ADEQUACY OF SIMULATOR HARDWARE AND ANALYTICAL MODEL FOR CA SSINI RADIOISOTOPE THERMOELECTRIC GENERATOR*

by

Edward I. Lin
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

ABSTRACT

The Cassini spacecraft is being developed for a mission to investigate Saturn and its rings, satellites and magnetoshpere. The spacecraft will be powered by three Radioisotope Thermoelectric Generators (RTG, see Fig. 1). The utilization of the RTG waste heat as a major heat source for thermal control of the Propulsion Module Subsystem (PMS) is an innovation that has never been attempted before, neither for Galileo nor for Ulysses, Since the flight RTGs (with nuclear fuels) will not be involved in any thermal testing for safety considerations, adequate simulators must be used as a substitute. Recent thermal development test has demonstrated that the RTGs can provide more heat than necessary to warm the PMS, and that the RTG end dome temperature is critical in determining the amount of heat entering the PMS cavity (a large Ml.1 blanket drapes over the propellant tanks forming the cavity) . However, analysis indicated that there was a large discrepancy between the "flight RTG" thermal model predictions and the test results based on an existing RTG simulator, especially with regard to the end dome temperatures. This raises two important questions: (1) Are the existing RTG simulators adequate for verifying the PMS thermal design in the spacecraft solar-thermal-vacuum (STV) test? (2) 1s the existing RTG thermal (SINDA) model adequate as an analytical tool for test-data interpretation and decision making?

Serious consideration of these questions ~~were~~ was made even more compelling by the fact that there now exist rather tight propellant tank temperature rachet requirements following the pressure regulator lockup after launch. Work was done which indicated that modifications on the RTG simulator hardware and the analytical thermal model are both necessary:

(a) Flight data from Galileo and Ulysses (missions to explore Jupiter and the sun, respectively), as well as past ground-test data were reviewed; there has only been one validation case performed for the analytical model, and without due attention to the end dome. Uncertainty with regard to the predicted end dome temperature appears great and needs to be quantified.

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(b) The RTG simulator shell is more than four times thicker than the flight unit, and the simulator interior is hollow whereas the flight unit is filled with heat source modules. Therefore, the existing simulator appears to afford a rather poor representation of both the conduction and radiation paths between the shell and the end dome.

(c) Solution approaches identified include an independent validation of the analytical model with past test data, appropriate modifications to the simulator hardware, test verification of the modifications, and a sensitivity analysis of the PMS temperature rachet scenario considering a suitably-determined end dome temperature uncertainty band.

Validation of the Flight RTG Analytical Thermal Model

The analytical thermal model for the flight RTG, developed by a contractor, has been relied upon as the sole guide with its analytical predictions for judging the RTG thermal behavior. The model was correlated once in 1988 by the cent ractor with the only set of vacuum test data available from the Engineering Unit. However, as a close scrutiny reveals, the previously correlated model (due to focus on power performance) under-predicts the end dome temperature by 10°C, over-predicts the flange temperature by 9°C, and over-predicts the mid-shell temperature by 14"C, as compared with test data. The model was found deficient in two important areas, i.e., the underestimate of radiative coupling between the end dome and the heat source support assembly, and the absence of radiative coupling between the dome/shell flanges and space. Each deficiency, when corrected, led to a substantial temperature change, Other modifications, less significant in comparison, were also made. The final validated model brings the end dome and flange temperature predictions to within 2°C of the test data, and results in a doubling of the radiative heat transfer from the RTG heat source support assemblies to the end domes.

More significantly, when the RTG is coupled to the interface ring, the support box and the spacecraft central body, the combined model predicts an inboard end dome temperature of 194°C after the validation, as opposed to 169°C before. This 25°C increase in the end dome temperature has a considerable impact on the amount of RTG heat entering the PMS cavity. Since no flight data are available now for the end dome temperature, effort is being made to acquire in-vacuum measurement during the upcoming qualification tests for the fueled flight units F5 and F2. These measurements will help to narrow down the end dome temperature uncertainty.

Modification of the RTG Simulator Hardware

The existing simulator was constructed to serve as both a thermal and structural mockup, hence containing expedient compromises. With the validated thermal model providing analytical guidance, the RTG simulator analytical model is examined, modified as necessary, and exercised to help determine the hardware modifications that are required to make the simulator better represent the RTG flight unit during the STV test. The poor representation of the conduction and radiation paths between the shell and end dome mentioned above will be specifically improved upon during hardware modification. The simulators have been constructed with 16 strip heaters held down with stainless steel straps, and the contact conductances between the shell and the heaters, and between the heaters and the straps, are a major empirical unknown, Analytical prediction and test data correlation iterates are relied upon to arrive at appropriate conductance values, Pragmatic solutions may involve varied emissivity patterns on the interior of the end domes, or other hardware implements, with quantification of the uncertainty band for the end dome temperature for use in the PMS design sensitivity analysis, This is an on-going effort and the resulting modifications to the simulators will be verified by a thermal vacuum test.

Verification Test for the Modified RTG Simulator

The planned test is intended to: (a) Verify the adequacy of the modified RTG simulator for use in the STV test. (b) Obtain data on end dome temperature uncertainty that will permit a prudent analysis of the PMS thermal control design particularly with regard to meeting the propellant tank temperature rachet requirements following the pressure regulator lockup.

This paper will report on the analytical model validation; the end dome temperature data from thermal-vacuum qualification test of the flight RTG unit F5, and other pertinent RTG flight data; the simulator hardware modifications; and the thermal vacuum verification test results for the modified simulator.

Several figures are attached to illustrate the scope and progress of this work. Fig. 1 shows the Cassini spacecraft and the RTGs. Fig. 2 provides a schematic of key RTG elements, revealing the complexity of the RTGs. Fig, 3 illustrates how the RTG heat is radiated and conducted into the PMS cavity. Fig. 4 presents the RTG thermal model node map, Figs. 5-13 present results of the analytical model validation runs (will be condensed for the paper), And Fig, 14 summarizes the good agreement obtained between the validated model predictions and past test data. Figures pertaining to the upcoming tests will also be included in the paper.

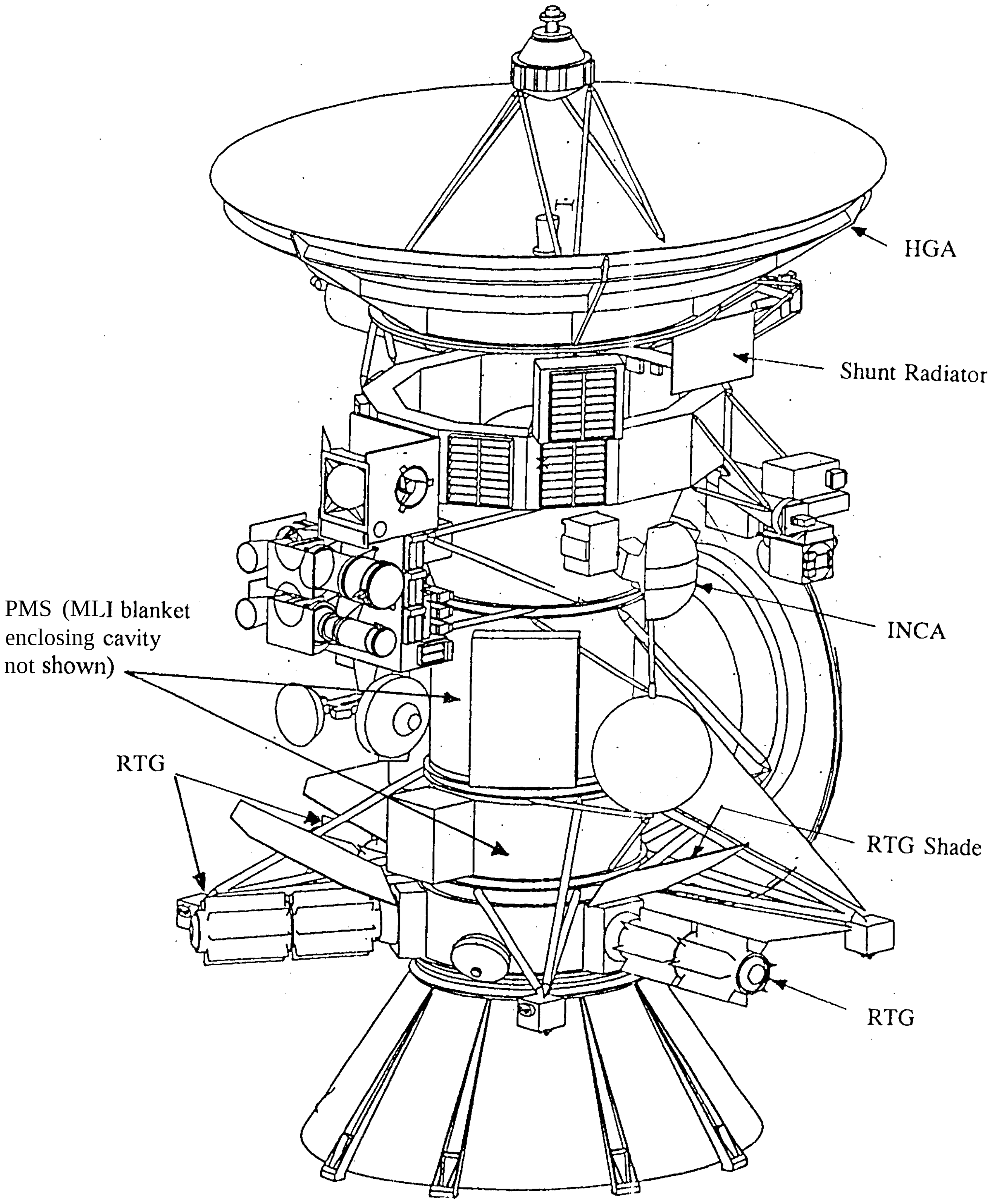
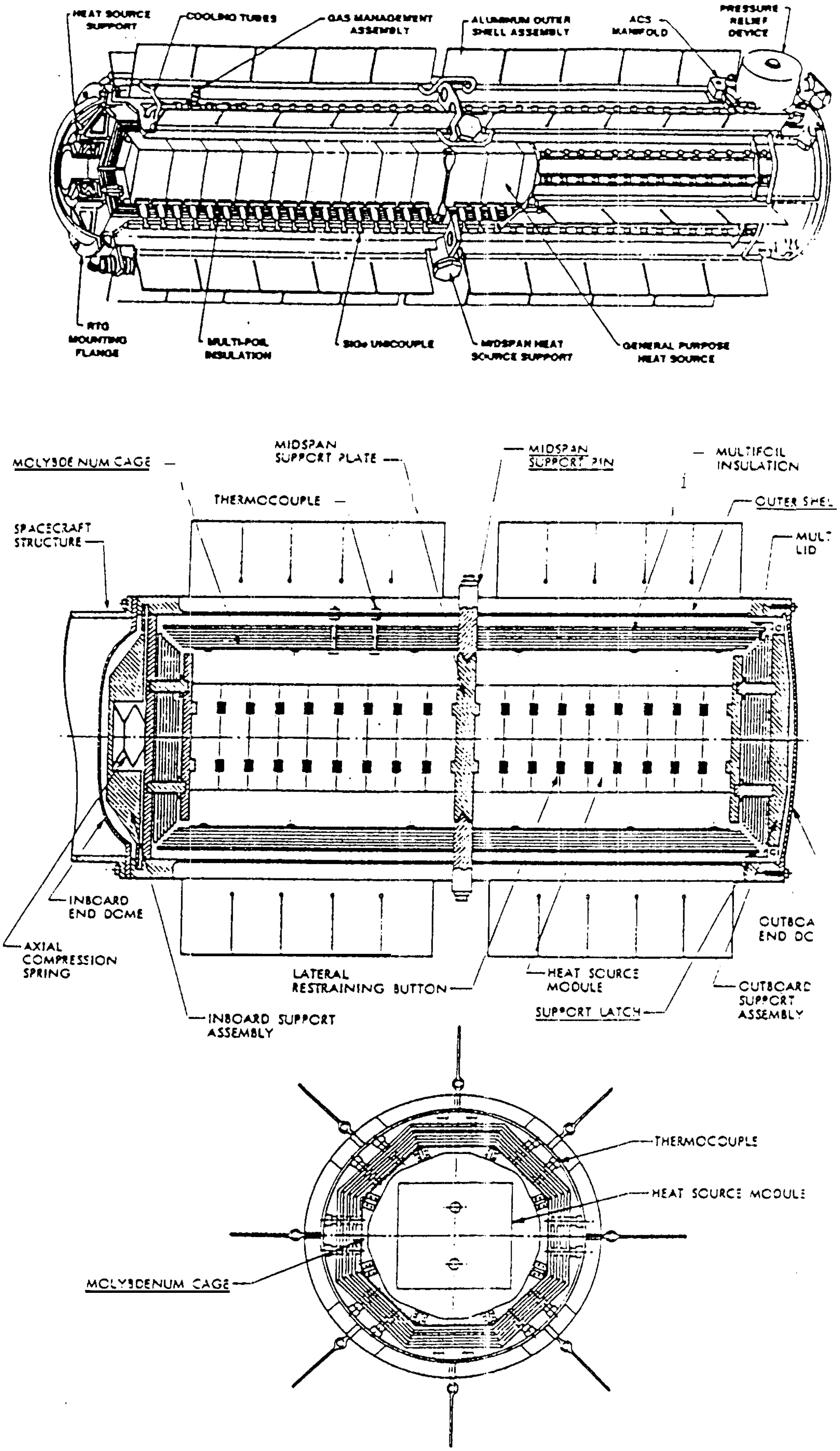


Fig. The Cassini Spacecraft and the RTGs



Fig, 2 Schematic of RTG Elements

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RTG Waste Heat Concept

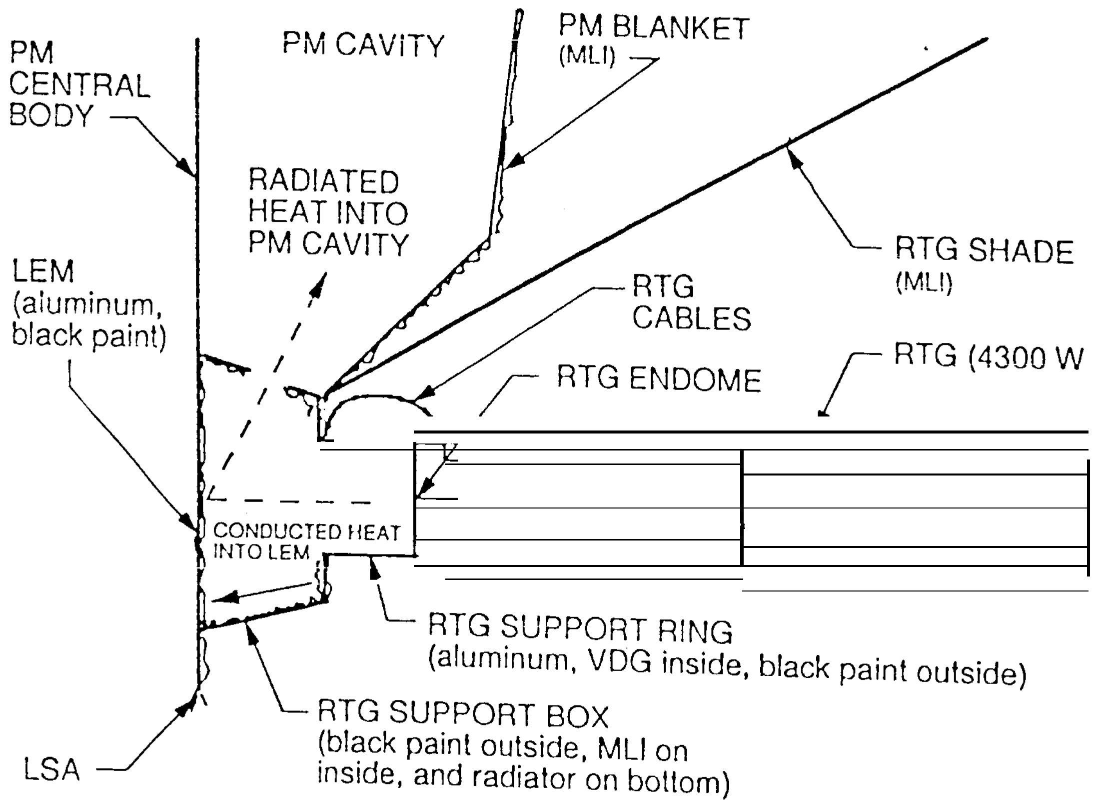

Fig. 3 Heat Radiated and Conducted From the RTG into the PMS Cavity

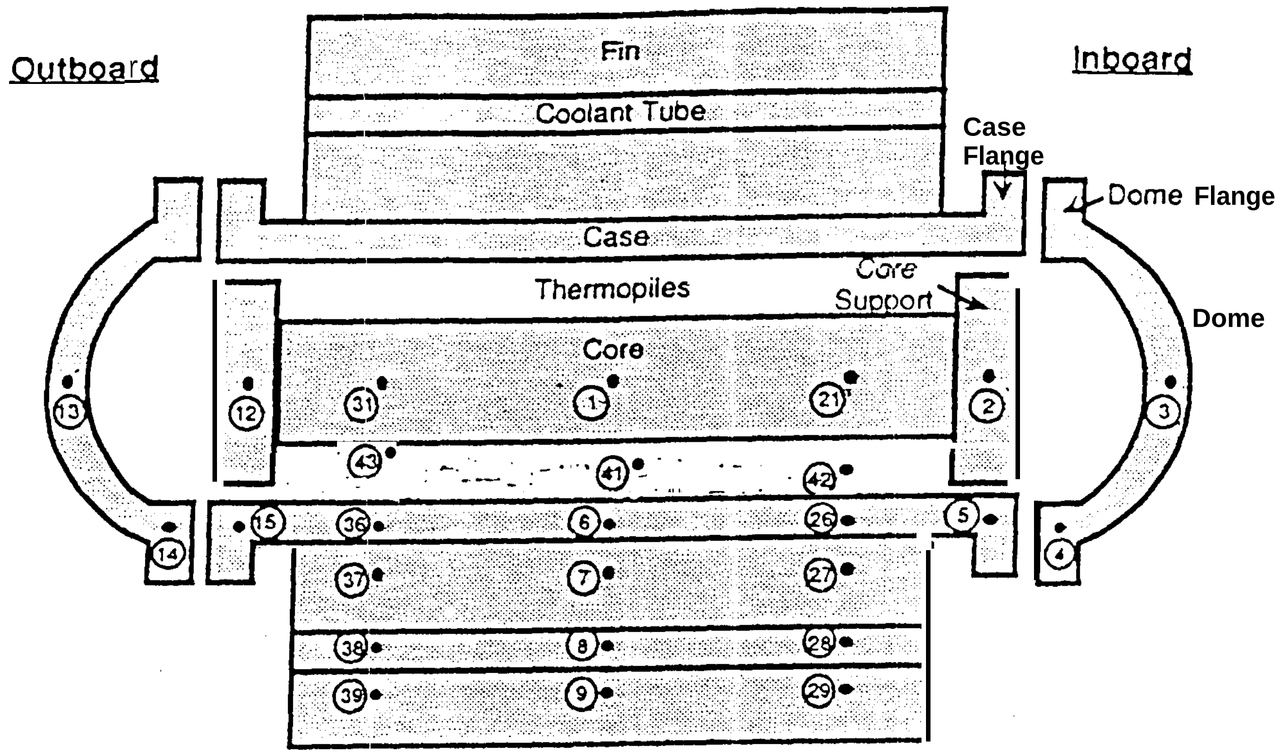

Figure 4 - RTG Thermal Model Node Map

NOTE: The temperatures presented in Figs. ~~8-16~~ 5–13 are in 'C and correspond **to nodes as defined in** the thermal model node map (R?.>] 4

OUTBOARD						I NBOARC
205.47	732.17	999.96	1076.68	1004.45	774.35	204.50
		616.86	673.95	619.03		
217.42	220.80	233.73	271.22	233.60	218.51	215.42
		218.61	251.33	218.48		
		210,91	241.39	210.79		
		180.05	201.66	179,97		

Fig. ~~8~~ 5 Results of Run # 1: Duplicating the "Baseline Predictions"

CUTBOARD						I NBOARD
190.21	743.59	%'5.36	1075.60	1000.00	766.73	189.45
		612.01	673.20	614.29		
197.57	201.75	228.66	270.81	228.58	199.73	195.85
		214.16	250.96	214.09		
		206.77	241.03	206.70		
		177.09	201.38	177.04		

Fig. ~~9~~ 6 Results of Run # 2: Adding Flange-to-Space Radiative Coupling

OUTBOARD						INBOARD
164.79	975.17	1046.87	1085.70	1056.67	1022.92	161.89
		638.81	679.03	643.69		
183.56	190.67	230.76	272.35	230.71	186.85	180.00
		216.02	252.31	215.97		
		208.50	242.29	208.46		
		178.36	202.28	178.33		

Fig. ~~10~~ 7 Results of Run #3: Deleting Lumped Conductance Between End Domes and Heat Source Support Assemblies

OUTBOARD						INBOARD
1[illegible].79	974.64	1046.46	1085.61	1056.31	1022.50	164.79
		638.35	678.96	643.26		
1[illegible].25	188.72	230.24	272.32	230.22	184.97	183.56
		215.56	252.28	215.54		
		208.08	242.26	208.06		
		178.05	202.25	178.04		

Fig. ~~11~~ 8 Results of Run #4: Increasing Contact Conductance Between the Shell Flange and Dome Flange

OUT BOARD						INBOARD
216.49	488.40	938.19	1064.52	938.99	492.42	216.81
		582.02	666.79	582.39		
212.01	212.24	225.85	269.06	225.79	211.67	211.49
		211.68	249.42	211.63		
		204.45	239.60	204.40		
		175.40	200.35	17S.36		

Fig. ~~12~~ 9 Results of Run #5: Adding Radiative Coupling Between End Domes and Heat Source Support Assemblies

CUTBOARD						1 NBOARD
211.68	471.24	950.35	1066.80	951.07	475.38	212.02
		588.36	668.11	588.68		
209.31	209.65	226.36	269.42	226.30	209.14	208.85
		212.14	249.74	212.08		
		204.87	239.90	204.82		
		175.71	200.56	175.67		

Fig. ~~13~~ 10 Results of Run #6: Reducing Conductance Between Nodes 2 and21, and Nodes 12 and 31

OUTBOARD						I NBOARO
210.80	470.22	947.05	1058.60	947.75	474.36	211.08
		585.99	659.44	586.30		
208.33	208.65	224.94	260.27	224.86	208.07	207.79
		210.79	241.76	210.71		
		203.57	232.47	203.50		
		174.60	195.29	174.55		

Fig. ~~14~~ 11 Results of Run #7: Including Radiative Coupling Between the" Mid-ring and Space

OUTBOARD						INBOARD
209,74	469.44	944.90	1055.32	945.61	473.60	210.04
		583.92	656.05	584.24		
207.04	207.35	222.94	256.78	222.87	206.80	206.54
		210.06	240.20	209.99		
		203.47	231.85	203.41		
		177.25	198.78	177.21		

Fig. ~~15~~ 12 Results of Run #8: Adding Shell-to-Fin Radiative Coupling

OUTBOARD						INBOARD
212.01	442.34	939.60	1054.36	940.17	445.71	212.31
		581.15	655.51	581.41		
208.16	208.41	222.71	256.66	222.64	207.94	207.73
		209.85	240.10	209.79		
		203.27	231.7s	203.22		
		177.10	198.70	177.06		

Fig. ~~16~~ 13 Results of Run #9: Fine-tuning Radiative Coupling Between End Domes and Heat Source Support Assemblies

-- “Validated Model Predictions”

Note: AU temperatures are in ‘C, Predictions by the validated 26-node model are bracketed <...>.
All other temperatures are test data from the Engineering Unit.

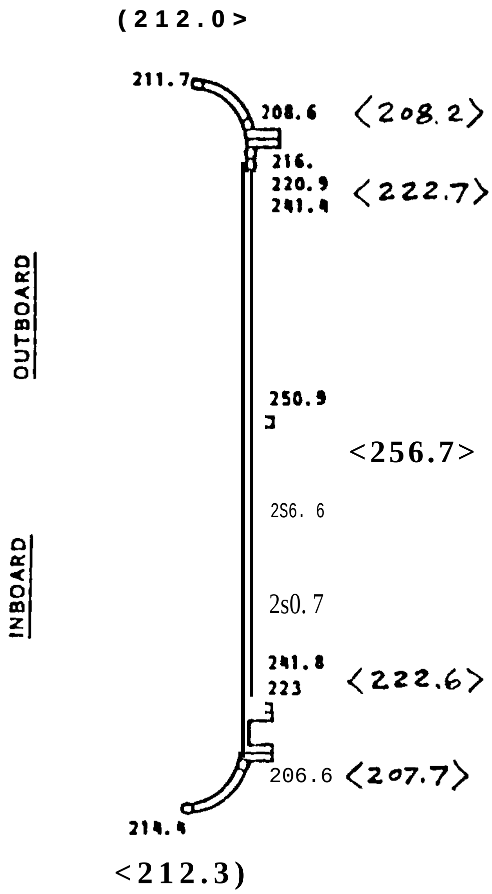

Fig. ~~17~~ 14 RTG Engineering Unit Test Data vs. Predictions by the Validated 26-Node Model