclined gages will measure individual flow rates.

c. Tested G. E. RTV-60 silicone rubber samples at 600°F - 650°F operating temperature. No deterioration thus far at 600°F.

d. All components in plumbing circuitry have been ordered except small tubing and fittings for pitot hookup.

10. Flight System Cold Vibration Model

Performed vibration test on heat source mass model at NSWC. After completion of sine and random vibration testing in the axial direction, preload was measured and found to have decreased 700 lbs from the 2000 lbs initial preload. Diagnostic disassembly revealed a material permanent compression of 0.019 inch total out of 4.0 inches of insulation. Personnel at NSWC feel that heat source fixture lost this preload during the sine test since this test is more severe. Additional testing is required to evaluate the problem.

B. Planned Next Period

1. GDS Testing

a. Deliver GDS-1 module to 3M for removal from the rest of the housing. The module will be divided up for further analysis by 3M, TES, JPL, and GA.

b. A report on the diagnostic disassembly of GDS-1 will be prepared. This report will cover the cool-down and physical disassembly of the generator. Any analytical results obtained prior to releasing the report, such as gas analyses, will also be included. A final report will be prepared presenting the findings of the detailed analyses yet to be performed.
2. Heat Pipe Testing and Development
   a. Continue the heat pipe life test.
   b. Battelle Columbus Laboratories personnel will travel to TES before November 17, 1978 to review the Statement of Work to conduct a heat pipe soldered joint evaluation per DOE suggested adjustments.
   d. A purchase requisition will be written to place B & K Engineering under subcontract to continue accelerated life testing and provide technical assistance to TES for analysis of life tested heat pipes.

3. Generator Vent System Tests
   a. Preparation of additional component and test fixture drawings.
   b. Continue writing test procedures.
   c. Continue fabrication of test components.

4. Thermal Insulation Properties
   a. Run vibration test on multifoil.
   b. Visit TECO to discuss fabrication of generator parts, and to observe progress on development tests.
   c. Start new load bearing tests on outgassed Min-K TE 1400 and CBCF-3.
   d. Check out guarded hot plate apparatus (scheduled for delivery approximately November 20).
   e. Fully define gas effect thermal conductivity tests.
   f. Start on vacuum load bearing fixtures.
   g. Start long-term in-gradient insulation tests when CBCF-3 becomes available.
5. Weld Attachments
   a. Complete dummy housing fin assembly inspection. Analyze resulting data, and assess practicality of current S/N-1 housing assembly sequence.
   b. Continue evaluation of weld parameters for the fueling end cover/housing weldment. Initiate plans for welding full scale dummy hardware in fueling chamber in January 1979.
   c. Initiate plans for weld development support for the GVS (generator vent system) fabrication.

6. Cold End ΔT Test
   Issue cold end ΔT test summary.

7. Emissive Coatings
   a. Finalize test plans, particularly the exposure conditions, for the NASA/Lewis (electrostatic charging) and Boeing (α and resistivity) space environmental degradation effects studies. Advise JPL of the selected exposure conditions. Prepare test specimens.
   b. Partially complete emissivity measurements by Boeing. Receive test specimen substrates from Aerojet, apply Z-93 coating and return to Aerojet for emissivity measurements.
   c. Prepare test samples and complete ambient temperature solar absorptivity measurements (Boeing). Assess the use of $\alpha_8$ measurements as a quality control tool.
   d. Continue long-term aging of adherence test coupons.
   e. Continue Z-93 coating application scale-up studies.

8. Electrical Receptacles
   a. Document SIG110027, Quality Control Acceptance Test Procedure, Electrical Receptacle, will be completed and released.
   b. Document LCP10032, Life and Cycle Test Procedure, Electrical Receptacle, will be updated to incorporate the scope of the revised receptacle test plan.
c. The sixty new Deutsch hermetically sealed receptacles will undergo 70°F and 400°F leak rate tests conducted by TES Quality Control.

d. Life performance (thermal aging) tests will be continued with two (2) receptacle/bimetal ring assemblies and seven (7) dummy receptacle/bimetal ring assemblies.

9. Characterization of the Flight System Auxiliary Cooling Loop
   a. Complete procurement of all remaining hardware.
   b. Complete draft of Performance Test Specification.
   c. Start assembly of simulated generator housing after return from plating.
   d. Complete Test Stand Assembly drawings.
   e. Initiate assembly of Test Stand.

10. Flight System Cold Vibration Model
   a. Perform heat source preload versus deflection repeatability tests with the test fixture.
   b. Retest the heat source mass model at NSWC. Preload will be checked after the sine test.

C. Problems

Continue evaluation of cause of relaxation of heat source preload as discussed in B.10 above.
TASK 17.0 - CAPITAL EQUIPMENT/FACILITIES REPORT

A. **Accomplishments**

1. Generator Assembly Glove Box Modifications - fabrication of parts by Vacuum Atmosphere Company is in progress (P.O. 81153).

2. Vacuum Outgassing Furnaces (2) - fabrication by Richard Brew Company is in progress (P.O. 81118).

3. Thermal Vacuum Chamber - fabrication by CVC Products is in progress (P.O. 81163).

4. Fueling Chamber Modification - fabrication of parts by Process Equipment Company is in progress (P.O. 81540).

5. Quality Test Equipment - Digital Thermometer was received (P.O. 83294). The fabrication of the Digital Multimeter is in progress (P.O. 83295).

6. Guarded Hot plate - fabrication by Dynatech Corporation is in progress (P.O. 81144).

7. Brush Recorder Preamplifiers - fabrication by Gould Incorporated is in progress (P.O. 81562).

8. Generator Outgassing Station - specifications were completed and a DOE approval request was sent October 3, 1978.

9. Mass Properties Test System - specifications were completed and a DOE approval request was sent October 10, 1978.

B. **Planned Next Period**

1. Continue detailed planning of piping and wiring for the Thermal Vacuum Chamber.

2. Vendor liaison with capital equipment vendors.

3. Complete facility excavation and construction for the Modified Fueling Chamber.

C. **Problems**

None.
MEMORANDUM

October 16, 1978
Refer to: SIG-WRM-1572


cc: G. Linkous, P. Dick

From: R. Menchen

Subj: Results of JPL/DOE/TES Technical Interface Meeting Held at TES on October 5-6, 1978.


Objective: Describe content and results of JPL meeting.

Conclusion and Implications: See action items in the list which follows.

Attendees

<table>
<thead>
<tr>
<th>JPL</th>
<th>TES</th>
</tr>
</thead>
<tbody>
<tr>
<td>R. Ivanoff</td>
<td>R. Menchen</td>
</tr>
<tr>
<td>A. Lockwood</td>
<td>W. Brittain</td>
</tr>
<tr>
<td>R. Becker</td>
<td>A. Lieberman</td>
</tr>
<tr>
<td>B. Muirhead</td>
<td>O. Davidson</td>
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<td></td>
<td>F. Schumann</td>
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<tr>
<td></td>
<td>S. Roedel</td>
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<td></td>
<td>T. Brown</td>
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<td></td>
<td>L. Resser</td>
</tr>
<tr>
<td></td>
<td>T. Hammel</td>
</tr>
<tr>
<td></td>
<td>V. Srinivas</td>
</tr>
<tr>
<td></td>
<td>M. Hallam</td>
</tr>
</tbody>
</table>

The two-day meeting covered mechanical, electrical and thermal integration problems as well as miscellaneous questions on existing specifications. Reference (1) outlines the technical areas covered. Basic results of the meeting are contained in the following list. Action items are denoted with an asterisk and a due date.
1. Thermal problems were discussed at length and are reported in Reference (2).

*10/21 2. JPL analysis of two worst cases for spacecraft/RTG orientation will be provided to TES.

3. There may be a plume problem but it is JPL's worry. No action now for TES.

*10/20 4. JPL will define clearances (at flanges) they require for deployment or launch. Launch will probably be the worst case. About 1/2" clearance is required.

5. TES will evaluate housing flanges for lightening up S/N-2 (and perhaps S/N-1).

6. Configuration of fueling end mounting lugs is okay.

*7. TES must check that fueling end cover weld crown is no greater than 1/8" (preferably less than 1/16").

8. TES will use JPL mounting bolts for vibration testing (include whole stackup with washers and torque value).

9. JPL will re-evaluate their Z = 0 datum location.

10. TES will supply JPL with a plot of length vs temperature for housing and total length.

*11. TES will look at scalloping radiator end flange to permit moving monoball in toward housing, thus reducing moment and perhaps flange thickness required.

12. Handling lug locations are okay but JPL will only use three (two on fueling end and one on radiator end).

*10/20 13. Cooling tube interface must be revised. JPL wants flared fittings. The problem is really between TES and 3M, and TES will change configuration to meet JPL need.

*1/1 14. JPL will place hot dimensions on interface control drawing. The variance of dimension tolerance with temperature will be supplied by TES.

*10/27 15. JPL will look at TES vent design to determine if okay. They will consider kinematics of vent release mechanism.
16. There is large difference in preliminary TES and JPL failure probability numbers due to micrometeoroid penetration of the heat pipes. The difference in results lies within the penetration model assumption. Don Owings will talk to Bob Banford of JPL to see what next step should be in determining whether a problem even exists.

17. The radiator/boom interface will be as shown in the JPL interface drawing.

* 10/27 18. Boom deployment loads are in JPL evaluation. JPL will supply TES with ring-out values.

19. If acoustics tests are performed, they can be done with RTG's as ETG's (of course, this introduces other problems).

* 11/6 20. JPL will look at whether interface connector should use 12 or 16 gauge pins.

21. If TES uses teflon insulation in cable it will have to be justified during PDR. (JPL prefers Kapton.)

* 22. JPL will come up with rationale why ground wire should be inside housing.

* 23. Cable through radiator must have conductive outside surface probably grounded at generator end. (JPL will tell us which end will be grounded.) JPL will supply information to S. Roedel on type of conductive wrap they have used.

* 24. TES will notify JPL if total weight projected ever exceeds 107 lbs.

* 10/13 25. JPL will check whether RTD's use 2 or 3 wires (TES will assume 2).

* 10/13 26. TES will evaluate within one week whether we want 3 or 4 RTD's for telemetry measurement.

* 10/13 27. JPL will supply TES with RTD spec used on MHW.

* 11/16 28. JPL will evaluate dynamics of spacecraft attachments to see if vibration test needs more sophistication in boom area. TES will proceed as if there is no mass simulator of boom.

29. JPL thermal and mass model requirements were discussed at some length and a list of requirements generated for each.

*11/6 JPL will provide DOE with both requirements and need schedule for models.
30. **Vibration analytical model needs:**
   
   **10/13** JPL will define TES requirement.
   **10/27** TES response to JPL after knowing what requirement is.

31. JPL will supply TES with a procedure on magnetics tests that were run on MHW RTG and ETG.

* **10/9**

32. V. Srinivas to call Len Stimson at JPL to resolve JPL's questions stated in JPL cooling analysis.

33. JPL will write a Shuttle requirement such that the RTG does not see the sun when in the Shuttle with bay doors open.

34. Current on-pad power requirement is 110 to 120 watts total.

35. JPL provided TES with latest launch sequence and a diagram of the Shuttle bay. (These have been distributed separately from this memo.)

36. **Spacecraft formal configuration control will probably take place around January 1, 1979. JPL understands our problems with this date and will think of the interface itself as being controlled.**
MEMORANDUM

27 October 1978

Refer to: SIG-FAS-1587

To: R. Menchen


From: F. Schumann

Subj: SIG Housing and Radiator - Moments of Inertia and Area Distribution (Task 5)

The attached charts provide the distribution of polar moment of inertia and cross-sectional area for the Galileo RTG housing and radiator. The calculations providing these distributions included the heat pipe saddles and the cooling fin stubs. The copper heat pipes and fins were omitted. The latter omission was taken because it was felt that the thin cantilevered fins provided little contribution to torsional or bending rigidity because of their inherent lateral instability.

The bending rigidity can be easily derived by halving the polar moment (as a result of symmetry) and multiplying by the modulus for 6061 aluminum at temperature. The two end closures of the housing were also omitted. If included the local rigidity at the ends would of course be very high.

This data can also be considered as a partial fulfillment of an action item requested by JPL.

/cs
MEMORANDUM

October 9, 1978

Refer to: SIG-JDS-1556

To: W. Brittain, T. Hammel, A. Lieberman, V. Srinivas, J. Segletes, W. Wachtl

From: J. Seebald

Subject: Analysis of Suggested Improvements in Radiator Design

Objective: To present quantitative effects of the following proposed changes in radiator design:

1. Replacement of the two groups of staggered fins (10 fins total) with 5 long fins located at the mid-point of every other pair of heat pipes and extending the full length of the radiator. Local radiator thickening may be required to keep ΔT's low.

2. Use a 0.140" root on the housing fins and a 0.080" root on cylinder fins instead of a 0.110" root on all fins.

Conclusion: Neither change appears to be sufficiently advantageous to warrant its incorporation into the radiator design.

Discussion: The proposed changes in the SIG radiator design mentioned above were analyzed because they seemed to hold promise for reducing the QL product of the longer heat pipes with minimal increase in generator weight. Unfortunately, neither change provided any significant reduction in the maximum value of QL, as can be seen in Table 1.

Results: Based on the data in Table 1, the following conclusions can be made:

a. Both changes reduced the heat pipe QL, but by an insignificant amount - less than 1%.

b. Change 1 reduced the module ΔT by 2.2°C, but the large increase in weight (>4.0 lbs.) makes this change unacceptable.

c. Although Change 2 reduced both weight and QL, the reductions were so small that they are not worth the complications involved in designing and manufacturing fins with two different root thicknesses.
# TABLE 1

**EFFECTS OF PROPOSED CHANGES IN RADIATOR DESIGN**

<table>
<thead>
<tr>
<th>Case</th>
<th>Nominal</th>
<th>Change 1*</th>
<th>Change 2**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder length (in.)</td>
<td>26.5</td>
<td>27.6</td>
<td>27.0</td>
</tr>
<tr>
<td>Fin root on hsg. (in.)</td>
<td>0.110</td>
<td>0.110</td>
<td>0.140</td>
</tr>
<tr>
<td>Fin root on cyl. (in.)</td>
<td>0.110</td>
<td>0.110</td>
<td>0.080</td>
</tr>
<tr>
<td>Number of fins on cylinder</td>
<td>10</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Average cylinder thickness (in.)</td>
<td>0.02</td>
<td>0.06</td>
<td>0.02</td>
</tr>
<tr>
<td>Maximum QL (w-in.) (20 pipes; BOL)</td>
<td>29°6</td>
<td>2888</td>
<td>2885</td>
</tr>
<tr>
<td>Module ΔT*** (°C)</td>
<td>10.0</td>
<td>7.8</td>
<td>9.5</td>
</tr>
<tr>
<td>Weight relative to nominal (lb.)</td>
<td>0</td>
<td>&gt; 4.0</td>
<td>&gt; -0.28</td>
</tr>
</tbody>
</table>

*Change 1 = 5 long fins on cylinder located at the mid-point of every other pair of heat pipes. Cylinder thickened to 0.100" between fins and nearest heat pipes.

**Change 2 = A 0.140" root thickness on housing fins and 0.080" on cylinder fins.

***Module ΔT = Maximum hsg. temperature at module - minimum hsg. temperature at module.
October 23, 1978

Refer to: SIG-TEH-1578

To: A. Lieberman, W. Menchen


From: T. Hammel

Subject: SIG/GLL Heat Losses/Power Summary


Objectives: To summarize SIG heat losses and power for in-house use and to recommend a Q to the module for 3M.

Conclusions: SIG BOL power is 230.0 watts for the improved heat source design, assuming \( T_{\text{hot}}/T_{\text{cold}} = 860/160^\circ \text{C} \) and extraneous resistance = 12.5%. Power drops to 227.5 watts for the standard heat source.

The recommendation on BOL Q to the module is 2232 and 2253 watts for the standard and improved heat sources, respectively.

Implications: 1. Use of the standard heat source instead of the improved one will cause a loss of 2.5 watts (e).

2. 3M's estimation of 40% extraneous resistance and power of 199 watts (e) for ETG-S/N 1 necessitates a revision (probably minor) to the above Q to the module recommendations for ETG-S/N 1.

Table 1 summarizes the heat loss and power data from recent SIG system studies (see the reference). From Table II and Figures 1 and 2 in the reference, the association can be made between the different element numbers and the various regions of the generator. Due to the nodal structure, it was impossible to segregate multifoil heat losses from multifoil edge heat losses. However, the multifoil edge effect was shown in the reference to increase system losses by 30 watts (t). This occurred by having the multifoil losses increase by 42 watts (t) and the multifoil-module stuffing losses decrease by 12 watts (t).
**TABLE 1**  
BOL HEAT LOSSES AND POWERS

<table>
<thead>
<tr>
<th>Insulation</th>
<th>Element Number*</th>
<th>Standard Heat Source</th>
<th>Improved Heat Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heat Losses (watts)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ends</td>
<td>239, 240</td>
<td>51.9</td>
<td>45.4</td>
</tr>
<tr>
<td>Corners</td>
<td>241, 242, 19</td>
<td>66.7</td>
<td>58.7</td>
</tr>
<tr>
<td>Multifoil/</td>
<td>20, 238, 248,</td>
<td>95.0</td>
<td>90.2</td>
</tr>
<tr>
<td>Multifoil edges</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multifoil-module</td>
<td>124, 247, 125,</td>
<td>14.6</td>
<td>12.7</td>
</tr>
<tr>
<td>Stuffing (F-frax)</td>
<td>128, 245, 126</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T/E module</td>
<td>158, 159</td>
<td>178.5</td>
<td>177.7</td>
</tr>
<tr>
<td><strong>Q_L total</strong></td>
<td></td>
<td>406.7</td>
<td>384.7</td>
</tr>
<tr>
<td><strong>Q inventory</strong></td>
<td></td>
<td>2460</td>
<td>2460</td>
</tr>
<tr>
<td><strong>Q (T/E)</strong>**</td>
<td></td>
<td>2053.3</td>
<td>2075.3</td>
</tr>
<tr>
<td><strong>Q module</strong>*</td>
<td></td>
<td>2231.8</td>
<td>2253.0</td>
</tr>
</tbody>
</table>

**Efficiencies (%)**

| | | | |
| Thermal | 83.5 | 84.4 |
| Thermoelectric **** | 11.14 | 11.14 |
| Power, W(e) | 228.7 | 231.2 |
| -Loss* | 1.2 | 1.2 |
| Net power, W(e), at receptacle generator end cover | 227.5 | 230.0 |

---

*See the Reference, Table II.

**Q (T/E) = Q inventory - Q_L total.

***Q module = Q (T/E) + Q_L (T/E module).

****Assumes R extraneous = 12.5%, \( \frac{T_H}{T_C} = 860/160°C \).
The estimations of Q(T/E) and Q module are straightforward and shown on the footnotes of Table 1. Teledyne Energy Systems has previously recommended Q module of 2241 ± 28 to 3M. This number is still valid (the average of standard and improved with ±28 covering the spread). 3M has recently predicted 40% extraneous resistance and output power of 199 watts(e) for ETG-S/N 1. This will likely have a minor effect upon system temperatures and Teledyne Energy Systems' recommendation of Q module. An evaluation of this effect is planned for the near term.

The adjustment of powers by 1.2 watts accounts for estimated losses in internal power leads and receptacle pins.
MEMORANDUM

TELEDYNE ENERGY SYSTEMS

10/25/78
Refer to: SIG-TEH-1589

To: W. R. Menchen, E. Skrabek


From: T. Hammel

Subj: SIG Insulation Thermal Conductivity Requirements (Task 5.3)

Ref: Hammel, T., "SIG Flight System Helium Pressure Buildup vs. Time," SIG-TEH-1276, 3/12/78

Objective: To present SIG thermal conductivity test requirements.

Conclusions: A large amount of data is required (See Table 1) for characterization of SIG performance (power/temperatures), especially at the time of fueling and prior to launch.

3M should obtain the Fiberfrax data. TES should obtain the remaining data, through TECO, Dynatech and TES testing.

Implications:

(1) A large unplanned cost to the SIG program.

(2) If xenon/helium results are not favorable ($k$ too high), frequent evacuation of RTG while on pad may be necessary to achieve the one-quarter power requirement.

Table 1 presents details of SIG thermal conductivity requirements. The data marked by asterisks needs to be obtained. The data marked by "P's" may be required. If the associated all helium and all xenon results show close agreement on a transverse to normal conductivity ratio, then this ratio may be used to obtain transverse conductivities for the gas mixtures. Otherwise the transverse points in gas mixtures must be measured. The 3M Company should obtain the Fiberfrax data for their recommended insulation configuration as noted on Table 1.
### TABLE 1
SIG Thermal Conductivity\(^{(1)}\) Matrix

<table>
<thead>
<tr>
<th>Material</th>
<th>Direction</th>
<th>SIG Location</th>
<th>Environment</th>
<th>Vacuum (^{(3)})</th>
<th>Argon (^{(4)})</th>
<th>(\text{Xe/He} (^{(5)}) 100/0</th>
<th>80/20</th>
<th>60/40</th>
<th>0/100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiberfrax 660 AH nanor(^{(2)})</td>
<td>Random</td>
<td>Module</td>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Min-K 1400</td>
<td>Normal</td>
<td>Ends</td>
<td></td>
<td>\x</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>\x</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>Corner</td>
<td></td>
<td>\x</td>
<td>*</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>*</td>
</tr>
<tr>
<td>Min-K 1800</td>
<td>Normal</td>
<td>End-Corner</td>
<td>\x</td>
<td>\x</td>
<td>*</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>*</td>
</tr>
<tr>
<td>CBCF-3</td>
<td>Normal</td>
<td>Ends</td>
<td>\x</td>
<td>\x</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>\x</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>Sides</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Multifoil (Mo/ZrO(_2))</td>
<td>Normal</td>
<td>Sides</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

\(x = \) data already obtained (some non-outgassed)

\(* = \) data needed

\(P = \) possible needed

\(^{(1)}\) All data should be obtained at four temperature points, 200, 450, 650 and 850 to 1000°C (depending upon insulation limit). (Exclude 200°C for all CBCF-3; additionally exclude 450°C for CBCF-3 in vacuum). All data should be obtained for post-outgassed insulations.

\(^{(2)}\) It is recommended that all Fiberfrax data be obtained by the 3M Company for their SIG recommended insulation configuration.

\(^{(3)}\) Pressure < \(10^{-4}\) Torr

\(^{(4)}\) Pressure = 1.0 atm.

\(^{(5)}\) Molar fractions shown; nominal total pressure = 1.0 atm.
The vacuum points are needed for long term SIG flight operation. The argon values are required for fueling transient analyses and to predict SIG power for the first power check after fueling in TES' "submarine." The xenon/helium data are necessary to evaluate system performance and meet a number of requirements:

a) An on-pad launch power of 110-120 watts(e).

b) Iridium PICS temperatures as close as possible to normal operating temperatures.

c) Keep hot junction temperature at or below nominal (860°C) during stowed operations.

The thrust resulting from the release of a xenon/helium gas mixture from the GVS needs to be evaluated and communicated to JPL.

The launch power requirement of one-fourth power can be achieved by a vacuum system (which requires frequent evacuation) or possibly a xenon/helium mixture. It is likely that a pure helium gas resulting from isotopic decay would affect insulation conductivities to the extent that power output would drop well below one quarter of its nominal value. The xenon/helium system is preferred (over vacuum) since it does not require frequent evacuation, probably gives acceptable power and depresses hot junction temperature while stowed. If a pure helium gas fill satisfies the aforementioned requirements, it will be necessary to add low pressure helium tests to the matrix on Table 1. These pressure points will be defined as necessary.

The SIG system is designed to an outward ΔP of 1.5 atm. Since it has been estimated that helium is generated at a rate of 0.62 atm/year (Ref.), and one year is the maximum time between fueling/xenon charging and launch, the maximum partial pressure of helium will be 0.62 atm. Hence, the maximum partial pressure of xenon can be 0.88 atm, which is the assumed initial fill pressure. Table 2, below, gives some data on the xenon/helium mixtures anticipated.

<table>
<thead>
<tr>
<th>Time from fueling/Xenon Fill (Months)</th>
<th>0</th>
<th>4</th>
<th>8</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium Pressure (atm)</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td>Xenon Pressure (atm)</td>
<td>0</td>
<td>0.21</td>
<td>0.41</td>
<td>0.62</td>
</tr>
<tr>
<td>Total Pressure (atm)</td>
<td>0.88</td>
<td>1.09</td>
<td>1.29</td>
<td>1.50</td>
</tr>
<tr>
<td>Xe/He Molar Fraction(%)</td>
<td>100/0</td>
<td>0.81/0.19</td>
<td>0.68/0.32</td>
<td>0.59/0.41</td>
</tr>
</tbody>
</table>

As noted in Table 1, the recommended Xe/He mixture for conductivity tests are 100/0, 80/20, 60/40 and 0/100, all at 1 atm. total pressure. As seen in Table 2 above, total pressure really varies over a range above and below 1 atm, but the effect is estimated to be quite low. As a check on this estimation, it is recommended that at least two further data points be taken (at 450°C or 650°C), such as 60/40 Xe/He at 1.5 atmospheres and 80/20 Xe/He at 1.1 atmospheres. These data can be readily obtained at Dynatech.
MEMORANDUM

27 October 1978

Refer to: SIG-VS-1586

To: W. Menchen, A. Lieberman,


From: V. Srinivas

Subj: SIG/GLL Temperatures in Stowed Condition - Telecon with Ray Becker of JPL (Task 5.3)

Objective: To disseminate information received during telecon and discuss its implications.

Conclusions: After the IUS/Spacecraft is released from the Orbiter, there is a 15-45 minute period during which the IUS attitude control motors cannot be activated. During this period the IUS/Spacecraft attitude may not be such that the solar and earth IR inputs to the RTG's are minimal. Since the earth IR and reflected solar inputs can be large, the RTG's may overtemperature. The worst case earth IR input (640 Btu/hour) and the worst case reflected solar input (337 Btu/hour) are comparable to the worst case direct solar input (687 Btu/hour).

Implications: More detailed analyses, including transient analysis, if necessary, must be made to accurately predict the SIG temperatures during the uncontrolled IUS coast. JPL should be asked to provide TES the following information, as soon as they become available.

(a) Details and results of JPL's spacecraft reflector evaluation study (see text for details).

(b) The exact duration of the uncontrolled IUS coast.

(c) Orbital dimensions and period.

(d) JPL's best estimate of the IUS/spacecraft/RTG orientation during uncontrolled coast.

(e) Any other information required in estimating the total earth IR and solar inputs to the RTG's.
I called Ray Becker to determine the status of JPL's detailed thermal analysis of the spacecraft when the RTG's are in the stowed condition. I also inquired if any additional information regarding events after IUS/Spacecraft deployment had become available. The following information was obtained:

1) Spacecraft/IUS temperatures for certain representative IUS/Spacecraft/RTG orientations will be sent to TES by 10/27/78.

2) After the IUS/Spacecraft is ejected from the shuttle cargo bay tilt table, there is a certain time delay before the IUS attitude control motors can be activated. During this time lag the IUS/Spacecraft attitude is essentially uncontrolled and, as such, under some conditions, the RTG's can receive direct solar, reflect solar as well as earth IR radiation. The exact duration of the uncontrolled IUS/S/C coast is not yet known but is expected to be in the range of 15 to 45 minutes. After their deployment from the shuttle cargo bay, the IUS/S/C will be in an elliptical orbit with the orbit perigee on the dark side of earth. The time period during which IUS/S/C will be in the earth's shadow is shorter than the total duration of uncontrolled IUS/S/C coast and, consequently, the S/C and RTG's may receive direct and reflected solar radiation.

3) JPL is evaluating the possibility of using aluminum plates with highly specular reflectance on the spacecraft sections behind the RTG's, arranged in such a manner that they reflect to space all radiation incident on them from the RTG's. Such reflectors in effect can eliminate thermal effects due to the presence of the spacecraft on the RTG's in the stowed condition. This type of reflector was considered for the Voyager S/C and RTG's. However, during the uncontrolled coast, under certain conditions, the reflector surface may reflect direct solar, reflected solar and earth IR on to RTG's. JPL should be requested to provide TES further details and results of the reflector evaluation study.

Discussion:

Even if the occlusion effects of the spacecraft can be completely eliminated by using specular reflectors, it is still necessary to ensure that the RTG's can maintain their temperature within limits when there is no interference from the spacecraft. Currently, the SIG radiator is sized to hold the average fin root temperature at 125°C at BOL, when the system receives 1 A.U. solar radiation (430 Btu/ft^2-hr) in a broadside attitude. However, as shown below, the sum of the worst case earth IR and reflected inputs to the RTG's is larger than the worst case direct solar input.

Worst case direct solar input = \( \alpha_s A_{\perp} S \)  

where, \( \alpha_s = \) solar absorptivity = 0.2

\( A_{\perp} = \) projected area (broadside attitude)
- 8 square feet
\( S = \) solar flux = 430 Btu/ft^2-hr

Worst case direct solar input = 687.3 Btu/hour.
Worst case earth IR = $\alpha_{e} A \_E$  \hspace{1cm} (2)

where,

$\alpha_{e} = \text{IR absorptivity} = 0.93$

$E = \text{earth irradiance} = 86 \text{ Btu/ft}^2\text{-hr}^*$

Worst case earth IR input = 639.2 Btu/hour

Worst case reflected solar input = $a \alpha_{S} A \_S$

where, $a = \text{earth's albedo} = 0.49^*$

Worst case reflected solar input = 336.8 Btu/hour

A preliminary analysis indicated that when the RTG receives both worst case earth IR and worst case reflected solar radiation (i.e., when the RTG is in a broadside attitude looking at the subsolar point), even if the spacecraft occlusion effects are assumed to be eliminated by using specular reflectors, the hot spot temperature on the housing would be about 145°C. More detailed analyses, including transient analysis, if necessary, must be made to accurately predict the SIG temperatures during the uncontrolled IUS coast period. JPL should be asked to provide TES the following information, as soon as they become available.

a) Further details and conclusions of the spacecraft reflector evaluation study.

b) The exact duration of uncontrolled IUS coast.

c) Orbital dimensions and period

d) JPL's best estimate of IUS/S/C/RTG orientations during the uncontrolled IUS coast.

e) Any other pertinent information.

*These values were obtained from an informal JPL memo to TES dated May 5, 1978.
MEMORANDUM

October 31, 1978
Refer to: SIG-DCA-1540

To: A. Lieberman

CC: W. Osmeyer, N. Strazza, W. Brittain, G. Linkous, W. Owings, W. Wachtel

From: D. Anderson, J. McGrew, J. Kim

Subj: Radiolytic Decomposition of Water in SIG/GLL Heat Pipes

Objective: Estimate energy deposition in heat pipe water from Jovian charged particles and radiation from the plutonium-fueled heat source. From energy deposition, estimate extent of radiolysis and its consequences

Conclusions: Radiolysis, mostly from Jovian electrons, decomposes water to the extent of about 140 parts per million during the SIG/GLL mission. Assuming the likely result that hydrogen and oxygen would accumulate at the condenser end of the heat pipe, the gas buildup would amount to about one inch for a 45 inch heat pipe, unless the gases are consumed by recombination or reactions with heat pipe constituents.

Implications: The small fractional decomposition is estimated to have no significantly deleterious effects on material properties of the heat pipe components. Heat transfer restrictions owing to gas blockage would have only minor effects on radiator efficiency.

1. Introduction

A recent question arose concerning the adverse effects on heat pipe performance of radiolytic decomposition of the water charge. Adverse effects may appear in the form of:

- Accumulation of non-condensable gases (H$_2$ or O$_2$) inside the heat pipe.
- Performance degradation of heat pipe constituents, notably the wettable CuO coating.

The radiations of interest include electron and proton fluxes, as specified in ES 512281 and penetrating nuclear radiation (gammas and neutrons) emitted by the radioactive heat source.

This report presents the results of analysis of energy deposition in water by the aforementioned radiation and the consequences of radiolysis in the Galileo mission.
2. Method of Analysis

Energy deposition was calculated according to different methods for the Jovian, charged-particle fluxes and the more penetrating neutrons and gammas. In the former case range-energy relations were used to calculate energy deposition in water. For neutrons and gammas, macroscopic energy absorption cross sections provided an estimate of volumetric energy deposition. A dissociation yield of 5 molecules per hundred electron volts* was used to relate gas production to energy deposition. Details of the spectral analyses in each case are given in the following paragraphs.

a. Charged Particles

Figure 1 shows a cross section of the SIG/GLL heat pipe configuration as presented in the GDS-1 Final Design Review. For simplicity, and conservatism** we assumed a minimum copper wall thickness of 10 mils; the water was assumed distributed throughout a tube of diameter 0.25 inch.

An average water density in the tube was computed at 0.18 gm/cm³ using a heat pipe charge of about 0.15 gm per inch of heat pipe length. The thicknesses of copper and water regions, therefore were 0.25 and 0.11 in units of gm/cm².

Energy deposition from electrons and protons was estimated by assuming fixed thicknesses of copper and water regions, regardless of orientation of the particle velocity vector relative to the heat pipe surface.

Range-energy relations in the form \( R = \delta E^n \) for both electrons and protons were utilized in the calculations. For particles with energies exceeding the threshold for penetrating the copper wall, a varying amount of energy deposited in the water was estimated from:

\[
\Delta^w = E_1 - \left[ E_1^{n_w} - \frac{R_w}{\delta_w} \right]^{1/n_w}
\]  

2. M.V. Vladimirova, Khim Vysokikh Energii 6, 458 (1972)

**Conservatism here means overestimating energy deposition in water. The 10 mil thickness represents the minimum wall thickness to meet structural criteria.
FIGURE 1. SIG/LLL HEAT PIPE CROSS SECTION
\[ E_1 = \left[ \frac{n_c^{E_0 - R_c}}{\delta_c^{E_0}} \right]^{1/n_c} \]

and \( E_0 \) = initial particle energy,
\( E_1 \) = residual energy after penetrating the copper wall,
\( R_w \) and \( R_c \) are the thicknesses of water and copper regions,
\( \delta, n \) \( w, c \) are the range-energy fitting parameters for water and copper regions.

From \( \Delta^W \) and the spectral flux of charged particles, \( \psi(E_0) \), the total energy deposition in water was calculated according to:

\[ \epsilon = \frac{1}{D} \int_{E_t}^{\infty} \psi(E_0) \Delta^W(E_0) \, dE_0 \quad (2) \]

where \( E_t \) = threshold energy for penetrating copper region
\( \psi \) = time-integrated spectral flux,
\( \epsilon \) = energy deposition density (energy per cm\(^3\))

and \( D \) = heat pipe inner diameter.

b. Neutrons and Gammas

For these radiations, peak values of the energy-integrated fluxes along the heat pipe length were used to calculate energy deposition. This was a very conservative simplification* since fluxes decrease significantly away from their maximum point in the heat source midplane about 5 inches from the heat source centerline.

*This conservatism, however, did not influence the estimate of total energy deposition owing to the insignificance of neutrons and gammas, as will be shown.
Attenuation of these radiations in the copper and water regions was negligible, hence, the energy deposition was calculated according to:

\[ \epsilon_\gamma = \Phi_\gamma \left< E \mu_a \right> \tau \]

or \[ \epsilon_n = \Phi_n \left< E \Sigma_a \right> \tau, \]

where \( \epsilon_\gamma, n \) = energy deposition densities, energy/cm\(^3\),

\( \Phi_\gamma, n \) = incident energy-integrated fluxes,

\( \left< E \mu_a \right> \) = spectral average of the photon macroscopic energy absorption coefficient weighted by incident energy,

\( \tau \) = mission duration,

and \( \left< E \Sigma_a \right> \) = spectral average of the neutron macroscopic energy absorption cross section weighted by incident energy.

The spectral averages in equation (3) were obtained using a representative neutron spectral measurement and a calculated emission spectrum for gammas.

3. Results

Differential fluence data for 12 orbits, shown in Table 1, for electrons and protons provided the \( \psi \)-functions in equation (2). The energy loss factor was calculated from equation (1) using range-energy fitting parameters given in Table 2. Threshold energies for penetrating the reference copper and water thicknesses are listed in Table 3.

The integrals of equation (2) were evaluated numerically using the aforementioned spectral and energy deposition data. The average energy deposition for electrons was \( 1.7 \times 10^{13} \) Mev/cm\(^3\). If it is assumed that no recombination of the decomposition products occurs, the cumulative gas buildup at the end of mission as a result of electron radiolysis is about 210 parts per million relative to the initial charge of water molecules.

Proton energy deposition was computed, using the same procedures, and the data of Tables 1–3, at about \( 2 \times 10^{11} \) Mev/cm\(^3\), producing non-condensible gases at the level of 3 parts per million. While the energy deposition per proton is greater by an order of magnitude than that for electrons, the relevant electron fluence spectrum exceeds that of the protons by about three orders of magnitude.
Table 1. Integral and Differential Peak Flux and Fluence of Jupiter Electrons and Protons

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Integral Peak Flux (cm(^{-2}) s(^{-1}))</th>
<th>Differential Peak Flux (cm(^{-2}) s(^{-1}) MeV(^{-1}))</th>
<th>Integral Fluence (cm(^{2}))</th>
<th>Differential Fluence (cm(^{2}) MeV(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>6 Orbits 12 Orbits</td>
<td>6 Orbits 12 Orbits</td>
</tr>
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<td></td>
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<td>6 Orbits 12 Orbits</td>
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<td>8.3(13)</td>
</tr>
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<td>1.7(13)</td>
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</tr>
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<td>8.2(11)</td>
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<td>5.8(11)</td>
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<td>1.5(11)</td>
<td>2.5(11)</td>
</tr>
<tr>
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<td>2.4(10)</td>
<td>3.2(10)</td>
</tr>
<tr>
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<td>2.9(5)</td>
<td>3.3(4)</td>
<td>9.2(9)</td>
<td>1.1(10)</td>
</tr>
<tr>
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<td>1.1(4)</td>
<td>3.7(9)</td>
<td>3.9(9)</td>
</tr>
<tr>
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<td>1.0(9)</td>
<td>1.1(9)</td>
</tr>
<tr>
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</tr>
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<td>100.0</td>
<td>5.9(2)</td>
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<td>2.0(7)</td>
<td>2.2(7)</td>
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</table>
### TABLE 2

**Range - Energy Fitting Parameters**

\[ R = \delta E^n \]

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<thead>
<tr>
<th>Medium</th>
<th>Protons</th>
<th>Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( n )</td>
<td>( \delta )</td>
</tr>
<tr>
<td>Copper</td>
<td>1.728</td>
<td>4.07 \times 10^{-3}</td>
</tr>
<tr>
<td>Water</td>
<td>1.793</td>
<td>1.95 \times 10^{-3}</td>
</tr>
</tbody>
</table>

---


**Range in gm/cm^2; Energy in Mev.

### TABLE 3

**Limiting Energies for Electrons and Protons to Penetrate Heat Pipe Copper and Water**

<table>
<thead>
<tr>
<th>Charged Particle</th>
<th>Minimum Energy (Mev)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Medium</td>
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<tr>
<td></td>
<td>Copper</td>
</tr>
<tr>
<td>Electron</td>
<td>0.6</td>
</tr>
<tr>
<td>Proton</td>
<td>10</td>
</tr>
</tbody>
</table>

---
Peak fluxes of neutrons and gammas emitted by the heat source were estimated at $1.4 \times 10^4$ n/cm$^2$-sec and $3.9 \times 10^5$ $\gamma$/cm$^2$-sec. These estimates were based on measured emission data, dose rate measurements, and numerical integrations employing the point-kernel approximation. The exposure duration was assumed to be 50,000 hours plus 2 years of ground storage, yielding neutron and gamma fluences of $3.4 \times 10^{12}$ and $9.5 \times 10^{13}$ particles/cm$^2$.

The average value of the energy absorption coefficient for gammas in water was calculated using spectral data shown in Table 4, and the energy-dependent absorption coefficient listed in Table 5. The resulting average coefficient, also indicated in Table 5 was 0.012 Mev/cm. (density = 1.0 gm/cm$^3$).

A similar calculation of the average energy absorption cross section for neutrons was performed using the generic, measured spectrum shown in Figure 2 and the cross section data given in Table 6. The average macroscopic cross section for neutrons was 0.19 Mev/cm. (density = 1.0 gm/cm$^3$).

Since neutrons and gammas are not attenuated significantly in the copper or water, energy deposition is given by the product of fluence and energy absorption coefficient or cross section. The results were $1.2 \times 10^{11}$ and $2 \times 10^{11}$ Mev/cm$^2$ for neutrons and gammas. Thus the contribution of heat source radiations is comparable to that for protons and all three are negligible compared with energy-deposition from electrons.

Therefore the total energy density deposited within the heat pipe volume by ionizing radiation is about $1.7 \times 10^{13}$ Mev/cm$^3$, leading to the initial production of about 140 and 70 ppm of hydrogen and oxygen gas, respectively. The production rate for these gases is quite small, so that partial pressures at the point of generation would be miniscule. The gases would for the most part be transported to the condenser end of each heat pipe where, if unreacted, a maximum gas column length of about 1 inch (for a 45 inch heat pipe) would accumulate by the end of mission.*

The pressure of the isolated, non-condensible gases in the vapor-free region would be the same as that for the operating heat pipe or about 2 atmospheres. Under these conditions it is possible that one or more of the following processes might occur as the column of non-condensible gases builds up during the mission:

1. Hydrogen diffusion through the heat pipe wall, thereby escaping the system,
2. Recombination of hydrogen and oxygen,
3. Dissolution of the $H_2$ and $O_2$ in water,
4. Oxidation of copper and the coating components,
5. Reduction of the coating components by hydrogen,
6. No significant reaction of the gases.

*Actually, the vapor/non-condensible gas interface would not be sharp. A transition region of approximately the same length as the computed vapor-free region is expected. The non-condensible gases would be distributed over a length of about 2 inches, with vapor pressure distributed in an inverse manner.
### TABLE 4
Gamma Spectral Flux From MHW Heat Source

<table>
<thead>
<tr>
<th>Energy Group</th>
<th>Energy Bounds (Mev)</th>
<th>Normalized Group Flux (photons cm$^{-2}$sec$^{-1}$)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>0.0037</td>
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<tr>
<td>2</td>
<td>0.044</td>
<td>0.5371</td>
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<td>4</td>
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<td>5</td>
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</tr>
<tr>
<td>6</td>
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<tr>
<td>20</td>
<td>6.0</td>
<td>$&lt;10^{-4}$</td>
</tr>
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</table>
TABLE 5
Gamma Energy Absorption Coefficients

<table>
<thead>
<tr>
<th>E (Mev)</th>
<th>$\mu_a$ (cm$^{-1}$)</th>
<th>$E \mu_a$ (Mev cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.025</td>
<td>0.0025</td>
</tr>
<tr>
<td>0.2</td>
<td>0.030</td>
<td>0.0060</td>
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<tr>
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<td>0.4</td>
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<td>0.023</td>
<td>0.0699</td>
</tr>
<tr>
<td>4.0</td>
<td>0.021</td>
<td>0.0840</td>
</tr>
<tr>
<td>5.0</td>
<td>0.026</td>
<td>0.1000</td>
</tr>
</tbody>
</table>

$< E \mu_a > = 0.012$ Mev/cm
FIGURE 2. NEUTRON ENERGY EMISSION SPECTRUM (AFTER MOUND LABORATORIES REPORT MLM-2226)
<table>
<thead>
<tr>
<th>E (Mev)</th>
<th>E Sigma_a (Mev cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.115</td>
</tr>
<tr>
<td>1.5</td>
<td>0.190</td>
</tr>
<tr>
<td>2.5</td>
<td>0.230</td>
</tr>
<tr>
<td>3.5</td>
<td>0.270</td>
</tr>
<tr>
<td>4.5</td>
<td>0.310</td>
</tr>
<tr>
<td>5.5</td>
<td>0.320</td>
</tr>
<tr>
<td>6.5</td>
<td>0.340</td>
</tr>
</tbody>
</table>

\(<E \Sigma_a> = 0.1^o \text{ Mev/cm}\)
Permeation data from Jost* suggest that only a small fraction of the hydrogen gas created by radiolysis would penetrate the heat pipe walls. Thus the first process is not expected to be important in this application.

The second process, recombination of the gaseous reactants, if favored, would mitigate any radiolysis problem and will not be considered further. Dissolution (process 3) would also have no measurable effect on performance.

The final 3 potential effects or processes all lead to approximately the same result. A portion of the heat pipe, up to two inches in length for a 45 inch heat pipe, will have reduced effectiveness in transferring heat via vapor transport and condensation. Although the maximum gas column length of two inches is greater than the limit identified in the performance specification**, its net effect on performance of the radiator sub-system would be minor for the following reasons:

- A gas-blocked region two inches long would have only a minor effect on the temperature distribution over the radiator and, therefore, radiator efficiency, i.e., the performance specification is conservative in this respect.

- The gas column would accumulate late in the mission when heat rejection requirements would diminish owing to decay of the radioactive heat source.

4. Discussion

The results presented in the preceding section indicate initial radiolytic gas production during the SIG/GLL mission of 200 ppm relative to the molecular water charge. The major assumptions which affect the precision of this estimate are:

1. Fixed regional thicknesses at 0.01 in. (copper) and 0.25 in. (water) for charged particle penetration.

2. Range-energy relations of the form \( R = 5E^n \) for electrons in copper and water.

---

*Jost, W., "Diffusion in Solids, Liquids and Gases, Academic Press, N.Y. (p. 305)

** SIG 1100041 (In preparation)
Approximation (1) tends to overestimate energy deposition in water. If the mean copper thickness were increased to 20 mils, the penetration threshold in copper would increase from 0.6 to 1.0 Mev. Electron spectral data shown in Table 1 suggest a reduction in computed energy deposition by a factor of 2 or 3, associated with this more realistic mean wall thickness.

Approximation (2) is difficult to assess without the original penetration data on which the approximate fitting was based. Examination of a range-energy plot in aluminum suggests that a single relation of the form $R = \delta E^n$ over an energy range from 0.1 to 10 Mev would deviate by less than a factor of 2 from the measured data.

Thus the uncertainties include a potentially pessimistic factor of 2 or 3 and a random error factor of $2^{\pm 1}$. We conclude that the calculated energy deposition represents an upper limit, given the specified fluence. The lower limit is smaller by about a factor of 10 than the estimate provided above.

---

October 6, 1978

Refer to: SIG-LLR-1551

To: W. Brittain, T. Brown, A. Lieberman, R. Menchen, F. Schumann


From: L. Resser

Subject: SPFA - SIG RTG Enclosure Seals (Task 10.2)


Objective:

To establish an allowable seal leak rate criterion for the RTG power section enclosure, update the single seal point failure (SPF) identification analysis and identify potential problem areas.

The single point failure analysis presented herein supersedes ref. (a) and expands on the information presented in ref. (b).

Conclusion:

A maximum leak rate criterion of $1.0 \times 10^{-8}$ scc He/sec-atm at $125^\circ$C ($257^\circ$F) is proposed for the RTG power section enclosure. This criterion is quite conservative being based on one (1) percent of the 3M Company's recommended allowance of oxygen in the couple.

There are twenty some single seal leak points in the hermetic sealed enclosure of the RTG power section. This quantity is consistent with previous generator designs and virtually impractical to eliminate.

A gas management valve, smaller and with a tighter seal capability than that used in GDS-1, will be required in order to meet vibration and enclosure leak rate criteria, respectively.

Also included in this analysis is a proposed in-process component, assembly and generator leak test program to validate the quality of the seals during the fabrication operations and an initial listing of sources of data which are available to justify the SPF in the design.
Introduction:

The SIG RTG is designed with a hermetic sealed enclosure to pneumatically isolate the inert cover gas surrounding the thermoelectrics and isotope heat source from the air atmosphere during pre-launch ground test, storage and spacecraft operations and during the first hour after launch. During flight, which follows RTG deployment from the spacecraft at approximately 11 hours after launch, the enclosure is punctured so that the internal environment of the generator will be exposed to the space vacuum.

Leak Rate Criterion:

The leak rate criterion for the RTG power section enclosure is conservatively set at a maximum of $1.0 \times 10^{-8}$ sec He/sec-atm at an operating temperature of 125°C ($257^\circ$F). This leak rate is calculated by using one (1) percent of the 3M Company's recommended oxygen limit of 0.3 mg/couple based on the one (1) year maximum that the RTG will be in an air environment. This calculation yields a $3.22 \times 10^{-7}$ sec He/sec-atm which is further rounded off to the $1.0 \times 10^{-8}$ sec He/sec-atm identified above.

Single Point Failure Identification:

Figure 1 identifies and graphically locates the seal leak failure points in the RTG hermetically sealed enclosure. The schematic code letters in circles identify the leak points. This code is used as a cross reference to Table 1 which identified the leak points in more detail.

Table 1 describes the SPF's which are identified in Figure 1. Here, the SPF's are grouped by type, described to some detail and quantity indicated. A total of twenty-two (22) single seal leak points are evident in the proposed RTG design. These include valve, threaded fittings, electrical receptacle insert, bi-metal bond joint, fusion type welds, and parent material. Of these, the gas mangement valve and valve attachment fittings are considered the most critical components from a leak view point since no reliability data base exists. The valve used on GDS-1 uses an elastomeric in the seat seal and appears to be unacceptable for the longer air exposure time planned for a RTG. In addition, the GDS-1 valve is an impractical size for the loads imposed during vibration.

Figure 2 presents a proposed seal leak test profile applicable to the component parts, sub-assemblies, assemblies and generator during fabrication and assembly operations. For each single point failure the leak test to be imposed is indicated. The reference drawing and/or part number shown in this table are "typical" since they are not scheduled for preparation in the immediate future.

Table 2 constitutes a partial bibliography of the data sources for justification of the SPF's in the RTG design.
FIGURE 1: SIG RTG ENCLOSURE SEAL SCHEMATIC
TABLE 1
SIG RTG SEAL LEAK FAILURE POINT IDENTITY

<table>
<thead>
<tr>
<th>Schematic Code</th>
<th>Item Description</th>
<th>No. of Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>VS</td>
<td>Valve seal - seat</td>
<td>1</td>
</tr>
<tr>
<td>VF</td>
<td>Valve/evacuation tube fitting</td>
<td>1</td>
</tr>
<tr>
<td>VC</td>
<td>Valve/atmosphere cap (optional)</td>
<td>*</td>
</tr>
<tr>
<td>ERs</td>
<td>Seal - electrical receptacle insert (SS20CB3/glass)</td>
<td>1</td>
</tr>
<tr>
<td>Bond</td>
<td>Joint - bimetal seal ring bond (Al 6061-T651/Ag/SS 304L)</td>
<td>2</td>
</tr>
<tr>
<td>CHw</td>
<td>Cover/housing (Al 6061-T651/Al 6061-T6)</td>
<td>2</td>
</tr>
<tr>
<td>TCw</td>
<td>Evacuation tube/cover (Al 6061-T6/Al 6061-T651)</td>
<td>2</td>
</tr>
<tr>
<td>TPw</td>
<td>Evacuation tube/plug (Al 6061-T6/Al 6061-T651)</td>
<td>1</td>
</tr>
<tr>
<td>BCw</td>
<td>Bimetal ring/cover (Al 6061-T651/Al 6061-T651)</td>
<td>2</td>
</tr>
<tr>
<td>DBw</td>
<td>Diaphragm/bimetal ring (SS 304/SS 304L)</td>
<td>1</td>
</tr>
<tr>
<td>RBw</td>
<td>Receptacle/bimetal ring (SS 20CB3/SS 304L)</td>
<td>1</td>
</tr>
<tr>
<td>Material</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hm</td>
<td>Housing (Al 6061-T6)</td>
<td>1</td>
</tr>
<tr>
<td>Cm</td>
<td>Cover (Al 6061-T651)</td>
<td>2</td>
</tr>
<tr>
<td>Rm</td>
<td>Receptacle shell (SS 20CB3)</td>
<td>1</td>
</tr>
<tr>
<td>Tm</td>
<td>Evacuation tube (Al 6061-T6)</td>
<td>2</td>
</tr>
<tr>
<td>Pm</td>
<td>Plug (Al 6061-T651)</td>
<td>1</td>
</tr>
<tr>
<td>Dm</td>
<td>Diaphragm (SS 304 Cond A)</td>
<td>1</td>
</tr>
</tbody>
</table>

*Redundant with valve seal.

Total: 22
FIGURE 2: SIG IN-PROCESS SEAL LEAK TEST PROFILE

COMPONENT: SIG 110021
Subassembly: SIG 110006
Crit: $1 \times 10^{-9}$ SCC/sec @ RT

Cover Assy

Leak Test: Proc: SIG 110021
Fix: SIG 110006
Crit: $1 \times 10^{-9}$ SCC/sec @ RT

Radiator End

Leak Test: Proc: TBD
Fix: TBD
Crit: $1 \times 10^{-9}$ SCC/sec @ RT

Receptacle/ Boss Assy
Proc: TBD
Crit: $1 \times 10^{-9}$ SCC/sec @ 400°F

Diaphragm Boss Assy
Proc: TBD
Crit: $1 \times 10^{-9}$ SCC/sec @ RT

Radiographic Test
Proc: TBD

NOTE: 1) Drawing and Part Numbers are GPS-1 and ETC - thus typical only.
2) Leak Rates are typical pending design formulation.
Refer to: SIG-LLR-1551  
October 6, 1978  
Page 6

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</tr>
</tbody>
</table>

**TABLE 2**

**SIG RTG SEAL LEAK FAILURE POINT**

**JUSTIFICATION BIBLIOGRAPHY**

1. Valve - seal
2. Valve - fitting
3. Valve - cap
4. Electrical receptacle
   - LCHPG-LLR-714, LCHPG Electrical Receptacle Test Program Review, Task 2.1.5
   - SIG-LLR-829, SIG Electrical Receptacle Acceptance Test Analysis and Assessment
   - SIG-LLR-1107, Electrical Receptacle and Bimetal Ring Life Test Data Reduction and Analysis Method
   - SIG-LLR-1141, SIG Electrical Receptacle Thermal Margin Leak Test Data Reduction and Analysis
   - SIG-LLR-1219, Assessment of Viking Deutsch Electrical Receptacle for Use in GDS-1
   - SIG-LLR-1238, SIG Electrical Receptacle/Bimetal Seal Ring Component Development and GDS-1 Receptacle Test Program
5. Joint - Bimetal
   - LCHPG-WJB-802, Development and Test Plan for GDS/ETG Electrical Feedthrough Attachment
   - SIG-JK-935, Preliminary Report on Thermal Aging and Intermediate Phase Growth for Al 6061/Ag/SS 304 Explosive Clad Weld Transition Joint Material
MEMORANDUM

10/20/78

Refer to: SIG-GWB-1576

To: W. Brittain, P. Collins, A. Lieberman, D. Trimmer, N. Strazza, R. Menchen


From: G. Budesheim

Subj: Arrhenius Model Technique Applied to Axially Grooved Heat Pipe Life Test Data for EOM Reliability Assessment (Task 10.4).

Ref: (a) SIG-GWB-1528, Analysis of Axially Grooved Heat Pipe Acceptance, Verification and Life Test Data, dated 22 September 1978

(b) SIG-JPC-1564, Re-evaluation of the Heat Pipe Life Test Effort. Results of the Meeting Held 11 October 1978, dated 12 October 1978


Objective: To describe the application of the Arrhenius acceleration rate model to the axially grooved heat pipe life test data for demonstration of EOM performance.

Conclusion: A description of the application of the Arrhenius rate model to the heat pipe test data and the method for demonstrating the probability of achieving a given performance at EOM is illustrated.

The results to be generated from this program become a direct input into the SIG-RTG degradation model currently being formulated.

Implication: In order to demonstrate the reliability at EOM, performance parameters must be identified and appropriate criteria established for the heat pipe.
Reference (a) identifies the problems encountered when axially grooved heat pipe life test data was statistically analyzed for thermal transfer ($\Delta T/Q$) and thermal transport ($Q_{\text{max}}$) characteristics. As a result of these problems, a revised test effort has been established at a TES in-house meeting held on 11 October 1978, (Ref. b). Based on information presented in Ref. (b), the following performance parameters will be analyzed using the Arrhenius model.

1. Thermal transport - $Q_{\text{max}}$ for an elevation of 0.5 in. on an individual pipe basis.

2. Thermal transfer - $\Delta T/Q$ for a fixed heat input (125 watt gross). $\Delta T$ for the evaporator ($T_1-T_5$, Fig. 1) and $\Delta T$ for evaporator - condenser ($T_1-T_8$) will be followed on an individual pipe basis.

3. Non-condensible gas build-up - gas slug length will be followed on a fixture average basis.

The heat pipe life test is being run at accelerated temperature rates with fixture temperatures of 125°C, 165°C, 185°C, and 225°C. The 125°C temperature is the nominal mission temperature. The Arrhenius model will be used to interpret the results of the accelerated rate testing. The Arrhenius equation for a degradation process ($\dot{R}$), at absolute temperature ($T$) is:

$$R(T) = \frac{dR(T)}{dt} = e^{A-B/T}$$  \hspace{1cm} (1)

When experimental data of $R$ vs. $1/T$ are plotted on semilog paper, a straight line is obtained with $A$ the intercept and $B$ the slope.

For an example of how this model will be used to make a reliability projection using heat pipe test data, assume $Q$ to be any one of a number of performance parameters. Refer to Figure 2 for a graph of hypothetical data from the life test for the four test temperatures. From the least squares linear fit of the data assumed to be linear for this example, $\dot{R}(T)=b(T)$. This is graphed in Figure 3. For the Arrhenius model to be valid this plot of $\dot{R}(T)$ must be linear. If it is not linear then there is more than one dominant chemical reaction rate.

The object of the Arrhenius model is to determine an acceleration factor which will give equal results when testing under higher temperature stress level ($T'$) for a shorter time than at lower stress level ($T$). To find the acceleration factor ($J$), equate the two stress level $T$ and $T'$. Then, for our linear example

$$(e^{A-B/T}) t = (e^{A-B/T'}) t'$$ \hspace{1cm} (2)

solving for real time $t$ we get,

$$t = e^{-B} \left( \frac{1}{T'} - \frac{1}{T} \right) t'$$

or, $t = Jt'$ where $J = e^{-B} \left( \frac{1}{T'} - \frac{1}{T} \right)$

Thus, the relationship between real life time and accelerated time has been established. Figure 4 is a typical graph of acceleration factor ($J$) as a function of stress level.
To continue with how this model is used for reliability assessment of the heat pipes, refer again to Figure 4 and see that at

- 225°C \( J = 3.0 \)
- 185°C \( J = 2.0 \)
- 165°C \( J = 1.5 \)
- 125°C \( J = 1.0 \)

This requires that heat pipes be on test for two years at 225°C, three years at 185°C or four years at 165°C to demonstrate a six year mission time at 125°C. Now, let’s assume that the heat pipe life test runs for four years.

Then, since we are interested in reliability at EOM from the fitted curves on Figure 2, take the mean and standard deviation for \( T = 225°C \) at two years, \( T = 185°C \) at three years and \( T = 165°C \) at four years and analytically combine them to obtain one distribution, with mean (\( \mu \)) and std. dev. (\( \sigma \)) representative of the 125°C case at EOM. This will be the distribution of the performance parameter \( Q \) at EOM. To establish a probability of acceptable performance, a minimum EOM criteria (\( \mu \)) must be established by the design group for \( Q \). From the distribution and the minimum criteria a demonstrated safety margin is calculated as:

\[
S_M = \frac{\bar{x} - \mu}{\sigma_x}
\]

From the safety margin and number of heat pipes in which data were used to find the EOM distribution, a reliability-confidence level is determined. This will be the EOM demonstrated reliability of performance parameter (\( Q \)).

The other parameter reliabilities are determined similarly. If these parameters are independent then they are analytically combined as series reliabilities. If they are not independent, a means for combining them must be established based on physics or empirical tests.

The enclosure presents a detailed application of the Arrhenius rate model to nickel-water heat pipe non-condensible gas generation test results.

Summary: To make EOM reliability assessment using the Arrhenius model for axially grooved heat pipes the following assumptions are made.

1. Individual heat pipe data can be used to determine a degradation trend.
2. Only one dominant chemical rate will be apparent in the temperature range of interest.
3. The acceleration factor will be sufficiently large to use one or more of the groups of data at accelerated temperatures.
4. A minimum level EOM criteria for the performance parameters can be established by the Design Analyst.
5. If the performance parameters are not independent, a method of combining results can be developed.

/cs
Heat Pipe Instrumentation
FIGURE 2
HEAT PIPE PERFORMANCE Versus Time
as function of various temperatures

\[ Q = a + bt \]

\( T = 125^\circ C \)
\( T = 165^\circ C \)
\( T = 185^\circ C \)
\( T = 225^\circ C \)

FIGURE 3
HEAT PIPE Degradation Rate
Versus Temperature

\[ \log P(T) \]

\[ \frac{1}{T} \text{ Absolute} \]
Figure 4
Heat Pipe Acceleration Factor
Versus Temperature Stress

$e^{-B \left( \frac{1}{T} - \frac{1}{T'} \right)}$

Multiple of Time on Test

$125^\circ C \quad 165^\circ C \quad 185^\circ C \quad 225^\circ C$

Stress Level

$T' - T$
Abstract

A study was made of the evolution of hydrogen gas in nickel-water heat pipes for the purpose of investigating methods of accelerated life testing. The data was analyzed in terms of a phenomenological corrosion model of heat pipe degradation which incorporates corrosion and oxidation theory and contains parameters which can be determined by experiment. The gas was evolved with a linear time dependence and an exponential temperature dependence with an activation energy of 1.03 x 10^-19 joules. A flow rate dependence of the gas evolution was found in the form of a thre0. The results were used to predict usable lifetimes of heat pipes operated at normal operating conditions from results taken at accelerated operating conditions.

I. Introduction

Heat pipes are finding applications as heat transfer and temperature control devices where long periods of trouble free performance are required. For design purposes, therefore, there is interest in determining methods for estimating the operating lifetime. What is meant by 'operating lifetime' depends on the type of heat pipe and the requirements placed on it in a specific application. With high temperature liquid metal heat pipes, structural failures sometimes occur and this is a well defined termination of life. In low temperature heat pipes, applicable to spacecraft thermal control, for example, catastrophic failures rarely occur. Instead, heat pipe performance continuously degrades as a result of (1) chemical reaction or decomposition of the working fluid with the generation of noncondensable gas, or (2) corrosion and erosion of the container and wick.

In an ordinary heat pipe all noncondensable gas is swept to the condenser end, forming a diffusion barrier to vapor flow and effectively reducing the available condenser area. In gas controlled, variable conductance heat pipes, the generation of additional noncondensable gas raises the operating temperature of the heat pipe above design conditions. Similar effects can result from a change in the chemical composition of the working fluid b, virtue of a change in its vapor pressure as a function of temperature.

Corrosion and erosion of the container and wick can be manifested as a change in the wetting angle of the working fluid as well as in the permeability, porosity, or capillary pore size of the wick. Solid precipitates resulting from corrosion and erosion are transported by the flowing liquid to the evaporator region where they are deposited when the liquid vaporizes. This leads to increased resistance to fluid flow in the evaporator, resulting in a decrease in the heat transport capacity of the heat pipe.

With these failure mechanisms, where continual degradation occurs, the operating lifetime can be defined as the period of time beyond which the operation of the heat pipe is below design specifications. Some heat pipe laboratories have been performing "life tests" under which heat pipes are held at normal operating conditions for many thousands of hours to determine the "operating lifetimes." This approach has limited applicability, however, for heat pipes which are required to function well for long periods of time. Progress in heat pipe development will be impeded if each time a new material combination, fabrication technique, or cleaning procedure is used, life tests of 10,000 hours or more are required. From a practical point of view, it is desirable to establish methods for performing life tests on an accelerated basis.

This paper is a report on one particular method of accelerated life testing of heat pipes which involves the use of a corrosion model based on the corrosion mechanisms. A study was made of hydrogen evolution in nickel-water heat pipes for a number of reasons: (1) this system represents a materials couple relevant to spacecraft applications; (2) it was of interest to accurately study hydrogen gas evolution which occurs during corrosion within the heat pipe, and which occurs in other materials systems with possible important heat pipe applications as well; and (3) the simplicity of studying a system consisting of pure (unalloyed) materials.

The primary objective was to formulate an accurate scaling law for the specific example of the water-nickel heat pipe which predicts the usable lifetime at reference (low) operating conditions from data taken at accelerated (high) operating conditions. This method of accelerated life testing is based on extrapolation from accelerated conditions to predict behavior at reference (normal) conditions. It is thus explicitly assumed that the chemical and physical mechanisms responsible for heat pipe degradation at accelerated conditions are the same in nature at the reference conditions. Similar ideas are used for other types of accelerated corrosion testing. It is emphasized that this work was not concerned with achieving compatibility between nickel and water. However, it was necessary to maintain sufficient control over the starting materials and fabrication techniques to allow the separation of temperature and fluid circulation effects.

II. Accelerated Corrosion Testing

Heat Pipe Materials and Construction

The heat pipes were constructed from nickel 200 materials. Containers were 17.5" in length with 1 1/2" OD and 0.035" walls. The layers of 350 mesh screen were installed and the end caps and closure tubes were machined from 1 1/2" and 1/4 diameter rods, respectively. Care was taken to ensure that all the heat pipes were as nearly the same as possible in terms of materials.
and construction procedures. All containers were constructed from nickel 2\textsuperscript{nd} with the same heat number, and the same was true of the screen and rods from which the end caps and closure tubes were constructed. Efforts were made during welding to use the same temperature and complete the weld in the same length of time for each heat pipe. A schematic diagram of the heat pipes operated with fluid flow is shown in Figure 1.

![Figure 1. Schematic diagram of heat pipes operated with fluid flow.](image)

In order to remove the oxide film produced on the internal surfaces of the heat pipes during welding, all heat pipes were baked out in vacuum \(10^{-4}\) torr for 2 hours and 26 minutes at 700\(^\circ\)C and then reduced in hydrogen for 30 minutes at 720\(^\circ\)C. A test specimen subjected to this procedure showed no visual evidence of oxide film remaining on internal surfaces. After vacuum bake-out and reduction in hydrogen, the heat pipes were stored for two to four weeks with plastic caps over the fill tubes. The heat pipes were evacuated to \(10^{-4}\) torr, outgassed at 100\(^\circ\)C, and then filled with 2.0 ml of triply distilled and degassed water just prior to testing. The water was degassed at 10\(^{-5}\) torr by holding the temperature at 80\(^\circ\)C for one hour; however, no analysis of the actual gas content remaining in the water was made. Copper-constantan thermocouples were spot-welded to the outside of the heat pipes and 2\textsuperscript{nd} long wire wound resistance heaters were installed on the evaporator sections prior to filling. Aerograde pipe insulating material was installed to allow four different condenser lengths 1\textsuperscript{st}, which permitted operating with different flow rates at the same temperature and vice versa.

### Measurement of Noncondensable Gas Evolution

As noncondensable gas is evolved during operation of a heat pipe, it is carried to the condenser end causing a blockage and consequent temperature profile along the outer wall. The amount of gas present may be calculated from the temperature profile assuming ideal gas behavior. If the condenser end is divided into \(N\) equal intervals and the temperature at the center of each interval is \(T_i\), then under steady state conditions the number of lb moles of gas \(n\) is given by the ideal gas law as:

\[
    n = \frac{5V}{R} \sum_{i=1}^{N} \frac{P_{gi}}{T_i} \quad (1)
\]

\[
    \ln (1), \Delta V \text{ is the volume of each interval, } R \text{ is the gas constant, and }
\]

\[
    P_{gi} = P_{v} - P_{vi} \quad (2)
\]

In (1), \(A\) is the volume of each interval, \(R\) is the gas constant, and \(P_{gi}\) is the partial pressure of gas at the center of the \(i\)th interval. \(P_{v}\) is the total pressure (the vapor pressure corresponding to the temperature in the adiabatic section) and \(P_{vi}\) is the vapor pressure in the \(i\)th interval.

A computer program was used to determine the quantity of gas in a heat pipe at any given time from the measured steady state wall temperature profile. This method is based on the assumption that the wick surface temperature, and hence the vapor-gas mixture, is very close to the wall temperature in the gas blocked region of the condenser. This has been found to be a valid assumption from the study of gas controlled pipes.\(^2\)

In practice, each pipe was divided into 3/4" elements with a thermocouple placed in the center of each interval. The thermocouple temperature readings were input directly into the computer program, which carried out the operations indicated by equations (1) and (2) and printed out the total number of lb moles of gas in the pipe.

### Results of Accelerated Testing

Based on previous studies of water heat pipes,\(^3\) it was assumed that the gas generation rate would be a strong function of the operating (vapor) temperature. For this reason all heat pipes were tested in a constant temperature chamber. The temperature of the chamber was unaffected by convective air currents in the room and could be held at \(\pm 0.5\)\(^\circ\)F of the set point, if changes in room temperature were not too sudden. However, rapid changes in the room temperature of \(\pm 3\)\(^\circ\)F, which occurred occasionally, were found to result in changes in the chamber temperature of \(\pm 1\)\(^\circ\)F. Thus, the chamber was effective in reducing ambient temperature variations, but did not entirely eliminate them.

Based on initial results, a test plan was drawn up to begin life testing of three reference condition heat pipes and five accelerated condition heat pipes held at higher temperatures. The three reference condition heat pipes were set operating in the constant temperature chamber (held at 80.0 \(\pm 0.5\)\(^\circ\)F) in a slight reflux mode at 85.0 \(\pm 0.5\)\(^\circ\)F and 0.12 watts.

The five accelerated condition heat pipes were held at constant temperatures of 135\(^\circ\)F, 150\(^\circ\)F, 165\(^\circ\)F, 180\(^\circ\)F, and 195\(^\circ\)F (isothermally) with zero flow rate. These isothermal heat pipes were held to within \(\pm 0.5\)\(^\circ\)F of the indicated temperature by completely wrapping the pipes with heat tape and covering with two layers of insulation. The temperature difference between any two points on a heat pipe was less than 0.5\(^\circ\)F. Thus, the fluid flow rate in the isothermal heat pipes was essentially zero. The only time fluid flow occurred was during the approximately one hour periods when the heat pipes were operated at 100\(^\circ\)F, as heat pipes, for the purpose of measuring the temperature profiles. In order to measure the amount of gas generated by high temperature exposure, the heat pipes maintained under isothermal conditions were taken out of the constant temperature chamber temporarily for removal of the heat tape and placed back in the chamber and
operated as heat pipes for the purpose of recording the temperature profiles. The heat pipes were rewrapped with 

*i*(revolved) with respect to the chamber for further high temperature exposure.

Accelerated testing under isothermal conditions was carried out for a number of reasons. When operated as a heat pipe (with fluid flow), the gas generated builds up as a function of time, blocking increasingly more condenser lengths. As a consequence, the vapor temperature in the adiabatic section can be held constant only if (1) the power is continuously decreased or (2) more condenser length is continuously uncovered. The first method requires a temperature controller for each heat pipe and allows the flow rate to decrease, while the second would require a great amount of time in maintenance if the insulation were moved by hand. With these heat pipes it was desired to study the dependence of gas generation on temperature alone, and not on flow rate. Thus, it was decided to examine the gas generation under isothermal conditions (with zero flow rate) and hold the temperatures constant over an extended period (1290 hours) using only the temperature controller on the chamber.

Contrary to expectations, as shown in Figure 2, a strong temperature dependence did not appear with the five heat pipes held at temperatures of 135°F, 150°F, 165°F, 180°F, and 195°F under isothermal (zero flow rate) conditions. The general behavior appears to be initial (possibly parabolic) passivation, but at much reduced rates compared to heat pipes operated with non-zero flow. Data taken with a heat pipe operating at 150°F with fluid flow is shown in Figure 2 for comparison. It thus appears that the flow rate is an important variable in gas generation in nickel-water heat pipes.

In order to examine the flow rate dependence together with the temperature dependence, eight heat pipes were operated at accelerated conditions up to 188 hours. The heat pipes employed in this phase of the program were the five tested previously with zero flow and the three reference condition heat pipes (from which sufficient reference condition data had been collected). All these heat pipes contained only a small amount of gas as a result of previous testing. It was initially intended to operate one set of four heat pipes at the same flow rate and different temperatures and a second set of four at the same temperature and different flow rates. These conditions could not be met exactly in practice. After establishing the accelerated testing conditions for each heat pipe, the power was reduced as gas was generated as a function of time in order to hold the temperature constant throughout the testing period. This was done because it was felt that the temperature dependence would be stronger than the flow rate dependence, as was found to be the case. The heat pipes were operated under the accelerated conditions (temperatures between 151 - 177°F and power levels between 4.4 - 9.0 watts) indicated in Figures 4 - 6. The power levels are the initial and final values, respectively. In all cases the time dependence appears to be linear within the accuracy of the data obtained. Beyond 100 hours of exposure the data may need correction because the area exposed to the insulating surface became decreased as gas built up in the condenser. The resulting reduction in gas generation as the temperature falls are quite small over small variations in the thermocouple reading, particularly for small amounts of gas (10°F in most cases). These heat pipes were operated at 85.0 ± 0.5°F for 1150 hours, except for two 60-hour periods (of approximately 2 hours) at 97°F. Within the scatter of the data, only a linear time dependence can be assumed. Sufficient accuracy was not obtained to determine an initial period of passivation. After 1150 hours at 85°F, the temperature was increased to 97°F in order to improve the accuracy of the gas measurements. A rapid increase in gas was noted beyond this point up to the total 1600 hours exposure indicating a change in the corrosion behavior.
along the condenser could be taken into account by an iterative method but the accuracy of the data does not appear to warrant such a treatment. For this reason, the curves were drawn with emphasis on the interval below 100 hours of exposure. Displacement in a number of the curves apparently resulted from unrecorded increases or decreases in the temperature.

Figure 4. Gas generation in accelerated condition heat pipes operated with fluid flow showing temperature dependence of gas evolution rate.

Figure 5. Gas generation in accelerated condition heat pipes operated with fluid flow.

III. Corrosion Model and Analysis

It is known that a clean nickel surface corrodes uniformly at a very small linear rate (0.001 mpy) after long duration exposure to distilled water at room temperature. No studies of the initial corrosion behavior of nickel in distilled water could be found in the literature. A phenomenological corrosion model is considered below which incorporates corrosion and oxidation theory and contains parameters which may be determined by experiment.

It is assumed that uniform corrosion occurs at all nickel surfaces by the operation of a great number of microscopic galvanic cells. At each cell nickel oxide, nickel hydroxide, or other corrosion product will be generated at the anode and hydrogen gas at the cathode according to reactions such as

\[
\text{Ni} + \text{H}_2\text{O} \rightarrow \text{NiO} + \text{H}_2 \quad (3)
\]

\[
\text{Ni} + 2\text{H}_2\text{O} \rightarrow \text{Ni(OH)}_2 + \text{H}_2 \quad (4)
\]

The corrosion product depends on the conditions under which the actual chemical reactions occur. For each mole of nickel oxidation product one mole of hydrogen gas is evolved. From previous studies it is reasonable to assume that a protective film of the oxidation corrosion product is formed during the initial exposure. Generally accepted theories of film growth during oxidation of metal surfaces assume diffusion through the film of cations away from the metal surface and anions toward the metal surface. The diffusing ions migrate from one position of minimum potential energy to the next. If \( Q \) is the height of the barrier between two potential energy minimums, the probability that an ion will pass over the barrier is proportional to \( e^{-Q/kT} \), where \( Q \) is called the activation energy, \( k \) is Boltzmann's constant, and \( T \) is the absolute temperature. This is the temperature dependence...
found experimentally in all gaseous diffusion. It should be mentioned that simple interpretation of (5) above is only one of several physical interpretations, which depend on the particulars of film growth theory.

Oxidation theory predicts passivating film growth will occur with a parabolic time dependence and an exponential temperature dependence. Hydrogen evolution in the heat pipes should thus be given by

\[ n(t, T) = B t^{1/2} e^{-Q/kT} \]

where \( n \) is the number of lb moles of hydrogen, \( t \) is the time, and \( B \) is a constant of proportionality. This time dependence has been found to describe hydrogen evolution from steel in boiling water, but is not common to the (long duration) corrosion of metals generally. Various other forms of time dependencies are also predicted by theory, depending on the particular assumptions made.

Over long exposure periods, uniform corrosion with a linear time dependence occurs more commonly. Thus, after the initial passivation the hydrogen evolution may be expected to obey

\[ n(t, T) = B t e^{-Q/kT} \]

In this case it is assumed that the film reaches a final thickness in the steady state, with the outer layer either going into solution or scaling off as solid corrosion product. The temperature dependence in (5) and (6) has been found for aluminum in water, mild steel in pure water, mild steel in NaOH, 18/9 stainless steel in H2SO4, and uranium in water.

Two other considerations which should be taken into account are the flow rate, discussed below, and the solution of oxygen and hydrogen in the water. Hydrogen gas in solution is reported to be present in solution at the solubility limit. Over long exposure periods, uniform corrosion, as shown in Figures 4-6, obeys a linear time dependence corresponding to the activation energies shown in Table 1. An explanation for this may be that the effective potential barrier is lowered by the electric field across the film created by the local corrosion cell.

The use of this corrosion model in accelerated corrosion testing is that the parameters \( B \) and \( Q \) can be determined experimentally from data taken under accelerated conditions by plotting \( \log n \) vs \( 1/T \). Having determined these parameters by measuring the gas evolution at accelerated conditions, the gas evolution at any time can be calculated from (6) for heat pipes operated at the reference condition.

### Analysis of Results

Except for the case of the initial exposure of the isothermal (zero flow) heat pipes, the data obey a linear time dependence corresponding to uniform corrosion, as shown in Figures 4-6. The data during initial exposure in the 10^-9 lb mole range was not of sufficient accuracy to allow identification of initial passivation. Plotting \( \log n \) vs \( 1/T \) results in the curve shown in Figure 7, indicating that corrosion in these nickel-water heat pipes is described by Eq. (6), within the accuracy of the data. Calculating the parameters \( Q \) and \( B \)

<table>
<thead>
<tr>
<th>Material</th>
<th>Environment</th>
<th>Temperature range (°C)</th>
<th>Activation Energy (10^-20 joules)</th>
<th>References</th>
</tr>
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<tr>
<td>Mild steel</td>
<td>air</td>
<td>below 570</td>
<td>31.3</td>
<td>20</td>
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<tr>
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<td>oxygen</td>
<td>550-650</td>
<td>20.6</td>
<td>24</td>
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<tr>
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<td>15.7</td>
<td>24</td>
</tr>
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<td>400-600</td>
<td>25.9</td>
<td>25</td>
</tr>
<tr>
<td>Uranium</td>
<td>air</td>
<td>310-345</td>
<td>13.8</td>
<td>26</td>
</tr>
<tr>
<td>Nickel</td>
<td>oxygen</td>
<td>360-440</td>
<td>14.6</td>
<td>26</td>
</tr>
<tr>
<td>Nickel</td>
<td>oxygen</td>
<td>500-1000</td>
<td>24.2</td>
<td>27</td>
</tr>
<tr>
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<td>5-20% NaOH</td>
<td>250-355</td>
<td>10.4</td>
<td>20</td>
</tr>
<tr>
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<td>40-80</td>
<td>10.1*</td>
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</tr>
<tr>
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<td>H2SO4</td>
<td>-100</td>
<td>8.63</td>
<td>21</td>
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<tr>
<td>304 Stainless steel</td>
<td>distilled water</td>
<td>38-149</td>
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</tr>
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<td>Iron</td>
<td>10% HCl</td>
<td>40-90</td>
<td>3.37*</td>
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<td>10% HCl</td>
<td>40-110</td>
<td>6.81*</td>
<td>28</td>
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<td>70% HNO3</td>
<td>10-120</td>
<td>8.47*</td>
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<td>Uranium</td>
<td>water</td>
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</tr>
<tr>
<td>Nickel</td>
<td>distilled water</td>
<td>36-81</td>
<td></td>
<td>22</td>
</tr>
</tbody>
</table>

* Calculated from data contained in referenced papers.
from the slope and intercept, respectively, results in:

\[ Q = 10.3 \times 10^{-20} \text{ joules,} \]

\[ B = 0.970 \text{ lb mole/hr.} \]

Figure 7. Accelerated testing data of Figures 4-6, \( \log_{10} \alpha \) vs 1/\( t^* \).

Table 2 compares the actual and predicted gas evolution in the reference condition heat pipes. The corrosion model over-predicts the gas evolution for the reference condition with the lower flow rate but predicts the gas evolution reasonably well at higher flow rates.

As discussed above, the flow rate appears to be an important variable in gas generation in these nickel-water heat pipes. This flow rate dependence appears to be in the form of a threshold, below which the corrosion rate is very low, and above which normal, uniform corrosion with hydrogen evolution occurs. As seen in Figure 3, a change in the gas generation rate appears to occur on changing the reference operating conditions from 85°F at 1.37 lb/hr (0.42 watts) flow rate to 97°F at 5.39 lb/hr (1.42 watts) flow rate. This change in behavior appears to result from the increase in flow rate and not from an increase in temperature. Comparison with the data in Figure 2 shows that gas generation in the high temperature, zero flow rate, heat pipes was low and similar to the behavior found at 85°F with 1.37 lb/hr flow rate. Furthermore, at flow rates above 4.7 lb/hr the dependence on flow rate does not appear in the data, as may be seen by a comparison of the gas generation curves in Figure 6 taken at the same temperature but at different circulation rates. It thus appears that the flow rate dependence is in the form of a threshold, below which gas evolution is very low and above which normal, uniform corrosion takes place.

The Reynolds number based on the wick wire diameter is of the order of \( 10^{-2} \), indicating laminar flow under all conditions in these heat pipes. Theoretically, the corrosion rate is proportional to \( f^{1/2} \) or \( f^{1/3} \) depending on the geometry of the surface, where \( f \) is the laminar flow rate. However, experimentally it is sometimes found that the corrosion rate remains low below a minimum (threshold) value of the flow rate and rapidly increases to a higher, nearly constant, value above this minimum. 13, 26, 28 A similar behavior was found with the heat pipes in this study. The precise value threshold flow rate \( f_t \) cannot be deduced from the data, but satisfies the inequalities \( 0.00137 < f_t < 0.00467 \text{ lb/hr.} \) (7)

As an example of accelerated life testing and the scaling law represented by Eq. (6), let it be assumed that heat pipes are required for a particular application to be operated at 85°F, but at a power input resulting in a flow rate greater than threshold. If the useful lifetime is considered to be limited by gas evolution in the amount of 2 x \( 10^{-8} \) lb moles, solving Eq. (6) for \( t \) results in a predicted lifetime of \( t_{\text{life}} = 1015 \text{ hours} \) \( \pm 9\% \).

IV. Conclusions

From a study of hydrogen evolution in nickel-water heat pipes it was found possible to predict using a scaling law, Eq. (6), based on consideration of the corrosion mechanisms, the lifetime of a heat pipe operating at reference conditions from data taken at accelerated conditions, provided the fluid flow rate is greater than a threshold value, Eq. (7). For flow rates less than threshold the hydrogen evolution rate is much reduced, but a precise lifetime cannot be calculated. However, this is not of great importance as the advantage of heat pipes lies in the area of large heat transport, which is the case covered by the accelerated testing model. Similar methods of accelerated life testing may be applicable to other types of heat pipes if sufficient information is known, or can be obtained concerning the degradation mechanisms.

Acknowledgments

The author wishes to thank Dr. B. D. Marcus for helpful discussions and Mr. G. L. Fleishman for the computer program used to calculate the noncondensable gas content used to calculate the temperature profile.
References


MEMORANDUM

October 23, 1978

Refer to: SIG-GWB-1581

To: W. Brittain, P. Collins, A. Lieberman, R. Menchen, N. Strazza


From: G. Budesheim

Subject: SIG Axially Grooved Heat Pipe Non-Condensible Gas Characteristics (Task 10.3)

Ref.: (a) SIG-LLR-1455, same subject dtd 10/3/78.
(c) SIG-PJC-1534, "Calculation of Non-Condensible Gas Slug Length for Heat Pipe Life Test," 9/26/78.

Objective: To present an updated quantity of non-condensible gas versus time trend analysis for the axially grooved heat pipes currently on test in life test fixtures 1 thru 5. The information supersedes that presented in ref. (a).

Conclusion: The amount of data available is insufficient to draw positive trend conclusions. However, the quantity of gas generated is not inconsistent with earlier B&K Engineering (supplier) tests. The higher temperature tests generate gas at a greater rate as should be expected.

Figure 1 presents the mean amount of non-condensible gas versus time by test fixture. During the first 150 ± 50 hours, all fixtures operated at 125°C and not at the temperatures indicated in the figure. The test is conducted in accordance with paragraph 5.2.2 of procedure LCP 10069 and the measured results reduced using technique defined in Ref. (b). At this point in the test, gas is still being generated. It is expected that this generator rate will level out as the life test time increases. It can be noted that the apparent slopes of the gas build up for fixtures 1 thru 3 are progressively greater for the higher temperatures which confirm the accelerated rate testing theory.
Figure 2 presents the mean amount of non-condensible gas versus time by fixture converted to the equivalent amount of gas blockage in the condenser end of the heat pipe at 125°C. The conversion is made by methods presented in Ref. (c).

Figure 3 shows the gas build up for three heat pipes on test by the supplier at an accelerated temperature of 218°C for up to 10,000 hours. Teledyne Energy Systems life test initial results at 225°C and 185°C compare favorably with these B&K Engineering tests.

With the limited amount of available data, no trend analysis or conclusions are made.
**Figure 1**

Axially Grooved Heat Pipe Non-Condensible Gas Versus Time Characteristics (B & K Engineering P/N LCP 10042-009-019)

- **Fixture 1**: 125°C
- **Fixture 2**: 160°C
- **Fixture 3**: 185°C
- **Fixture 4**: 225°C
- **Fixture 5 (Panel)**: 125°C
FIGURE 2
AXIALLY GROOVED HEAT PIPE B.R.S. LENGTH AT 125°C
VERSUS TIME CHARACTERISTICS (B & K ENGINEERING
P/N LCP 10042-009 & 019)

- ○ FIXTURE 1 125°C
- ○ FIXTURE 2 160°C
- △ FIXTURE 3 185°C
- □ FIXTURE 4 225°C
- ○ FIXTURE 5 (PANEL) 125°C

GAS BLOCKAGE LENGTH (INCHES)

0.5
1.0
1.5
2.0

TIME (HOURS)
0 2000 4000 6000 8000 10000
Fig. 3  Accelerated life test results (AL-5, 4-D, LT-57) AT 218°C.
MEMORANDUM

October 26, 1978

Refer to: SIG-GWB-1585

To: W. Brittain, P. Collins, A. Lieberman, R. Menchen, N. Strazza


From: G. Budesheim

Subject: Sintered Wick Heat Pipe Non-Condensible Gas Characteristics, Task 10.3

Refs.:  
(c) SIG-PJC-1534, "Calculation of Non-Condensible Gas Slug Length for Heat Pipe Life Test," dtd. 9/26/78.

Objective: To present an updated quantity of non-condensible gas versus time trend analysis for the sintered wick (Hughes Aircraft) heat pipes currently on test in life test fixtures 1 - 5. The information updates that presented in Ref. (a).

Conclusion: The amount of data available is insufficient to draw trend conclusions. However, the quantity of gas generated is within the range that may be expected, with higher temperature tests generating gas at a greater rate.

Implications: No further analysis of the sintered wick heat pipe data is contemplated, except on request, since these pipes are not scheduled to be installed on SIG generators.

Figure 1 presents the mean amount of non-condensible gas versus time by fixture. It should be noted that during the first 150 ± 50 hours all fixtures operated at 125°C and not at the temperatures indicated in the figure. The test is conducted in accordance with paragraph 5.2.2 of procedure LCP10069 and the measured results reduced using the technique defined in Ref. (b). At this point in the test, gas is still being generated at a high rate. It is expected that this high rate will level out as the life test time increases.
It can be noted that the apparent slopes of the gas build up is progressively greater for the higher temperature pipes which confirms the accelerated rate testing theory.

Figure 2 presents the mean amount of non-condensable gas versus time by fixture converted to the equivalent amount of gas blockage in the condenser end of the heat pipe at 125°C. The conversion is made by methods presented in Ref. (c).

Additional updates to this data are not scheduled since all analyses on sintered wick heat pipes has been discontinued. Data, however, will continue to be recorded. Discontinuation of the analysis is predicted on the selection of the axially grooved heat pipe design for the SIG generators.
FIGURE 1
SINTERED WICK HEAT PIPE: NON-CONDENSIBLE GAS VERSUS TIME CHARACTERISTICS (HUGHES AIRCRAFT LCP, 10003-068 & 018)

- Fixture 1: 125°C
- Fixture 2: 150°C
- Fixture 3: 175°C
- Fixture 4: 225°C
- Fixture 5 (Panel): 125°C

Non-Condensible Gas x 10^6 (liter moles)

Time (Hours)
FIGURE 2
SINTERED WIH heat pipe, G.B. LENGTH AT 125°C
VERSUS TIME CHARACTERISTICS (HUGHES AIRCRAFT
CP 10003-003 & 013)

- FIXTURE 1 125°C
- FIXTURE 2 160°C
- FIXTURE 3 195°C
- FIXTURE 4 225°C
- FIXTURE 5 (PANEL) 125°C

GAS BLOCKAGE LENGTH (INCHES)

TIME (HOURS)
MEMORANDUM

23 October 1978
Refer to: SIG-WJB-1580

To: W. Osmeyer, D. Trimmer


From: W. Barnett

Subject: 3M Trip Report October 5 - 6, 1978

Objective
Observe initial stages of the diagnostic disassembly of Module M-7.

Conclusions
1. Indirect evidence strongly suggests that follower hang-up is a significant factor contributing to module degradation.

2. Additional degradation factors, if any, and their relative significance remain to be identified.

Implication
Continue following M-7 diagnostic findings.

The initial stage of the diagnostic disassembly by 3M of Module M-7 was observed by the writer and H. Kling/Fairchild. Disassembly was performed by Bob Budowetz (technician) under the supervision of R. Ericson. Operations were also monitored by L. Ellis/Sandia. Occasional 3M observers included J. Hinderman, D. Wald, W. Mitchell and R. Reyle, and others.

Background - Module M-7 is a ten couple series connected device. GDS-1 employs a series-parallel thermoelectric circuit couple and cold end hardware design is the same as that employed in GDS-1. The heater block is tantalum (another difference from GDS-1).

I. Analysis of 3M M-7 Leg Resistance Data by H. Kling/FI

A tabular listing of leg resistances over the operations time period 10,831 thru 12,680 hours (nominal module failure at approximately 11001 hours) was presented by H. Kling, Table I, with several interesting interpretations as follows:

- The whole module underwent some temporary perturbation at 12,516 hours as evidenced by a "peak" in the resistance of all "N" and "P" legs.
Generally all "N" legs exhibited a stable resistance/time behaviour - i.e., moderate decrease in resistance, presumably due to Gd foil interaction.

In contrast to the "N-leg" resistance behaviour, all P-legs exhibited a moderate increase in resistance with time. However, selected P-legs, showed a sharp upward inflection in the mΩ/time curve at some point in time.

This "resistance-time inflection" is very evident for P-legs #4 and #8 and appears to be just initiated for P-legs #12 and 14. Thus, particular attention should be paid to these elements during diagnostic evaluation in the search for possible clues to degradation mechanism(s).

II. Impurity Analysis of Test Environment

The module static gas cover (xenon) was equilibrated with a somewhat larger evacuate and baked out stainless steel elbow. A gas sample was taken for "mass spec" analysis. The elbow contained a "nude" tungsten filament light bulb and a pressure reducing adjustable leak valve which was connected to a partial pressure analyzer.

Based on the relative life of the "nude" light bulb (i.e., versus life in other known high purity atmospheres) R. Ericson qualitatively estimated that the atmosphere is reasonably good - i.e., probably < 10 PPM oxygen and water vapor.

III. Electrical Resistance Checks Before, During and After Removal of Module from Test Chamber

A. General observations prior to cool-down.

- Both N and P legs exhibited intermittent fluctuations in resistance (i.e., μΩ to ohm range).
- The majority (7) of the N-legs were in the mΩ resistance range while the majority of the P-legs (6) were in the Ω+ range.
- Module to ground resistance was approximately 800 KΩ (hot).

B. General Observations During Disassembly

The resistance profiles of high resistance legs through the various stages of module disassembly are summarized in Table II together with spot checks of module/ground resistance (i.e., not dielectric check).
III. Sublimation Deposits

The following visual observations of deposits or reaction products were noted at various stages of module disassembly.

- Reddish coloration in insulation adjacent to end of one hot side heater.
- Grey-black deposit on internal cold surface of test fixture (presumed to be Se or Se X). A portion of this deposit appeared to rub off on the insulation blanket around the module during removal from the "T" test fixture.
- Deposits and reaction products on all metallic cold side components of the module and support fixture.
- Fiberfrax module insulation in the vicinity of the P-legs contained fine dark grey-black deposit and some larger specular crystalline particles.

IV. Visual Observations During Module Insulation Removal

Pertinent observations during removal of the module insulation (Fiberfrax type stuffing) and subsequent in-situ visual examination of the elements are as follows:

- All P-legs were "loose" (i.e., moved with minimal force such as encountered during careful removal of the insulation).
- One P-leg exhibited a visual gap (several mils) between the leg and the hot shoe.
- In general, the N-legs were not readily displaced during insulation removal. However, in one case the N-leg was "loose" enough such that hot shoe could be easily rotated about the N-leg axis.
- One N-leg, #5, was fractured longitudinally and appeared to be "loose."
- Adherence of insulation particules to the P-leg surface prohibited close examination of the element surface particularly in the area of the partition. However, the occurrence of "copper extrusion" was apparent on the surface of all P-elements at the cold end - a "wart like" growth, typically approximately 0.1" diameter x 1/16" high.

General Discussion

It appears obvious that follower hang-up is a contributing factor to "loose" elements and high and variable leg resistance values. However, the following questions require resolution:
What is the mechanism for follower hang-up effecting an N-leg? Presumably, the N-leg material is relatively immune to dimensional changes due to sublimation or creep.

Is the problem of P-leg follower hang-up aggravated by excessive creep and sublimation? What is the split of element dimensional change between the hot and cold side of the partition? Or, has the partition functioned in the predicted manner?

J. Hinderman/3M stated that the differential expansion encountered during module cooldown should lead to a slight reduction in the spring load. These calculations should be reviewed.

An additional question regarding sublimation which should be addressed is, "Which sublimation predictive model, 3M or JPL, best matches the observed magnitudes of P-leg sublimation?"
# Table I

Analysis of 3M Module M-7 Data by H. Kling/Fairchild

Resistance by Leg - Temperature Corrected - Milliohms

<table>
<thead>
<tr>
<th>Time Hrs</th>
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<th>2</th>
<th>3</th>
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<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<tr>
<td>11001</td>
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TABLE II
SUMMARY OF HIGH RESISTANCE\* LEGS NOTED
DURING DISASSEMBLY OF MODULE M-7 AT 3M
\*Typically > 300 MΩ

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<tr>
<th>Leg Identification Number</th>
<th>900°C Prior to Cool Down</th>
<th>400°C During Cool Down</th>
<th>200°C During Cool Down</th>
<th>R.T. In Fixture</th>
<th>R.T. Out of Fixture</th>
<th>R.T. at Disassembly Location</th>
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Module to Ground Resistance ~ 800 KΩ

Refer to: SIG-WJB-1580
MEMORANDUM

11 October 1978

Refer to: SIG-JPC-1559

To: D. Trimmer, T. Hammel, A. Lieberman

CC: N. Strazza, W. Brittain, P. Brennan (B&K Engineering), V. Srinivas, J. Seebald, W. Wachtl

From: P. Collins

Subj: Oscillations Within a SIG Heat Pipe When Operated as a Refluxer. Task 16.2


2) BK045-1000 "SIG Heat Pipe Spin Test Fixture"

3) BK045-1001 "SIG Heat Pipes for Spin Testing"

Objective: To determine the effect of reservoir length and tilt angle (from the vertical) on the operation of a SIG heat pipe in the refluxing mode.

Conclusions: The effect of reservoir length on pipe performance is shown in Figure 11. The postulated thermal performance trend is given in Figure 12. The optimum design point where the ideal working fluid is present is probably non-realistic. It assumes a uniform return of the liquid to the evaporator. If the pipe is not aligned parallel to the g field, the liquid will return along some preferred path which will effect the evaporator AT's. Therefore it is recommended that the \( L_T/L_R \) design should be greater than \( L_T/L_R \) ideal to assure heat pipe operation.

Implications: The current design point \( L_T/L_R = 11 \) is satisfactory and will assure 1 g heat pipe operation in the refluxer mode.

Test Specimen:

Heat pipe serial #SP-12 manufactured and spin tested by B&K Engineering under P.O. 81134 was used. The configuration is as follows:

- Straight heat pipe \( L = 53" \)
- Mass charge \( M = 9.75 \text{ gm} \)
- Liquid area \( A_L = .011 \text{ in}^2 \)
- Vapor area \( A_V = .037 \text{ in}^2 \)
Test Fixture

The heat pipe spin test fixture shown schematically in Figure 1 was used. This fixture was also manufactured by B&K Engineering under P.O. 81134.

Test Procedure:

The heat pipe temperature profile shall be recorded as a function of time for the following operating modes:

- 6" Reservoir - vertical orientation
- 7.5" Reservoir - vertical orientation
- 4.5" Reservoir - 60° from the vertical

Each mode shall be operated with 70 and 100 watts input at each of two vapor temperatures \( T_V = 194°F \) and \( 257°F \). The vapor temperature \( T_V \) shall be measured at T/C #9 (see Figure 1). The oscillations will be recorded only when the vapor temperature is within 5°F of the required temperature.

The various reservoir sizes shall be obtained by locating the heat pipe in the fixture to give the correct reservoir size. The thermocouples shall maintain their positions relative to the fixture.

Test Results:

Figures 2 through 10 presents for all conditions where oscillations were observed, the temperature history at T/C #3. Some oscillations were observed at T/C #4 in the cases as indicated. The remainder of the pipe always appeared stable.

Table 1 summarizes the observed oscillations and the average \( \Delta T \)'s measured for all test conditions. The average \( \Delta T \)'s between the evaporator and the heat pipe vapor temperature were calculated using the following equations:

\[
\Delta T_1 = \frac{T_3 + T_4}{2} - T_9 \quad \text{First evaporator}
\]

\[
\Delta T_2 = \frac{T_7 + T_8}{2} - T_9 \quad \text{Second Evaporator}
\]

where \( T_3 \) is the time weighted average at T/C location #3. When oscillations were observed at T/C #4, \( T_4 \) was used in the above equation in lieu of \( T_4 \).

Figure 11 is a plot of \( \Delta T_1 \) vs. \( \frac{L_T}{L_R} \) and \( \Delta T_2 \) vs. \( \frac{L_T}{L_R} \) for the 70 and 100 watt vertical test conditions. Data at \( \frac{L_T}{L_R} = 11.8 \) was taken from Reference (1).
Discussion of Test Results

Figure 11 presents the actual average ΔT's recorded for various reservoir sizes. Figure 12 presents the writer's opinion of the expected and observed ΔT trends in a vertical refluxer with varying liquid reservoir sizes. The ideal situation would be the point where the working fluid* inventory is equal to the ideal mass charge of a vertical refluxer. If the reservoir's volume is increased beyond this point, the quantity of working fluid will decrease with a resultant increase in ΔT. When the volume of the reservoir is equal to the total charge volume, no liquid is available for heat piping hence the ΔT increases asymptotically.

If the reservoir size is decreased beyond the ideal condition the additional working fluid begins to form a column of liquid in the first evaporator. The slug will be stable until it reaches a certain size where the heat input to the slug is sufficient to cause the slug to become unstable. When this point is reached the average ΔT in the first evaporator will decrease slightly because of the oscillations, then increase as the oscillations become more severe. The average ΔT in the second evaporator will decrease to the point of being sub-cooled. The liquid surging past the second evaporator will cool it beyond its nominal operating temperature.

This theory was postulated as a result of the actual measured ΔT's graphed in Figure 11. For this test \( \frac{L_T}{L_R} \) critical is equal to 4.1 for \( T_V = 194^\circ F \) and 4.0 for \( T_V = 257^\circ F \). The \( \frac{L_T}{L_R} \) ideal probably exists somewhere between 4.0 and 7.0. Beyond \( \frac{L_T}{L_R} = 7 \) oscillations start occurring.

The oscillations observed when the heat pipe was inclined 60° from the vertical are different from oscillations measured in the vertical mode (see Reference (1)). The large ΔT's measured in the second evaporator probably result from the manner in which the liquid is returned to the evaporator. With the pipe inclined from the vertical the liquid will return to the evaporators in a puddle which, because of gravity, prefers the bottom few grooves. The side and top grooves are starved for liquid causing the overall ΔT to rise. The period of oscillation is very different in the 100 watt, 194°F case. The shape of the slug in the evaporator influences the heat transfer into it and probably caused the measured increase in cycle time.

*Working fluid is defined here as the active portion of the mass charge. It does not include the inactive fluid in the reservoir.
Thermocouples
Typical 13 Places

Fig. 1. SIG heat pipe instrumentation
FIGURE 2

9-26-78

7% 3

EVAPORATOR - 70 WATTS
TRIM 303 WATTS
AIR 21 PSI/G
TEMP 7% 9 - 194°F
RESERVOIR 6 INCHES

\[(T_2)_{ave} = 3.14, \ \circ F\]
FIGURE 3

9-27-78

$\frac{T/C 3}{T/C 4}$ NOT SYNCHRONIZED

EVAPORATOR
TRIM
AIR
TEMP. % 9
RESERVOIR
100 WATTS
312 WATTS
IN ADD.
NO
6 ZUCK
FIGURE 4

9-27-78

Tc 3

Tc 9

Tc 9

Tc 9

EVAPORATOR
70 WATTS
TRIM
500 WATTS
AIR
19.5 PSIG
TEMP.
RESErVOIR
257 °F
6 INCHES

T3 = 275 °F

TIME (m) SECONDS
FIGURE 5

9-27-78

FIG 3

TIME (SECONDS)

0

100 WATTS

50 WATTS

21 FSEC

62°F

K & E CORPORATION

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FIGURE 6

9-29-78

$\frac{T}{T_0} = 2.16$

$T_e = 210^\circ F$ observed

$T_e + 10^\circ F$ oscillations

E\VAPORATOR 300 WATTS
TRIM 200 WATTS
REL TEMP. 74$^\circ C$ 186$^\circ F$
RESERVOIR 7.5 INCHES
FIGURE 8

10-4-78

T/C 3

EVAPORATOR 70 WATTS
TRIM 200 WATTS
AIR 15 PSI
TEMP T/C 9 194°F

60° ANGLE

\[ T_3 = 216°F \]

\[ T_4 = 212°F \pm 2.5 \]
FIGURE 9

Evaporator Trim Air Temp. % H 980°F

20° Angle

T2 = 224°F

Time in Second
FIGURE 10

10-6-78

TRIM 140 WATTS

TEMP 269° F

60° ANGLE

T2 = 270°
Figure 12

Postulated trend for the $\Delta T$ vs $L_I/L_R$ curve for a heat pipe operating as a reclaimer in a $g$ field.

Available working fluid building up. Slug small enough to be stable. $\Delta T$ increasing to be stable. $L_I/L_R$ increasing. Slug small enough to be stable. $\Delta T$, drops initially when slugging first occurs. Then increases as the slugging becomes more violent.

$H_\text{cr} = \left( \frac{L_I}{L_R} \right)_{\text{critical}} \Rightarrow$ no working fluid

Available working fluid building up. Slug small enough to be stable. $\Delta T$ increasing to be stable. $L_I/L_R$ increasing. Slug small enough to be stable. $\Delta T$, drops initially when slugging first occurs. Then increases as the slugging becomes more violent.

$H_\text{cr} = \left( \frac{L_I}{L_R} \right)_{\text{critical}} \Rightarrow$ no working fluid

$\Delta T_{\text{nominal}}$ (no $g$ field)
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For 194°F:

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For 257°F:

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</table>

No oscillations
MEMORANDUM

5 October 1978

Refer to: SIG-JPC-1565

To: G. Budesheim, D. Trimmer


From: P. Collins

Subj: Problems Associated With The Axially-Grooved Heat Pipe Acceptance, Verification and Life Test Data, Task 16.2

Ref: 1) "Analysis of Axially-Grooved Heat Pipe Acceptance, Verification and Life Test Data," SIG-GWB-1528, 22 September 1978

2) "Quality Assurance Data and Performance Test Results for SIG Life Test, -009 Light Wall Heat Pipe Assemblies," BK033-1017, March 1978

Objective: To explain the problems associated with the thermal transfer and transport testing of the axially-grooved heat pipes and to make recommendations for their solution. Reference 1) summarizes the problems of the acceptance, verification and initial life test data recently taken at TES.

Conclusion: The thermal transfer data problems are formidable and would require excessive time and money to solve. The thermal transport data can be improved to a degree, however many of the related problems cannot be solved in a timely fashion. Since the same information acquired from thermal transfer and transport testing can be obtained indirectly through destructive tests and because the failure modes being tested for are secondary to the more probable failure modes, the bulk of the testing effort and data analysis should be shifted back into perspective.

Implications: A revision of the heat pipe life test plan and procedure will be required.
Recommendations:

1) Measure the thermal transport performance of each pipe after 1 year of testing and at the end of the life test only. The one year would simulate the only point in the mission where the wick is actually required. Compare the results on a one-to-one basis.

Relatively good thermal transport data can be taken by avoiding the high and low elevations and increasing the spread between test elevations as much as possible. Accurate delta temperature data is not required to measure the maximum transport providing the change in delta temperature of the heat pipe can be measured.

2) Eliminate the analysis of thermal transfer data.

3) Concentrate the test efforts on the non-condensible gas tests and the destructive and NDT tests.

4) Incorporate into the destructive test plan, checks to determine any change in the surface wetting property.

The analysis of the axially grooved heat pipe acceptance, verification and life test data has indicated considerable editing of the raw data is required before acceptable results are obtained (see Reference (1)). The validity of this data reduction approach is questionable. Editing of the raw test data was required because of the difficulties associated with conducting the thermal transfer and transport tests. These problems can be divided into four categories: 1) instrumentation problems, 2) test fixture problems, 3) data interpretation problems and 4) test elevation problems. All four categories effect the thermal transport data where as the transfer data is effected only by the first three. These problem areas will be discussed in terms of their effects on the transport and transfer data. Other problems such as those associated with maintaining the life test and the non-condensible gas tests are not discussed.

Instrumentation Problems

The thermocouples are attached to the heat pipe using aluminum tape and clamps. The two T/C leads are placed at the proper location on the heat pipe 180° around the circumference from the heat input or rejection area and fastened with tape. The clamps or "keeper bars" secure the thermocouples to the pipe and the pipe to the fixture. Any heat losses through the keeper bar will influence the thermocouple. This could be alleviated by thermally insulating the keeper bar from the heat pipe.

Because the thermocouples are located 180° around the circumference from the heat input area, the true evaporator temperature is not measured. This effect is small in the condenser because of the low heat flux. The solution would be a redesign of the test fixture heaters which is not practical.
Fixture Problems

The heat pipe life test fixtures were designed by B&K Engineering and are given in LCP10024 and LCP10025. Certain problems have existed with these fixtures which influences the thermal transfer and transport test data. The heat losses vary from pipe to pipe because of thermal coupling between neighboring pipes and the fixture. The evaporator heat losses vary at least 10% across the fixture and are a function of which pipes are being tested and their locations relative to one another on the fixture. Hence the heat losses can vary from test to test. Determination of accurate heat losses for every possible test configuration is impractical. As a result the actual heat load carried by the pipe cannot be measured exactly. The condenser heat losses are greater and influences the operating temperature of the heat pipe which indirectly effects the heat losses off the evaporator. The solution to the problem would be a redesign or modification of the test fixture.

The elevation for the entire fixture is measured at the top pipe. The remaining pipes fall within ± .050 inches or 5% of the total elevation span of the B&K heat pipes. The error in the measured burnout point would be proportional. The problem could be resolved if the elevation of each pipe was measured individually prior to the test. This would be very impractical because of the time required.

The heat pipes are clamped to the fixture with a thin layer of thermal grease in between. Because of this mechanical interface, there exists a possibility of non-uniform heat input. This, as will be discussed later, can cause problems in measuring the heat pipe's maximum transport. Pipes with this problem should be re-installed with the assurance of a continuous layer of thermal grease in between.

Data Interpretation Problems

The problem of determining the burnout point of a heat pipe is not new with the SIG heat pipes. The problem occasionally arises in the heat pipe industry for many reasons. One being how to apply the definition of burnout to test data. The burnout point has been defined for the SIG life test as that point where the beginning of the evaporator first experiences a dry out condition in the wick. This is measured by a change in slope of the delta temperature vs. power input curve (ΔT vs. Q). Because a stable operating condition can exist with a partially dried out wick, the burnout point can be difficult to determine. Depending on the location of the thermocouples and influences of the test fixture, the initial starting point of the burnout may be sensed immediately or masked until the dry out progresses further into the wick. The change in slope of the ΔT vs. Q curve may even appear gradual at first making the determination of burnout even more difficult. At times a change in slope has been observed without any indication of a burnout (i.e., the pipe continued to carry substantial power beyond the change in slope point). The probable cause is a premature burnout of one or two of the grooves as a result of high heat fluxes due to non-uniform heat input. The same can occur with the Hughes pipes resulting in a wick dappled with dried out regions. This makes the burnout point extremely difficult to determine.
Test Elevation Problems

When testing the heat pipes at an adverse tilt, any overcharge will form a puddle in the condenser which effects the true elevation of the pipe. This effect is more pronounced at low elevations. The true elevation is the height difference between the liquid levels in the evaporator and condenser. If the overcharge is substantial and the test elevation sufficiently small there exists a possibility of the puddle acting as a refluxer (i.e., gravity aided return of the liquid) and producing a much higher transport capability than expected. Hence the low elevations should be avoided when performance testing the heat pipes. Some of the initial test data was taken at the low elevations before the problem was realized.

All the problems discussed above have to some degree contributed to the data problems described in Reference 1. The sum total of the associated errors is sufficient to cause havoc with the data. The negative delta temperatures measured on the B&K heat pipes at low powers is one result. Since the axially grooved heat pipe has an inherently good thermal performance characteristic, the delta temperature is harder to measure. The measurement error is on the same order as the actual temperature difference at the low powers. Large variations in the thermal transport performance in the B&K life test pipes was expected. Reference 2 gives the B&K Engineering predictions of the transport performance at 60°C and 90°C. A 60% variation of the maximum transport was predicted and would be on the same order at 125°C (TES test temperature).

Summary

Long before the heat pipe life test began, the decision was made to measure the thermal transport performance with time. This course of action has merit because there are conceivable failure modes where the maximum transport might degrade with time. These failure modes are remote and should be considered secondary to the most probable ones such as non-condensible gas generation or some catastrophic failure. The heat pipe's thermal conductance (ΔT/Q) is obtained as a result of the thermal transport tests. Since additional test work is not required to acquire this data, the data was to be analyzed with time as a measure of any evaporator film coefficient degradation. This failure mode is even more remote than the maximum transport degradation modes.

The two conceivable failure modes effecting the transport and transfer properties are: 1) a degradation of the wick's wetting properties and 2) wick blockage. The occurrence of both of these modes can be determined indirectly through the non-destructive (X-ray) and the destructive tests already planned. Both the X-rays and the destructive tests will determine if any wick blockage exists. The surface morphology will be a possible indication of any change in the wetting properties.

A quick survey of the generator/mission requirements indicates that the heat pipe relies on its wick for just a short period of time at the beginning of the mission. From the time the generator is fueled until it first enters a zero g environment, the heat pipe will be operated as a vertical refluxer. The wick will be required in the zero g environment only when the spacecraft is not spinning. When spinning the acceleration forces surpass the capillary forces aiding the return of the liquid to the evaporator. As a result, any failure of the wick would have no effect on the mission after the final spin up to 5 RPM. Theoretically,
the wick's performance needs only to be proven for approximately one year. However, this would not be good design practice.

Because of the difficulty of obtaining good thermal transfer and transport data on such a large scale and because the end result of this testing can be obtained indirectly by other means it is recommended that the scope of the thermal transfer and transport test be severely limited, and put into perspective with other more important tests.

/cs
To: G. Budesheim, D. Trimmer


From: P. Collins

Subj: Re-evaluation of the Heat Pipe Life Test Effort - Results of the Meeting Held on 11 October 1978 (Task 16.2)

Ref:

2) "Problems Associated with the Axially Grooved Heat Pipe Acceptance, Verification and Life Test Data", SIG-JPC-1565 dated 5 October 1978.


4) Heat Pipe Life Test Procedure, LCP 10069

Objective: To present the change in scope of the heat pipe life test effort as outlined in the 11 October 1978 meeting.

The following changes will be made to the heat pipe life test and will be incorporated in the test plan LCHPG-JPC-825 and the test procedure LCP 10069:

1) The Hughes heat pipes will remain on life test, however no additional thermal transport tests will be performed. The following data will be taken on the Hughes pipes for engineering information only and will not be submitted to Reliability for analysis:
   - Temperature profiles - monthly
   - Gas test data - monthly

The removal and destruction of the test pipes will be accomplished as planned.
2) The B&K performance evaluation tests will be limited to the following:

- Record the heat pipe temperature profile on a monthly basis and submit the measured $\Delta T$'s to Reliability for analysis. The temperature differences recorded shall be $\Delta T_1 = T_1 - T_6$ and $\Delta T_2 = T_1 - T_8$. See reference 4 for T/C locations.

- Measure the maximum transport of each B&K heat pipe every 6 months. The test elevation shall be $-.50 \text{ inch } \pm .05 \text{ inch}$ and the test temperature shall be $257^\circ F$. In order to reduce the thermal effects of neighboring heat pipes, the pipes being burnout tested at any one time shall be at least 2 positions away from any other operating pipe. This data shall be submitted to Reliability for analysis.

- Perform the non-condensible gas test every month. Submit data to Reliability for analysis. During the non-condensible gas test one pipe from each fixture will be probed as a check on the computer routine for calculating the quantity of non-condensible gas.

The removal and destruction of the test pipes will be accomplished as planned.

/cs
MEMORANDUM

24 October 1978
Refer to: SIG-MEH-1573

To: D. Trimmer


From: M. Hallam

Subject: TRW Emittance Data for Z-93 Thermal Control Paint - Task 16.7

Objective

To report recent TRW total hemispherical emittance ($\varepsilon_{TH}$) for Z-93.

Conclusions

The $\varepsilon_{TH}$ values obtained by TRW for temperatures within the SIG operating range are somewhat lower than expected values (i.e., 0.90 - 0.91 versus 0.93).

Implications

Additional measurements of $\varepsilon_{TH}$ should be obtained to establish valid design data. Any $\varepsilon_{TH}$ value that is less than 0.93 at the design temperature will require an increase in radiator weight.

Under subcontract to TES, the Thermophysics Section of TRW has recently measured the total hemispherical emittance, $\varepsilon_{TH}$, of Z-93 thermal control paint in the temperature range 25-150°C. The values so obtained, as transmitted informally to TES by telecon on September 20, 1978, are given in the Table.

These values are somewhat lower than the values that were anticipated on the basis of previous TRW measurements of the total hemispherical emittance of Z-93 (made under the KIPS program) and of MS-74 (a paint that is similar to Z-93 in chemical composition and optical properties and for which data were obtained under the SIG program). The current data for Z-93 also differ markedly from values reported in the literature. These discrepancies are illustrated in the Figure. It should be noted that the comparatively high TRW $\varepsilon_{TH}$ values for Z-93 and MS-74 at temperatures of, respectively, 125 and 130°C could be due at least in part to non-symmetrical sample temperature distributions and to instrumentation difficulties encountered during these 1977 tests (Ref. telecon, J. Brown (TRW), October 20, 1978).

The preceding considerations indicate that additional measurements of the total hemispherical emittance of Z-93 are required. Plans are being formulated to have such tests conducted at Boeing and Aerojet.
Z-93
TRW EMITTANCE DATA
Received by Telecon on September 20, 1978

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*Average of 16 inspection measurements, one per quadrant, on four 4-inch X 4-inch samples.
TOTAL HEMISPHERICAL EMITTANCE OF Z-93 and MS-74 AS A FUNCTION OF TEMPERATURE, as reported by TRW, Lockheed, IITRI, and NASA-Goddard. TRW 1977-78 data for Z-93 and MS-74 were measured for TBS under the KIPS and SIG programs. All TRW data are ± 0.02, except for the 1978 data, which are ± 0.005. Lockheed data were received by telex (10/78). Lockheed 1966 data are ± 0.03. The IITRI room-temperature point is from a 1974 IITRI data sheet for Z-93.