ANALYTICAL THERMAL MODEL VALIDATION FOR CASSINI RADIOISOTOPE THERMOLELECTRIC GENERATOR

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ABSTRACT

The Saturn-bound Cassini spacecraft is designed to rely, without precedent, on the waste heat from its three radioisotope thermoelectric generators (RTGs) to warm the propulsion module subsystem, and the RTG end dome temperature is a key determining factor of the amount of waste heat delivered. A previously validated SINDA thermal model of the RTG was the sole guide to understanding its complex thermal behavior, but displayed large discrepancies against some initial thermal development test data. A careful revalidation effort led to significant modifications and adjustments of the model, which result in a doubling of the radiative heat transfer from the heat source support assemblies to the end domes and bring up the end dome and flange temperature predictions to within 2°C of the pertinent test data. The increased inboard end dome temperature has a considerable impact on thermal control of the spacecraft central body. The validation Process offers an example of physically-driven analytical model calibration with test data from not onty an electrical simulator but also a nuclear-tiled flight unit, and has established the end dome temperatures of a flight RTG where no in-flight or ground-tat data existed before.

INTRODUCTION

The Cassini spacecraft has been developed for a mission to investigate Saturn and its rings, satellites and magnetosphere. The spacecraft will be launched in October 1997 and powered by three Radioisotope Thermoelectric Generators (RTG, see Figure 1). The utilization of the RTG waste heat as a major heat source for thermal control of the Propulsion Module Subsystem (PMS) is a new concept that has never been applied before, neither for Galileo nor for Ulysses (missions to explore Jupiter and the sun, respectively). Thermal development test was conducted using an electrically heated RTG simulator to demonstrate that the RTGs can provide a significant part of the heat necessary to warm the PMS (Mircles and Stultz, 1994), and it was found that the RTG end dome temperature is critical in determining the amount of heat entering the PMS cavity (a large MLI blanket drapes over the propellant tanks forming the cavity, not shown in Figure 1 for clarity). However, analysis indicated that there was a large discrepancy between the flight RTG therms! analytical model predictions and the test results based on the RTG simulator, especially with regard to the end dome temperatures (the initial model/test deviation on the end dome temperature was as large as 62°C). This raised questions concerning the adequacy of the simulators as well as the analytical model.

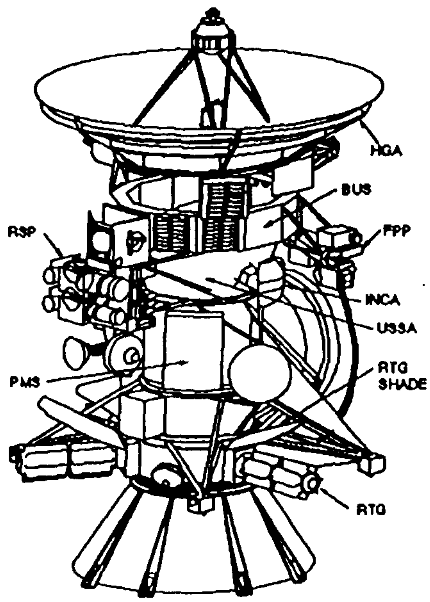


FIG. 1 THE CASSINI SPACECRAFT

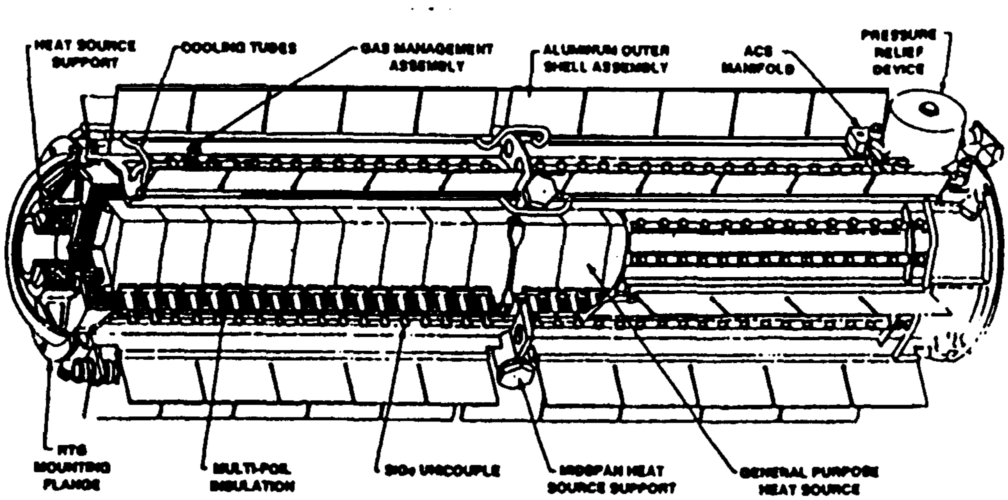


FIG. 2 THE RTG

This paper addresses the adequacy of the analytical model. The model was developed a number of years ago by General Electric (GE) under a contract with JPL. It deals with the complex design and thermal behavior of the RTG that arc to some degree reflected in Figure 2. The model with its analytical predictions had been relied upon as the sole guide for interpreting the RTG thermal behavior. However, an investigation of the model revealed that: (1) the end dome temperature had not been GE's focus of attention either during the model development or validation phase, because their primary interest had always been in the power generation performance; (2) there had been only one validation case performed for the model over the years, and it was based on the only set of vacuum test data available from the Engineering Unit (which was an electric simulator, not a nuclear-fueled flight unit). Consequently, a large uncertainty surrounded the predicted end dome temperatures, and the situation called for an independent validation of the model with special attention paid to heat transfer in the end dome areas.

First, the model was revalidated using the same GE data for the Engineering Unit. This led to significant model modifications and improved agreement between model predictions and test data. However, a review of flight data from Galileo and Ulysses as well as past ground-test data indicated that no end dome temperature data existed for any flight RTG, therefore it was proposed that the inboard end dome tcmpcraturc bc measured during the thermal vacuum acceptance test of a flight unit. With the cooperation of DOE's Mound Laboratory, the measurements were made and the results firmly established the validity of the model. This paper reports on the process and results of this validation effort and presents the end dome temperatures for a free-standing fueled flight RTG.

THE ANALYTICAL MODEL, ENGINEERING UNIT TEST DATA, AND PRIOR CORRELATION

The analytical model is a 26-node reduced version of GE's full-blown, several-hundred-node detailed SINDA model, and has a node map as shown in Figure 3. The reduced model was needed as a component of the Cassini analytical model, used in various subsystem level analyses, and had been calibrated with the detailed model. It contains sufficient details but also many simplifications; e.g., the mid-shell node 6 (of length 28 in.) is significantly larger than the shell-end nodes 36 and 26 (of length 5 in. each). The model was correlated by GE in 1988 with the only set of vacuum test data that they obtained from the Engineering Unit which electrically simulated a flight RTG (Loffreda, 1982). However, as a close scrutiny revealed, 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 tcmpcmturc by 14°C, as compared with the test data (note that the predictions arc given in Figure 4 and the test data in Figure 13). The model was found deficient in two important areas; i.e., the underestimate of radiative coupling between the end dome

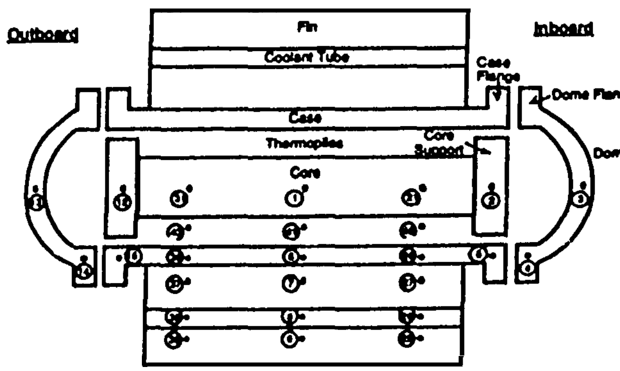


FIG. 3 THE MODEL NODE MAP

and the heat source support assembly, and the absence of radiative coupling between the dome/shell flanges and space, The correction of each deficiency led to substantial temperature changes, as will be detailed in what follows.

MODIFICATIONS AND ADJUSTMENTS OF THE MODEL

Numerous numerical experiments and parametric runs were made to probe the sensitivity of model parameters. All model modifications and adjustments were made with physical justifications, atthough input values of radiation conductors and contact conductances involved approximations consistent with the fidelity of a reduced thermal model. The following summary describes the model modifications made, the rationale involved, and the consequences in terms of computed temperatures which are displayed in accordance with the node map of Figure 3.

STEP #1: Set *power*= 4100 W, *sink* temperature = 37.8°C, and remove the fudge factor 0.85 on theRADKs between apace and the RTG shell/fins. The objective was to duplicate the baseline predictions that GE obtained in 1988. The resulting temperature distribution is shown in Figure 4 which brought us back to the correct starting point.

OUTBOARD						INBOARD
205.47	752.17	999.96	1076.68	1004.4s	774.35	204.s0
		616.06	673.95..	619.03		
217.42	220.60	233.75	271.22	232.60	218.s1	215.42
		218.61	251.2s	218.48		
		210.91	241.29	210.79		
		180.05	201.66	179.97		

FIG. 4 STEP #1 RESULTS [BASELINE PREDICTIONS)

STEP #2: Flange temperatures (both of the dome and shell) were too high as compared with the test data Radiative coupling between flange and space was absent, which physically should have been represented. Pertinent as-built data were confirmed which indicate that the shell flange is painted black but the dome flange is not. However, the dome flange is bolted to the shell flange with 22 bolts, and the bolt heads and flange arc probably highly oxidized as a result of high temperature exposure. An emissivity of 0.5 was therefore assumed for the dome flange. The dome is painted black both inside and outside. The consequences of the modifications arc that the flange

OUTBOARD						INBOARD
190.21	743.99	99s.s6	1075.60	1000.OO	766.73	189.45
		612.01	627.70.	614.29		
197.57	201.7s	228.66	270.81	22s.s6	199.73	19s.ss
		214.16	250.96	214.09		
		206.77	241.03	206.70		
		i n . w	201.38	177.04		

FIG. 5 STEP #2 RESULTS

temperatures drop 20°C, the dome temperatures drop 15°C, and the mid-shell temperature is hardly changed. See Figure 5.

STEP #3: Dome temperatures were too low as compared with the test data, and temperature gradients across the gsps between the end domes and heat source support assemblies looked excessively high, The linear conductor linking nodes on both sides of the gap (i.e., nodes 2 & 3, and nodes 12 & 13) was intended by GE as a lumped conductance incorporating effects of conduction and radiation. However, parametric studies indicate that m appropriate (higher) level of radiative coupling between the end dome and heat source support assembly will increase the heat flow across the gap, thereby lowering the temperature gradient across the gap, and raising the end dome temperature to a level consistent with the test data. This is done in several steps. First, delete the lumped conductance between nodes 2 and 3, and between nodes 12 and 13. The consequences are that the end dome temperatures drop 26°C, and flange temperatures drop 15°C, indicating the significance of heat transfer across the gap. The inboard-outboard asymmetry becomes more pronounced, which reflects the real design differences between the two ends. Also, a large temperature drop across the bolted interface between the shell and dome flanges is observed. See Figure 6.

OUTBOARD						INBOARD
164.79	975.17	1046.27	1085.70	1056.67	1022.92	161.89
		6ss.81	679.03	643.69..		
1ss.s6	190.67	2S0.76	272.35	230.71	186.85	160.00
		216.02	2s2.s1	21s.97		
		20s.s0	242.29	208.46		
		178.36	202.26	178.33		

FIG, 6 STEP #3 RESULTS

STEP #4: This temperature drop across the bolted flange interface (as high as 7°C) is much greater than expected because the two flanges arc bolted together by 22 bolts. Contact conductance is increased from 10.5S to S3.0 W/°C between nodes 4 & 5, and between nodes 14 & 15. The latter value is estimated by invoking m interface conductance correlation reported by Aron and Colombo (1963). The consequences are *a* more reasonable temperature drop across the bolted interface on both ends, i.e., 1.5°C. See Figure 7.

OUTBOARD						INBOARD
167.79	974.64	1046.46	10SS.61	1056.31	1022.s0	164.79
		638.35	678.96	643.26		
187.2s	188.72	220.24	272.32	230.22	184.97	1s2.%
		215.56	2s2.2s	215.s4		
		208.08	242.26	208.06		
		178.05	202.2s	178,04		

FIG. 7 STEP #4 RESULTS

STEP #5: Add radiative coupling between the end dome and the heat source support assembly. The RADKs are approximate because the surface geometries and emissivities of the heat source support assemblies arc complicated; they may have to be further adjusted. Consequences: End dome temperatures rise by about 50°C, and flange temperatures rise by about 26°C. The inboard-outboard asymmetry is substantially diminished. See Figure 8.

OUTBOARD						INBOARD
216.49	4ss.40	9s6.19	1064.52	938.99	492.42	216.81
		582.02	666.79	582.39		
212,01	212.24	22s.2s	269.06	225.79	211.67	211.49
		211.6s	249.42	211.63		
		204.45	2s9.60	204.40		
		175.40	200.35	175.36		

FIG. 8 STEP #5 RESULTS

STEP #6: The radiative coupling parameters added in STEP #5 were based on the assumption that Nodes 2 and 12 arc located at the pressure plate stud. However, the Lockheed-Martin (formerly GE) collaborators who arc familiar with the RTG hardware and analytical model thought they might have been located near the top of the preload stud (both studs located in the end dome region), and suggested reducing the conductance between Nodes 2 and 21, and between Nodes 12 and 31. Hence, the conductances in question were reduced by 15% approximately. Consequences: The dome temperatures drop 5°C, and flange temperatures drop 3°C. The heat source support assembly temperatures drop 17°C, and mid-shell temperature is little changed. See Figure 9.

OUTBOARD						INBOARD
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	2s9.90	204.82		
		175.71	200.s6	175.67		

FIG. 9 STEP #6 RESULTS

STEP #7: The shell temperatures (especially that of Node 6) were substantially higher than the test data. The RTG mid-ring was found not represented in the model. Hence, incorporate radiation coupling between the mid-ring and space into the RADK for mid-shell to space. Consequences: The mid-shell temperature drops 9°C, and the end dome temperatures drop 10C. See Figure 10. (Note that GE's detailed RTG model treated the mid-ring to space radiative coupling and predicted 5°C lower for the mid-shell than did the original 26-node model, thus qualitatively corroborating these results.)

OUTBOARD						INBOARD
21O.M	470.22	947.0s	10ss.60	947.7s	474.36	211.02
		585.99	659.44	586.30		
208.33	20s.65	224.94	S60.27	224.86	20s.07	207.79
		210.79	241.76	210.71		
		203.57	232.47	203.s0		
		174.60	195.29	174.55		

FIG. 10 STEP #7 RESULTS

STEP #8: The shell temperatures are still high in comparison with the test data Radiation coupling between the shell and fins were not accounted for in the model. Their incorporation in the model may further lower the shell temperatures. Thus, view factors between the shell and the various fin nodes arc estimated by using data contained in Hamilton and Morgan (1952) and incorporated into the model. Consequences: The mid-shell temperature drops 4°C, end shell temperatures drop 2°C and end dome and flange temperatures drop 1°C. The shell temperatures arc now quite close to the data. See Figure 11.

OUTBOARD						INBOARD
209.74	469.44	944.90	105s.22	945.61	473.60	210.04
		583.92	6s6.0s	$64.24		
207.04	207.35	222.94	2s6.72	222.27	206.s0	206.54
		210.06	240.20	209.99		
		203.47	alas	203.41		
		177.25	198.78	177.21		

FIG. 11 STEP #8 RESULTS

STEP #9: Figure 11 indicates that the radiation coupling between the end dome and heat source support assembly maybe adjusted higher (by about 28%) to fine-tune the end dome and flange temperatures. Consequences: The end dome temperatures rise by 2°C, and flange temperatures rise by 1°C. See Figure 12, which shall be referred to as the "validated predictions".

OUTBOARD						INBOARD
212.01	442.34	9s9.60	10s4.26	940.17	445.71	212.31
		581.15	655.51	581.41		
202.16	208.41	222.71	256.66	222.64	207.94	207.73
		209.6s	240.10	209.79		
		203.27	2.31.7s	203.22		
		177.10	198.70	177.06		

FIG. 12 STEP #9 RESULTS (VALIDATED PREDICTIONS)

THE FINAL CORRELATION

Figure 12 shows that the totality of the above modifications and adjustments finally brings the model predictions to a very close agreement with the Engineering Unit test data. The model predictions vs. test data comparison is summarized in Figure 13, where predictions by the validated model arc bracketed <,..>, and all other temperatures arc test data from GE's Engineering Unit. It is evident that the agreement displayed here is appreciably better than that offered by the "baseline predictions" (Figure 4). While all modifications have nontrivial contributions toward the final correlation, the most crucial step which helps align the end dome temperature predictions with thdest data is the appropriate radiative coupling between the end domes and heat source support assemblies. It is noted that these modifications have brought the end dome and flange temperature predictions to within 2°C of the test data and resulted in a doubling of radiative heat transfer from the heatsource support assemblies to the end domes (e.g., from 54 W of STEP #l to 108 W of STEP #9, for the inboard end).

More significantly, due to this doubling of heat transfer to the end domes, when the RTG is coupled to the spacecraft central body, as in the integrated Cassini configuration, the combined model predicts an inboard end dome temperature at least 30°C higher after the validation than it did before the validation. This substantial increase in the end dome temperature has a considerable impact on the amount of RTG heat entering the PMS cavity. However, heat transfer in the integrated configuration is treatedelsewhere.

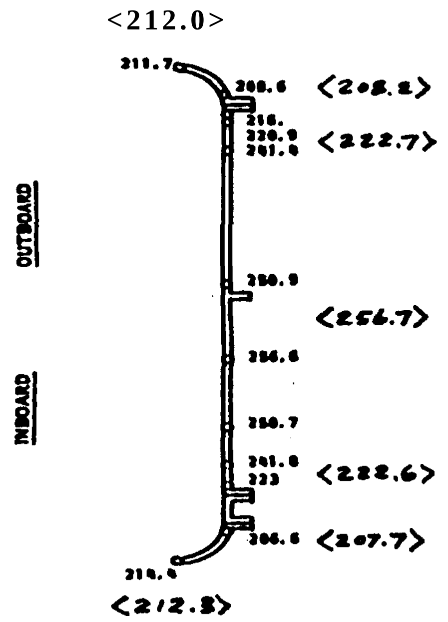
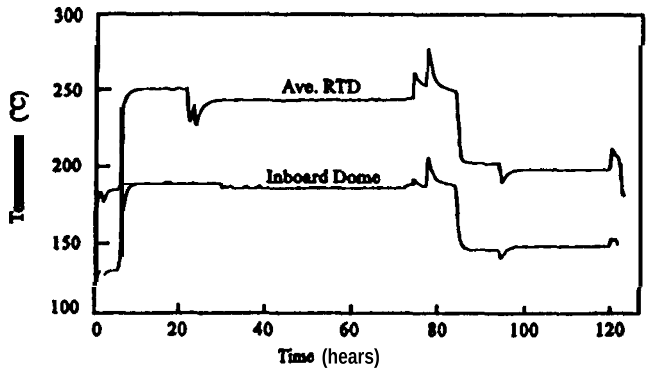


FIG. 13 VALIDATED MODEL PREDICTIONS [BRACKETED) VS. TEST DATA (°C)

FURTHER VALIDATION WITH F-2 FLIGHT RTG ACCEPTANCE TEST DATA

Since GE's Engineering Unit was an electric simulator and not a nuclear-fueled flight unit, it was highly desirable to acquire vacuum data from a fueled flight unit forfurther validation ofthe model. Upon JPL's request, an effort was made by DOE'S Mound Laboratory (i.e., EG&G Mound Applied Technologies), with assistance from Lockheed Martin personnel, to obtain end dome and shell temperature measurements during the thermal vacuum acceptance test of the fueled flight unit F-2. The shell temperature measurements were obtained with flight temperature transducers that arc already in place on the RTG while the end dome temperature measurement (being an afterthought) was obtained by using an IR probe placed inside the vacuum chamber, The results arc shown in Figure 14 (particularly the 30 hours of stable data before start of the vent test at Hour 70). The



FIG, 14 F-2 RTG ACCEPTANCE TEST DATA

IR probe was calibrated using an oil-bath setup as well as a hot plate. Both calibration approaches yielded a consistent correction factor of 22°C at the temperature reading of around 200°C. Applying this correction factor to the lower curve of Figure 14, the end dome temperature is determined to bc 208°C. The shell temperature at the "RTD" (Resistance Temperature Device) location (approximately 7 in. from the inboard dome flange interface plane), as shown in Figure 14 and with no correction necessary, is 244°C. The F-2 was running with a net thermal power of 4120 W, and the sink (or chamber shroud) temperature wcs 27°C.

A computer run was made with the validated analytical model (without any further model adjustments) using these F-2 test conditions. The calculation yielded an end dome temperature of 210°C and a shell temperature at the "RTD" location of approximately 240°C. A comparison between these predictions and the test data is prcscntcd in the table below. The agreement is rather satisfactory, and the validity of the RTG analytical model is thus firmly established.

	F-2 Test Data	Model predict
Inboard Dome T(°C)	208	210
Shell-RTD T(°C)	244	240

CONCLUSIONS

This paper has presented the proms and results of validating the RTG analytical thermal model that was constructed for usc in the development of the Cassini spacecraft. The validated model predictions show excellent agreement with twosets of test data, one from a simulated Engineering Unit and the other from a flight RTG. 'tie flight unit end dome temperature data, previously nonexistent, were atso established in the process, It has been demonstrated that model modifications and adjustments must be made on physical grounds, with greater rigor placed on crucial aspects (e.g., the end dome temperature in this case) while approximations and fudge factors applied in less critical areas, commensurate with the fidelity and intended application of the model, Analytical model validation is therefore not so much a black art as some may perceive it to be but an empirical science driven by physical considerations at the core and practiced with judicious approximations where necessary. Furthermore, it is shown that an improperly validated model can seriously misguide design decisions, as can an improperly calibrated instrument misread test data The calibration of the IR probe with two different approaches increased the credibility of the F-2 cud dome temperature measurement, and the special effort expended to acquire the critical data from a nuclear-ficlcd flight RTG, atthough difficult, proved to be exceedingly valuable. Validating a model with onc set of test data is not quite enough; at least a second independent act is needed to query and confirm the validated model.

ACKNOWLEDGMENT

The RTG thermal analytical model discussed in this paper was originally developed by Lockheed-Martin (previously GE Valley Forge). The validation process described herein was actively supported by W. Tobery and J. Loffreda of this company. The F-2 RTG end dome temperature data and the JR probe calibration data were obtained through a special effort by B. A. Tolson and T. J. Hoyt of EG&G Mound Applied Technologies, with assistance provided by Lockheed-Martin's W. Tobery and R Reinstrom. W. Tobery also played a key role in interpreting the IR probe calibration data The author is indebted to these colleagues as their contributions have been essential to the conclusive validation of this model. 'he author also wishes to thank his JPL colleagues J. Stultz, V. Mireles and G. Tsuyuki for their participation in numerous technical discussions. The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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