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THERMAL-STRUCTURAL ANALYSIS OF LARGE SPACE STRUCTURES: A REVIEW OF RECENT ADVANCES

Earl A. Thornton

Department of Mechanical Engineering and Mechanics
School of Engineering
Old Dominion University
Norfolk, Virginia 23508

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Flight Dynamics Laboratory
AF Wright Aeronautical Laboratories
Air Force Systems Command
Wright-Patterson AFB, Ohio 45433

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Donald B. Paul
DONALD B. PAUL, Project Engineer
Structural Integrity Branch
Structures and Dynamics Division

Davey L. Smith
DAVEY L. SMITH, Chief
Structural Integrity Branch
Structures & Dynamics Division

FOR THE COMMANDER

RALPH L. KUSTER, JR., Colonel, USAF
Chief, Structures and Dynamics Division

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Recent advances in thermal-structural analysis of large space structures are reviewed. Thermal-structural analytical challenges faced by structural engineers are highlighted and uncertainties that arise in predictive analyses are identified and discussed. Current modeling techniques and characteristics of thermal-structural response are illustrated. Areas for further research are discussed, and the need for fundamental thermal-structural experiments is cited.

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FOREWORD

This report reviews recent research in thermal-structural analysis of large space structures. The work was initiated during a visit of the author to the Flight Dynamics Laboratory in August 1981 and completed at the Department of Mechanical Engineering and Mechanics, Old Dominion University, Norfolk, Virginia during the spring of 1982.

The work was sponsored by the Flight Dynamics Laboratory (AFWAL, FIBE), Air Force Wright Aeronautical Laboratories, Air Force System Command, Wright-Patterson Air Force Base, Ohio 45433, under contract AFWP-81-1155-435. The work was monitored by Dr. Donald B. Paul, Project Engineer, Structural Integrity Branch, Structures and Dynamics Division. The author would like to gratefully acknowledge the assistance of Dr. Paul for many helpful discussions. The author would also like to express his appreciation to Mr. Allan R. Wieting and Dr. L.B. Garrett of the NASA Langley Research Center for their support in thermal-structures research for large space structures.

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INTRODUCTION

The flights of Columbia have given added impetus to large space structures research. The United States is developing large space structures that will be placed in earth orbit during the last two decades of this century and early in the next century. These structures of unprecedented size and complexity fall into two classes: large antennas and space platforms. Potential missions include communications, advanced scientific applications, earth observation, and remote sensing. Early structures under consideration are deployable antenna concepts to be transported to low earth orbit in the space shuttle. Platform structures under consideration include both deployable concepts and structures to be assembled in orbit from components transported to orbit by the shuttle.

Concepts of orbiting space structures that are under development present structural analysts with significant challenges in analysis and design. The large size of these structures make them distinct from past earth satellites. Deployable antenna concepts up to 100 m (328 ft.) and erectable structures of several hundred meters in diameter are under consideration. To gain low weight and high stiffness, the structures typically employ open, latticework construction. Designs include pretensioned, cable-stiffened structures and space trusses. To achieve low weight and high stiffness and to minimize thermal distortions, the designs make extensive use of advanced composite materials.

An important design constraint is controlling structural deformation within close tolerances. Operational requirements for a 100-m antenna design can limit surface distortions to a few mm. Such stringent operational requirements have focused attention on analysts' capabilities for predicting small deformations with high accuracy. An important factor emphasizing the need for effective analysis methods is that the size of the proposed structure will prohibit the ground testing customary for past earth satellites.

NASA has been researching large space structures since about 1973. Large space structures activities from 1973 to 1979 are reviewed in reference 1. In January 1978, the Large Space Systems Technology (LSST) office at NASA Langley hosted the first of four annual conferences focused on LSST technology developments. The proceedings of these conferences (refs. 2-5) provide a good review of LSST research and development. In addition, papers presented at AIAA conferences such as the 21st Structures, Structural Dynamics and Materials Conference held in Seattle, Washington in May 1980 and the 16th Thermophysics Conference held in Palo Alto, California in June 1981 are an important source of information on basic research activities. Several important references from these conferences will be cited later in this paper. A special NASA bibliography (ref. 6) provides a selection of annotated references to unclassified reports and journal articles that were introduced into the NASA scientific and technical information system between January 1, 1979 and June 30, 1981.

The control of large space structures' deformations within small tolerances requires careful consideration of several effects on the structural response. Thermally induced forces are only one of several on-orbit loads that must be considered including pretensioning, orbital positioning thrusts, gravity gradient forces, and atmospheric drag.

The determination of thermal forces is a complex, interdisciplinary problem requiring consideration of orbital mechanics, heat transfer, and structural mechanics. Several studies that appear in references 1-6 have considered isothermal structural analyses (e.g., buckling and vibration behavior), but not many studies have included thermal effects. A few studies using simplified techniques (refs. 7 and 8) have estimated the behavior of orbiting trusses, but there has been little systematic, fundamental research on thermal-structural response of large space structures. Structural analysts have not fully recognized that thermal analysis of many large latticework structures may be impractical using available computer programs because of the great number of unknowns required to analyze such structures. In addition to the large computational cost of analyzing large space structures, there are significant uncertainties in the three key analyses required to predict large space structures' thermal deformations accurately: (1) heat load analysis, (2) thermal modeling and temperature analysis, and (3) structural modeling and deformation analysis.

The purposes of this report are to identify uncertainties in the thermal-structural analysis of large space structures, and to review recent advances in modeling, analysis, and understanding of thermal-structural responses of large space structures. Typical heat load, thermal and structural analysis requirements for large space structures will be discussed by using a design of a future large spacecraft to illustrate specific modeling and analysis characteristics. This report covers the following topics: selected design details of a spacecraft design concept--a microwave radiometer; heat load predictions for orbiting structures; important features of thermal modeling and temperature analysis; and characteristics of structural modeling and deformation analysis. Throughout the report, uncertainties in the analyses are noted and recent advances are highlighted.

SECTION II

MICROWAVE RADIOMETER SPACECRAFT

The design details of a microwave radiometer illustrate a few of the complexities of thermal-structural analysis. The microwave radiometer spacecraft (MRS) concept was employed in a NASA-sponsored study to develop a computer program for the design of Large Advanced Space Systems, LASS. In this report, the details of LASS and the microwave radiometer concept are taken from Leondis (ref. 9) and Garrett (ref. 10).

Microwave Radiometry

Passive microwave radiometry can be used in remote sensing of soil moisture to support crop forecasting. Microwave frequencies that penetrate clouds, haze, and ground cover are monitored, and a large aperture, smooth-surface antenna is required to capture and focus the low-signal Earth radiation on sensors. The resulting measurements are brightness temperatures that are functions of soil ambient temperatures and emissivity, where the emissivity is strongly dependent on soil moisture content. The proposed MRS system would be placed at orbital altitude of 650 km or more with a 60°-plus, sun-synchronous orbit inclination. The antenna would have a 725 m diameter, a focal length of 575 m, a surface accuracy of approximately 6 mm, and a pointing accuracy of 0.01 degree.

Spacecraft Details

The MRS structure and supporting systems are shown in Figure 1. The structure is a graphite composite, tetrahedral truss made from hollow tubes with a RF reflective mesh (aluminized Kapton) attached to offsets on the concave surface. Graphite composite support beams and Kevlar tension cables provide control for feed horns mounted on a graphite composite feed beam located at the focal point of the reflector. The dish is a spherical segment with the feed beam oriented normal to the spacecraft velocity vector. Truss designs may have a very large number of members and joints. A tetrahedral truss can be regarded as a collection of tetrahedra arranged about a center point to form concentric hexagons called rings. The MRS tetrahedral truss concept shown in Figure 1 is a relatively small four-ring truss with

MICROWAVE RADIOMETER

ORBIT ALT: 650km
DIAMETER: 725m TOTAL
FOCAL LENGTH: 575 m

SURFACE ACCURACY: 6mm APPROX
POINTING ACCURACY: 0.01 DEG
COEFF THERM EXPAN: 10^{-7} 1/K

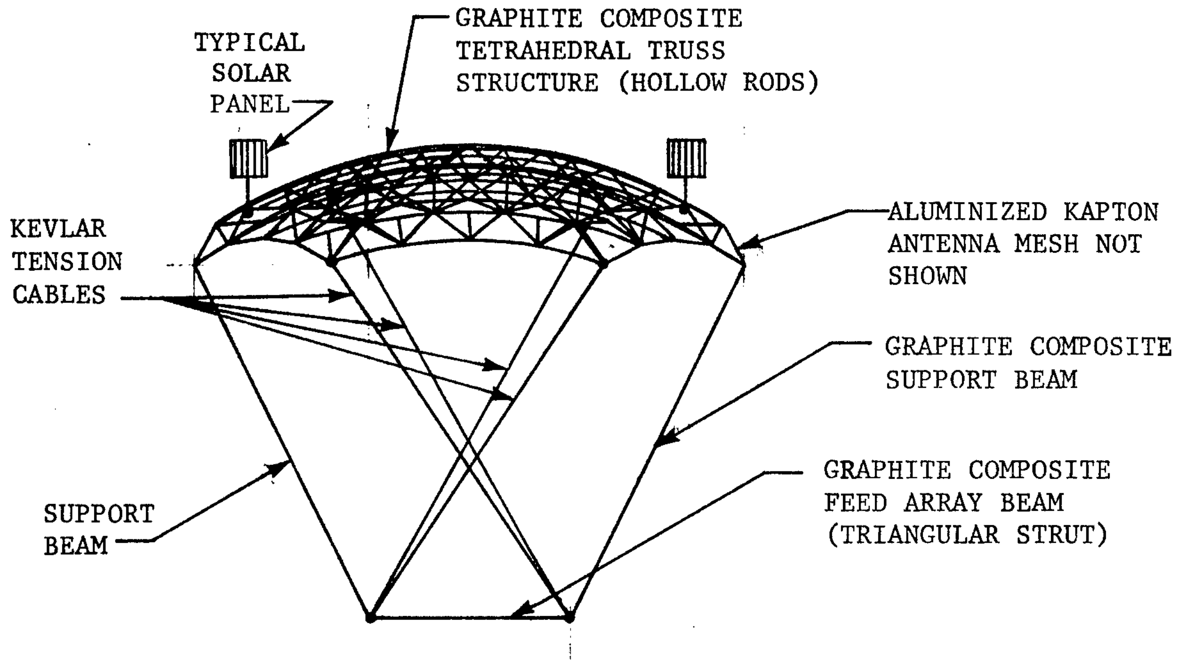

Figure 1. Microwave radiometer spacecraft, reference 10.

109 nodes and 420 members. Other concepts discussed in references 9 and 10 include more complex designs such as a 12-ring truss with 901 nodes and 3,852 members.

Altitude control is provided by an annular momentum control device and eight liquid oxygen/liquid hydrogen thrusters. The spacecraft is assumed to undergo one maneuver every five orbits with maneuver rates and accelerations of 10^{-4} rad/sec and 10^{-6} rad/sec^2, respectively. Orbital velocity makeup is provided by four larger thrusters. Three propellant tanks carry a three-year fuel supply, and the MRS is designed for a 15-year lifetime.

The MRS system is representative of many large space structures characterized by large latticework structures, pretensional cables, tubular tension and compression members, and extensive use of advanced composite materials.

SECTION III

HEATING ANALYSIS

Heat Loads

An orbiting space structure may be heated by environmental and on-board heat sources. The sun and earth are the primary environmental sources. On-board heating can come from many sources such as prime power systems, electronics equipment, and heat rejection systems.

Environmental heating rates, the sum of solar flux, earth-emitted radiation and earth-reflected radiation (albedo), depend strongly on altitude and orientation of structural members. Heating rates on members of a structure may vary significantly with member orientation and vary strongly with time during the orbit. Heating rates can be reduced by as much as 95% during spacecraft passage through the earth's shadow; hence, shadow dwell time is important. Fundamental concepts of spacecraft orbital heating are described in reference 11, and a computational procedure for predicting environmental heating on structural members is described in reference 12. Representative orbital data is tabulated in Table 1 for a geosynchronous earth orbit (GEO) and for a low earth orbit (LEO).

Table 1. Orbital Data

			TRANSIT TIME (sec)	
ORBIT	PERIOD (sec)	ALTITUDE (km)	UMBRA	PENUMBRA
GEO	86,400	35,800	4,200	130
LEO	5,400	280	2,200	8

The earth's shadow has two regions: (1) The umbra, which is totally shadowed from the sun, and (2) the penumbra, which is only partially shaded. Table 1 gives the transit times of a structure through the umbra and penumbra in GEO and LEO. Since the transient time through the penumbra is negligible compared to that through the umbra, the penumbra can be disregarded and the structure can be considered to have entered the umbra directly.

In flat truss structures there may be several members with a common orientation so that these members experience the same heating throughout the orbit. A heating analysis of a curved structure, such as the spherical MRS tetrahedral truss shown in Figure 1, must consider all members individually because there are no similarities in orientation. Mahaney and Strode (ref. 12) discuss environmental heating on an earth-facing parabolic tetrahedral truss in an ecliptic plane orbit, and two results (Figures 2 and 3) may be used to illustrate details of structural heating rates.

Figure 2 presents heating histories of four members on the main diagonal of a parabolic truss in GEO. The heating behavior can be explained by considering a typical member such as member 3. The heating of member 3 is almost a maximum at the satellite noon position ($t = 0$) since the member is nearly perpendicular to the solar flux. As the truss orbits the earth, the member changes orientation and the heating decreases until, at almost 90 degrees, the member is nearly parallel to the solar flux vector and the heating is almost zero. As the truss motion continues, member 3 changes orientation, and the heating increases until the truss enters the earth's shadow at 171.3 degrees. During shadow transit the member receives only earth emission heating, about 8.25 W/m^2. At 188.7 degrees the structure leaves the earth's shadow, and the heating increases instantly (because the penumbra is neglected) to 1273 W/m^2. As the orbit continues, the heating decreases as before. While the above description is for member 3, the other members behave similarly. Figure 2 shows the heating histories of other members which vary from member to member since their orientations are slightly different. Figure 3 presents the heating histories of the same four members in LEO. There are two major differences: (1) The magnitude of the heating is greater because this orbit is closer to the earth (earth-emitted heating is 332 W/m^2 in LEO versus 8 W/m^2 in GEO, and albedo heating has a maximum of 420 W/m^2 in LEO versus 10 W/m^2 in GEO); and (2) shadow transit covers about 41% of the orbit in LEO versus only about 4.8% in GEO.

On-board heating may be more important than environmental heating in future large space structure thermal-structural effects. The Air Force Office of Scientific Research (AFOSR) is initiating research for the

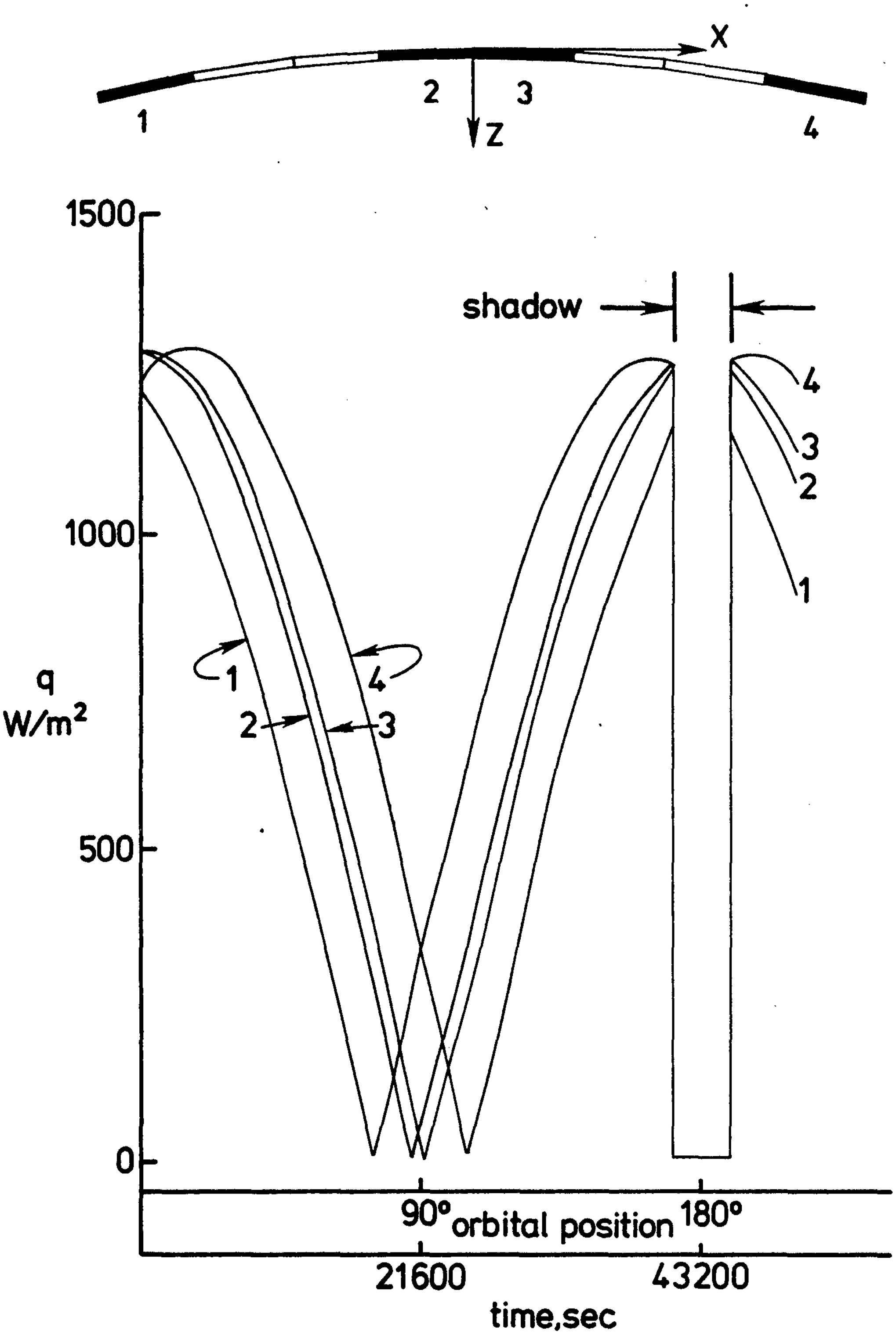

Figure 2. Heating histories for parabolic truss in GEO, reference 12.

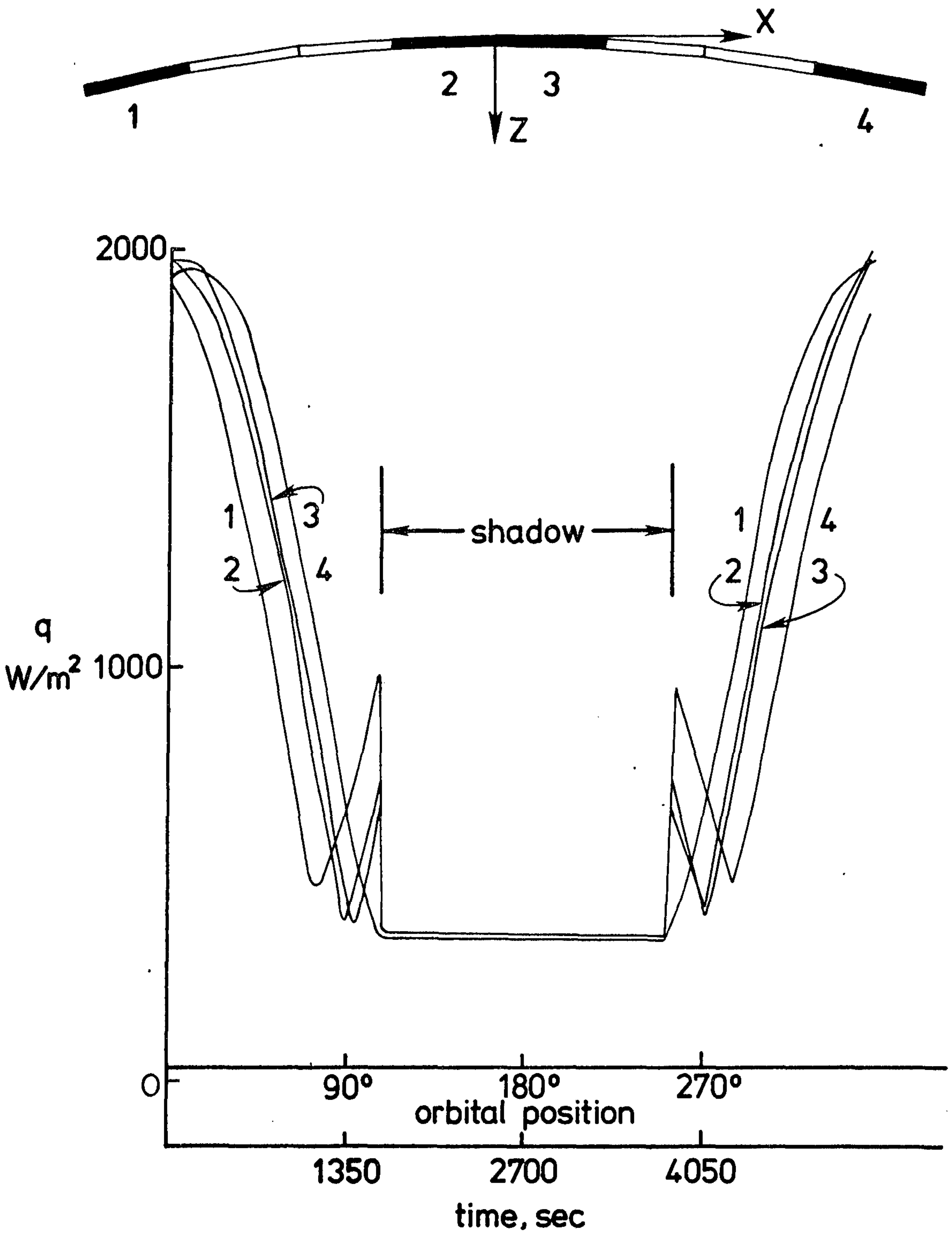

Figure 3. Heating histories for parabolic truss in LEO, reference 12.

development of new prime power sources for high-energy space systems. A conference held in Norfolk, Virginia in February 1981 (ref. 13) indicated the need for the development of prime power systems of 10- to 100-kW output. Thermal management of waste heat could have a more significant effect than environmental heating because of higher levels of the on-board heating, and because heating distributions from on-board heat sources will be more localized. There has been very little published research on the effect of on-board heating. One study of a two-tier flat truss structure in LEO (ref. 14) showed that without on-board heating there was no appreciable curvature of the truss, but non-uniform, on-board heating of the truss induced small truss curvatures.

Shadowing Effects

For large space structures like the MRS system (Figure 1) there are three types of shadowing effects: Shadowing of the structure by opaque surfaces such as the solar panels; partial shadowing by large semi-transparent surfaces such as the antenna mesh; and shadowing of structural members by slender, opaque up-sun structural members. Detailed consideration of any of these shadowing effects is difficult because of the complex geometry involved and the time-dependent character of the problem. Few results have been published on the effects of shadowing the structure with opaque surfaces such as solar panels. The consideration of such effects is closely related to the conduction-radiation heat transfer problem and can be handled (presumably) by available computer programs such as TRASYS. An annotated list of structural heat transfer programs appears in reference 15. Partial shadowing of large space structures by antenna meshes is discussed in references 9 and 16. These analysts use a mesh transmissivity that depends on mesh characteristics (e.g., openings per inch) and the angle of incidence between the heating vector and the mesh normal. Chambers, Jensen, and Coyner (ref. 16) show a mesh transmissivity variation for a wire mesh with 14 openings per inch. It indicates that for angles of incidence less than 60° about 90% of incident heating is transmitted but for angles of incidences between 60° and 90° the transmissivity drops very sharply to zero. Thus the mesh can cause complete shadowing of the structure at points during an orbit, and a detailed consideration of mesh shadowing is critical for defining structural heating.

Consideration of shadowing by slender, opaque up-sun structural members has been customarily omitted in latticework structures such as trusses. This assumption has been questioned (ref. 17) particularly for nearly planar, earth-facing structures. For these structures, significant shadowing can occur when the solar vector is nearly tangent to the orbital path. O'Neill and Zich (ref. 17) describe a computer program developed to quantify the complex solar shadowing inherent in lattice-type structures. The program computes incident heat fluxes at specified points on each member considering partial shadowing of adjacent members. The effects of slender-member shadowing at a typical point on a truss member are illustrated by the temperature history shown in Figure 4. The numerous short-duration drops in temperature indicate the passage of shadows of adjacent truss members. The large, longer-duration temperature drop near the center of the history denotes passage through the earth's shadow. The process of predicting the details of slender-member shadowing effects is quite complex and therefore is expensive for a truss with hundreds of members. There is an important question which deserves study: Is the consideration of slender-member shadowing effects required for accurate prediction of structural deformations?

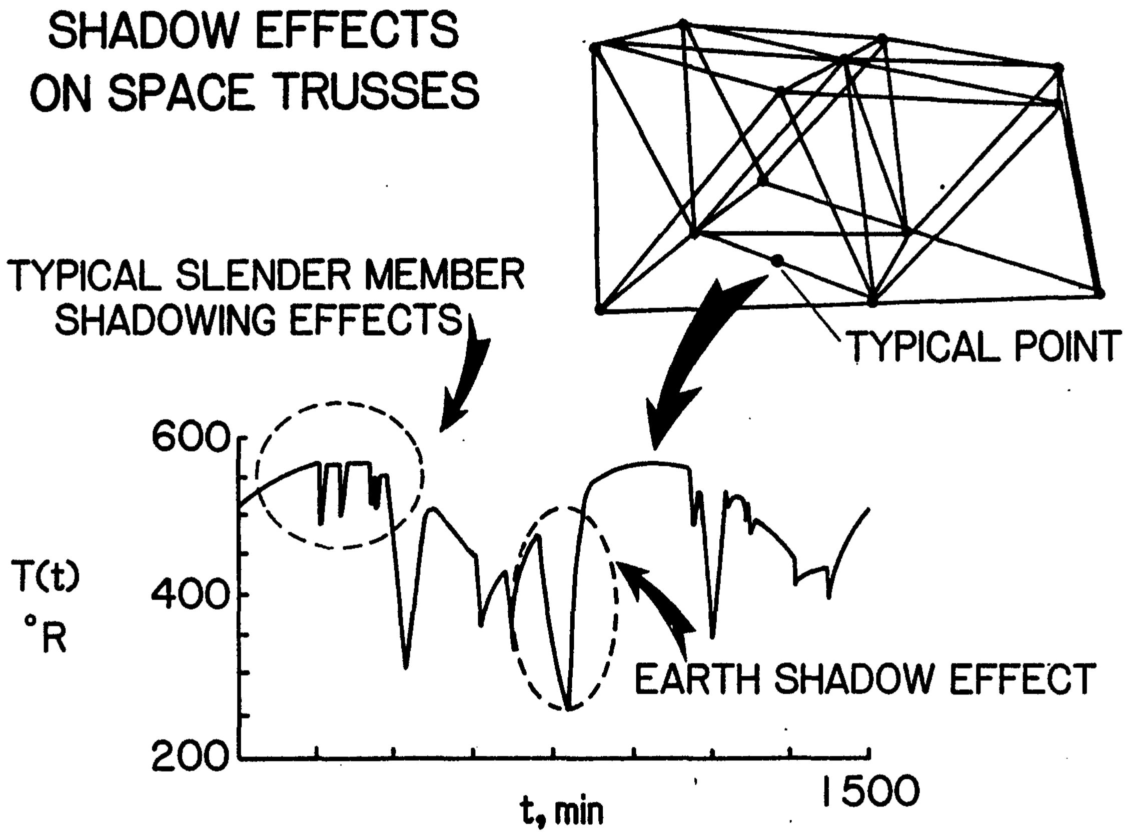

Figure 4. Slender member shadowing effects at a typical point in a space truss, reference 17.

SECTION IV

THERMAL ANALYSIS

A typical member of a space structure experiences conduction heat transfer combined with radiation heat exchanges from nearby structural members and other spacecraft components. The discussion herein is limited to the unique thermal analysis problems of large latticework structures such as the MRS shown in Figure 1.

Thermal Modeling

In an open latticework structure, radiation exchanges between members can be neglected in comparison to incident heating and emitted radiation. Chambers et al. (ref. 16) show that the view factor between two nearby members in an open structure is typically less than 0.001, indicating that almost all of the radiant energy emitted by a member is lost to space. In general, structural members' temperatures vary along their lengths and around their perimeters. Most truss members are hollow rods (tubes) and internal radiation may be significant. Taking all of these details into account, thermal analysis of a large truss is impractical because of the prohibitively large number of unknowns required. Consequently, a number of simplifying assumptions are customarily made to permit thermal analysis at acceptable costs. Simplified thermal models are discussed in references 7, 16, and 18-20. In the following discussion, models for bare members or members with surface coatings are considered; modeling considerations for insulated or shielded members are discussed by Brogren, Barclay, and Straayer (ref. 7).

Structural-member temperature distributions depend strongly on material and surface properties. In general, material and surface properties are temperature-dependent and vary throughout the orbit. Representative properties (ref. 7) shown in Table 2 indicate the temperature dependence of the thermal conductivity and specific heat for two typical structural materials: aluminum and graphite epoxy. Thermal properties of composite materials such as graphite-epoxy are difficult to measure and not readily available. In

Table 2. Thermal properties of large space structures (ref. 7).

ALUMINUM

6061 T-6 WITH HEAVILY ANODIZED SURFACE

TEMP. (K)	THERM. COND. (W/m-K)	SPECIFIC HEAT [kJ/(kg K)]
0	74.72	.004197
20	224.20	.012560
30	194.30	.041870
90	190.50	.439600
200	160.00	.741100
260	152.00	.821400
300	151.90	.875000
370	160.30	.936100
420	162.50	.979700
480	165.10	1.005000
530	167.40	1.026000
590	168.90	1.044000
640	170.00	1.076000
700	171.90	1.114000

$\rho = 2713 \text{ kg/m}^3$

$\alpha_s = 0.42$

$\varepsilon = 0.84$

GRAPHITE-EPOXY COMPOSITE

60% FIBER VOLUME; 50% AXIAL PLIES, 50% ±45° PLIES

TEMP. (K)	CIRCUMFERENTIAL THERM. COND. (W/m-K)	SPECIFIC HEAT [kJ/(kg K)]
0	~0	.000419
120	3.884	.338000
170	5.993	.479000
220	8.032	.620000
270	9.714	.783000
330	10.140	.976000
400	11.140	1.080000
810	16.980	1.660000

$\rho = 1633 \text{ kg/m}^3$

$\alpha_s = .916$

$\varepsilon = .80$

addition, little information is available about the stability of these properties in long-duration exposure to the hostile environment of space.

Table 2 shows that the thermal conductivity of aluminum is much higher than the thermal conductivity of the graphite-epoxy composite material. Temperature distributions in members made from these materials differ significantly, and these differences have an important effect upon the required analytical models. For instance, Brogren, Barclay, and Straayer (ref. 7) show that the temperature variation around the perimeter of an aluminum tube (ratio of outside diameter to wall thickness = 25) subject to solar heating in LEO is negligible. However, they show that the temperature variation around the perimeter of a graphite-epoxy tube (ratio of outside diameter to wall thickness = 100) is significant. At a typical point in LEO, the temperature of the side of a tube exposed to solar heating was 352 K while the shaded side of the tube registered 262 K.

In addition to the temperature variation around the tube perimeter, member temperatures may vary along their length due to axial conduction. For trusses, a member's mean temperature can be denoted as $T(x,t)$ where x is an axial coordinate and t is time. The mean temperature satisfies the energy balance equation:

$$- \frac{\partial}{\partial x}\left[kA \frac{\partial T}{\partial x}\right] + \sigma \varepsilon T^4 p + \rho c A \frac{\partial T}{\partial t} = a p_q q(t) \tag{1}$$

where k is the thermal conductivity, A is the cross-sectional area, σ is the Stefan-Boltzmann constant, ε is the emissivity, and p is the member radiation perimeter; ρ is the density, c is the specific heat, a is the surface absorptivity, p_q is the projected perimeter for incident heating and $q(t)$ is the incident heating rate. Equation (1) shows that a member's axial temperature variation depends on the combination of conduction and radiation heat transfer. In references 18-20, there are studies of typical truss-member temperature distribution using the finite-element method. Temperature distributions of aluminum- and graphite-epoxy composite members differ significantly. Aluminum members have a more nonuniform temperature distribution than composite material members. Temperature distributions along composite members are so nearly uniform that if joints are neglected it is valid to assume that a single truss member is isothermal. With the finite element approach (refs. 18 and 19), one isothermal finite element per member can be used, or with the finite difference network-type approach (refs. 9 and 16), each member can be represented as a single node. In both cases, the conduction term can be neglected in equation 1 to yield an ordinary differential equation for each member:

$$\sigma \varepsilon T^4 p + \rho c A \frac{dT}{dt} = a p_q q(t) \tag{2}$$

where the temperature is a function only of time, T(t). Thus, for trusses with composite members, each member's mean temperature can be computed separately by solving equation 2. Temperatures in a truss with composite members can be computed easier than in a truss with aluminum members where each member's spatial temperature distribution must be computed. Equation 2 can be solved in closed-form (ref. 17) to yield a transcendental equation which is solved by Newton-Raphson iteration or can be solved by a combination of finite differencing in time and Newton-Raphson iteration (refs. 18-20).

The isothermal concept is widely used for preliminary design analysis of large space structures such as the MRS system. Chambers, Jensen, and Coyner, (ref. 16) modify the radiation term in equation 2 with a correction factor to account for heat conduction around the tube perimeter; graphs of correcton factors for cylindrical and square tubes are given versus a characteristic tube parameter. Chambers et al. also describe an approximate method of computing the diametrical temperature difference due to perimeter heat conduction and interior radiation heat transfer. Calculation of these temperature gradients is important in determining bending deflections that result in a reduction of the structural-member column buckling allowable load. Temperature distributions in the cross-section of laminated composite tubes may also be important for the long-term fatigue behavior of the composite, but little research has been performed to evaluate this effect.

Thermal Response

As the preceding paragraph indicates, the space structure material determines the required thermal model and may determine the method of computing the thermal response. Certainly for all-composite material structures, the isothermal-member model is an excellent approximation and leads to an uncoupled thermal-analysis approach where equation 2 is solved separately for each member. For a metallic structure or a non-homogenous structure with both metallic and composite members (e.g., joints), a more general analysis is required to determine member spatial-temperature distributions as a function of time. In general, a set of coupled, nonlinear equations of the form

$$[C(T)]\{\frac{dT}{dt}\} + [K(T)]\{T\} = \{Q(t)\} \tag{3}$$

is solved for the temperatures $\{T(t)\}$ at discrete nodal points in the structure. The coefficient matrices [C(T)] and [K(T)] contain the structures' capacitance and conductance properties and depend on the nodal temperatures. The vector {Q(t)} represents time-dependent nodal heat loads. The coefficient matrices may be formed from either a finite-difference network-type model or a finite element model. Nonlinear, time-dependent equations such as equation 3 are typically solved by finite differencing in time.

To illustrate characteristics of large space structures' thermal response, Figures 5-8 present results of analyses of aluminum and graphite-epoxy trusses. A three-member module of an orbiting truss (Figure 5) is useful for illustrating temperature distributions in aluminum members. The temperature distribution on the members at a typical point in a GEO is shown in Figure 6. The solid line computed with a refined mesh of ten conventional finite elements per member represents typical aluminum-member temperature distributions. The other curves shown in Figure 6 represent temperature distributions computed using three different finite element models as a part of a study (ref. 20) focused on the development of more efficient thermal finite elements.

Transient temperature histories for four members of a graphite-epoxy tetrahedral truss are shown in Figures 7 and 8. The temperature histories shown in these figures were computed using the isothermal member concept, and they correspond to the heating histories for the same members shown in Figures 2 and 3. Figure 7 presents the temperature histories of four members on the main diagonal of a parabolic truss in GEO. Notice the similarity between heating histories in Figure 2 and the temperature histories. This similarity occurs because the members change orientation slowly with respect to the solar flux. The slow change in heating, coupled

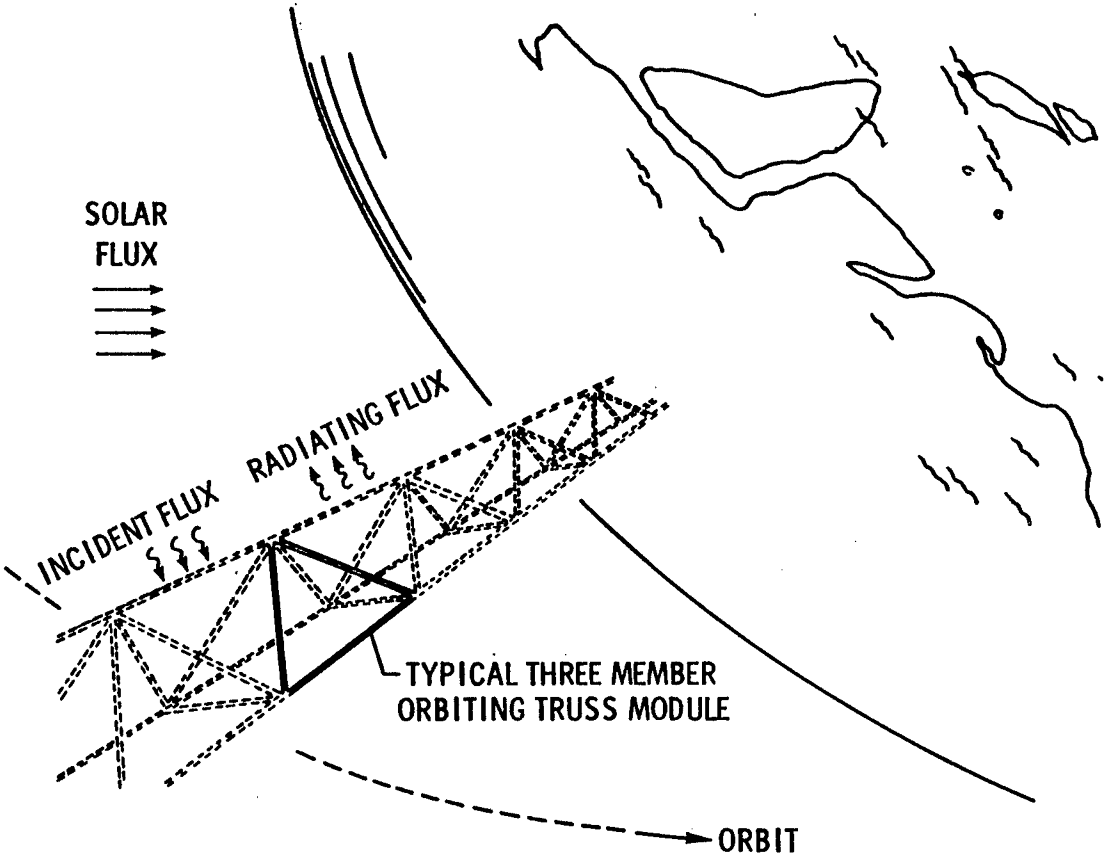

Figure 5. Orbiting truss space structure, reference 20.

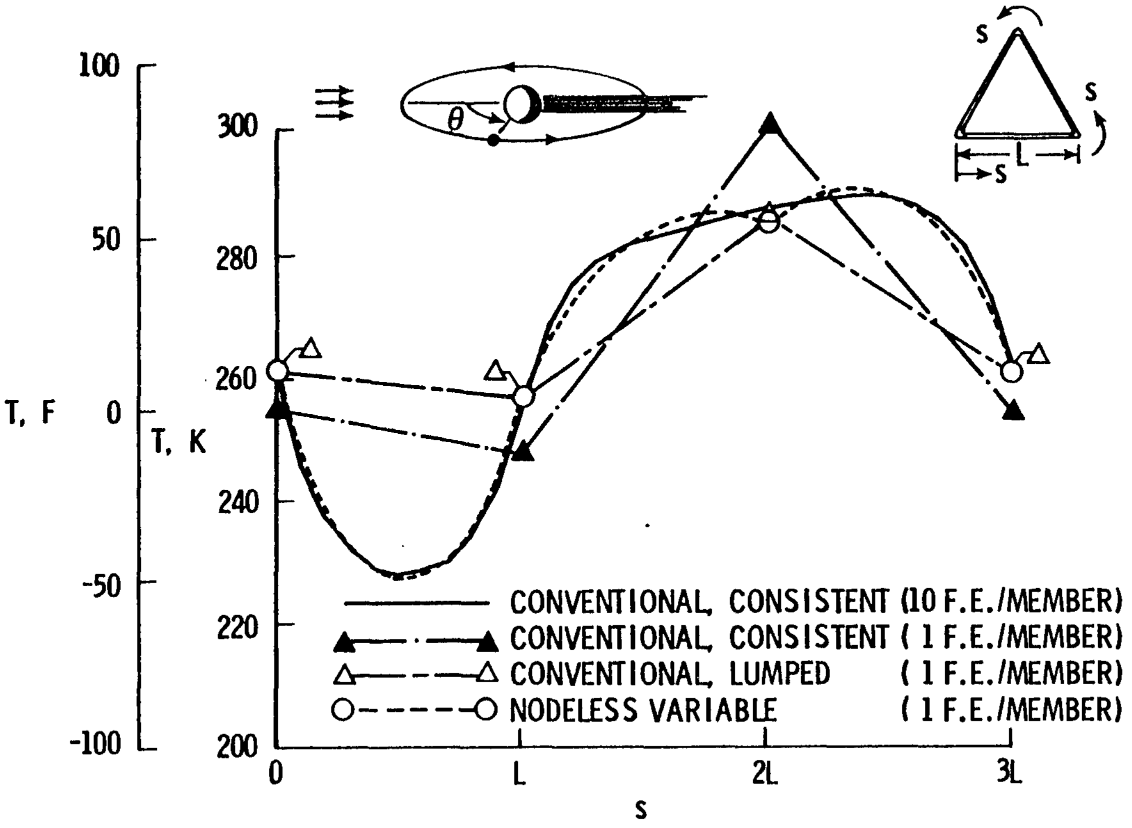

Figure 6. Comparative temperature distribution of a three member orbiting truss at θ = 60 degrees, reference 20.

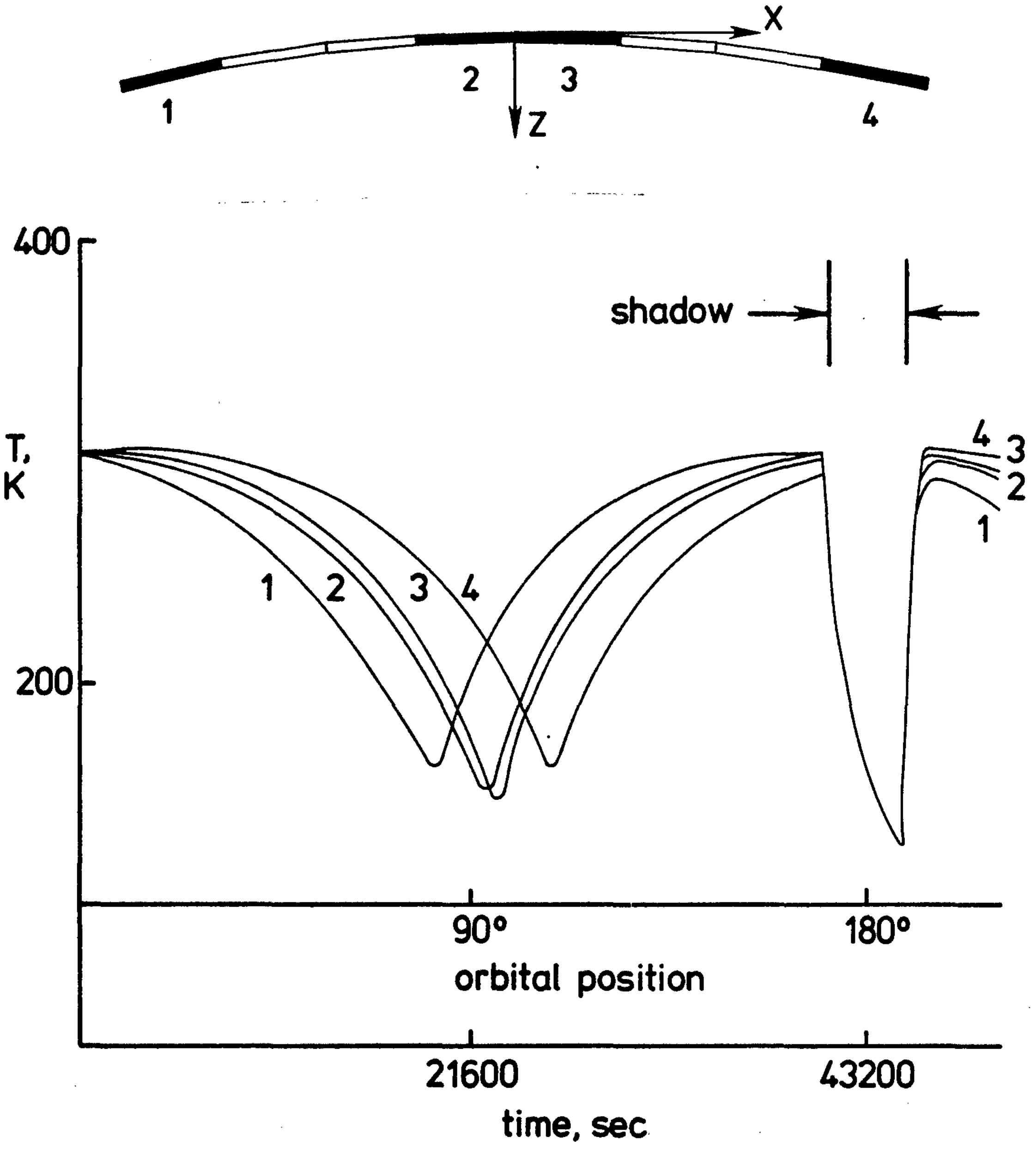

Figure 7. Temperature histories for parabolic truss in GEO, reference 12.

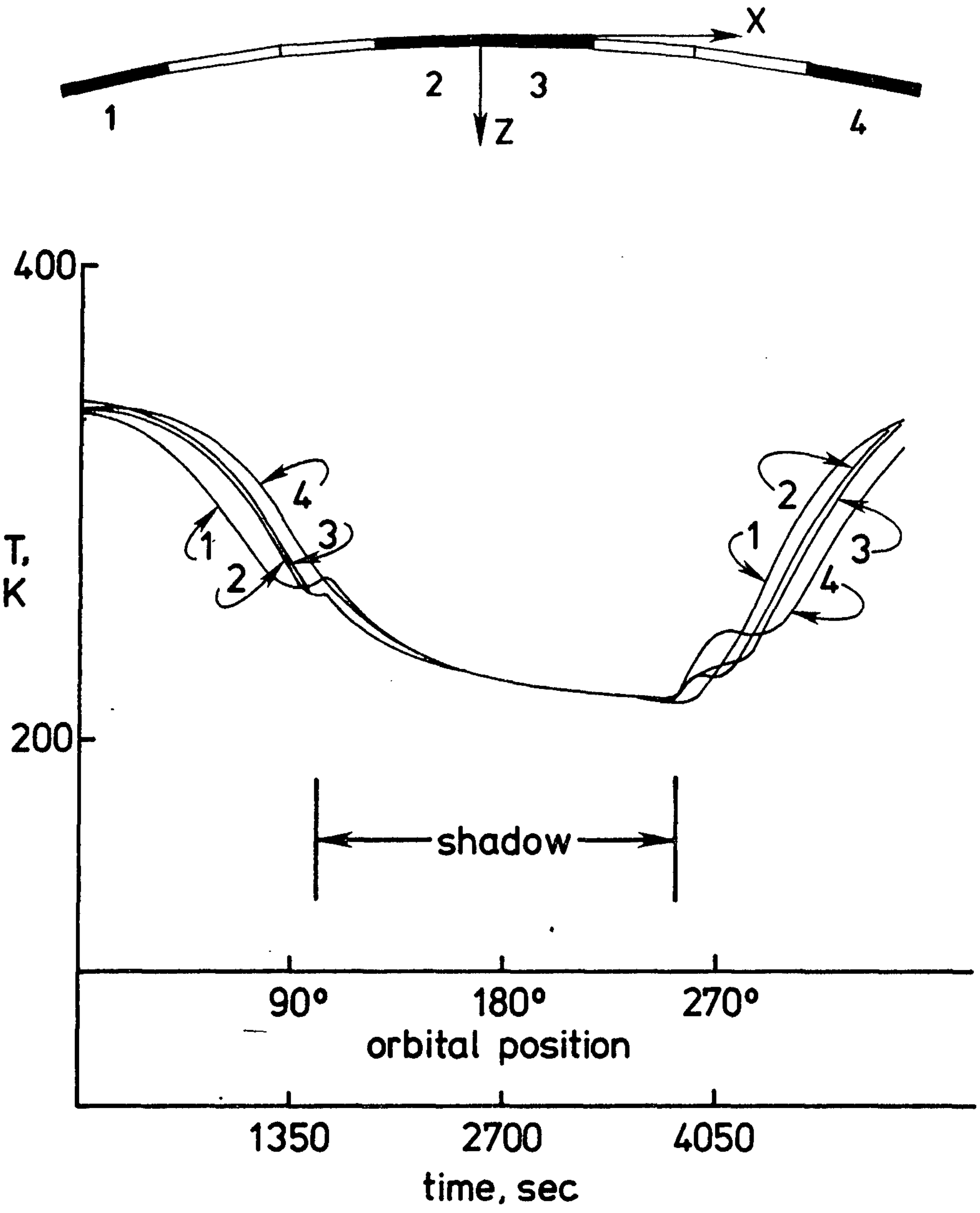

Figure 8. Temperature histories for parabolic truss in LEO, reference 12.

with the low thermal mass and large emissivity of the members means that truss members stay very close to radiation equilibrium temperature thoughout most of the orbit. The exception to this behavior is in the earth's shadow. When the heating falls off suddenly upon shadow entry, member temperatures fall quickly because of their low thermal mass to approach a new, much lower radiation equilibrium temperature. Upon shadow exit, the abrupt rise in heating causes a corresponding rise in temperature on the order of 0.2 K/sec (0.36 F/sec).

Figure 8 presents the temperature histories of the same four members in LEO. As before, the temperature histories are similar to the heating histories; however, there are two important differences. First, in LEO the truss is never at radiation equilibrium. Radiation equilibrium is not achieved because the shorter orbital period causes the heating rates to change much faster. Thus the transient term in equation 2 has a much greater effect in LEO than in GEO. Secondly, the much greater heating of the earth increases the magnitude of the temperatures, but it also moderates temperature excursions.

Other advances in thermal modeling and analysis of spacecraft and satellite antennas, in addition to those of latticework structures appear in references 21-23, papers from the AIAA 16th Thermophysics Conference.

SECTION V

STRUCTURAL ANALYSIS

In most analyses of the thermal-structural responses of orbiting large space structures, the thermal input is regarded as a known function of time. This approach, based on uncoupled analyses, assumes that structural deformations are small enough that absorbed heating and temperature distributions are unaltered by the structural deformations. In uncoupled thermal-structural analyses, structural deformations and stresses are determined as the final step in a sequential computation of heat loads, thermal response, and structural response. In some problems, however, structural deformations may be large enough to alter heat loads and temperature distributions, requiring a coupled thermal-structural analysis. The following discussion first considers uncoupled thermal-structural analyses. Then a brief review of thermally induced vibrations describes current research in coupled thermal-structural problems.

Structural Modeling

The thermal structural response of a complex space structure like the MRS system shown in Figure 1 is usually computed from a finite element model. The complete structure is represented as an assembly of elements chosen to represent the structural characteristics of the beams, cables, and truss members. The thermal environment affects the structural analysis in two ways: (1) the structure's material properties may be temperature-dependent, and (2) equivalent thermal forces and moments depend on integration of the temperature distributions over member volumes. Two types of structural models have been considered: Discrete models in which finite elements are used to represent structural members in detail, and continuum models which replace a lattice-type structure with repetitive geometry by an equivalent elastic continuum such as a beam or a plate.

The discrete model approach gives the best representation of the space structure's mass, stiffness, and equivalent thermal loads. A number of general purpose programs such as NASTRAN, SPAR, or SAP are available to perform such analyses. With the exception of pretensioned cables and membranes, major structural components like trusses and beams exhibit linear behavior and can be analyzed effectively using available finite elements. However, pretensioned cables and membranes are known to have significant nonlinear force-deflection characteristics and warrant nonlinear analysis (refs. 24 and 25). Little information is available on effective modeling methods for these structural components either in the isothermal state or with thermal effects. A recent study of isothermal vibrations and buckling of a pretensioned cable-stayed column (ref. 26) showed that: (1) experimental verification of analytical models is difficult; (2) structural imperfections are important; (3) dynamic loading affects the required pretension; and (4) stay (cable) slackening may produce significant nonlinearities. There is a clear need for further study of cable and membrane behavior in large space structures particularly in the presence of the thermal environment.

Using the discrete finite-element model approach for a large space structure can lead to analytical models with a large number of nodes. However, structural mass and stiffness matrices are highly banded, and computational costs may be acceptable. Mahaney and Strode (ref. 12) show for tetrahedral trusses that matrix semi-bandwidth is of the order of ten percent of the number of nodal unknowns.

Continuum models (refs. 27 and 28) have been developed as a practical solution method for overall response and preliminary design studies. The continuum models are shear flexible beams and plates. Equivalent elastic constants are developed for the continuum models in terms of material properties and geometry of the original lattice structure. For overall isothermal structural behavior such as vibration and buckling, continuum models give excellent agreement in numerical examples for beam- and plate-like lattice grids. The accuracy of the approach for more realistic space structures has not been evaluated. In realistic large space structures with thermal loads, there are a number of effects that limit the usefulness of continuum models. For instance, in a dished lattice-type structure, temperatures vary significantly from member to member and with time as the structure continuously changes its orientation with the solar vector. Consideration of this type of temperature distribution and local temperature dependence of material properties is beyond the capability of continuum models. Nevertheless, continuum models are useful in preliminary design;

the LASS program (ref. 10) uses the concept of an analogous structure based on continuum modeling to reduce the cost of structural analysis.

Material Properties

Advanced composite materials are widely used in large space structures because of their high stiffness and low coefficients of thermal expansion (CTE). Reliable material data is a prerequisite to accurate thermal-structural response predictions. The determination of this data for advanced composites in the space environment is difficult and is the subject of current research. The major environmental parameters in the space environment are low pressure (high vacuum), ultraviolet radiation, ionizing radiation, and thermal cycling. References 29-33 describe these environmental effects and present recent advances in measurement of the CTE and the effects of space environment. The CTE of a composite member depends on the laminate layup and the material properties of individual lamina. Johnson, Kural, and Mackey (ref. 34) present a compilation of CTE data for composite materials, and a procedure for computation of lamina properties by lamination theory. The temperature variation of the longitudinal CTE for a graphite-epoxy tube laminate is shown in Figure 9. For this material, temperature dependence affects the low-temperature response of the member. The stability of structural material properties in a long-term space environment is not well understood. Experiments described in reference 31 indicate that significant changes occur in CTE because of the combined effects of vacuum and thermal cycling. There is a clear need for continued materials research to further the understanding of this kind of behavior in the space environment.

Structural Response

In an uncoupled thermal-structural response analysis using a discrete model, the large space structure displacement response $\{u(t)\}$ is computed from the general structural dynamics equation of motion:

$$[M]\{\ddot{u}\} + [C_d]\{\dot{u}\} + [K]\{u\} = \{F_T(t)\} \tag{4}$$

where $[M]$ is the mass matrix, $[C_d]$ is the damping matrix, $[K]$ is the stiffness matrix and $\{F_T(t)\}$ are the equivalent nodal forces due to the

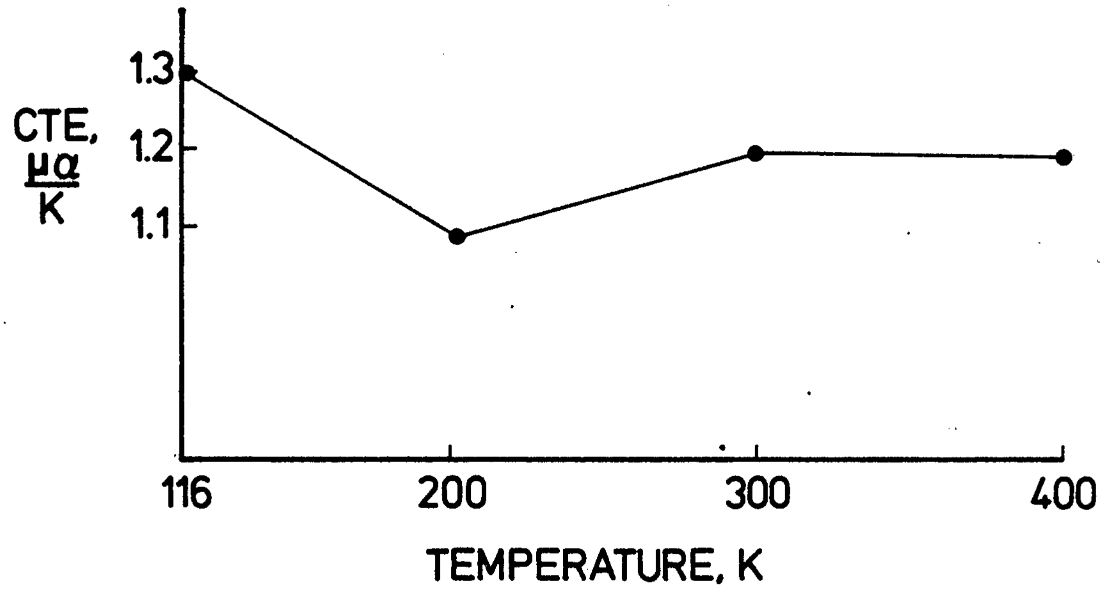

Figure 9. Temperature dependent coefficient of thermal expansion for T300/5208 graphite epoxy ($90/0_4/90$) laminate, reference 12.

time-dependent member temperature distributions. The mass matrix is independent of temperature, but the damping and stiffness matrices are implicit functions of temperature because of temperature dependence of material properties. Thus, in numerical solutions to equation (4) these matrices must be updated periodically to account for temperature variations throughout the orbit. Most thermal-structural analyses of large space structures neglect the dynamics effects in equation (4) to use a quasi-static response analysis defined by:

$$[K]\{u\} = \{F_T(t)\} \tag{5}$$

and perform a sequence of static analyses at selected points in the transient thermal response. The solution of equation (5) requires significantly less computational effort than the solution of equation (4) and is a permissible approximation provided that thermally-induced oscillations do not occur. Thermally induced oscillations and coupled thermal-structural analyses will be discussed in the next section.

To illustrate characteristics of the structural response of a large space structure, typical deformations of a 43-m diameter parabolic tetrahedral truss (Figure 10) are shown in Figures 11 and 12. The transient thermal-structural response was computed quasi-statically (ref. 12) for the 109-node, 420-element truss in GEO using the temperature histories shown in Figure 7.

Structural response may be characterized by the change in diameter of the truss, by a shear deformation between the faces, and by out-of-plane distortions of the faces. Figure 11 shows the change in diameter of the diagonal of the parabolic truss in GEO. The change in diameter follows the temperature histories in Figure 7. For instance, as the members cool during the part of the orbit from 0 degrees to 90 degrees, the diameter of the truss decreases. Then, as the members heat from 90 degrees to shadow entry, truss diameter returns to its undeformed length. When member temperatures fall abruptly after shadow entry, truss diameter decreases abruptly. Then at shadow exit member temperatures rise and truss diameter returns once again to its undeformed length. Figure 12 presents the shear deformation of the parabolic truss. The shearing deformation is computed from the displacements u_1 and u_2 of two joints (Figure 12), and the two faces of the

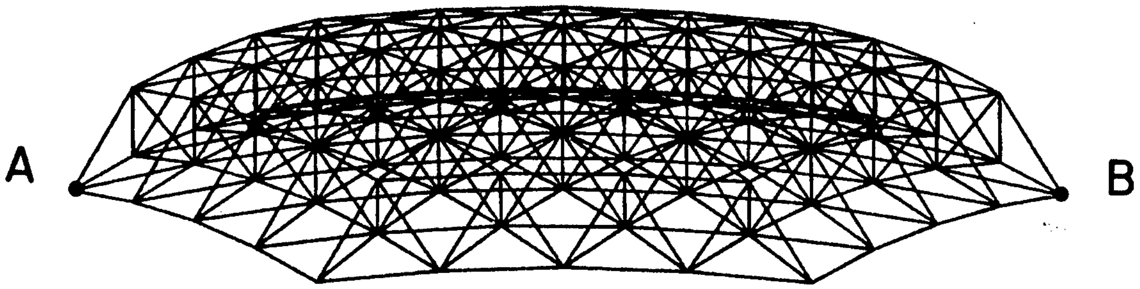

Figure 10. Parabolic tetrahedral truss, reference 12.

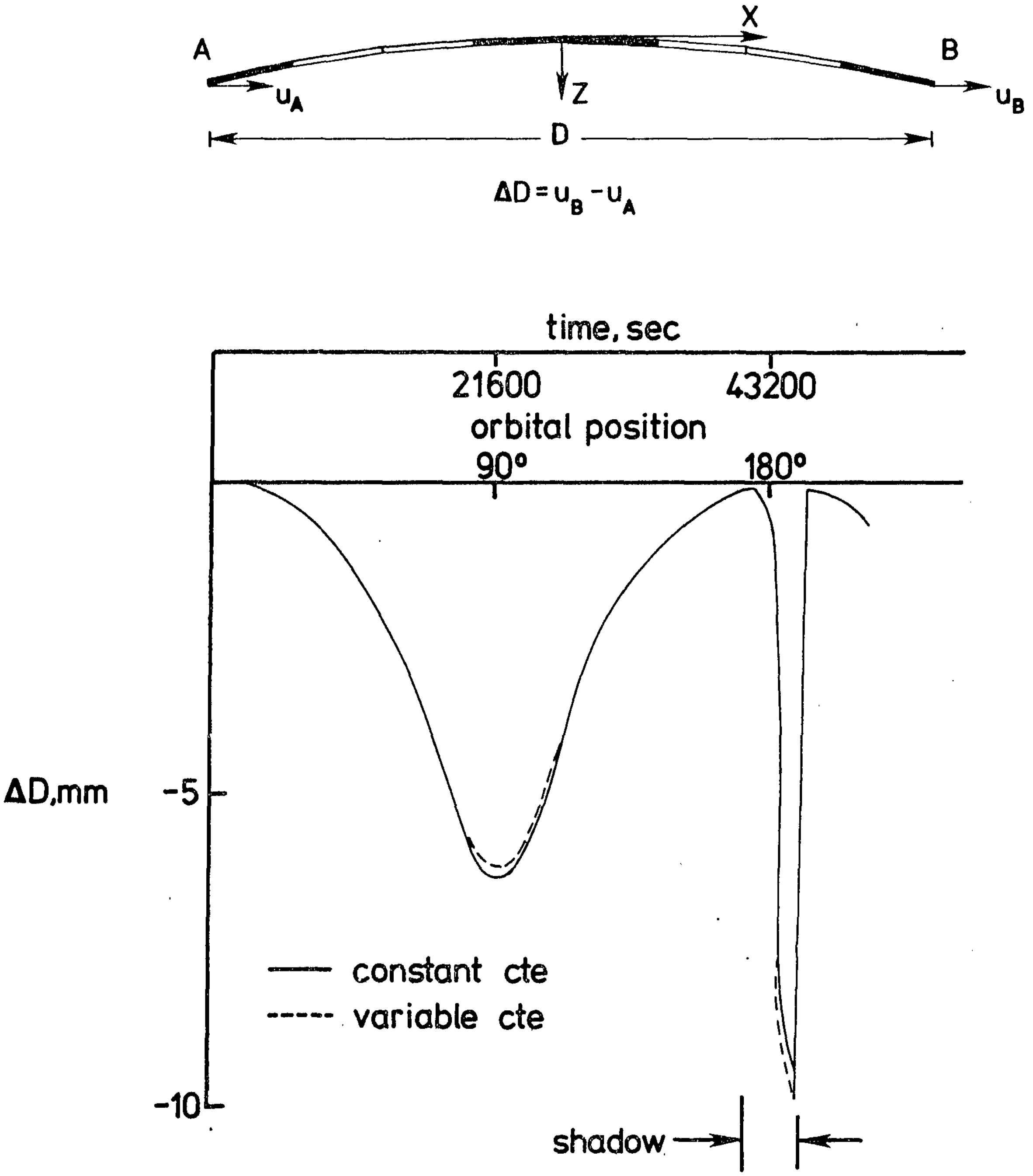

Figure 11. Truss change in diameter history, reference 12.

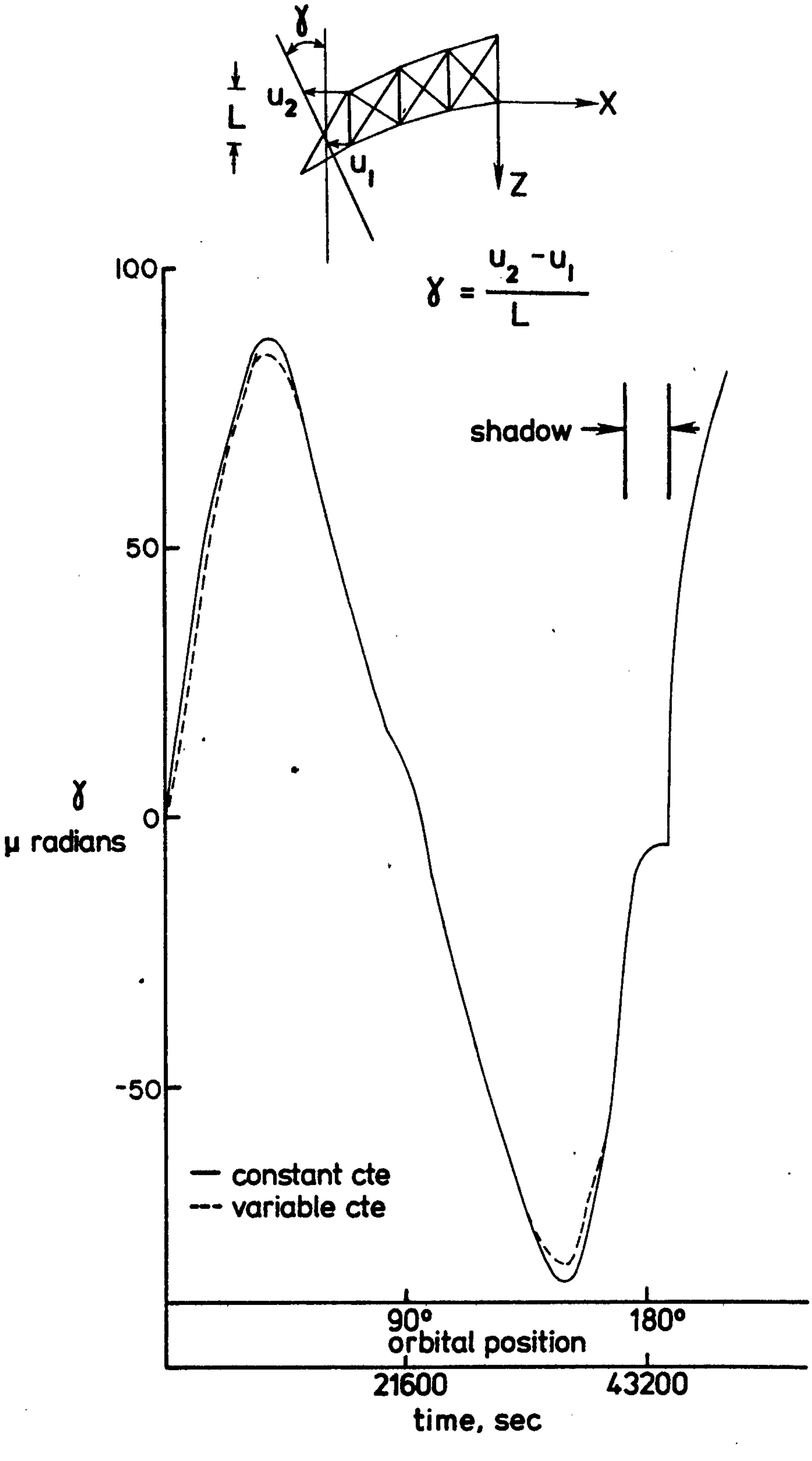

Figure 12. Truss shearing deformation history, reference 12.

truss shear with respect to each other because of changes in length of the core members. As the faces of the parabolic truss shear, they experience an out-of-plane distortion. The maximum normal nodal displacement was about 1 mm; the maximum root mean square (RMS) out-of-plane distortion was 0.6 mm. In contrast, a flat truss exhibits no out-of-plane surface distortion. As the structure orbits, the deformation of the core members causes the faces to shear with respect to each other, but the faces remain perfectly flat.

A basic question in thermal structural-response analyses is the sensitivity of the deformations to errors in the structure's material properties. Some insight into deformation sensitivity to material properties can be gained by considering a flat tetrahedral truss in GEO. In this orbit, temperature computations show that members are at radiation equilibrium temperature except at orbit positions where solar heating passes through a minimum and temperatures are changing rapidly. Figure 7 shows that these rapid changes occur at 90, 180, and 270 degrees (not shown) in the orbit, but at other orbital positions temperatures change slowly and are quite close to radiation equilibrium. In addition, displacement computations (ref. 12) have shown that the change in diameter of a flat truss can be calculated exactly by modeling the truss with one member of length equal to the truss diameter. From equation (2) we can write the radiation equilibrium temperature T_e as:

$$T_e = \left[\frac{a p_q q(t)}{\sigma \varepsilon p}\right]^{1/4} \tag{6}$$

and from solid mechanics the member diameter change ΔD is:

$$\Delta D = \alpha D(T_e - T_o) \tag{7}$$

where α is the CTE, D is the diameter, and T_o is a reference temperature. Equations (6) and (7) provide a simple approach for estimating truss diameter change throughout most of the orbit. Figure 13 compares the change in diameter AB of a flat truss of the same diameter as the parabolic truss shown in Figure 10. The diameter change computed from the rigorous approach in equations (2) and (5) is compared to the diameter change

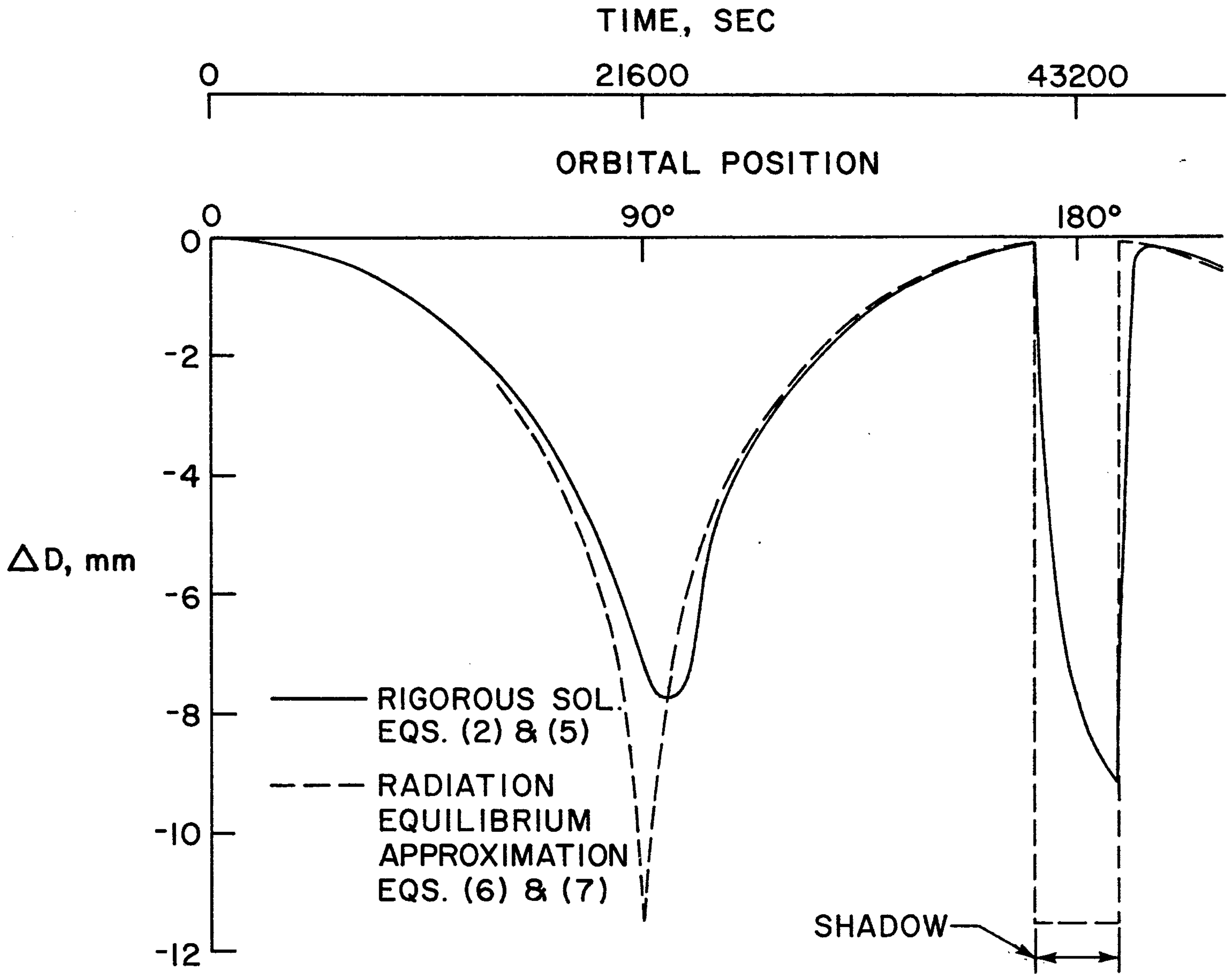

Figure 13. Change in diameter of flat truss in GEO.

computed in equations (6) and (7). The results show good agreement for most orbital positions.

The radiation equilibrium approach identifies controlling material properties for structural deformation in GEO. The important parameters are a, the absorptivity for solar radiation; ε, the surface emissivity; and α, the coefficient of thermal expansion. Other parameters such as the thermal conductivity, specific heat, and modulus of elasticity do not appear in equations (6) and (7) and do not appreciably affect member deformations. From equations (6) and (7) it is possible to evaluate the sensitivity of the deformation ΔD to errors in a, ε, and α. Differentiating the equations with respect to each parameter and using the chain rule for partial derivatives show that the (RMS) error in the deformation ΔD expressed as a ratio ω_D is:

$$\omega_D = \left[\omega_\alpha^2 + \frac{1}{4}(\omega_a^2 + \omega_\varepsilon^2)\right]^{1/2} \tag{8}$$

where ω_α is the error in the CTE, ω_a is the error in absorptivity, and ω_ε is the error in the emissivity. Equation (8) shows for equal errors in the parameters that the CTE error is the dominant parameter. For a 10% error in each parameter, the error in the computed deformation is about 12% which demonstrates the dominance of the CTE.

Thermally-Induced Vibrations

Thermally-induced vibrations of beams and plates were studied by classical analytical methods from 1956-1958 (ref. 35). The studies showed that structural inertia assumes importance only in exceptional cases, and that for most analyses inertia effects may be disregarded to permit quasi-static, thermal-structural analyses. Very thin beams and flat plates were the exceptions. For these structural components, thermal shock introduced structural vibrations with amplitudes up to twice the corresponding quasi-static deflection. A measure of the potential for thermally-induced vibrations was identified as:

$$B = \left[\frac{t_T}{t_M}\right]^{1/2} \tag{9}$$

where t_T is a characteristic time of the structure's temperature response and t_M is a characteristic time of the structure's displacement response. For heat conduction problems, the characteristic thermal response time is defined by $t_T = L^2/\kappa$ where L is a characteristic length and κ is the material thermal diffusivity. The characteristic structural response time is one of the structure's vibration periods. The classical studies showed that thermally-induced vibrations occur when the ratio B is about one.

Thermally-induced vibrations of space structures became known during the flight of the OGO-IV spacecraft in the 1960s. On that flight a 18-m (60-ft.) experiment boom sustained a solar-induced large amplitude oscillation which severely compromised spacecraft performance. A detailed study of the problem (ref. 36) showed that a coupled thermal-structural analysis predicted thermally induced, torsional-flexural vibrations consistent with the observed phenomena. The study showed that the thermally-induced vibration could be eliminated by increasing the boom torsional rigidity. Flight data from later satellites support this conclusion.

The NASA Goddard Space Flight Center has more recently been developing generalized techniques to study thermally induced motions and control systems for large space structures. Basic theoretical concepts can be found in reference 37. A review of current activities and software from a NASA Goddard-sponsored effort titled "Integrated Analysis Capability (IAC) for Large Space Systems" appears in reference 38. The IAC software system integrates large computer programs for system dynamics (DISCOS), thermal (NASTRAN, SPAR, SINDA, TRASYS), structural (NASTRAN, SPAR) and controls analysis (ORACLS, SAMSAN, MODEL) to permit interdisciplinary studies of large space structures.

Although large space structures have potential for thermally induced oscillations as noted by several researchers (e.g., references 37 and 39), there is little on-going research in this area, particularly on large complex systems such as the MRS system (Figure 1). The NASA Langley Research Center, however, is planning to conduct basic experiments on thermally-induced beam vibrations in a simulated space environment. This activity, planned for late 1982, is taking place in the Structural Dynamics Branch under the direction of Dr. Larry D. Pinson.

SECTION VI

CONCLUDING REMARKS

This report reviewed recent advances in thermal-structural analysis of large space structures. A NASA design for a microwave radiometer system (MRS) was used to illustrate characteristics of a large space structure design. Large space structures' heating, thermal, and structural analysis methods were also reviewed. Typical analytical modeling techniques and response characteristics were discussed and illustrated for tetrahedral trusses. Uncertainties in thermal-structural analysis methods were highlighted.

Important areas for thermal-structural research that were identified include: (1) spacecraft self-shadowing effects on structural response; (2) effects of large prime-power systems on spacecraft thermal-structural behavior; (3) better knowledge of material properties and their effects on long-term structural response; (4) improved computer program capability to model and analyze nonlinear pretensioned structural components and (5) better understanding of thermally-induced structural vibrations. Additional computations with large structures are needed to further delineate problems because computations with preliminary structural designs have only partially identified problems in analysis capabilities. Additional computations should be performed with better-defined structures with realistic properties and heat loads. Further areas for improvements in capabilities and efficiency of computer programs will undoubtedly be identified. Finally, many of the uncertainties will be resolved only through the interplay of analysis and experiment. There is a definite need for fundamental thermal-structural experiments to validate thermal-structural analysis of large space structures.

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