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Comparative Thermal Analysis of the Space Station Freedom Photovoltaic Deployable Boom Structure Using TRASYS, NEVADA, and SINDA Programs

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ABSTRACT

The proposed Space Station Photovoltaic Deployable Boom has been analyzed for operating temperatures. The boom glass/epoxy structure design needs protective shielding from environmental degradation. The protective shielding optical properties (solar absorptivity and emissivity) dictate the operating temperatures of the boom components. The Space Station Boom protective shielding must also withstand the effects of the extendible/retractable coiling action within the mast canister. A thermal analysis method was developed for the Space Station Deployable Boom to predict transient temperatures for a variety of surface properties. The modeling procedures used to evaluate temperatures within the boom structure incorporated the TRASYS, NEVADA and SINDA thermal analysis programs. Use of these programs led to a comparison between TRASYS and NEVADA analysis methods. Comparing TRASYS and NEVADA results exposed differences in the environmental solar flux predictions.

THE NASA SPACE STATION PROGRAM will use a Photovoltaic (PV) power generating system to provide the required power. The Space Station incorporates four PV modules which provide the required 75 kW of power for a 15 year service life. The design of the PV solar arrays will incorporate advanced array technology, such as flexible blankets and wrap through electrical contacts, to meet performance requirements. The PV system hardware, as defined in this paper, contains solar array blankets, a beta gimbal joint, containment boxes, a mast canister, and an extendible/retractable mast as shown in Fig. 1.

The baseline design for the extendible/retractable mast, also referred to as a boom, is a continuous three-longeron lattice structure generating a deployed triangular cross section with a 32.3 in. diameter. A section of the mast is composed of three longerons, six battens and six diagonal guide wires. The longeron boom design will provide a high stiffness-to-weight ratio to withstand bending loads from solar array blanket tension forces. The diagonal guide wires are stainless steel, while the mast longerons and battens are fabricated from "S"-glass/epoxy which requires a protective shielding from environmental degradation. This degradation may develop from atomic oxygen at low earth orbit, UV radiation, high vacuum of space, and thermal cycling. The solar absorptivity and emissivity of the protective shielding or coating dictate the operating temperatures of the boom components. The protective coating must also withstand the extendible/retractable coiling action within the mast canister. These requirements generated the need to accurately predict Space Station Boom temperatures for a variety of surface properties and orbit conditions.

METHOD OF ANALYSIS

The thermal analysis method used in studying the operating temperature of the boom incorporated three thermal analyzer programs: TRASYS, NEVADA and SINDA. The Thermal Radiation Analysis System (TRASYS) was incorporated to predict heating rates from environmental radiant heat sources (collimated solar flux, earth albedo flux, and earth thermal flux) and the node network radiation interchange. The TRASYS geometric mathematical model (GMM) included boom physical geometry, surface properties, and orbit information. TRASYS output included transient heating rates and radiation conductor values.

The Systems Improved Numerical Differencing Analyzer (SINDA) is a generalized thermal analysis program. The program solves lumped parameter representations of physical problems governed by diffusion-type equations as a resistor-capacitor (R-C) network which represents a thermal system. The SINDA thermal mathematical model (TMM) included the TRASYS output, node thermal capacities, and the conduction network. SINDA output was transient temperatures.

The Net Energy Verification And Determination Analyzer (NEVADA) program serves the same purpose as TRASYS and was incorporated to generate comparative results. NEVADA is a software package consisting of several programs in which a Monte-Carlo mathematical technique is applied to a ray tracing procedure for the thermal radiation exchange calculations. The NEVADA program does not assume collimated heat sources (solar flux for the boom analysis), thus enabling greater accuracy than with TRASYS for the calculation of view factors, and heating fluxes for sparse structures. The flow path of the boom thermal analysis is shown in Fig. 2.

THERMAL ANALYSIS

The Space Station Boom thermal analysis was generated with the intent of evaluating the effect of various surface properties on transient temperatures. Due to symmetry of the boom, only one bay section of the boom was modeled (Fig. 1). The TRASYS and NEVADA models both represent identical sections of the Space Station Boom. For accurate results, TRASYS modeling required each component to be divided into several smaller components. The TRASYS model separated the longerons and battens into four and nine segments (nodes), respectively, to accurately model the components based on their length to diameter ratio. Within TRASYS the results from the component sections were averaged to correspond one-for-one with the SINDA nodes. The diagonal wire dimensions restricted the use of this technique to improve results. The diagonal wires were modeled as single nodes in TRASYS. The NEVADA and SINDA boom models use a single node to represent each component (three longerons, six battens and six diagonal wires). The Space Station Boom thermal analysis incorporated three possible cases for solar absorptivity and emissivity surface properties (Table I).

A typical boom structure, like the Space Station Photovoltaic Deployable Boom, is composed of many structural components. The transient exposure of each boom component with respect to the environmental heat sources (sun and earth) affects its heat absorption and emission. The conductivity and thermal capacitance of the boom components also affect transient temperatures. For this analysis the conduction between connecting components was assumed zero giving worst case maximum and minimum temperatures.

The Space Station Boom analysis assumed a circular orbit at an altitude of 250 nmi. The boom is maintained in a sun pointing attitude throughout the orbit. The Space Station boom orbit is defined with a beta angle of 0.0°. The beta angle is the angle between the orbit plane and a vector from the center of the earth pointing to the sun. A beta angle of 0.0° represents the orbit during the autumnal and vernal equinoxes (fall and spring). This beta angle provides the longest possible solar illumination time per orbit on the boom (0.962 hr in solar flux and 0.598 hr in eclipse). The environmental constants used within TRASYS were:

Solar constant	450.00 Btu/hr ft^2
Planetary (Earth) constant	77.00 Btu/hr ft^2
Earth albedo	.35

DISCUSSION OF RESULTS

Figure 3 displays the SINDA longeron node 101 transient temperatures for both TRASYS and NEVADA heating predictions. The longerons represent unshaded boom surfaces. The boom components were given an initial temperature of 70.0 °F. Roughly 10 orbits (15 hr) were required for the longerons to reach their maximum temperature profiles. Figure 3 revealed small temperature differences for the TRASYS and NEVADA cases due to variations in their absorbed heating rates. Comparing the TRASYS and NEVADA incident fluxes on the longeron surfaces in Table II reveals the cause of the transient temperature differences in Fig. 3.

Unlike TRASYS, the present version of NEVADA does not include automatic evaluation of orbit locations at the solar eclipse shadow entry and exit positions. NEVADA could analyze these points using small orbit steps or combining additional computer runs to evaluate the shadow points. In this comparative thermal analysis the NEVADA flux data for each node was extrapolated using TRASYS shadow entry and exit positions. Examination of Table II reveals small differences in TRASYS and NEVADA solar incident fluxes. Figure 4 graphically displays the TRASYS and NEVADA solar incident fluxes on longeron node 101. Both TRASYS and NEVADA use identical environmental constants, but resulted in slightly different levels of solar incident fluxes. Further subdivision of the TRASYS longeron nodes may improve the flux differences.

Table III shows the effect of TRASYS and NEVADA heating rates on maximum and minimum longeron temperatures for the three cases analyzed. Figure 5 graphically displays longeron node 101 transient temperatures for the three cases.

The two main concerns in analyzing the batten temperatures were, the affects of component shadowing on battens, and orientation angles. Referring to Fig. 1, battens 1101, 1103, and their symmetric nodes, 1104 and 1106, are fully exposed to the solar flux in a sun tracking orbit. The symmetric batten nodes 1102 and 1105 may be positioned where the solar flux is partially or completely shadowed by other batten components.

Table IV displays the TRASYS and NEVADA heating rate effects on maximum and minimum batten temperatures for the three cases analyzed. The temperature results for the symmetric battens 1101, 1103, 1104 and 1106 (Table IV) indicate that the TRASYS integrated orbital absorbed heating rates were larger than the NEVADA heating rates. The opposite trend occurred for the symmetric battens nodes 1102 and 1105 in all three cases. Figure 6 graphically displays SINDA batten transient temperature results for case 1 based on TRASYS and NEVADA output.

To understand the batten temperature differences, a graph comparing TRASYS and NEVADA incident solar fluxes is included (Fig. 7). The constant 0.0 Btu/hr ft^2 heating rate shows that TRASYS batten 1102 is completely shadowed from the solar flux. The only TRASYS heating associated with batten node 1102 is from reflected solar, earth albedo and earth thermal heating. The batten is completely shadowed from the direct solar flux. The NEVADA results (Fig. 7) show a direct solar flux of about 10.5 Btu/hr ft^2 is incident on the batten. This can result in average differences in temperature prediction between the two programs ranging from 35 °F for case 1, to 1 °F for case 3.

When evaluating sparse structures like the Space Station boom, the direct solar source should not be treated as a collimated heat source, as in TRASYS. The NEVADA user has the option of using source divergence half-angle (16 min for the Space Station orbit) where TRASYS does not. The source divergence half-angle is the angle associated with the source (sun) based on its size and distance from the earth. The NEVADA simulation of the solar flux results in conical shadows, not the TRASYS continuously parallel shadows from a collimated source. This more accurate NEVADA method for shadow simulation increased the heating rates and temperatures for battens 1102 and 1105. When the source divergence half-angle of 0.0 min was used in NEVADA, the TRASYS and NEVADA direct solar heating rates were both 0.0 Btu/hr ft^2.

Batten 1102 is oriented normal to the solar flux, therefore, if the separation between the Space Station battens were increased, or batten diameters decreased, the NEVADA program would predict an increasing direct solar flux on batten 1102. TRASYS batten 1102 would still be completely shadowed from the direct solar flux. Therefore, for sparse structures like the Space Station Deployable Boom, NEVADA provides a more accurate incident solar flux prediction for components where shadowing may occur.

From Fig. 1 it is apparent that almost no solar flux shadowing occurs for the diagonal wires except at or near their intersection. Two sets of diagonals wires were symmetric and received equal amounts of solar flux in a sun tracking orbit. The SINDA transient temperature results for TRASYS and NEVADA symmetric diagonal wire nodes 2101, 2102, 2104 and 2106 and symmetric nodes 2103 and 2105 are shown in Table V. TRASYS and NEVADA output data produced similar SINDA maximum and minimum diagonal wire temperatures for the three cases analyzed.

Figure 8 illustrates the effect of surface coating optical properties (solar absorptivity to emissivity ratio) on the Space Station Deployable Boom longeron steady state temperature. A broad range of absorptivity to emissivity ratio was analyzed with respect to longeron temperature. TRASYS low-earth-orbit heating rates were averaged for the steady state energy balance. The temperature predictions do not include shadowing or radiant energy from other Space Station components.

CONCLUDING REMARKS

The Space Station Deployable Boom thermal analysis revealed differences in TRASYS and NEVADA predicted solar incident fluxes. The results obtained from modeling the sparse structures revealed that certain TRASYS batten components received no direct solar flux, while the same NEVADA components receive direct solar flux. The TRASYS program assumes that the direct solar flux is perfectly collimated, thus, parallel TRASYS surfaces could be completely shadowed. The NEVADA program has the option of supplying a direct solar source divergence angle to simulate a conical shadow. This conical shadow simulation principle within NEVADA gives a more accurate incident solar flux prediction for sparse structures like the Space Station Deployable Boom where components shadowing may occur.

The effect of shadows on the Space Station Deployable Boom longerons and diagonal wires was not a major concern in a sun tracking orbit. The environmental heating results from both TRASYS and NEVADA for the sun tracking orbit produced similar SINDA temperature profiles. Other orbit conditions (for example, polar or feathered orbits) or movement in the boom components may result in shadows which could produce large temperature differences.

REFERENCES

1. "Thermal Radiation Analysis System, TRASYS II, User's Manual," MCR-73-105 REV-5, Martin Marietta, 1983.

2. J.P. Smith, "SINDA User's Manual," Rev. 3, Lockheed Engineering and Management Services Co., Houston, TX, 1983.

3. R.C. Turner, "NEVADA Software Package User's Manual," Version 14, 9th edition, Turner Associates Consultants, Incline Village, NV, July 1988.

4. "Space Station Program WP-04, Proposal for Solar Array Assemblies," Vol. 1, LMSC-F177627, Astronautics Division, Lockheed Missiles and Space Co., June 15, 1987.

TABLE I. - BOOM SURFACE OPTICAL PROPERTIES

Case	Surface	Solar absorptivity, X	Emissivity, Y	X/Y
1	Aluminized Kapton tape	0.16	0.03	5.33
2	Silicone aluminum paint	.29	.30	.97
3	Dow Corning white paint DC-007	.19	.88	.22

TABLE II. - TRASYS AND NEVADA INCIDENT FLUXES
ON LONGERON NODE 101

Time, hr	Solar		Earth albedo		Earth thermal	
	TRASYS	NEVADA	TRASYS	NEVADA	TRASYS	NEVADA
	Incident flux, Btu/hr ft^2					
0	146.3	142.5	50.6	51.9	25.0	24.8
.130		145.3	45.2	44.4	25.0	25.2
.260		141.5	27.5	26.2	26.6	25.2
.391		141.1	1.6	1.8	26.3	25.6
.482	↓	[a]141.1	0	[a]0	27.3	[a]25.6
.483	0	[a]0		[a]0	27.3	[a]25.6
.521		0		0	27.6	27.0
.651					27.6	26.5
.781					26.8	26.6
.911					27.6	26.0
1.042		↓		↓	27.6	27.1
1.079	↓	[a]0		[a]0	27.4	[a]25.6
1.080	146.3	[a]141.1	↓	[a]0	27.4	[a]25.6
1.172	146.3	143.8	1.6	1.7	26.3	26.6
1.302	146.4	141.7	27.5	26.2	26.6	25.5
1.432	146.5	145.9	45.2	43.5	25.0	24.6

[a]NEVADA extrapolated data.

TABLE III. - TRAYS AND NEVADA EFFECTS OF LONGERON
MAXIMUM AND MINIMUM TEMPERATURES

Case	Solar absorptivity	Emissivity	TRASYS		NEVADA	
			Longeron temperature, °F			
			Maximum	Minimum	Maximum	Minimum
1	0.16	0.03	322.9	293.2	320.5	290.6
2	.29	.30	90.7	39.2	88.7	37.3
3	.19	.88	-29.8	-62.8	-31.5	-64.9

TABLE IV. - TRASYS AND NEVADA EFFECTS ON BATTEN MAXIMUM AND MINIMUM TEMPERATURES

(a) TRASYS

Case	Solar absorptivity	Emissivity	Nodes 1101, 1103 1104, and 1106		Nodes 1102 and 1105	
			Batten temperature, °F			
			Maximum	Minimum	Maximum	Minimum
1	0.16	0.03	234.0	205.4	52.8	41.4
2	.29	.30	37.1	-13.0	-58.2	-78.9
3	.19	.88	-58.3	-91.8	-94.3	-110.4

(b) NEVADA

Case	Solar absorptivity	Emissivity	Nodes 1101, 1103 1104, and 1106		Nodes 1102 and 1105	
			Batten temperature, °F			
			Maximum	Minimum	Maximum	Minimum
1	0.16	0.03	223.4	196.0	88.9	75.3
2	.29	.30	29.5	-16.9	-43.6	-66.7
3	.19	.88	-63.1	-93.6	-92.8	-110.1

TABLE V. - TRASYS AND NEVADA EFFECTS ON DIAGONAL WIRES MAXIMUM AND MINIMUM TEMPERATURES

(a) TRASYS

Case	Solar absorptivity	Emissivity	Nodes 2101, 2102 2104, and 2106		Nodes 2103 and 2105	
			Diagonal wire temperature, °F			
			Maximum	Minimum	Maximum	Minimum
1	0.16	0.03	251.4	197.7	367.4	276.7
2	.29	.30	55.5	-31.4	126.7	-8.3
3	.19	.88	-45.7	-98.7	-11.8	-89.4

(b) NEVADA

Case	Solar absorptivity	Emissivity	Nodes 1101, 1103 1104, and 1106		Nodes 1102 and 1105	
			Diagonal wire temperature, °F			
			Maximum	Minimum	Maximum	Minimum
1	0.16	0.03	279.4	217.2	336.7	255.4
2	.29	.30	70.8	-25.5	107.2	-15.1
3	.19	.88	-43.6	-98.5	-24.9	-96.6

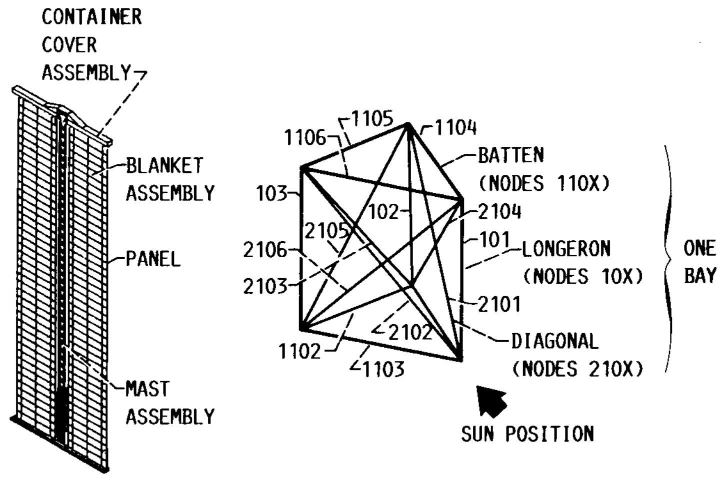

FIGURE 1. - SPACE STATION PHOTOVOLTAIC DEPLOYABLE BOOM AND THERMAL ANALYSIS NODE CONFIGURATION.

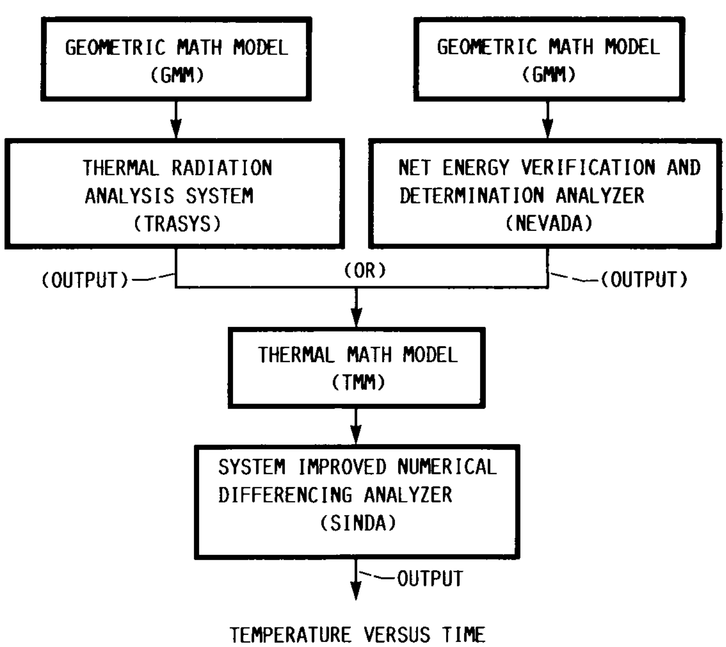

FIGURE 2. - LeRC THERMAL ANALYSIS FLOW PATH.

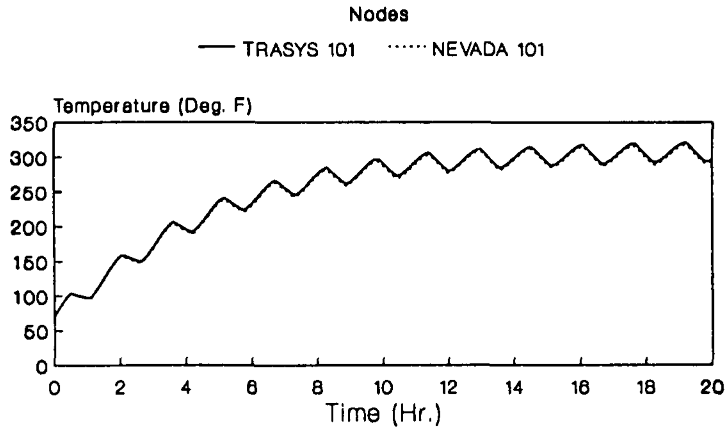

FIGURE 3. - TEMPERATURE PREDICTIONS BASED ON TRASYS AND NEVADA OUTPUTS, LONGERON NODE 101, CASE 1.

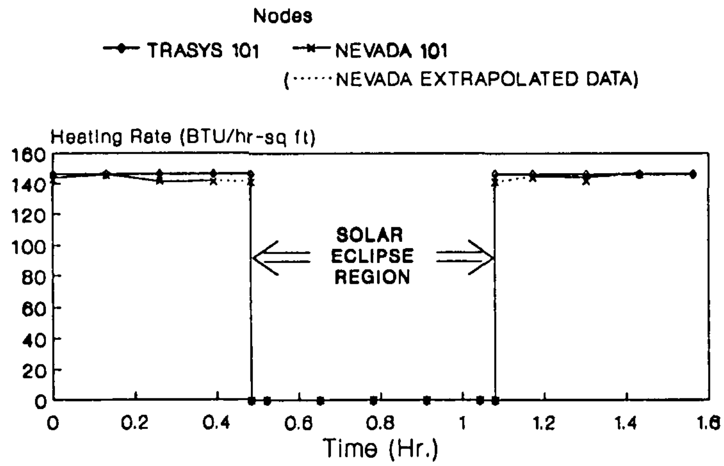

FIGURE 4. - TRASYS AND NEVADA INCIDENT FLUX PROFILES, LONGERON NODE 101 (SOLAR FLUX ONLY) CASE 1.

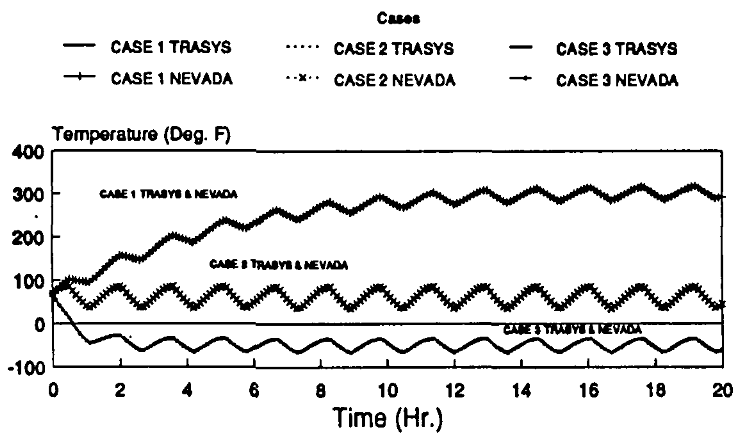

FIGURE 5. - TEMPERATURE PREDICTIONS BASED ON TRASYS AND NEVADA OUTPUTS, LONGERON NODE 101 CASE 1, CASE 2, CASE 3.

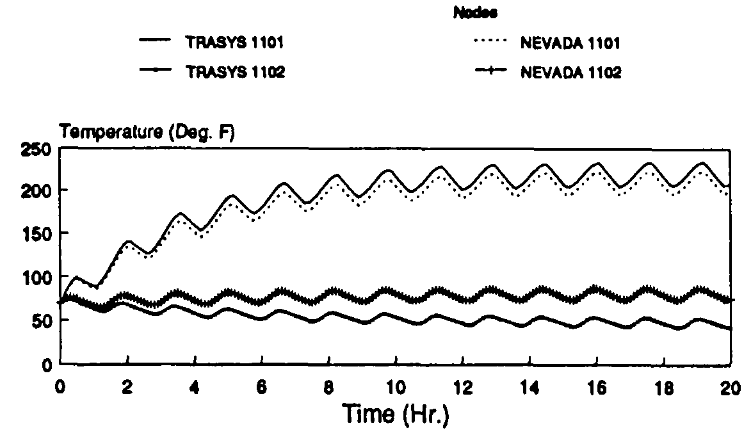

FIGURE 6. - TEMPERATURE PREDICTIONS BASED ON TRASYS AND NEVADA OUTPUTS, BATTEN NODES 1101, 1102 CASE 1.

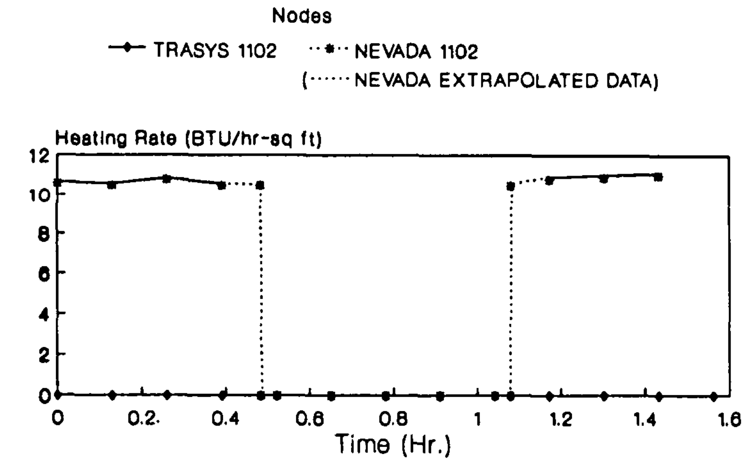

FIGURE 7. - TRASYS AND NEVADA INCIDENT FLUX PROFILES, BATTEN NODE 1102 (SOLAR FLUX ONLY) CASE 1.

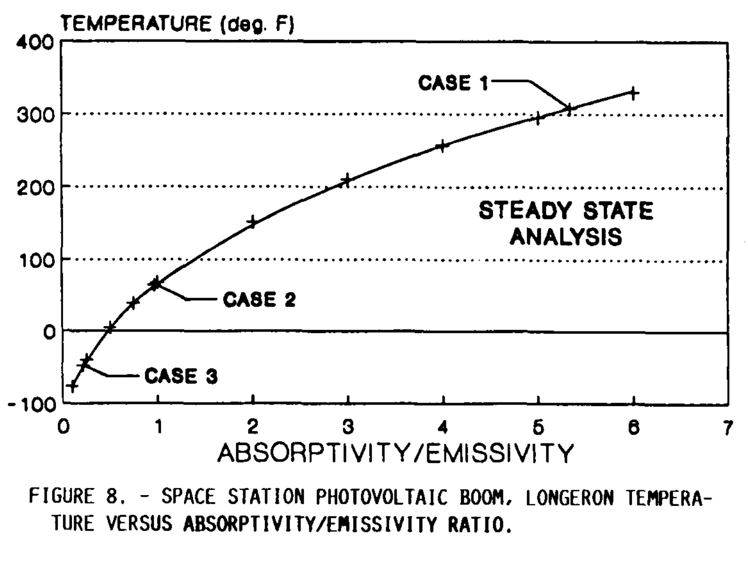

FIGURE 8. - SPACE STATION PHOTOVOLTAIC BOOM, LONGERON TEMPERATURE VERSUS ABSORPTIVITY/EMISSIVITY RATIO.

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