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Semi-Annual Technical Progress Report

The technical progress achieved during the period 29 March 1993 through 26 September 1993 on Contract DE-AC03-91SF18852, Radioisotope Generators and Ancillary Activities is described herein.

This report is organized by the program task structure as follows:

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Task 1

Spacecraft Integration and Liaison

PROGRESS BY MAJOR TASK

TASK 1 SPACECRAFT INTEGRATION AND LIAISON

During this report period information was gathered and developed in response to requests for data resulting from the JPL RTG Inheritance Review. The review was held by JPL near the end of the previous report period and evaluated the heritage of the RTG design and hardware for use on the Cassini mission. Information involving historical records of problems and anomalies experienced during the Galileo and Ulysses programs was forwarded to JPL for study. Also, the F-5 flight spare was reviewed to consider whether its extended storage and the effects of storage temperatures and radiation exposure had compromised its serviceability for Cassini. The conclusion of the review was that long term storage of the F-5 generator does not preclude its use as flight spare for the Cassini mission. At the end of this report period, information was being developed that suggested it may be advisable to measure and evaluate adjustment of the F-5 axial heat source preload. Additional data is needed to decide if a preload adjustment is warranted and is expected to be developed during the next report period.

Agreement was reached during this report period on a plan to verify the qualification status of the GPHS RTGs for the Cassini dynamic environment. The plan calls for a number of studies, and includes the possible use of spacecraft and launch vehicle dynamic suppression techniques. If such measures prove inadequate to verify qualification, the plan provides for possible dynamic testing of F-5, beginning first with low level tests and advancing to higher levels if necessary. An initial RTG test planning meeting was held at Mound, and JPL has prepared a draft test plan which is under review at Martin Marietta.

Task 2

Engineering Support

TASK 2 ENGINEERING SUPPORT

Specifications/Drawings

ECNs were prepared and processed through CCB approval in support of uncouple production activities and ETG/RTG fabrication.

Engineering Tests

PRD Dynamic Testing:

JPL suggestions were incorporated into the PRD dynamic test environments. New accelerometers were purchased for the PRD dynamic qualification testing. The new shaker was installed in the vibration test laboratory and it was demonstrated that the new control system was capable of properly regulating the new shaker (both bare head and with the test fixture in place) and attaining the PRD vibration test levels. Acceptance level dynamic testing of the qualification unit PRD was successfully completed.

PRD Bellows Testing:

For the PRD bellows, testing per the preliminary disposition of NR784321 (qualification bellows failure) was completed. The data supported the theory that gas was present inside all of the bellows. The original qualification bellows and the seven prime bellows that failed testing at operating temperature (180°C) were returned to the vendor for rework. The vendor, Parker Metal Bellows Co., performed tests on all of the units including a leak test on S/N 32. No leaks were found. Metal Bellows reworked S/N 32 and returned this unit to Martin Marietta for acceptance testing. Acceptance leak and force tests at room and operating temperatures were performed. The unit passed all tests, indicating a successful rework. S/N 32 was designated as the new qualification bellows. The remaining seven prime bellows were reworked by Metal Bellows and returned to Martin Marietta for acceptance testing. All seven units were successfully leak tested and will be force tested in the next reporting period.

F-5 RTD Harness Failure Analysis:

The RTD cable removed from F-5 at Mound was received at Valley Forge for failure analysis. The measured RTD and insulation resistances were all within acceptable limits. Upon receipt, x-rays of the potted connector showed a broken wire in Pin A-B. No discrepancies were found in the RTD header x-rays, and the RTD sensors were too dense for the available x-ray system to evaluate. During the first thermal vacuum test (280°C), all four sensor resistances went off scale with only RTD #4 returning to normal readings during

cool down. Post thermal vacuum test x-rays showed three completely broken wires and three others with only several strands intact. A second thermal vacuum test verified that the RTD headers and sensor were performing normally and that the failures were in the connector potting boot. After removal of the potting boot and potting, the failed wires were metallographically evaluated using optical microscopy, SEM, EDS, SAM, and XPS. The failures were found to be predominantly intergranular and are attributed to embrittlement that is associated with brazing of the wires to the connector pins. A failure analysis report, 2262-MHW-015, has been issued and the redesign of the cable is in progress.

Government Laboratories Interface

An evaluation was performed of the new non integral clad vent set weld shield. The evaluation included assessment of the new shields impact on thermal performance, dynamic capability, and mass increment. The review found no thermal or dynamic performance considerations that precluded adoption of the new shield. The added mass of the new shield contributed about five ounces per generator. The mass increment will be included in discussions with JPL on the RTG Requirements Specification which is still under negotiation.

Support was provided in the evaluation of clad vent set hardware being fabricated at the Y-12 plant in Oak Ridge, TN. Substantial effort was expended in dispositioning frit vent assembly hardware and reviews were conducted of fabrication procedures and specifications. Material Review Board (MRB) disposition of nonconforming hardware was also provided through membership in the heat source MRB led by Mound.

Support was provided to Mound in dispositioning MRB actions related to Q-1 C-seal leakage and the return of the unit to Valley Forge for refurbishment. Also during this report period Martin Marietta personnel went to Mound to remove the F-5 RTD wire harness for return to Valley Forge for evaluation. The E-2 harness was installed on F-5 for monitoring temperatures during long term processing at Mound.

Martin Marietta also provided support for a readiness review team assembled by DOE to evaluate the status of preparations for fuel pellet and fueled clad fabrication activities at Los Alamos National Laboratory.

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Task 3

Safety

TASK 3 SAFETY

RTG Safety Reports

Titan IV Data Book: The eighth meeting of the RTG Working Group (RTGWG) for the Titan IV Data Book (for the Cassini mission) was attended in April 1993 at the NASA Lewis Research Center (NASA LeRC). Initiation of efforts to define accident scenarios was followed by a prolonged period of debate and investigation into the approach to be pursued. Because of the complexity and magnitude of the effort perceived by the working group, the assistance of Martin Marietta Astro Space was proposed to consolidate potentially large number of scenarios into a manageable number consistent with previous missions.

A technical interchange meeting (TIM) between the RTGWG and INSRP was also attended at NASA LeRC in April 1993. This purpose of this meeting was: (1) for the RTGWG to bring INSRP up to date on the Titan Databook activities, and (2) for INSRP to discuss their concerns pertaining to the Databook. The perception existed among many of the attendees that there was still considerable inertia slowing the Databook activity. INSRP urged that the Databook content and schedule be pursued diligently. INSRP also acknowledged the impetus from NASA headquarters and the Air Force for the RTGWG to pursue an in-depth PRA (Probabilistic Risk Assessment) approach for the scenarios. This approach was contributing to the problems in the Databook effort.

Meetings of the RTG Working Group and the Accident Scenario Subpanel were held at NASA LeRC during the month of May. Subsequently, several group telecons were conducted to discuss comments and changes needed in the master logic diagrams (MLD) for the accident outcome conditions (AOC).

A letter was transmitted to NASA/LeRC via DOE expressing concern over the proposed scheme of accumulating the outcomes of various similar accidents into a few broad, general categories of accident outcome conditions (AOCs) and "pinching off" or neglecting the contributing events. It was indicated that this approach would not be amenable to performing consequence and risk analyses, since these analyses are location, demographic, and meteorologic specific, and therefore cannot be related to a generalized accident environment. The resulting concern was that the proposed approach would not provide the detail needed for the RTG safety analysis reports (SARs). NASA/LeRC responded to this concern by assuring DOE that they are committed to supplying the description and detail of events and environments needed.

Several AIC-to-AOC and AOC-to-FE event diagrams were received during July from Martin Marietta Launch Systems and General Dynamics for review. Comments were prepared and transmitted back to these two contractors for their consideration. Copies were also sent to NASA/LeRC and to Aerospace Corporation as requested by NASA. A meeting of the RTG Working Group (RTGWWG) in August was attended at Martin Marietta/Denver to review the preliminary or strawman event sequence diagrams for the Cassini mission.

A design trade study status meeting on the Space Vehicle Destruct System (SVDS) was attended at NASA LeRC. Based on the findings presented at the meeting, a payload fairing (PLF) mounted system using a tube (i.e., gun barrel) launched projectile (TLP) appeared to offer the best combination of effectiveness, safety, and overall reduced risk. This assessment is contingent upon Range Safety accepting loss of SVDS capability at PLF jettison.

RTG Safety Assessment/Reporting:

Following a review of the RTG Safety Assessment (RSA) report with DOE, additional changes were made in the text. The RSA was issued as a final report in May, with correction pages being subsequently issued also.

Earlier this year, NASA made the decision to include an inadvertent reentry arising from a faulty Earth gravity assist (EGA) maneuver into the potential accidents to be addressed in the Cassini EIS. The timing of this decision in relation to the schedule for completing the draft EIS (then set for June 1993) precluded an in-depth analysis of the reentry response of the GPHS-RTG and the potential consequences. In order to provide some insight into the RTG response, limited reentry analyses of the GPHS were performed. Preliminary ablation results only for the GPHS aeroshell were obtained for three cases at a reentry velocity of 63,815 fps (19.5 Km/sec) with a shallow entry angle of -7 degrees, and steep angle entries at -60 and -90 degrees. All evaluations were analyzed for face-on stable orientations of the GPHS module. This analysis was conducted using the SINRAP (SINDA based Reentry Analysis Program) computer code which was tailored to model: (1) the ablation of the aeroshell; (2) radiation and conduction in parallel between internal GPHS components; the thermal conductivity of CBCF infiltrated with air; and (3) the heat flows between the aeroshell and GIS interface. The SINRAP code has the capability to model either the face-on stable or random tumbling orientations of the GPHS module.

The results for the three EGA reentry cases are summarized in Table 3-1.

Table 3-1. Results of the Face-On Stable Orientation Reentries

	Reentry Angle		
	-7°	-60°	-90°
	← Face-on Stable →		
Orientation			
Altitude of Early Release	317,000 ft.	243,000 ft.	236,000 ft.
Time of Local Burn-Through	21.7 sec.	2.2 sec.	1.9 sec.
Altitude of Burn-Through	189,700 ft.	127,300 ft.	121,100 ft.

The time of local burn through at the thinnest section of the broad face was estimated using the recession rate occurring when the last ablatable node in the thermal model had half of its thickness ablated. This was necessitated by the node combining technique used in the model. Additional ablation results were obtained for low random tumbling (RT) orientation reentries of the GPHS modules, at -7 and -90 degrees. The results for these two cases are summarized in Table 3-2.

Table 3-2. Results of the Low Random Tumbling Orientation Reentries

	Reentry Angle	
	-7°	-90°
Altitude of Early Release, ft.	317,000 ft.	236,000 ft.
Peak Clad Temperature ¹⁾ , °F	3,470	2,612
Time at Peak Clad Temp. ²⁾ , sec.	55	35
Recession ³⁾ , mils	70	88

- 1) Graphite-Iridium eutectic temperature is 4220°F.
- 2) Measured from time of module release from RTG (i.e., start of reentry analysis).
- 3) Minimum broad face thickness is 184 mils

For reference, Figure 3-1 shows the ablation history for these trajectories.

Figure 3-1. Average Recession Over Each Face - Random Tumbling

The results indicate that, if the modules were released from the RTG converter with a broad face stable attitude and the broad face normal to the flow at reentry angles between 6 and 90 degrees, complete ablation of the module broad face would occur, with some additional ablation of the side walls. These same results were obtained in analyses performed by APLJHU and NASA/Ames. If the initial motion of the modules when released was tumbling, the analyses indicate that complete ablation through the faces of the module would not occur. With these results (especially for the broad face stable mode) conjecture arose as to whether the GISs would be released from the aeroshells and what their subsequent response would be. The schedule developed for publishing the EIS was not, however, amenable to pursuing more in-depth reentry analyses. Thus, the potential for release of the GISs from the modules and their subsequent reentry response were not analyzed.

NASA greatly stressed their desire to include quantitative assessment of the consequences to the public arising from this EGA reentry accident in the EIS. In order to provide input to NASA for this purpose, DOE and their safety program contractors performed a consequence assessment based on a parametric bounding estimate of the plutonia fuel state arising from the potential reentry environment. It should be realized that any release of fuel to the reentry environment was hypothesized and not based on any analytical or experimental evidence.

A draft event sequence tree was prepared by Martin Marietta Astro Space to depict the best estimate of the events associated with the response of the GPHS RTG from an unplanned reentry arising from a malfunction during the VVEJGA maneuver around Earth. The purpose of this tree was to arrive at estimates of the probabilities of plutonia fuel release and its physical state resulting from reentry. It should be realized that this tree was prepared largely on the basis of engineering judgment. Analysis in the given reentry regime, with the exception of similar work conducted for the Galileo mission, had heretofore not been evaluated in any previous space program. The advanced techniques needed to perform these detailed reentry analysis were not available but are currently being developed.

A meeting was attended at DOE with the DOE Cassini safety program contractors to discuss the draft event sequence tree. The structure of the tree was modified by consensus of the parties participating, and conditional probabilities for the individual events were developed. This tree, along with the resulting source terms, was submitted to NASA by DOE for use in supporting the EIS.

Computational Fluid Dynamics Program Development:

(For Application to GPHS EGA Reentry Analysis)

Previous reentry studies of the GPHS module for the Galileo and Ulysses missions identified several aspects of the aerothermal analyses in which improvements in the modeling and analytical techniques would enhance the acceptability and credibility of the results. A task was initiated to pursue improvements in aerothermal analyses to include the following:

- modeling nonequilibrium radiative heating
- coupling of the radiative and convective heating models
- predicting the convective heating distribution with ablation
- determining the flow-field distribution of total enthalpy

- predicting the effect that ablation produces on radiative heating
- modeling nonequilibrium thermochemistry of air and ablation products
- predicting the heating distribution for orientations other than face-on stable
- extending the ablation model for carbon well into the sublimation regime (including melting).

Several flow-field codes were assessed to establish their ability to address the complex chemically reacting flow surrounding the ablating GPHS module during an extremely high velocity reentry. A combination of the NASA Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA) flow-field code and the Langley Optimized Radiative Nonequilibrium (LORAN) code was selected as being the most promising starting point.

The LAURA code is a fully conservative, finite-volume, Navier Stokes solver. The code has been successfully applied on the National Aerospace Plane (NASP), the Aero-assisted Flight Experiment (AFE), Project Fire, and other NASA studies. The basic features of the LAURA code are shown schematically in Figure 3-2. The Total Variational Diminishing (TVD) scheme is an important capability for the GPHS reentry problem because the bow shock and other strong gradients in the flow must be accurately resolved in order to compute the chemistry properly. However, the LAURA code does not treat ablation. Modifications to include ablation, as shown in Figure 3-3, are being developed because of the critical importance of ablation phenomena on GPHS response.

Only the axisymmetric option of the LAURA code is currently planned to be used. The body-normal and radial-adaption (to align with the bow shock) grid-generation technique will be extended to include a fast axisymmetric elliptic grid-generation scheme. The most significant extension of LAURA involves the chemistry model. The current chemistry is an 11-species, clean-air, chemical nonequilibrium and two-temperature thermal nonequilibrium model developed at NASA Ames. To account for ablation, a 13-species carbon-air gas model (including but not limited to O, O₂, N, N₂, NO, NO⁺, C₁, C₂, C₃, CN, CO, CO₂, and e⁻) is being developed.

Equilibrium-catalytic and wall-blowing (ablation) capabilities are planned to be developed within LAURA. The carbon ablation model will be coupled to the flow-field solution. A steady-state energy balance will be performed to include convection, diffusion and radiation heat transfer.

- Fully-Conservative Navier-Stokes Formulation
- Finite-volume (Flux-Balance) Approach
- Upwind (TVD) Solution Algorithm
- Loosely Coupled Radiation Effects
- Nonequilibrium Gas Chemistry
- Flexible Point-Implicit Solution Scheme
- High-Altitude Thermal-Nonequilibrium Effects

Figure 3-2. Current LAURA Code Capabilities

SURFACE ABLATION EFFECTS

- Steady-State Surface Energy Balance
 Include Surface Heat-Transfer Effects due to Convection, Mass Diffusion and Radiation
- Surface-Recession Rate Predicted as Part of the Flowfield Solution

Figure 3-3. Proposed Improvements to the LAURA Code to Include Ablation

The LORAN code computes radiative transport using either a tangent-slab or an approximate three-dimensional approach. The tangent-slab approach is being used for the GPHS module analyses due to its reliability and affordability. LORAN contains all of the required radiative mechanisms, provided scattering (particle erosion) is not a concern. However, only O, N, N₂, O₂, NO, and their ions are included. Carbon ablation products (reactants for C-N-O chemistry) will be added

The extension of the LAURA and LORAN codes for application to the GPHS reentry is being accomplished by computing increasingly complex, relevant test cases that can be compared with experimental data or existing solutions. Improvements to the algorithm and gridding, specific to the GPHS, will be developed. The carbon chemistry will then be implemented and numerical strategies devised to address high blowing rates.

Several test cases have been exercised using the LAURA code. The initial test case was the hypersonic, laminar, perfect gas flow over a sphere (RN = 0.25 in.). This case was chosen in order to compare results with a viscous shock layer (VSL) code. The LAURA and VSL predicted surface pressure distributions are shown in Figure 3-4. The agreement is excellent. Small differences in surface heat transfer predictions, Figure 3-5, for this case are not surprising. The VSL technique is known to slightly under predict spherical heating rates.

The LAURA grid-generation technique was then extended to compute a more relevant test case. The flow over a flat-faced (axisymmetric) cylinder was computed to compare with shock tube data. The freestream conditions and wall temperature are the same as the initial spherical test case. The effect of corner rounding on the surface pressure distribution is shown in Figure 3-6. The corresponding surface heat transfer rate is shown in Figure 3-7 along with the shock tube data. Considering nonequilibrium effects in the shock tube, the agreement with the LAURA perfect gas model predictions is good.

The diameter of the flat-faced cylinder was then increased to represent the GPHS. A series of cases was then performed to increase the velocity into the GPHS reentry range. The effect of Mach number on surface pressure is shown in Figure 3-8. For these high altitude reentry cases (284 K ft.), the wall temperature was set at 2500° R. The heat transfer rate distribution over the flat-faced cylinder is shown in Figure 3-9. Note that, as expected, the peak heating occurs on the rounded corner. The pressure and temperature contours for the highest velocity case ($M_\infty = 55.7$) are shown in Figures 3-10 and 3-11, respectively. The LAURA predictions show that the bow shock at this high altitude is considerably spread out (see Figure 3-10).

Figure 3-4. LAURA Code Test Case. Surface Pressure Distribution Over a Sphere

Figure 3-5. LAURA Code Test Case. Heat Transfer Rate Distribution Over a Sphere

Figure 3-6. Effect of Corner Radius on Surface Pressure Distribution Over a Flat Faced Cylinder

Figure 3-7. Effect of Corner Radius on Heat Transfer Rate Distribution Over a Flat Faced Cylinder. Comparison of LAURA Code Prediction with Shock Tube Data

Figure 3-8. Effect of Mach Number on Surface Pressure Distribution Over a Flat Faced Cylinder

Figure 3-9. Effect of Mach Number on Heat Transfer Distribution Over a Flat Faced Cylinder. Cylinder Radius, R , Representative of GPHS

Figure 3-10. Flow Yields Isobars Over a Flat Faced Cylinder. High Altitude, High Mach Number Reentry Environment.

Figure 3-11. Flow Field Isotherms Over a Flat Faced Cylinder. High Altitude, High Mach Number Reentry Environment.

Nonequilibrium air calculations using the LAURA flow field code were made for the $\gamma_e = 7^\circ$, $V_e = 19.4$ Km/s entry trajectory. The calculations were made at 58 Km altitude, where the peak radiation heat flux is expected to occur. The LAURA output (pressure, temperature, concentration) were input to the Loran nonequilibrium radiation code, and the radiation field was calculated over the GPHS module front face. Plots of the flow field and radiation code output were generated and compared to the design correlations currently used in a subroutine of the SINRAP code (Reference 1). Figure 3-12, from the LAURA flow field code, shows detailed pressure contours over the front face of the GPHS module. As expected, the pressure is fairly constant in the stagnation region and decreases rapidly as the flow rounds the corner. Flow over most of the surface is subsonic. The sonic point is located at about contour #6 in the corner detail.

The LAURA Code Chemical-Kinetics Subroutine, Kinetic.F, which calculates reaction-rate coefficients was modified to include carbon-air ablation products. Fourteen additional species, and 33 additional reactions were incorporated.

A test case was run with a 1" diameter graphite hemisphere at 30.5 Km/s. The sphere had a 3000°K, fully catalytic wall, and a prescribed surface mass-flux. The wall $\dot{m}$ was varied between 0 and 15% of the freestream ρV . Viscous shock layer calculations were made at the same conditions. Comparison of heat flux, pressure, and species distribution show good agreement between calculations.

Figure 3-12. Pressure Contours

Figures 3-13 and 3-14 show heavy particle translation temperature and vibration temperature contours, respectively. The stagnation region is nearly isothermal, at around 15000°K. Comparing Figures 3-13 and 3-14 indicates that the flow approaches thermal equilibrium. The vibrational and translational temperatures are nearly equal in the stagnation region. Figure 3-15 shows surface pressure around the body.

Figure 3-16 shows convective and radiative heat flux. The radiant flux is from the LORAN Code and includes detailed transmission calculations. Radiant flux is shown to be about twice the convective heat flux for this case. Peak total heating does not occur at the stagnation point, but at the corner.

Note that the radiation flux is calculated using an uncoupled flow field. When the radiation effects are included, the shock layer will cool off and will decrease in thickness. This will result in lower gas emission, and a smaller volume of radiating gas, both of which lower the radiant flux to the wall. The analysis above represents an upper bound on radiant heating at least for the pure air case.

Figure 3-13. Transitional Temperature Contours

Figure 3-14. Vibrational Temperature Contours

Figure 3-15. Surface Pressure on a Flat Faced Cylinder

Figure 3-16. Surface Heating Over a Flat Faced Cylinder (Uncoupled Radiation)

Comparison of LAURA/LORAN Results with Previously Used Correlations: Table 3-3 compares several LAURA/LORAN calculated parameters with the correlations previously used in the RTG Safety Analysis. Several important differences are highlighted.

Table 3-3. LAURA/LORAN vs. SINRAP Parameters

	LAURA/LORAN	Reference 1 (SINRAP)
P_W/P_∞	3460	3456
P_S/P_∞	3000	3445
δ	.0886 ft.	.0435 ft.
q rad	2797 BTU/ft ² s	5280 BTU/ft ² s Suttles, et al 3920 BTU/ft ² s Nerem & Strickland

$\delta_S/S_\infty = 18.3$ Based on Equilibrium Air

Surface pressure calculations are in excellent agreement between the LAURA calculations and the SINRAP correlations. Pressures after the shock are somewhat different; LAURA predicts greater pressure variation through the shock layer than the SINRAP correlations.

Shock standoff at the stagnation point was calculated using the correlations in Reference 1. Equilibrium air properties were used to generate the density ratio across the normal shock, which was used in the shock standoff correlation. The LAURA shock standoff was measured directly from the output. As Table 3-3 shows, these values differ by a factor of two. The cause of this substantial difference is being studied.

Radiant heating at the stagnation point was also calculated. As shown in Table 3-3, the LORAN prediction, using the uncoupled flow field as input, is about 1/2 of the value calculated using the recommended correlation by Suttles, Sullivan, and Margolis.

This difference is surprising. The LORAN calculation is based on the uncoupled flow field and represents an upper bound on radiation heat flux to the wall. Reference 2 indicates that a further 30% reduction in radiant heat flux to the wall is expected when fully coupled effects are included. A coupled LAURA/LORAN calculation will probably result in a radiant wall flux of about 1/3 the value given by the SINRAP correlation. These differences are being reviewed.

Carbon Ablation Model: A wall ablation model is required to supply coupled mass flow and species boundary conditions at the wall.

The standard β' and H_w curves are developed using the following assumptions:

1. Self similar flat plate boundary layer flow.
2. Equilibrium chemistry in the gas layer adjacent to the walls (usually based- on JANAF thermochemistry).
3. Prandtl, Lewis Number= 1.
4. Equal diffusion coefficients.
5. Carbon vapor partial pressures at the wall are equal to the species vapor pressure at the given P_{wall} and T_{wall} .

These assumptions reduce the wall boundary condition to a series of curves which give mass transfer (β') and resultant gas enthalpy as an explicit function of wall temperature and pressure, as shown in Figure 3-17.

Figure 3-17. Carbon Sublimation in Air Equilibrium Vaporization - JANAF Thermochemistry

The LAURA Code explicitly calculates all required species concentrations and gradients, so assumptions 1 through 4 are not required. A wall boundary condition is required, however, to calculate mass flow of various species from the wall. The equilibrium vaporization assumption (#5) will substantially overpredict the wall ablation in low pressure, high temperature environments.

A wall ablation model has been developed which accounts for finite carbon vaporization using the Langmuir-Knudsen equation as outlined in Baker, Reference 3. Vaporization coefficients for carbon species C_1 through C_4 have been included, using the values of Dolton, Reference 4.

The effects of nonequilibrium vaporization can be approximated by retaining the first four previous assumptions and updating the β' curves using the nonequilibrium vaporization model. The β' curves become a function of mass transfer coefficient as well as temperature and pressure. Figures 3-18 and 3-19 show examples for 0.5 and 10 atmospheres. Comparison of the figures shows the effects of the decrease in nonequilibrium vaporization at high pressures.

Figure 3-18. Carbon Sublimation in Air Nonequilibrium Vaporization (0.5 atm pressure)

Figure 3-19. Carbon Sublimation in Air Nonequilibrium Vaporization (10 atm pressure)

Nonequilibrium vaporization effects at the high temperature and low wall pressures typical of the RTG reentry trajectory are substantial. For example, Table 3-4 shows these effects for $P_W=1/2$ ATM, $T_W=3900^\circ\text{K}$, $C_H=.03$ lb/ft²s.

Table 3-4. Equilibrium/Nonequilibrium Comparison

	Equilibrium Vaporization JANAF Thermochemistry	Nonequilibrium Vaporization JANAF Thermochemistry
β'	7.94	2.35
C_H/C_{H0}	.276	.52
M	.094 lb/ft ² s	.0525 lb/ft ² s

For a condition fairly close to the peak radiation heating point of the 7° trajectory, these preliminary data suggest a substantial reduction in ablation rate, on the order of 80%, will result when finite vaporization rates are accounted for.

Carbon-Air Chemical Kinetics: Of the current set of 65 C-N-O chemical reactions, certain of these will dominate the results at a given temperature and pressure, while others will be negligible. The chemical kinetics and thermochemistry subroutines in the LAURA code have been modified to run in a stand-alone fashion. This modified coding will be used to screen reactions parametrically over the range of temperature and pressure of interest and determine which ones can be eliminated for a given case. This should result in a reduced chemistry set and greatly reduce LAURA run time.

LAURA Code Implementation: The effort in this area was directed toward selection of the optimum computer system for speed, accuracy, and ease of operation. For this purpose, the perfect gas LAURA model of the flow over a flat-faced axisymmetric cylinder was run for comparison to results shown earlier. It was found that, because of the large number of system users, the turnaround time on the VAX increased to unmanageable proportions. Consequently, two additional approaches were pursued. First, conversion and implementation of LAURA on the Hewlett Packard 9000 series 700 workstation was effected and is currently being debugged. A second effort was initiated to modify the LAURA code to provide ASC II output files rather than binary to aid in comparison of results from system to system.

LORAN Radiation Code: The LORAN Code has been converted to run on the SUN workstations. The test case, shown in Figure 3-20, is the Fire II Flight Experiment. This experiment was conducted to support the Apollo Program. This case was selected because substantial nonequilibrium gas radiation heat flux data is available for this configuration. The flight was a blunt beryllium sphere segment, which entered at 11.3 Km/s; radiant intensity measurements were made at several locations.

LORAN run time for nonequilibrium air radiation over the entire configuration was about four hours, using the tangent slab approximation. Figure 3-21 shows the radiant heat flux predicted at the wall at 76 Km (249 Kft) altitude. Figure 3-22 shows a plot of input translational and vibrational temperatures at the stagnation point. Note that about half of the shock layer is in thermal nonequilibrium. Figure 3-23 shows input species mass fractions at the stagnation streamline and indicates moderate ionization, with almost complete dissociation over most of the shock layer. Comparison with flight data is ongoing.

Figure 3-20. FIRE II Flight Test Configuration - LORAN Computational Grid

Figure 3-21. FIRE II Flight Test Configuration - Radiant Flux at Wall

Figure 3-22. FIRE II Flight Test Configuration - Stagnation Pt. Temperature

Figure 3-23. FIRE II Flight Test Configuration - Stagnation Pt. Mass Fractions

The LORAN code has been successfully modified to include monatomic carbon atoms in its non-equilibrium radiation calculation. Results are being reviewed for consistency and physical reasonability. Addition of other neutral atomic species will proceed as property data is obtained.

Modification work to include a molecular species has begun. The first added molecular species will be CO_2 , instead of the C_3 species originally proposed. Substantial data exist for the total and spectral emissive characteristics of a CO_2 -air mixture. These data should provide good experimental verification of the LORAN radiative transport calculations.

References

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3. Baker, R.L., "Graphite Sublimation Chemistry Non-Equilibrium Effects", AIM J. Vol. 15, No. 10, p. 1391-1397.
4. Dolton, J.A., Mauer, R.E., and Goldstein, H.E., "Thermodynamic Performance of Carbon in Hyperthermal Environments", AIAA Progress in Astronautics and Aeronautics, Vol. 21, pp. 169-201.

Risk Analysis Program

A meeting was held at the Martin Marietta Astro Space San Jose facility in April 1993 with the Biological and Environmental Effects and the Meteorological Subpanels of INSRP. The purpose of the meeting was to give these INSRP subpanels an introductory overview of the development of the Martin Marietta codes and to present comparative results with other recognized risk codes.

A code module was implemented to compute the atmospheric dispersion coefficients with the latest methodology suggested by U. S. EPA (doc. PB86-103660). This is a state-of-the-art model. It replaces the simple sigma-z/sigma-y Gaussian formulations by using different equations applicable to different conditions and different locations in the boundary layer. Due to the complex nature of turbulence, the state of the boundary layer is, in reality, characterized by a number of different dispersion regimes. With the use of applicable scaling parameters and diffusion data, the new code option models each regime separately. Whenever the vertical distribution of material is not truly Gaussian, which is representative for most releases in the surface layer, the module directly employs the cross-wind integrated concentration at the surface to derive the air and ground concentrations. Hence, the current version of SATRAP offers the choice of three methods for diffusion modeling: (1) Gaussian puff dispersion based on the atmospheric energy dissipation rate and the random-force model; (2) conventional Gaussian plume dispersion with the Briggs correlations, simulating the typical Pasquill-Gifford curves; and (3) the EPA method as described above.

Testing of the Sehmel-Hodgson model for deposition velocity with different release conditions has detected a error in the published equations. Communication with the author (at PNWL) resulted in a proper value being obtained for the coefficient in question and reasonable results have subsequently been produced.

Several options for determining when to terminate the dispersion analysis were implemented.

- Puff center reaching the ground level or zero altitude.
- Minimum concentration level reached at the puff center.
- Maximum advection time defined.
- Level of material depletion due to deposition.

The receptor grid design was finalized with the option of a user-defined grid scale distance and the number of nested grids. For each analysis, up to six nested grid levels are possible.

Based on a review of current literature, the ingestion dose model is being revised. It will incorporate Pinder's treatment of uptake by oranges and make use of the sophisticated modeling of animal/feed dynamics in Kirchener's PATHWAY model. PATHWAY documentation also referred to an article on animal inhalation. A simplified calculation has shown that this path (animal inhalation) may be significant for plutonium, even though it is insignificant for the isotopes studied using PATHWAY. Hence, this path will be retained in our model even though it was excluded from PATHWAY. In addition to PATHWAY, the MACCS validation process is being followed. This NRC code is being beta tested by Rocky Flats and Savannah River. It has a substantial ingestion model capability. The key is whether the beta testing comes up with good inputs for plutonium, since in most NRC applications, Pu is a minor isotope. In fact, many ingestion dose evaluations explicitly exclude Pu.

An additional output option has been implemented in the HIAD (High Altitude Aerosol Dispersion) code. Specifically this is to produce the total population dose resulting from the dispersion of source terms in 20 latitude bands. This evaluation was executed with the new worldwide demographic data furnished by NUS. Also, a possibility to calculate the results from a given latitude of injection is now possible. The previous version only computed a combination of injections resulting from the orbit inclination input.

In summary, HIAD offers the following option outputs:

- 1) Worldwide concentrations before latitude band distribution;
- 2) Latitude band's integrated concentrations for each exposure interval;
- 3) Isotope contribution to each dose pathway;
- 4) Pathway doses in each latitude band receptor; and
- 5) Population dose in each latitude band receptor.

Additional modifications have been made also to the GEOTRAP (Global Transport of Radiological Particulates) code as follows:

- The high altitude dispersion parameters can be now set by the user, as opposed to previous settings from hard-coded empirical curves.
- The optional cloud splitting process was added with a new option called cloudshearing. This consists of tracking three data points around each dispersed cloud to detect excessive shearing effects from space-varying wind components. Previously, the cloud could only be subdivided when reaching a maximum or critical size. This method is expected to produce a more realistic result when using the cloud splitting option.

- The final altitude of arrival can be defined by the user. GEOTRAP provides two levels of altitude to record the cloud footprints.
- A new algorithm was implemented to process the footprints created by the subclouds from different sources or cloud-splitting processes. The deposition and overlapping of these sub-clouds on the ground create several patches of arbitrary shapes and sizes. A uniform, predetermined grid scale will be impractical to produce realistic results. Calculating the concentrations in these areas must include: 1) determining which sub-clouds overlap each other; and 2) relying on a grid scale determined by the smallest standard deviation of the related sub-clouds. Using the mergesort method and the linked-list concept, the new algorithm provides a fast and effective way to post-process the concentration outputs of any footprint shape. Compared to the earlier version, which extensively used the computer hard disk to sort and rearrange the deposition records, this method reduces the processing time by at least a factor of 10. Several tests yielded satisfactory results and also provided useful insights on the dispersion of different particle sizes.
- The revision of the dose calculation module for GEOTRAP is currently in progress.

Databases: During this period, several databases have been revised and set up for ready use.

Isotope - The isotope database for the SPARRC family codes was loaded. This database provides information such as: half-life, decay time, atomic weight, and possible daughter products.

Demographic Update - The worldwide demographic data from NUS (doc. "World Demographic Update Through 1990 for Space Nuclear System Safety Analyses" June 12, 1992) has been implemented in receptor database for HIAD and GEOTRAP. For HIAD, the population density is required for 20 latitude bands, while for GEOTRAP the same data is needed for the 720 equal-area cells. The appropriate land and sea fractions in each receptor were also implemented.

Dose Conversion: Dose Conversion Factors for cloudshine and groundshine pathways (doc. Health Physics, Vol. 38, No. 4), and for ingestion pathway (NUREG-0172) were also loaded for initial code testing. These values will be superseded by the ICRP-30 values.

GRAM90 Global Meteorological Data: GRAM90 is NASA's Global Reference Atmosphere Model. It consists of a set of FORTRAN 77 computer programs plus large data files. GRAM90 can generate wind vectors, pressure, temperature, and density of the atmosphere at any latitude-longitude location globally, at any altitude 0 to 120 Km, for any month of the year. It does so using realistic perturbations of the zonal mean values of these parameters. The perturbations are based on highly developed sets of measurements and theoretical models.

The GRAM90 programs and data files were previously obtained from NASA's COSMIC code center on two tapes. During this period, the programs were installed, compiled, and executed on a local microvax computer system. Two preliminary programs were run to convert the data files to the proper format for input to GRAM90. Then Job Control Language procedure files were produced to permit compilation and execution of the program. One test run was conducted for the month of October 1997, the Cassini launch date. The program successfully output wind vectors along a trajectory above the launch site (latitude 28.5, longitude 80.53).

Ingestion Dose Model Development: Work continued on development of a plutonium 238 environment and food chain model for use with the SPARRC system of codes. The previous model is the current NRC food chain model and was found to have a number of deficiencies. Specifically, in July a model for rainsplash was acquired; an experiment doing field studies of rainsplash was obtained to calibrate the model. Rainsplash had been identified during the Galileo/Ulysses analyses as a dominant pathway for crop contamination by Pu oxide.

The dosimetry sub-module PARDOS was revised and tested along with the associated database. The calculation of radiological doses as functions of particle-size and solubility class were implemented. The models coded were applied first to the transport code GEOTRAP and will be propagated to other codes later.

Inhalation Pathway: The initial version of the dose module PARDOS was designed primarily for small-size source terms, although source particle size was available to the module for use in its dose calculations. In this first version of PARDOS, it was assumed that all released materials were in inhalable form. For a defined isotope, this traditional approach used a unique Dose Conversion Factor (DCF) for each body organ. This approach is typical of the majority of radiological consequence codes (CRAC2, MACCS, etc.).

In contrast to the applications for which most of these codes are used, the RTG safety analysis requires a detailed calculation of the inhalation dose pathway which must cover up to 20 particle-size bins. Based on ICRP Publication 30, DCF values for a given particle size depend on the isotope's solubility class and the deposition fractions in 3 lung compartments. Implementing an on-line interpolation of these deposition fractions, PARDOS is now capable of computing the organ DCF values of any given particle size. For each defined isotope, the code retrieves the necessary factors from the new inhalation DCF database, computes all the applicable organ DCF values, and then factors in the effective

inhaled fraction. This approach is responsive to previous comments in that it will enable one to deal with the same particle size bins in both the meteorology model and the health effects model.

Inhalation from Resuspension: Although resuspension contributes to dose by the inhalation pathway, it was decided to compute and record, separately from direct inhalation from the source cloud, the concentrations and exposure doses from resuspension inhalation. This will allow determination of its contribution separately, and will enable sensitivity studies on key parameters to be made. Initial evaluations of the resuspension air concentration using the current PARDOS resuspension formulation (from WASH-1400) have shown results close to those of the Ulysses Mission SER formulation. Development of an improved resuspension model may be possible based on other sources currently being investigated.

Ingestion Pathway: Using guidance from ICRP Publication 30, the ingestion dose pathway is being revised to be more specifically applicable to PU-238. Since the ingestion DCF values are based on the transfer fraction (f_1) which is defined for specific pathways or time exposure intervals, a thorough review of the computation flow must be re-examined. For example, for the seafood pathway, a uniform transfer f_1 of E-3 is used, while for other food doses, values of 1 E-5 and 1 E-4 are recommended for the first year and subsequent years, respectively. Therefore, the code has to select appropriate DCF values for each pathway and has to compute relative contributions in long term doses for the first and the subsequent year of exposure. The following food doses are currently computed in the ingestion pathway:

- Produce and vegetable consumption
- Meat consumption
- Milk consumption
- Water consumption
- Seafood consumption

As an option output, the contribution of each pathway to the collective dose can be printed for comparison.

Groundshine and Cloudshine Pathway: Although the contribution to total dose from external irradiation is minimal for Pu-238, a complete dose calculation requires that both groundshine and cloudshine doses be implemented. These two pathways have been revised to use the latest DCF values from D. C. Kocher (Health Physics 45, Vol. 4, p.665, 1983). Kocher's Oak Ridge codes were also used for the previous standard DOE external DCFs. Test runs of these new DCFs produced lower external doses, about a factor of 2, when compared with previous methods (using DCF values from Health Physics 38, Vol. 4).

Database: During this period, several new DCF databases have been set up. At this stage, the number of isotopes entered are still limited, but the extension to a larger group can be done.

- **Inhalation DCF Database:** From ICRP Publication 30, the DCF values for 1 micron AMAD are classified by solubility class (D,W, or Y) and organ. Contributing fractions from lung compartments, f_{N-P} , $f_{T.B}$, and f_P are also recorded. As described earlier, this database will enable the on-line DCF computation for any given particle size.
- **Ingestion DCF Database:** Based on ICRP-30 and DOE-EH0071 publications, the DCF values for specific body organ were entered. These values are classified with three possible values of the GI tract-to-body fluid transfer factor f_1 : 1 E-3, 1 E-4, and 1 E-5.
- **Cloudshine and groundshine DCF database:** Since the values for these two pathways are published only as equivalent effective doses, not organ by organ, the individual organ DCFs have been deduced from the weighting factors (ICRP-26) that were presumably used in the computation of the single "effective dose" value published.

Other Implementation: As suggested in the last INSRP meeting (April 1993), the list of organs for which organ doses will be calculated were revised. Keeping the same number of organs (7), PARDOS will now evaluate the doses for lung, liver, bone surface, red bone marrow, thyroid, gonad, and skin. These organs reflect a better health effect model for PU238 in terms of internal and external doses.

The maximum number of exposure time intervals has been increased from three to ten, to provide consistency in option outputs with other codes of the SPARRC suite. This will permit the evaluation of dose over more time intervals instead of just 0 to 1 year, 1 to 50 years, and 0 to 50 years, as before.

Safety Test Program

Final revisions were made to the Safety Test Program Plan based on decisions made during the March meeting, and it was subsequently published and distributed. Sketches of test hardware configurations and interface considerations for the RTG end-on impact test were transmitted to LANL for their review and comment. Verbal comments were received from LANL on the proposed hardware configurations. LANL also requested an itemized list of materials for the tests. This list was provided and was to be used by Sandia for their environmental assessment. Based on a tentative schedule, the safety test hardware will be shipped to LANL near the end of the first quarter of 1994.

A meeting was held with LANL to review the proposed RTG hardware to be used in the safety test program and to discuss test techniques. As part of the discussion on the technique to be used for the RTG end-on impact tests, it was concluded that the potential for secondary damage to the GPHS test modules was too large to consider using the turn-around technique of propelling the concrete target into the RTG test article. A viable technique for capturing or diverting the concrete target after impacting the RTG did not appear to be easily attainable. As a result, the decision was made to pursue the approach of propelling the RTG test article by rocket sled into the stationary concrete target. This approach is not without complication, since there are potential problems in repositioning the RTG (rotating it from vertical – to accommodate loading of the preheated test module stack – to horizontal for the end-on impact orientation) and securing it sufficiently on the sled to withstand the rapid acceleration.

Task 4

Qualified Unicouple Production

TASK 4 QUALIFIED UNICOUPLE FABRICATION

During this 29 March to 26 September 1993 semi-annual reporting period, uncouple production transitioned from qualification lot production (Task 4) to flight uncouple production (Task 5). As a major program milestone, qualification lot uncouple production through the final stuffing and wrapping operation was completed in May 1993. In conjunction with completing the manufacturing effort for the final stages of qualification lot uncouples, production readiness was achieved for:

- Cold Stack Assembly
- Silicon Nitride Coating of Hot Shoe Spacers
- Nickel Plating of: Tungsten Compensators
Copper Pedestals
3847P2 (new) Heat Shunts
- Couple Preassembly
- Uncouple Assembly
- Stuffing/Wrapping of the Uncouple Assembly

These accomplishments marked the completion of production readiness for all uncouple processes and enabled full E-6 uncouple production. A summary of operator training and certification, process readiness, and production readiness at the end of May 1993 is shown in Table 4-1. The final status of qualification lot production is provided in Table 4-2.

Significant items related to qualification lot production are discussed in the following sections.

Couple Preassembly N-P Bond Joint Failures Engineering completed its investigation into the two N-P bond joint failures at the couple preassembly level which occurred in mid-February 1993. A final report detailing the study which included SEM and metallographic examinations was issued (Ref. Cassini Memo 219). Engineering concluded that the failures were isolated instances likely due to inadvertent overstressing (possibly during handling). Furthermore, the engineering investigation did not identify any product faults indicative of a process problem.

Radiator Attachment Assembly

As a close-out to an issue generated during qualification lot machining of radiator attachment assemblies, an evaluation of the assembly in which the machined thickness of the heat shunt wall against the molybdenum compensator is towards the minimum allowed

by the drawing tolerances was completed. The conclusion of the analysis (Ref. Cassini Memo 210), which is supported by unicouple cold beam deflection test data, confirmed that assemblies which meet the drawing requirements are suitable for flight use.

**Table 4-1. Status of Training/Certification, Process Readiness, and Production Readiness
(30 May 1993)**

Process	Training and Certification	Process Readiness	Production Readiness
Vacuum Casting	Complete	Completed WE 9/8/91	Completed 11/5/91
Powder Blending	Complete	Completed WE 9/8/91	Completed 12/20/91
Hot Pressing (N-Type)	Complete	Completed WE 11/1/91	Completed 12/20/91
Hot Pressing (P-Type)	Complete	Completed WE 10/20/91	Completed 12/20/91
Hot Pressing SiMo	Complete	Completed WE 1/26/92	Completed 2/28/92
Hot Pressing N-P Bond	Complete	Completed WE 1/26/92	Completed 11/9/92
Machining TE Parts			
Pellets & Segments	Complete	Completed WE 2/2/92	Completed 9/11/92
Hot Shoe Fabrication	Complete	Completed WE 2/16/92	Completed 11/9/92
First Bond	Complete	Completed WE 5/10/92	Completed 1/14/93
Silicon Nitride Coating	Complete	Completed WE 5/24/92	Completed 2/16/93
Second Bond	Complete	Completed WE 9/13/92	Completed 3/9/93
Nickel Plating			
Moly Compensators	Complete	Completed WE 7/12/92	Completed 2/16/93
Electrical Insulators	Complete	Completed WE 7/12/92	Completed 2/16/93
Stainless Steel Pressure Pads	Complete	Completed WE 10/25/92	Completed 2/16/93
Tungsten Compensators	Complete	Completed WE 11/6/92	Completed 3/30/93
Copper Pedestals	Complete	Completed 4/8/93	Completed 4/8/93
Electrical Connectors	Complete	Completed 2/16/93	Completed 2/16/93
Heat Shunts	Complete	Completed 5/3/93	Completed 5/3/93
Couple Preassembly	Complete *	Completed WE 9/27/92	Completed 3/30/93
Cold Stack Assembly	Complete *	Completed WE 8/30/92	Completed 5/3/93
Radiator Attachment Assembly	Complete *	Completed WE 7/19/92	Completed 3/9/93
Unicouple Assembly	Complete *	Completed WE 10/25/92	Completed 5/24/93
Stuffed and Wrapped Unicouple	Complete *	Completed WE 11/1/92	Completed 5/24/93

* Training Complete, Certification of Operators Not Required
WE = Week Ending

**Table 4-2. Cassini RTG Program Unicouple Hardware Production Status
 (27 June 1993)**

	Qualification Lot				
	Total Starts	Total Accepted	Actual Yield *	Total Planned Starts	Planned Yield
Vacuum Castings	91	90	98.9%	91	92.9%
Powder Blends	45	42	93.3%	45	94.3%
Hot Pressing	172	165	95.9%	172	85.7%
N-P Bonds	40	34	85.0%	40	85.7%
Pellets	3196	1838	67.0%	3196	78.6%
Segments	3582	2739	89.1%	3582	78.6%
Hot Shoes	1558	1235	88.6%	1558	78.6%
First Bonds	790	736	93.2%	790	74.3%
Coated First Bonds	688	591	85.9%	688	85.7%
Second Bonds	450	411	91.3%	450	85.7%
Nickel Plating	2394	2300	96.1%	2394	90.0%
Couple Preassembly	397	367	92.4%	397	85.7%
Brazed Radiator Assembly	495	455	91.9%	495	90.0%
Machined Radiator Assembly	435	351	98.0%	435	88.6%
Cold Stack	342	290	85.5%	342	90.0%
Coated Spacers	560	405	92.0%	560	85.7%
Unicouple Assembly	279	234	84.2%	279	87.1%
Wrapped Unicouple Assembly	233	225	97.0%	233	95.8%

* Cumulative Actual Yield is computed as the ratio of the Total Number Accepted (ITD) to the Total Number Completed and processed through Inspection (ITD). The difference between Total Starts (ITD) and Total Accepted (ITD) is a combination of hardware in-process that has not been completed through Inspection, and hardware that has been rejected.

◆ Production complete.

Cold Stack Assembly

During early April 1993, while completing the last portion of qualification lot cold stack assemblies, an intermittent occurrence of oxidation (discoloration) during brazing increased in frequency. This development initiated a full engineering investigation into the oxidation problem. During this investigation, which lasted roughly one week, brazing of cold stack and unicouple assemblies was limited. Testing was conducted to find or eliminate potential causes. One strong suspicion was that moisture, oxygen, and/or other contaminants in the graphite fixtures were being driven out during the brazing cycle and causing oxidation. As an engineering evaluation, a small group of fixtures were vacuum fired at 1600°C and then used for cold stack assembly. No oxidation was evident after the cold stack brazing cycle. Following this result, production was continued using only the 1600°C baked-out graphite fixtures. The graphite fixtures are stored in nitrogen dry boxes when not in use. Although production had resumed using the baked-out graphite fixtures and oxidation had not reoccurred, engineering continued to search for other possible contributors to the oxidation problem. A representative from the gas supplier, Air Products Metals Processing (R&D), visited the facility and conducted a check of the hydrogen and nitrogen gas quality and also reviewed the brazing operation. No problems were identified. Qualification lot production of cold stack assemblies was completed at the end of April with a yield of 85%.

Nickel Plating

At the start of this reporting period, production readiness had been completed and E-6 nickel plating production was initiated for four of the seven parts requiring plating. The activities to achieve production readiness on the remaining three parts, tungsten compensators, copper pedestals, and heat shunts, is provided below.

Tungsten Compensators: The DOE production readiness review for nickel plating of tungsten compensators was held on 30 March 1993. A review of qualification lot data, which showed a 100% acceptance yield, also identified that the final portion of qualification lot plating production included a supplemental electrocleaning of the tungsten compensators in Oakite as part of the pre-plating cleaning process. This cleaning was performed via MRB direction to ensure that part stains were removed prior to plating. Since plating with electrocleaning consistently produced satisfactory results, the electrocleaning in Oakite was incorporated into the plating specification. Following this process/specification update, E-6 tungsten compensator plating production was initiated with DOE approval.

Copper Pedestals: Using new prime tumbled parts, four lots of pedestals were plated for demonstration of process/production readiness. All parts passed visual inspection and the plating thickness on each lot was also satisfactory. Following a DOE process/production readiness review on 8 April 1993, approval was granted to proceed with E-6 nickel plating of copper pedestals.

Heat Shunts: The demonstration plating runs on five lots of etched P2 heat shunts were completed in early April 1993. (Reference the September 1992 - March 1993 prior Semi-Annual Technical Report for a thorough discussion on the development of the etching process to rework an undesirable surface condition.) All five lots passed visual inspection requirements. Interior surface plating thickness on three of the five lots did not meet the minimum thickness requirement of .00005", with thickness values reported in the .000047" to .000035" range. Engineering conducted a review of GPHS plated heat shunt data to determine the validity of the .00005" minimum limit on the interior surfaces. Issues such as plating thickness variation from part edge to center, thickness variation within a plating lot, and the effect of Met Lab sample preparation technique on measured thickness were also examined. Following this engineering review, final resolution to interior plating thickness on the heat shunt was reached. The minimum plating thickness on the interior brazing surface was revised to .00003". This change was incorporated into the nickel plating specification. Based on this limit, all demonstration runs completed on P2 etched parts met the nickel plating thickness requirement. In parallel with the thickness evaluation, a group of plated P2 heat shunts were used to build radiator attachment assemblies. This was conducted to show that the etched P2 part configuration is acceptable at the next higher assembly level. Results from these test assemblies confirmed earlier assembly work, which showed that the P2 part could be assembled and brazed satisfactorily. Based on these positive results, DOE approval for process/production readiness was achieved on 5 May 1993.

Unicouple Assembly

Qualification lot unicouple assembly production was completed in the last week of April. A large percentage of qualification unicouple assemblies (47A303931G1) produced during April were placed on non-conformance report for foreign material in the unicouple braze joint (tungsten compensator/copper pedestal). The acrylic binder (M50A1) used in unicouple brazing assembly evaporates during the braze cycle leaving a small amount of black carbonaceous material on the surface of the braze joint. This is typical for brazing when using a hydrocarbon for an assembly aid. GPHS-RTG program accepted unicouples have been reviewed and found to have this black foreign matter at the braze joint. This

properties of the braze joint. Concerns were raised about potentially loose carbon particles, therefore removal (cleaning) of the carbon was the desired approach. Per MRB direction, the braze joints on unicouple assemblies were successfully cleaned by swabbing (cotton Q-tip wet with isopropyl) and then blowing with nitrogen. MRB has implemented this cleaning process on all unicouple assemblies with foreign material in the braze joint. After cleaning, the uncouples were re-inspected and virtually all the assemblies were accepted, thus improving the overall final process yield. To eliminate this nonconforming attribute in future production, the RA4C2 assembly specification was revised to include the cleaning (swabbing/blow drying). Since small crevices and recessed areas in the braze joint make it difficult to remove all the foreign matter, the use of a visual standard that limits the allowable level of black foreign matter after cleaning was included in the revision. The standard was selected from GPHS accepted uncouples. The start of E-6 uncouple assembly production was conducted to the revised specification.

18 Couple Module: 18-10

During this reporting period the assembly of the first 18 couple module, 18-10, was completed, and following processing the unit was put on life test. As of 26 September 1993 the 18-10 module has accumulated 1272 hours at the accelerated hot shoe temperature of 1135°C. Performance continues to be good with all measured parameters in agreement with previously tested GPHS and MHW modules.

Significant events during the module final assembly included replacement of the four uncouples that were damaged during riveting operations. The damage was originally identified by increased uncouple resistance. Evaluation of the damaged uncouples showed three of the four assemblies contained fractures in the N-segment. For the fourth uncouple no external cracks or fractures were observed. The fracture locations were generally within 5 mils of the tungsten cold shoe in the fillet formed during the second bonding operation. This location is also where standard uncouple beam deflection tests typically produce failures. Resistance measurements on the four damaged uncouples showed that the increased resistance across the N-segment/cold shoe joint was nearly equal to the resistance increases suffered after riveting/swaging.

Investigations were conducted to determine the cause of the failures. These included a study of the fabrication data and a review of the tooling used for the 18 couple module riveting operations. The fabrication data study could not identify why the N-segment bonds would be more susceptible to failure than uncouples installed into GPHS 18 couple modules. The tooling review, however, revealed differences between the 18-10 and GPHS

module tooling. As a result, two significant modifications were made. First, a rivet gun alignment tool was added to control both rivet orientation and loading of the electrical connectors during riveting. Secondly, a manual tool for swaging the pop rivets was replaced by a pneumatic tool. Both of these tools had been used in the GPHS program but not identified in the 18 couple module manufacturing planning instructions. Both tools have been added to the planning master. It has been concluded that improper loading caused by the use of incorrect tooling was the cause of the failures.

During May, assembly of 18-10 proceeded as far as attachment of the radiator base plates. Available base plates, however did not have the required stripe of PD224 high emissivity coating. To minimize schedule impact the radiator plates from Module 18-3, which had been tested for about 1580 hours during the GPHS program, were used. Existing radiator plates in stock were subsequently coated with the PD224 paint for use on future 18 couple modules. In June, the module proceeded up to the assembly of the multi-pin connector. During connector assembly operations in early July, one of the six hot side thermocouples was found to be open. MRB approved the use of the module without a sixth thermocouple as the remaining five were considered adequate for data collection purposes.

Table 4-3 summarizes the room temperature resistance and Si_3N_4 coating weight data for the unicouples in module 18-10.

Module 18-10 was delivered to the component test area on 8 July 1993 for thermal vacuum testing. Module 18-10, the first of three planned 18 couple modules, contains unicouples from the early part of the qualification lot production. The purpose of testing is twofold. First, an assessment of the thermoelectric performance is made at the normal hot shoe temperature of 1035°C comparing power output, internal resistance, and open circuit voltage with previously tested GPHS program 18 couple modules. Second, the effectiveness of the Si_3N_4 coating is evaluated from a trend of isolation resistance (foil to thermoelectric circuit). For the first two of the three modules coating effectiveness is evaluated at an accelerated temperature of 1135°C. A sharp decrease in this resistance is not expected until after 2000 hours at 1135°C. For the third module testing is conducted at 1035°C.

The 18-10 module was brought up to a 1035°C hot shoe temperature over a three week period in accordance with a procedure developed during the MHW and GPHS programs. Comparison of initial performance with GPHS module 18-7 is given in Table 4-4. Comparison of the initial normalized power output and internal resistance with the average

Table 4-4. Comparison of Initial Performance of Modules 18-10 and 18-7

	Module 18-7	Module 18-10
Heat Input, Watts	162	162.6
Hot Shoe, C Average	1035.6	1033.4
Hot Shoe Range C	12	7.5
Cold Strap, C Average (8 T/Cs)	293.9	285.4
Cold Strap Range (8T/Cs)	9.7	9.0
Cold Strap Average (12 T/Cs)	290.0	280.8
Cold Strap Range (12 T/Cs)	21.3	19.8
Load Voltage, Volts	3.504	3.501
Link Voltage, Volts	0.164	0.163
Current, Amps	2.520	2.596
Open Circuit Voltage, Volts	6.353	6.355
Normalized Open Circuits (8T/Cs)	6.293	6.239
Normalized Open Circuits (12 T/Cs)	6.258	6.199
Average Couple Seebeck Coefficient (8)	499×10^{-6}	495×10^{-6}
Internal Resistance, Ohms	1.065	1.041
Internal Resistance Per Couple (Avg)	0.0592	0.0578
Power Measured, Watts (Load + Link)	9.246	9.485
Power Normalized, Watts (8 T/Cs)	9.072	9.142
Power Normalized, Watts (12 T/Cs)	8.970	9.027
Isolation		
Circuit to Foil, Volts	-1.55	-1.86
Circuit to Foil, Ohms	9.2K	18K

Table 4-5. Comparison of Initial Normalized Power Output and Internal Resistance with the Average Initial Values of the GPHS Modules

1035°C Operation			
	18-10 (t = 0)	18-10 22 Hours	GPHS 18 Couple Modules (t = 24 Hours)
Load Voltage	3.65 V	3.65 V	3.65 V
Normalized Power (1035°C/300°C)	9.03 W	9.06 W	9.06 W (Average) Range 8.84 to 9.29 W σ 0.18 W
Internal Resistance	57.8 m Ω	58.4 m Ω	58.9 m Ω (Average) Range 57.2 to 61.0 m Ω

The module 18-10 trend is falling within the data base indicating a similar Si_3N_4 coating quality. Figures 4-2 and 4-3, respectively, show internal resistance and power output trends compared to GPHS module 18-8. Agreement is very good, indicating the same thermoelectric performance.

Table 4-6. Comparison of Initial and 1216 Hour Performance of Module 18-10 at 1135°C

	Initial 8/4/93	t = 1216 hours 9/24/93
Heat Input, Watts	191	191.4
Hot Shoe, C Average	1136.2	1135.1
Hot Shoe Range C	3.9	3.7
Cold Strap, C Average (8 T/Cs)	309.5	307.4
Cold Strap Range (8T/Cs)	10.8	11.3
Cold Strap Average (12 T/Cs)	304.6	302.4
Cold Strap Range (12 T/Cs)	22.3	22.6
Load Voltage, Volts	3.501	3.508
Link Voltage, Volts	0.189	0.187
Current, Amps	3.168	3.113
Open Circuit Voltage, Volts	7.151	7.369
Normalized Open Circuits (8T/Cs)	6.324	6.507
Normalized Open Circuits (12 T/Cs)	6.284	6.466
Average Couple Seebeck Coefficient (8)	4.99×10^{-4}	5.132×10^{-4}
Internal Resistance, Ohms	1.093	1.180
Internal Resistance Per Couple (Avg)	0.0607	0.0656
Power Measured, Watts (Load + Link)	11.691	11.503
Power Normalized, Watts (8 T/Cs)	9.143	8.969
Power Normalized, Watts (12 T/Cs)	9.028	8.857
Power Factor	40.987×10^{-5}	40.17×10^{-5}
Isolation		
Circuit to Foil, Volts	-1.676	-1.134
Circuit to Foil, Ohms	5.22K	13.6K

Figure 4-1. Isolation Resistance – Module Circuit to Foil for Cassini Module 18-10 and the GPHS and MHW Modules Operated at 1135°C

Figure 4-2. Internal Resistance Ratios of Cassini Module 18-10 and GPHS Module 18-8

Figure 4-3. Power Factor Ratio for Cassini Module 18-10 and GPHS Module 18-8

18 Couple Module: 18-11

Assembly of module 18-11 was initiated in June 1993 with the lay-up of the thermopile insulation assembly. Towards the end of September 1993, all 18 unicouples had been inserted, base wrapped, and formed. Insertion, forming, and riveting operations on module 18-11 are being used to provide operator and inspector training for E-6 thermopile assembly work. The unicouples for module 18-11 were randomly selected from the qualification lot production. In accordance with a DOE request, several of the unicouples which were selected had been processed (by rework) through double peroxide cleaning (at the first bond level prior to silicon nitride coating). This was done to address DOE concerns of performance from this non-standard processing.

Following the connector forming operations, electrical inspection identified a unicouple with a large resistance increase (from 23.2 to 64.2 milliohms). A replacement unicouple has been identified and will be replaced in October 1993. An evaluation of the removed unicouple will also be conducted to determine the cause of failure.

Task 5

ETG Fabrication, Assembly, and Test

TASK 5 ETG FABRICATION, ASSEMBLY, AND TEST

Unicouple Fabrication

With the completion of production readiness for the tail end unicouple fabrication steps, efforts were focused on completing E-6 unicouple production during this reporting period. The upfront unicouple processes of vacuum casting through to hot pressing continue their strong performance with yields above 90% and production well ahead of schedule. The status of flight unicouple hardware production at the end of September is provided in Table 5-1. For E-6 unicouple fabrication, significant progress was made during this six month period in the completion of higher level assemblies, first bond to stuffed wrapped unicouple assembly. A summary of the percent of E-6 production complete at the beginning and end of this reporting period for the higher level assemblies is shown in Table 5-2. At the end of September 1993, 76% of E-6 unicouple assemblies were completed (and accepted) through inspection. Based on this progress, the goal of completing E-6 unicouple production at the end of October is expected to be met or exceeded.

Significant issues related to the production of flight unicouple hardware during this reporting period are discussed in the following sections.

N-P Bond/Hot Shoes

At the start of this reporting period, N-P bonding for both E-6 and E-7 was underway. In May 1993, fabrication of E-6 N-P bonds was completed and E-7 production was 50% complete. Machining and final inspection of E-6 hot shoes continued into June. As the inspection of the tail end of E-6 N-P bond production progressed, a trend in decreased hot shoe strength and increased resistance was identified. Additionally, the frequency of hot shoes failing the 22 kg proof load test had increased. These changes in strength, resistance and proof load failure rates were generally within specification (or process control) limits. As a result, the overall E-6 process yield was not impacted. Despite this outcome, the data did reveal that the N-P bond process had moved off optimum and that engineering action was needed to reverse the trend.

The engineering investigations into this matter focused mainly on two parameters, flatness and bonding temperature. By the end of June, proper performance of the lapping table had been verified and the flatness achieved on the polishing table was under evaluation. To evaluate the bonding temperature, instrumented N-P bond tests at 1285°C were run in hot press #2 (HP-2) and hot press #3 (HP-3). The data indicated that a 6°C increase was needed for HP-2 and a 20°C increase was needed for HP-3. To verify these temperature adjustments, two N-P bonds were fabricated during the last week in June. Lot 101 was

Table 5-1. Status of Unicouple Production as of 29 September 1993

	E-6				
	Cumulative ITD			Total Planned Starts	Planned Yield
	Total Starts	Total Accepted	Actual Yield *		
Vacuum Castings	54	54	100%	54	95.0%
Powder Blends	26	26	100%	26	96.0%
Hot Pressing	149	143	96.0%	149	90.0%
N-P Bonds	40	36	90.0%	40	90.0%
Pellets	3020	2444	80.9%	3020	85.0%
Segments	3921	3629	92.6%	3921	85.0%
Hot Shoes	1503	1358	96.4%	1503	85.0%
First Bonds	1260	1162	94.1%	1260	82.0%
Coated First Bonds	1168	1086	93.0%	1168	90.0%
Second Bonds	1017	834	84.8%	1017	90.0%
Nickel Plating	8232	8172	99.3%	8568	93.0%
Couple Preassembly	831	644	88.7%	831	90.0%
Brazed Radiator Assembly	1019	823	86.1%	1103	93.0%
Machined Radiator Assembly	961	825	85.8%	961	92.0%
Cold Stack	824	739	91.6%	824	93.0%
Coated Spacers	840	742	88.3%	840	90.0%
Unicouple Assembly	722	518	88.5%	746	91.0%
Wrapped Unicouple Assembly	509	387	99.5%	668	97.0%

	E-7				
	Cumulative ITD			Total Planned Starts	Planned Yield
	Total Starts	Total Accepted	Actual Yield *		
Vacuum Castings	59	58	98.3%	59	96.0%
Powder Blends	28	26	96.3%	28	96.8%
Hot Pressing	141	139	99.3%	142	92.0%
N-P Bonds	32	29	100%	39	92.0%
Pellets	3699	2811	87.0%	3699	86.5%
Segments	3809	1695	93.2%	3809	86.5%
Hot Shoes	1488	671	94.8%	1488	86.5%
First Bonds	730	533	94.8%	1212	85.6%
Coated First Bonds	480	348	94.6%	1000	92.0%
Second Bonds	289	177	97.3%	897	92.0%
Nickel Plating	4536	3951	99.5%	8589	94.4%
Couple Preassembly	123	23	95.8%	810	92.0%
Brazed Radiator Assembly	483	333	88.1%	912	94.4%
Machined Radiator Assembly	201	88	96.7%	876	93.6%
Cold Stack	54	24	85.7%	780	94.1%
Coated Spacers	200	155	96.9%	840	92.0%
Unicouple Assembly				726	92.8%
Wrapped Unicouple Assembly				650	97.6%

* Cumulative Actual Yield is computed as the ratio of the Total Number Accepted (ITD) to the Total Number Completed and processed through Inspection (ITD). The difference between Total Starts (ITD) and Total Accepted (ITD) is a combination of hardware in-process that has not been completed through Inspection, and hardware that has been rejected.

Table 5-1. Status of Unicouple Production as of 29 September 1993 (Cont'd)

	E-8				
	Cumulative ITD			Total Planned Starts	Planned Yield
	Total Starts	Total Accepted	Actual Yield *		
Vacuum Castings	82	77	95.1%	79	96.8%
Powder Blends	35	31	96.9%	35	97.4%
Hot Pressing	160	158	98.8%	178	93.6%
N-P Bonds				49	93.6%
Pellets	952	-		3672	87.9%
Segments	2995	1932	87.9%	3791	87.9%
Hot Shoes				1804	87.9%
First Bonds				1516	88.5%
Coated First Bonds				1256	93.6%
Second Bonds				1122	93.6%
Nickel Plating				10856	95.5%
Couple Preassembly				1014	93.6%
Brazed Radiator Assembly				1140	95.5%
Machined Radiator Assembly				1060	94.9%
Cold Stack				976	94.9%
Coated Spacers				1024	93.6%
Unicouple Assembly				908	94.2%
Wrapped Unicouple Assembly				810	98.0%

* Cumulative Actual Yield is computed as the ratio of the Total Number Accepted (ITD) to the Total Number Completed and processed through Inspection (ITD). The difference between Total Starts (ITD) and Total Accepted (ITD) is a combination of hardware in-process that has not been completed through Inspection, and hardware that has been rejected.

Table 5-2. Summary of Accomplishments for E-6 Unicouple Assembly

	% of E-6 Production Completed Through Inspection	
	March (3-28-93)	End of September (9-29-93)
First Bonds	32%	100%
Second Bonds	7%	92%
Cold Stack	0%	96%
Couple Preassembly	0%	86%
Unicouple Assembly	0%	76%
Wrapped Unicouple Assembly	0%	59%

bonded in HP-2 at 1306°C and lot 102 was bonded in HP-3 at 1315°C. Further N-P bond production for E-7 was halted until an evaluation of hot shoe data from these verification lots was completed. This approximate one month delay in N-P bonding did not cause a schedule delay, since hot shoe machining for E-7 was previously running six weeks ahead of plan.

The processing of the final lots of E-6 hot shoes through inspection was completed in July. An overall acceptance yield of 96% was achieved. Concurrent with this, engineering verified the proper operation of the lapping table with polished compacts meeting the 0.3 mil flatness requirement. Inspection of hot shoe lots 101 and 102 was also completed in July providing hot shoe strength data.

For lot 101, three hot shoes failed at 22 kg and the strength of the high and low resistance hot shoes was relatively low, 34 and 31 kg. All failures were in the SiMo-N material. The first bond load at failure was 14.5 kg. For Lot 102, no hot shoes failed at 22 kg and the strength of the high and low resistance hot shoes was good, 34 and 40 kg. The first bond load at failure was 15.75 kg. In order to (1) further understand this variability of hot shoe strengths at a given N-P bond temperature, and (2) meet production commitments, it was decided to cautiously proceed with E-7 N-P bond production.

The following approach was taken to continue with E-7 N-P bonding: 1) fabricate a set of two N-P bonds (one in each hot press); 2) expedite the machining of the two N-P bonds into hot shoes; 3) determine the strength and resistance properties of the hot shoes; and 4) use this most recent data to set the parameters for the next bonding set. Once again, the main parameter addressed was bonding temperature, since earlier work confirmed that the parameters of SiMo compact flatness, titanium shim condition and cleanliness were satisfactory. During the months of August through September an additional six N-P bonds were fabricated for E-7 to verify the bonding temperatures of 1306°C in HP-2 and 1315°C in HP-3. These runs were performed in groups of two (one in each hot press) and hot shoe strength data was reviewed before bonding the next group. A summary of the results for these N-P bond lots (101 through 108) is shown in Table 5-3. Due to the good results obtained on these successive runs, there was no need to modify the bonding temperature in HP-2 or HP-3. A review of the data in Table 5-3 shows favorable values with a near-zero incidence of 22 kg proof load failure and hot shoe strengths at or above the production averages.

Table 5-3. Hot Shoe Inspection Data

N-P Bond Lot #	Date N-P Bonded	N-P Bonding Temp (°C) and Hot Press	N-P Bond Reaction (%)	Avg. Hot Shoe Elect. Resist. (mΩ)	Qty of Hot Shoes Failing Proof Load Test	High Res Hot Shoe Load at Failure (kg)	Low Res Hot Shoe Load at Failure (kg)	1st Bond Reaction (%)	Sliding Weight Tester Avg. 1st Bond Load at Failure (kg)	Final Disposition
UHPBP0101	6/21	1306/2	30	0.098	3 (SiMo-N)	34	31	32	14.5	ACCEPT
UHPBP0102	6/25	1315/3	24	0.093	0	34	40	34	15.75	ACCEPT
UHPBP0103	7/29	1315/3	33	0.094	0	38	40	38	13.5	ACCEPT
UHPBP0104	7/30	1306/2	29	0.084	0	36	42	40	13	ACCEPT
UHPBP0105	8/16	1315/3	30	0.102	0	42	43	43	13.75	ACCEPT
UHPBP0106	8/13	1306/2	28	0.101	0	40	39	42	14.25	ACCEPT
UHPBP0107	9/2	1315/3	27	0.088	0	32	40	37	16.5	ACCEPT
UHPBP0108	9/3	1306/2	25	0.102	0	41	41	33	12.5	ACCEPT
10/13/93	CASSINI PRODUCTION									
	AVG	N=50	29	0.095	0.5	36	38	39	14.3	
01/13/93	CASSINI QUAL									
	AVG	N=28	28	0.101	0.4	37	39	38	15.1	HP3 SiMo Not Bonded
	CASSINI QUAL									
	AVG	N=3	27	0.098	0.3	42	43	37	14.8	HP3 SiMo Bonded
	CASSINI QUAL									
	AVG	N=3	28	0.094	0	37	39	39	14.1	HP2 SiMo Bonded
	CASSINI PR									
	AVG	N=10	30	0.089	0.7	33	36	38	ND	
	GPHS PRODUCTION									
	AVG	N=213	24	0.099	0.5	41	42	38	13.1	
	CASSINI SPEC LIMITS	1300±20°C	35 max. (process control limit)	0.135 max	Test all at 22 kg	30 min. (process control limit)	30 min. (process control limit)	45 max.	7.5 min.	

Engineering work to verify the optimum bonding temperatures has been concluded with 1306°C in HP-2 and 1315°C in HP-3 selected for continued E-7 production.

As identified in the engineering investigation, temperature is a major factor in the N-P bonding process. To gain increased control of the bonding temperature, the specification was revised to include instrumented N-P bond runs. At a minimum, these temperature check-out runs are to be performed for each hot press after every fifteen N-P bonds or every four months. This frequency is designed to monitor temperature drift during production. Additionally, instrumented N-P bond runs are required to be conducted after repair or replacement of furnace components that could potentially affect the furnace thermal performance.

Thermoelectric Parts Machining

The machining and inspection of thermoelectric (T/E) parts for E-6 was essentially completed in August 1993. The machining of pellets, segments, and hot shoes for E-7 is progressing smoothly with a significant amount of machining completed. Pellet machining for E-7 represents a significant improvement over E-6 results. At the end of September 1993, E-7 pellet production was 88% complete (accepted through inspection) with a yield of 87% (just above the panned value of 86%). The production data for machining of E-7 segments and hot shoes is similarly favorable with yields at 93%. Improvements in yields are attributed to increased operator attention in the machining/handling steps and the peroxide cleaning method which was incorporated in April 1993.

During May of this reporting period, personnel in the parts machining process successfully completed an effort to increase the number of pellets and segments produced from a compact. In general, the number of wafers obtained per compact has been increased from three to four. This additional wafer is a consequence of preventing material loss during the mold loading operation (prior to hot pressing) and careful alignment of the compact during the first (facing) wafering slice so that minimum material is removed. As a secondary step, the number of pellets and segments produced per wafer has also been increased by refining the alignment procedure of random length pieces prior the slicing operation. The combined result of these modifications, which have been incorporated into the work station planning, is a potential increase of 135% in parts per compact. Thus, the average quantity of pellets produced per compact is increased to 100 parts compared to the 72 by the former method. Similarly, the average number of segments is increased from 320 to 425. This increase of 135% cannot always be guaranteed due to compact variations, however, data collected to the end of September shows that increased output is being obtained on ~90% of the compacts being machined.

First Bond Assembly

Fabrication of E-6 first bonds was completed during this reporting period. Production for E-7 is proceeding smoothly. Fifty percent of E-7 first bonds are complete and an acceptance yield of 95% is being achieved. Up through to September 1993, all first bond assembly production was performed in the existing (old) GPHS-RTG program bonding furnaces for fabrication of flight first bond assemblies. The new Brew bonding furnaces were being used only to produce flight second bond assemblies.

In April 1993, successful first bond demonstration runs were performed in the new Brew bonding furnaces. Three bonds per run are obtained in the new furnaces in comparison to

two bonds per run in the old GPHS equipment. In May 1993, DOE concurrence to proceed with the production of flight hardware in the new Brew Furnaces was achieved. Following this, new specifications were issued for first bond assembly in the Brew furnaces. Due to the level of effort needed to support the second bond voiding problem, the actual transfer of first bond production work from the old furnaces to the new equipment was delayed until September. During this interval, bonding operations in the existing GPHS furnaces had been satisfactory to maintain production schedules. Since there was a lengthy interruption in first bonding in the new furnaces, engineering bonding runs were performed to re-orient the operator and ensure proper performance of the furnaces. Following successful completion of these runs, first bond flight production work was initiated mid-September. Bonding results from the new furnaces will be monitored to ensure that high acceptance yields are maintained.

As an issue related to first bond assembly, engineering completed an effort to establish more specific accept/reject criteria for blisters produced during bonding. Blisters are typically at the cold end of the pellet. SEM studies of first bond and second bond cross-sectioned blister samples were conducted. Blisters up to 95 mils in width were evaluated. Results indicate that pellet and segment chemistry and microstructure remain normal adjacent to the blisters. Engineering concluded that blisters are a superficial feature which do not impact uncouple performance. The analysis was documented in Cassini Memo 234. ECN-0324 to the first bond specification, which defined dimensional acceptance criteria for blisters, was approved in September 1993.

Silicon Nitride Coating

Coating of E-6 first bond assemblies was completed during this reporting period with a 93% yield. Production readiness for coating hot shoe spacers was completed early May 1993, and E-6 production requirements were subsequently fulfilled. Final E-6 yield for hot shoe spacer coating was 88%. All E-6 coating work and the initial portion of E-7 production was performed using the existing GPHS program NAV-TEC furnace. The new CVD coating equipment was not used for production until August 1993.

For the new CVD furnace, checkout and qualification coating runs were completed in April 1993. Based on positive results from these runs, DOE concurrence to use this new equipment for flight coating production was obtained on 3 May 1993. On first bonds coated in the CVD furnace, the weight gain, deposition and etch rates, chlorine level, coating thickness and TGA results were satisfactory. Based on metallographic examination, the

coating appears to be more continuous and adherent than hardware coated in the NAV-TEC furnace. Results of TGA (Thermoelectric Gravimetric Analysis) tests of first bonds coated in the new CVD furnace is consistent with TGA data of product coated in the old NAV-TEC furnace. After receiving approval, new specifications were issued for use of the CVD furnace. Subsequent production was delayed, however, due to the identification of an error in the furnace calibration procedure. Calibration of the NAV-TEC was normally performed with the gas flow turbulator removed. Previous calibration of the CVD furnace was conducted with the turbulator in place. Calibration of the CVD furnace (with the turbulator removed) was repeated and the process specification (CP5A3) was updated to ensure the proper calibration method is performed.

Following calibration, a malfunction of the chlorine analyzer, coupled with service water leaks and a series of CVD furnace component failures further compounded the delay. Difficulty with the chlorine analyzer was encountered in June. Chlorine content on silicon wafers are measured for each coating run as a method of process control. The erratic behavior of the chlorine analyzer (x-ray fluorescence spectrometer) caused coating production to be severely limited, and halted preparations for coating flight hardware in the new CVD furnace. A vendor repair of the detector high voltage connections and replacement of the home switch was necessary. Also, the 75 ppm chlorine specimen used as the original low level standard was found to be defective (contaminated) and was replaced with an established GPHS specimen having 130 ppm chlorine level. With the repair completed, a new calibration curve was generated and silicon nitride coating production using the NAV-TEC furnace resumed.

During the second week of June, a heater element/lead in the CVD furnace shorted out. The defective furnace zone was replaced with a unit from the second (not yet installed) CVD furnace. Then, during the third week in June, a water leak in an overhead cooling line damaged the CVD furnace controller for the bubbler tank recirculating bath. During the ensuing downtime the copper tubing for cooling and service water was replaced with PVC. The timing of this work was advantageous since it did not cause any additional production delays. Replacement of the copper tubing should prove beneficial during future operations as it will prevent disruptive water leaks. The bubbler tank controller was repaired in early August. Silicon wafer calibration and a first bond start-up evaluation run were then completed in the CVD furnace to verify its proper operation. With positive results from these runs, flight coating production in the CVD furnace was finally initiated. Since its start in early August coating of E-7 hardware has been conducted solely in the CVD furnace with

satisfactory results. At the end of September, E-7 coating production was 37% complete for first bonds and 20% complete for hot shoe spacers.

Second Bond

During this reporting period E-6 second bond production was completed and production for E-7 was initiated. The final yield for E-6 was 85%. At the end of September, E-7 production was 20% complete. Of significance during this six month time period was the effort expended to resolve a perimeter voiding problem at the P-leg pellet to segment bond. Tungsten clips used for fixturing the assembly were a key factor in the evaluation of the voiding problem. As a consequence of the work performed, the concept of modifying the second bond fixture evolved. A complete discussion of these activities is provided in the following text. The summary is presented in chronological order.

During May 1993, difficulties were experienced in the fabrication of E-6 second bond assemblies. The first problem encountered was the shortage of satisfactory tungsten bonding clips. Bonding clips are made of tungsten wire (.035" dia. nominal) and are single use tooling employed in the assembly fixture. The supply of the first group of residual bonding clips, which worked satisfactorily, was exhausted. The delivery of new tungsten wire from ORSAM Sylvania was slipped due to vendor difficulties. A second group of residual bonding clips, which were available, did not exhibit the same behavior as the first group of residual clips. Excessive perimeter voiding or a negative fillet at the "P" segment to pellet interface was occurring with the use of the second group of residual bonding clips. This voiding problem caused the weekly second bond acceptance yield to decrease to approximately 60%, which is a sharp variation from the prior cumulative yield of 90%. Historical data from GPHS-RTG and early Cassini work have shown that poor bonding at the P pellet to segment interface is typically attributed to an improper match between N and P segments. While an inadequate match between N and P segments was considered a potential contributor for the poor bonding results, it was also concluded that the second group of residual bonding clips did not provide the necessary clamping force during the bonding thermal cycle. Based on this assessment, E-6 second bond production was virtually halted in mid-May until new tungsten clips were available. This action was taken to prevent a high rate of second bond rejection which would consume accepted first bond assemblies.

To minimize the impact on production, sourcing worked aggressively to accelerate the delivery of tungsten wire and its subsequent fabrication into clips. An alternate supply of wire was procured from Rembar Inc. At the end of May, sample clips were fabricated from

this Rembar material. In addition to this alternate tungsten material, sourcing was successful in getting ORSAM Sylvania to ship an initial amount of tungsten wire at the end of May.

At the start of June, the fabrication of new clips using alternate tungsten wire material from Rembar was completed. Bonding trials initially showed that Rembar wire clips provided acceptable results. This positive result did not hold true in repeated production as the P-pellet/segment voiding problem persisted. The post bond condition of the Rembar clips showed that these clips provided almost no clamping force on the bonding assembly (i.e., clips leaned over or fell off). It was postulated that this post bond condition of near zero clip force relates to having inadequate compressive force during the actual bonding process, and as a result contributes to the voiding problem.

With the unsuccessful use of Rembar wire, production of second bonds was halted until the third week of June when tungsten clips fabricated from GTE wire were available. Bonding results with the GTE wire were only slightly improved. To maintain production, operators initiated weighing of segments to aid in selecting matching pairs. This method was less than optimum and caused production to be slowed. At the end of June, approximately 50% of E-6 second bond production had been completed with the cumulative yield at 81%. Prior to the occurrence of voiding and clip problems, the second bond process yield was over 90% in the beginning of May.

To resolve the voiding problem and thus improve the process yield, engineering support was increased during June. All aspects of the bonding process were evaluated (i.e., temperature, clip performance, segment material, etc.). The evaluation eventually focused on two areas: (1) P-type material and (2) tungsten clip performance. It was not unexpected that these two elements were the principal issues addressed, since past experience has shown that bond success is sensitive to matching of N- and P-type segments, and the initiation of the voiding problem was coincident with the depletion of the first set of residual clips.

An evaluation of the segment material was completed at the end of June. Scanning electron microscopy of "good bonding" and "poor bonding" N-type and P-type segment materials using the porosity end slices was performed. The n-type segment material is inhomogeneous with the "good" material containing slightly more silicon rich areas. The P-type segment material is more homogeneous (i.e., more alloyed) relative to N-type with the "good" P-type material containing less silicon rich areas. It is known that the N-type material

melts at a lower temperature than the P-type material. The second bond process is thought to occur by liquid phase bonding (i.e., further homogenization of the N-type material and "melting" of the P-type material). Blisters are generally present on the P-type material only.

Compact data were reviewed with respect to powder blend lot, hot press thermocouple control temperature, applied load, Seebeck, density, and electrical resistivity. These data, together with second bond results, indicate that density and hot press temperature are most critical. For P-type compacts, a density near 3.53 g/cm^3 and a control thermocouple temperature near 1300°C , in which the material is on the verge of incipient melting, are desired. For the N-type compact, a control thermocouple temperature of 1230°C is desired. Based on this review, the hot press controller temperatures in Hot Press #3 were modified, and fabrication of new compacts using existing powder blend lots was started the first week in July. Two P-type segment compacts, lots 24P and 25P, were hot pressed at 1305°C . Following hot pressing, these compacts were expedited through segment machining since, as later revealed, they possessed the characteristics which allowed increased success in second bonding.

With regard to clip performance, bonding trials in early June established a direct correlation between satisfactory pellet/segment bonds and clips that remained vertical after bonding (i.e., clips that still produced compressive force following the bonding cycle). Early in July, multiple attempts were made at heat treating the clips (1200 to 1400°C for times ranging from 2 to 60 minutes) prior to bonding. This approach provided intermittent bonding successes, but no set of heat treating time/temperature parameters was found that provided repeatable results. An alternate option explored was increasing the clip opening from $9/16"$ (P7 configuration) to $3/4"$ (P9 configuration). Bonding trials showed that this modification to the clips yielded the most promising results. Based on these data, the production of E-6 second bonds was restarted mid-July at a limited rate using lot 18 P segments and increased ($3/4"$) clip opening. From the restart date until the end of July, approximately 125 second bonds were fabricated with the acceptance yield in the 75 to 80% range.

In parallel with the fabrication of new segment material and the evaluation of tungsten clips, existing segments produced during process readiness were also examined. Bonding trials were successfully completed using P-segments from two (pre-qualification lot) process readiness compacts. These compacts, which were later re-identified as lots 34P and 35P, originated from prime qualification lot powder blends which were hot pressed and partially machined on engineering tickets. In conjunction with a thorough review of the processing documentation, segment lots 34P and 35P were accepted through MRB and upgraded for

E-6 use with DOE approval. Use of lots 34P and 35P began in early August and replaced the use of lot 18P. It should be noted that approval to use lots 34P and 35P was a significant accomplishment since it provided suitable P segment material for both the completion of E-6 second bond production and also roughly one-quarter of E-7 production needs. During August, 340 second bond assemblies were produced with acceptance yields ranging from 80-85%. The voiding problem continued to be held in control. The significant amount of production in August was a major step towards recovering lost time. Segment material Lots 34P and 35P were used during this month with tungsten wire bonding clips having an opening of 3/4". Segment Lots 24P and 25P which were hot pressed at 1305°C, completed machining and inspection at the end of August. Several bonding tests with Lot 24P segments were conducted with acceptable bonds resulting. Lot 24P was phased into production during September 1993 with acceptable results. The process yield has steadily increased with the use of lots 34P, 35P, and 24P. At the end of September with 20% of E-7 production complete, the yield was 97%.

Second Bond Static Load Fixture

In conjunction with the effort to put second bond production back on course, a separate activity to improve the process was initiated near the end of July. Similar to the fixturing used for first bond, Engineering explored the use of a graphite frame static load fixture for second bond. Trial 'proof of concept' runs using a modified first bond fixture (for bonding only the P leg) provided good results (no voids and desirable fillet). As a notable point, the modified first bond static weight fixture obtained satisfactory second bonds on segment material that previously did not bond well with tungsten clips. As an initial test to partially demonstrate the acceptability of a static load fixture, the hot shoe N-P bond joints of two assemblies built with the modified fixture were strength tested. The failure loads, which were above average at 14.4 kg and 15.0 kg, demonstrated that the new fixture does not adversely impact hot shoe strength. At the end of July a meeting was held to define the requirements of a prototype static load second bond fixture and also consider the necessary verification tests. During August, the design and fabrication of a prototype fixture was completed. Bonding tests were conducted with satisfactory results. The prototype fixture design provides separate weights for the N and P legs. Bonding trials with the prototype fixture demonstrated that the most successful means of achieving good pellet/segment alignment was to use tungsten clips to temporarily clamp the assembly together and apply thinned M50A1 binder to the segment/pellet joint.

At this point, an EMQ and management internal meeting was held to review the bonding results and finalize the requirements for the verification test plan. The following conclusions were reached:

- Freeze the static load fixture design based on the current prototype design.
- Build two additional fixtures which will represent actual production fixtures. A total of three fixtures is needed for verification test runs.
- Proceed with demonstration runs required by the test plan (all three bonding tiers will be used).

At the end of August, the two additional fixtures were completed and the verification test plan was issued. (Ref. Cassini Memo 232).

The demonstration runs consisting of fifteen second bonds fabricated with the static load fixture were completed in September. Results were good with all assemblies acceptable for bond quality, visual, electrical, and dimensional criterion. One assembly failed thermal profile requirements by 5°C for one minute. This was due to a controller problem caused by improper reset of the unit. In accordance with the test plan, four of the assemblies were submitted for destructive evaluation and eight assemblies were forwarded for fabrication into uncouples (at least four uncouples are necessary for the test plan). At the end of September, destructive evaluation of N-P bond strengths was completed on two of the second bond assemblies. Results were acceptable with failure loads of 14.8 and 13.0 kg. Evaluation of the demonstration runs will continue into October, with production readiness projected for the end of October.

Based on the positive results of the static load fixture, efforts were also started to provide additional fixtures which would be needed for production. Fabrication of ten additional fixtures was authorized.

Radiator Attachment Assembly

The major issue related to radiator attachment assemblies during this reporting period was the machining of the assembly. Difficulties were continually encountered with the vendor (Sheffield). Problems ranged from improper machining/drilling which caused dimensional non-conformances to poor workmanship (gouges, scratches). While many of the problems were able to be reworked and/or accepted through MRB, the need for rework and reinspection caused delays. Multiple visits were made to the vendor in an attempt to rectify this problem. The low vendor initial yield (~60%) continued to be a major concern. Subsequent to these visits and after a re-review of past vendor performance, it was

concluded that an alternate approach must be exercised. In mid-August an effort to move the machining task in-house (to Building B machine shop) was initiated. The primary motivation for this decision was the inadequacy of Sheffield's tooling and overall inconsistency in workmanship. By the end of August the design/fabrication of new tooling (fixtures) for in-house machining were completed and machining demonstration runs on 16 assemblies were conducted. The inspection results of these demonstration runs were very good with a 93% yield. Based on these positive results, production readiness was approved 15 September 1993. Actual machining of flight assemblies in-house was started towards the end of September. This start was nearly coincident with the start of E-7 radiator machining. As a result, the E-7 yield status will provide a good measure of performance.

Electrical Insulators

Residual insulators were plated and machined for the complement of E-6 cold stack assemblies and are also being used for the initial portion of E-7.

For the new replacement insulators, WESGO completed the action items to 1) check the the body lot (C-1209) machining process to ensure the substrate was not damaged, and 2) evaluate GPHS insulators to determine if they were heat treated.

In April, heat treated metallized samples (identified as C-1209 body group 2D) were delivered which had an "improved" machined surface condition on the body lot substrates (2" X 2" X .020").

Modulus of Rupture (MOR) testing on group 2D samples provided the following results:

Alumina Body MOR (Heat Treated After Machining)	=	31 ksi
Metallized Insulator MOR (Heat Treated After Machining)	=	57 ksi avg 65 ksi max 47 ksi min

It is significant to note that this data meets the former GPHS-RTG M4C2 specification requirement of metallized insulator Avg MOR ≥ 50 ksi and Min MOR ≥ 30 ksi. A M4C2 specification revision was completed in May, which modified the MOR requirement based on engineering analysis and test of the insulator strength requirement. (For details of the analysis and test results reference PIR-1RS1-CC-6956 and the Cassini September 1992 through March 1993 Semi Annual Technical Report.) The revised requirement states that the Avg MOR minus two times the standard deviation of the sample lot shall be a minimum of 20 ksi (Avg MOR $-2\sigma \geq 20$ ksi).

Based on a dye penetrant absorption test, WESGO determined that GPHS (residual) metallized parts were heat treated. In relation to this, Martin Marietta engineering has completed cold stack beam deflection and adherence/peel testing of heat treated insulators. Results of these strength tests show that heat treated insulators are acceptable. The strength of the insulators is comparable to GPHS data.

While the improved strength of the metallized Group 2D sample insulators resolved the earlier low modulus of rupture problem, an engineering visual review of the Group 2D parts generated a new concern. The Group 2D parts had a higher incidence of pits/pinholes (.5 to 1.0 mil dia.) in the coating than previous samples and GPHS residual parts. A meeting was held with WESGO on 11 May 1993 to address the pinhole concern and to also lay out a schedule for the delivery of the replacement insulator lot. As a consequence of this vendor visit, two actions were taken to resolve the pinhole problem: (1) WESGO shall perform additional trial coating runs to minimize or eliminate pinholes; and (2) Martin Marietta will develop visual standards which define the acceptance/rejection of metallization defects including pinholes.

Following this vendor meeting, Martin Marietta Engineering conducted additional evaluations of Group 2D parts to determine if pinholes were detrimental. The end result of these evaluations, which included SEM analysis for braze penetration, was that pinholes were not a cause for rejection. Despite this conclusion, however, it is still beneficial to minimize pinholes to simplify the visual inspection process. At the end of June, WESGO submitted several sets of metallized insulators that were coated using different mesh sizes. After review by Martin Marietta engineering and QA, one set was deemed acceptable for thickness and surface condition. Based on this, the desired mesh size was selected and sourcing authorized WESGO to produce the prime (flight) lot acceptance samples.

As per WESGO's promise date, body lot and metallized acceptance samples for the replacement lot were received from WESGO in mid-July. At the end of July, the engineering evaluation of the metallized samples was completed. This included modulus of rupture strength (58.7 ksi avg), metallization thickness (0.5 mil avg), and visual examination. Pieces from this metallized sample lot were included into the visual standards. These additional samples represent a balance between accepting the small pit/pinhole (0.5 mil to 1.0 mil diameter) surface feature in the metallized coating, while requiring WESGO's coating process to perform near optimum. Further support for this addition to the visual standards is provided in the fact that many GPHS insulators had a similar surface appearance.

In the first week of August, the QA evaluation of body lot grain size and porosity were satisfactorily completed. WESGO was then authorized to begin fabrication of the 1000 metallized insulators for the replacement lot. The first shipment of 1000 pieces was received in late September and is presently undergoing QA acceptance tests. After the first shipment of 1000 pieces is evaluated and accepted, WESGO will be permitted to fabricate the balance of the order (2800 pieces). This two part delivery strategy is being exercised to protect the limited amount of body lot material available.

Hot Shoe Spacers

In April, at the start of this reporting period, a dual path approach was being worked with AlSiMag to provide new alumina hot shoe spacers for E-6: (1) reworking the laser machined hot shoe spacers, and (2) fabricating new die formed spacers per Martin Marietta direction. As activities progressed, it became evident that AlSiMag could deliver die formed spacers to satisfy the E-6 production demands. The separate effort to rework the laser machined spacers was halted. (Details on the progress made on this effort are provided in the February 1993 through April 1993 Monthly Technical Reports). The first portion (~900 pieces) of the new die formed hot shoe spacer lot was completed by AlSiMag and delivered the first week of May (as promised) one month ahead of the initial schedule. A sample group of these parts were processed through silicon nitride coating with no incidents of cracking. Quality acceptance testing of this new die formed hot shoe spacer lot was completed first week of June. In addition to the QA acceptance tests, engineering completed an evaluation of the spacers which included grain size, SEM edge examination, modulus of rupture strength, coating and uncouple braze cycling. Both QA tests and Engineering evaluations concluded that the new spacer lot is acceptable. Silicon nitride coating of these spacers for E-6 was initiated with no cracking or contamination problems.

Based on these successful results, AlSiMag was authorized to complete the production of hot shoe spacers. The balance of the order was received at the end of July. This second delivery consisted of two separate vendor firing lots. At the end of September, one firing lot of spacers had been accepted with QA testing nearing completion on the second firing lot.

Foil/Cloth Production

The inner moly frame assemblies for E-6, E-7, and E-8 were completed during this reporting period.

The rework of the E-6 shell and fin assembly (from the GPHS program) to apply boron nitride coating to the inboard C-seal surface was completed. The E-6 shell and fin assembly is now ready for future converter assembly operations

Proof pressure and pressure drop testing of the E-7 fin/tube assemblies was completed and accepted. Shipment of the E-7 shell and fin/tube assemblies to the vendor for EB welding was made. The EB welding and radiographic inspection of this shell fin assembly was completed. Following this, the assembly was subjected to the ACS flow pressure drop test. The measured pressure drop of 16.0 psid exceeded the requirement of 12 psid. EMQ personnel are currently checking out the test set-up to determine if the measurements are correct.

E-6 Foil Insulation Assembly: The manufacturing walk-through for E-6 thermopile lay-up was completed in July. Operators have been successfully trained for lay-up and welding operations. As part of the training process, a mock-up lay-up assembly was built under EMQ supervision. The inner, middle, and outer ring assemblies (spot welding of clips to rings) for E-6 were completed during this period. The retaining bands for E-6, E-7, and E-8 were also fabricated. These parts are required for thermopile foil insulation assembly lay-up. The process planning for the 47J305231G1 thermopile foil insulation assembly was completed and approved. A process readiness review with DOE for the lay-up of the E-6 thermopile assembly was held on 30 July 1993. DOE concurrence to proceed with the lay-up was obtained.

Following the approval of process readiness, lay-up of the thermopile foil insulation assembly was initiated in early August. Assembly of levels 1 through 3 was completed. Both end retaining bands were spot welded to the -900 ring and clip assemblies. Several early welds produced burn-throughs and holes near the panel edges. The welding techniques were subsequently modified to prevent reoccurrences by: 1) inserting a molybdenum shim beneath the seams to prevent Astroquartz fibers from getting caught in the welding zone; 2) moving weld locations 1/8" from an edge; and 3) changing the electrode finishing procedure from manual sanding to polishing in a drill press to produce a rounded electrode and consequently reduce sticking. At the end of August, the retaining bands at level 3 were attached (welded) into place. During the band attachment process, several foil panels became distorted as a result of over tensioning the bands. By mid-September, replacement foil panels were fabricated, inspected, and installed. Retaining bands were then attached. In place of a new retaining band, a splice repair of one intermediate band was performed. A modified assembly technique was used to prevent the overtightening previously experienced.

Work was then initiated on the lay-up of level 4. Progress was halted, however, due to improper fit (~17 mils) over the alignment pins on the first level 4 foil/cloth layer. EMQ personnel began an investigation to resolve this problem. Drawing dimensions for individual panels, as well as the foil assembly at level 3, have been reviewed by design engineering. In addition, several level 4 layer 1 panels, the foil assembly itself, and the inspection tool used during level 3 operations have been reinspected. Two sources have been identified for the 17 mil misfit. The increase in distance between the fold line and hole center line from the last panel in level 3 and the first panel in level 4 was not enough to accommodate the simultaneous increase in cloth insulation thickness from 4 mils (M9A2) to 8 mils (M9A3) that occurs between levels 3 and 4. In addition, panels from level 4 were found to be at the limit or to exceed drawing tolerance for dimension C. Test panels of level 4 - layer 1 cloth will be produced using the thinner (M9A2) material and used to check the fit of subsequent foil panels. Final resolution to this level 4 panel misfit situation, which will likely require MRB approval to use M9A2 in place of M9A3 in one or two cloth layers, is expected in early October.

Thermopile Assembly: A draft of the process readiness plan and thermopile assembly training requirements was reviewed by EMQ team members. The concept presently under consideration is to divide thermopile assembly process readiness into two steps, 1) uncouple insertion and base wrapping, and 2) connector forming, riveting, and wrapping. For training of insertion operations, agreement was reached to include the use of converter assembly tooling in 18 couple module (18-11) assembly at the end of September. Tooling for transfer of the E-6 foil assembly to thermopile assembly operations has been completed. Accumulation of tooling for thermopile assembly operations (uncouple insertion, forming, riveting, etc.) will begin in October 1993.

Q-1

The Q-1 converter was received from EG&G Mound on 10 June 1993 for replacement of uncouple C-seals which were found to be leaking in excess of allowable requirements. The converter was maintained in storage at Martin Marietta until a gas purging system needed to provide positive gas flow during C-seal replacement was available. A schematic of the gas purging system is shown in Figure 5-1.

Figure 5-1. Schematic of the Gas Purging System for Q-1

Unicouple C-seal replacement operations were initiated on 21 July 1993 and were completed on 10 August 1993. Approximately 475 unicouple C-seals were replaced. The quick disconnect fitting located downstream of the GMV was also found to be leaking and it was replaced. Gas purging during seal replacement operations, frequent gas sampling and frequent gas exchanges were successfully used to minimize, monitor, and control the oxygen intake into the converter during seal replacement operations. Gas analysis indicated 126 PPM O_2 and 41 PPM H_2O in the converter after seal replacement operations were completed. Leak testing after seal replacement indicated the Q-1 converter met specification leak rate requirements. The measured leak rate at ambient temperature was 0.07 psi loss in six hours versus a requirement of <0.20 psi loss in six hours.

The Q-1 converter was installed into the shipping container using new barrel nuts and new mounting bolts. The Q-1 converter and engineering readout console were shipped to Mound Laboratory on 24 August 1993, one week ahead of schedule. The hardware safely arrived at Mound on 25 August 1993.

Task 6

Ground Support Equipment

TASK 6 GROUND SUPPORT EQUIPMENT (GSE)

There was no significant activity during this period.

Task 7

RTG Shipping and Launch Support

TASK 7 RTG SHIPPING AND LAUNCH SUPPORT

Martin Marietta supported launch site planning activities by providing RTG data and commenting on various RTG handling approaches for moving and installing the RTGs on the spacecraft. Presently the primary topic under discussion related to the RTGs is handling of the generator at the launch pad and the methods to be used to transport the RTGs from ground level up to launch facility level 14 where they will be attached to the spacecraft. Various means are under discussion and at the end of this report period a single preferred concept had not been identified.

Development of the new shipping container was also supported, particularly the activity related to preparations for the up coming thermal qualification test to be conducted at Mound. The test procedure prepared by Mound has been reviewed and comments returned for Mound consideration. As a contingency step in the event that the RTD indications become unreliable during the test, Martin Marietta has proposed that the external thermocouples mounted on the shell be used instead to monitor thermal performance.

Task 8

Designs, Review, and Mission Applications

TASK 8 DESIGNS, REVIEWS, AND MISSION APPLICATIONS

8.1 Galileo/Ulysses Flight Performance Analysis

Since their launch into space, the F-1, F-4 (Galileo) and F-3 (Ulysses) RTGs continue to operate as predicted. Figures 8-1 and 8-2 indicate the data and its agreement with the prediction models. The data update is through June 1993 for Galileo and April 1993 for Ulysses. Galileo RTGs now have nearly 35,000 hours (four years) of space operation each and the Ulysses RTG has in excess of 20,000 hours (over two years). Both are expected to meet or exceed their end-of-mission power delivery specification. It should be noted that Ulysses data is estimated since no direct readout of current is made at the RTG.

Figure 8-1. Galileo RTG Power (F-1 and F-4)

Figure 8-2. Ulysses RTG Power (F-3)

8.2 Individual and Module Multicouple Testing

Life testing of two Build #3 and two Build #4 multicouples continued during this reporting period at the Martin Marietta test facility. The multicouples were operated at normal RTG operating temperatures (1065°C heat collector/280°C cold cushion) with a -6 volt bias applied between the multicouple negative terminal and ground. One of the multicouples (Build #4 - M042-10) was exhibiting increased power degradation, primarily due to loss of open circuit voltage. This is indicative of a loss of Δt through the multicouple which may be caused by degradation of the hot or cold side bonds. A destructive examination plan to evaluate this multicouple was submitted to DOE on 30 August 1993 and subsequently approved for implementation. Life testing was suspended and multicouple M042-10 was removed for post test diagnostic examination. This multicouple had accumulated approximately 18,000 hours of operation when it was removed from the test chamber. Visual and optical examination produced no findings which would explain its performance. Non-destructive examination (radiography) is scheduled to be performed in October and

destructive examination is scheduled to be completed by December 1993. The performance of the two Build #3 multicouples and two Build #4 multicouples prior to test shutdown is shown in Figure 8-3. These multicouples have accumulated 18,027 hours to 18,428 hours of operation.

Figure 8-3. Multicouple Build #3 and Build #4 Performance Trends

Build #4 multicouple M042-10 was replaced in the test facility (vacuum station #3) by Build #5 multicouple M042-G4. This multicouple was removed from the Build #5 Fairchild test module which had operated for approximately 2000 hours prior to test shutdown. Testing was halted at Fairchild because of unwanted reactions occurring in the electric heat source which resulted in minor contamination of the multicouples (aluminum carbide deposits on heat collector, alumina spacer, and wrap). The thermopile wrap and alumina spacer were replaced on multicouple M042-G4 and it was mounted in the Martin Marietta test facility. Life testing of Build #5 multicouple M042-G4 and the remaining Building #3 and Build #4 multicouples will be resumed in October 1993.

Life testing of two Build #5 multicouples continued in vacuum station #5 during this reporting period. The two multicouples being tested are M042-5 (without GaP) and M043-19 (with GaP). Life testing was suspended several times during the reporting period. The first occurred when RGA data indicated an increase in CO partial pressure in the test chamber due to unwanted heater reactions. Testing was halted on 27 April 1993 and both test stations were examined. Evidence of reaction products were found only in the test station of multicouple M043-19. Testing was resumed with M043-19 being operated at a heat collector temperature that is 50°C below normal RTG temperatures to minimize heater reactions. Testing was also suspended in August to permit regeneration of the vacuum cryopump and an automatic shutdown occurred on 17 September 1993 due to failure of the heat collector thermocouple in multicouple M043-19. Testing was resumed on 20 September 1993 and is continuing.

Multicouple M043-19 has been operating for a total of 8771 hours. It is currently operating at reduced hot side temperatures but previously operated at normal and accelerated hot side temperatures as shown in Table 8-1. Multicouple M042-5 is being operated at normal RTG temperatures. It has accumulated a total of 8319 hours of operation. The performance trends for both Build #5 multicouples are shown in Figure 8-4.

Table 8-1. Multicouple M043-19 Test History

Hot Junction Operating Temp (°C) .	Time at Operating Temp (hours.)
1000	1838
1050	3753
950	3180
Total	8771

Figure 8-4. Performance Trends for Two Build #5 Multicouples

8.3 Structural Characterization of Candidate Improved N and P Type SiGe Thermoelectric Materials

The purpose of this task was to determine matrix grain size and second phase structures and morphologies of improved SiGe materials using scanning and transmission electron microscopy. The work on this task was performed at the Department of Materials Science and Engineering, University of Virginia. The work has been completed and the results were documented in a final report which was distributed to DOE in May 1993.

Task 9

**Project Management,
Quality Assurance,
Reliability,
Contract Changes,
CAGO Acquisition,
and
CAGO Maintenance/Repair**

TASK 9 PROJECT MANAGEMENT, QUALITY ASSURANCE, AND RELIABILITY

9.1 Project Management

Contract required weekly reports, monthly reports, quarterly reports and data submissions were delivered on schedule. Cassini Monthly Status Reviews were held in April and August. An overall Cassini Monthly Program Review was supported in July. A Quarterly Meeting was supported in May.

Contract Modifications M006 and M013 were definitized this period. Change proposals were submitted for Contract Modifications M022 (Q-1 ETG Refurbishment) and M023 (Dynamic Qualification Testing of F-5). A change proposal is in process for Contract Modification M026 (Qualification of Redesigned RTD Cable Assembly).

The annual rollout of the Martin Marietta PMS planning package for FY'94 was completed this period.

An updated WBS Dictionary (Document No. RR16) was submitted 26 August 1993.

A successful DOE review of the Cassini Property Management System was completed this period. Only minor findings resulted.

Attached are the updated Cassini RTG Program calendars for 2Q93 and 3Q93 showing program meetings and important program-related events.

No significant Environmental, Health, and Safety incidents occurred this period.

9.2 Quality Assurance

Process Readiness and Production Readiness Reviews

Production readiness reviews were approved for the following uncouple manufacturing processes:

- Cold Stack Assembly
- Silicon Nitride Coating of Hot Shoe Spacers
- Nickel Plating of: Tungsten Compensators
Copper Pedestals
3847P2 (new) Heat Shunts
- Couple Preassembly
- Uncouple Assembly
- Stuffing/Wrapping of the Uncouple Assembly

All uncouple processes are now approved for flight production.

Process readiness was approved for thermopile foil insulation assembly. Work is proceeding toward process readiness for the remaining converter fabrication processes.

Quality Plans and Documents

DOE Order 5700.6C was reviewed and a report was drafted addressing the implementation of the order on the Cassini program. It is anticipated that only minor changes will be necessary to the Cassini Quality Plan. No other plans were prepared during this period.

Quality Control of Fabrication

18 Couple Module: During this period, inspection support was provided for the fabrication of the 18-10 module. The test facility was checked out and the 18-10 module placed on test. It is currently operating at the specified temperature of 1135°C with no problems noted to date.

Converter Hardware: The E-7 fin and tube assembly was successfully welded at EBTEC. Three flex hoses were leak tested. Two passed the initial test, but the third had a small leak and required rework. The E-7 assembly is presently on non-conformance report due to failure to meet ACS pressure drop requirement (Ref. Task 5 discussion). The PRD bellows assemblies failed testing due to trapped air. They were successfully reworked by the vendor. Inspection support was provided to the converter fabrication area. Major tasks included welder certification, inspection of foil/cloth lay-up process, inspection of tooling, and accumulation of materials.

Testing of the PRD devices was initiated in September. Some problems were noted with the facility and are being addressed.

Q-1 Converter: QC support was provided to the successful rework of the Q-1 converter. It was reworked and returned to Mound ahead of schedule.

Unicouple Production: Production of unicouple parts and assemblies continued. Yields in most processes were good during this period. Yields in thermoelectric machining were significantly improved due to resolution of some process problem and productivity improvements suggested by the High Commitment Work Team. Process problems were noted in the second bond, machined radiator attachment and brazing operations. Bond voiding problems in the second bond process were resolved and work on a static loaded bonding fixture has completed trials and is nearing implementation. This fixture is expected to provide further yield approvals. The machining of radiator attachments has been moved in-house to resolve continuing vendor related dimensional and burr defects. Demonstration runs have been completed and in-house machining has begun.

In the brazing process, isolated instances of incomplete melting of the braze shims has occurred. The brazing furnaces were profiled and determined to be operating near the low end of the allowed temperature range. Adjustments have been made to the furnace temperature controller settings to resolve the problem.

Material Review Board: One Class I NR was written during this period. It addressed pressure drop in the cooling tubes of the E-7 assembly. Engineering evaluations are being made and no disposition has been made on this NR.

Quality Assurance Audits

Quality systems audits were performed to evaluate Inspection Practices and Records Retention. No significant findings were noted and both audits were closed.

Process audits were performed to evaluate the following processes:

1. Parts Preparation (Thermoelectric Parts Machining)
2. Cold Stack
3. Second Bond

No significant findings were noted in these audits. Minor findings were addressed and all three audits have been closed.

Quality Assurance Status Meeting

QA Status meetings were held in April, June, August and September. The Quality Assurance System and related Cassini program activities were discussed. Several action items were assigned and, as of this date, all have been addressed and closed. Topics discussed included status of converter fabrication, 18 couple module fabrication/test, uncouple production, audits, QA organization, F-5 RTD cable, and the PRD.

Task H

CAGO Acquisition (Capital Funds)

TASK H CONTRACTOR ACQUIRED GOVERNMENT OWNED PROPERTY (CAGO) ACQUISITION

GFY'93 CAGO requirements were forwarded to DOE and authorization to acquire the items was received. Procurement has been initiated.

H.1 CAGO - Unicouple Equipment

Production of first bonds for flight hardware in three of the new Brew bonding furnaces was initiated during this period (14 September 1993).

Silicon nitride coating production in the new CVD silicon nitride coating furnace was initiated on 10 August 1993. Since that time all production silicon nitride coating has been in the new furnace. The second new CVD furnace will be installed in place of old NAV-TEC furnace when sufficient confidence in the reliability of the installed CVD furnace is achieved.

H.2 CAGO - ETG Equipment

A subcontractor for the installation and checkout of the gas management system for the Loading and Assembly Stations (LAS) and the refurbishment of the LAS has been selected. Placement of the subcontract is in progress.

H.3 CAGO - MIS

Acquisition of software upgrades and the PMS workstation, as approved by DOE, is in progress.

Cassini RTG Program Calendar

As of 30 June 1993

2nd Qtr 1993

	M	T	W	T	F	S	S	FW
A P R I L	29	30 Production Readiness Review Couple Preassembly & Nickel Plating of Tungsten Compensators	31	1 Clad Vent Set Review - ORNL - Reinstrom	2	3	4	14
	5	6	7 Cassini Titan IV RTG Working Group #8 - NASA Lewis - Hemler	8 Process/Production Readiness Review Nickel Plating of Copper Pedestals	9	10	11	15
	12	13 Risk Prog Review w/INSRP Vendor Visit (AIS/Mag) Hot Shoe Spacers - Laurens, SC - Braun/Serent	14 Martin Marietta San Jose Hemler/Cockfield	15 CVS Working Group - Pittsburgh, PA - Reinstrom	16	17	18	16
	19	20 F-5 RTD Harness Replacement - Mound - Reinstrom, et al	21 Semi-Annual Reports Due to DOE DOE Property Management Audit DOE/Bonnie Griffin-Smith	22 Cassini Overall Program Monthly Review - Germantown - Hemler, et al	23 Cassini Monthly Review DOE/Martin Marietta - Germantown - Hemler, et al	24	25	17
	26	27	28 QA Status Meeting - Valley Forge - Saydah, et al	29	30	1	2	18
M A Y	3 Production Readiness: Cold Stack Assembly Coating Hot Shoe Spacers Process/Production Readiness: Ni Plating of Heat Shields Qualification of: Brew Furnace CVD Coating Furnace	4	5	6 Mod M013 Fact Finding Meeting - DOE San Hemler/Waks/Hanson	7	8	9	19
	10	11 WESGO - Belmont, CA - Braun/Boylan/Serent	12	13 Data Book Safety Meeting - NASA-Lewis - Hemler/Bradshaw	14	15	16	20
	17	18	19 AIAA Annual Meeting - Arlington, VA	20	21	22	23	21
	24 Production Readiness Review for Unicoyle Assembly & Stuffed and Wrapped Unicoyles	25	26	27 Quarterly Program Review - Germantown - Hemler/Reinstrom/Hanson/Braun	28	29	30	22
				AIAA Banquet				
J U N E	31 Holiday	1	2	3	4	5	6	23
	7	8 Dyanamic Test Planning Meeting - Mound - Reinstrom/Kauuffman	9 Accident Scenario TIM - Martin Marietta - Denver Hemler/Bradshaw	10	11	12	13	24
	14	15	16 QA Status Meeting - Valley Forge - Saydah, et al	17	18	19	20	25
	21	22	23	24 Monthly Reports Due to DOE	25	26	27	26

Cassini Calendar

As of 29 September 1993

3rd Qtr 1993

	M	T	W	T	F	S	S	FW
JULY	28	29	30 Cassini Program Monthly Review - Valley Forge - Hemler, et al	1	2	3	4	27
	5 HOLIDAY	6	7 Safety Meeting - Germantown - Hemler, Bradshaw	8	9	10	11	28
	12	13	14	15	16	17	18	29
	19	20	21 Cassini Overall Program Monthly Review - Germantown - Hemler, Reinstrom, Hanson	22	23 Monthly Reports Sent to DOE	24	25	30
	26	27	28 Ground Operations Working Group - KSC - Reinstrom	29	30 Thermopile Fabrication (Foil Lay-Up) Process Readiness Meeting	31	1	31
AUGUST	2	3	4	5 EIS Input Meeting - Germantown - Hemler, Bradshaw	6	7	8	32
	9	10 QA Status Meeting - Valley Forge - Saydah, et al	11 Cassini RTG Program Monthly Review - Valley Forge - Hemler, et al	12 Vendor Visits: Sheffield & Engelhard Braun, Sereni	13	14	15	33
	16	17	18 EIS Meeting at SAIC - McLean, VA - Hemler, Bradshaw	19	20	21	22	34
	23	24 Clad Vent Set HW Disposition - ORNL - Reinstrom Monthly Reports Due to DOE	25	26	27	28	29	35
	30	31	1 RTG Panel Sequences Review Martin Marietta - Denver, Colorado - Hemler, Bradshaw	2	3	4	5	36
SEPT	6 HOLIDAY	7	8 Cassini Quarterly Review - Los Alamos - Hemler, Reinstrom, Braun	9 Fuel Fabrication Preparation Review - Los Alamos - Reinstrom	10	11	12	37
	13	14 Risk Assessment Seminar Martin Marietta - Denver, Colorado - Bradshaw	15 In-house Machining Rad. Attach. Assy Prod. Readiness	16	17	18	19	38
	20	21	22 Internal RTD Design Review - Valley Forge - Risk Assessment Seminar General Dynamics - San Diego, CA - Braun, Rosko	23	24 Monthly Reports Due to DOE	25	26	39

**DATE
FILMED**

11 / 22 / 93

END