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THERMAL/STRUCTURAL DESIGN VERIFICATION STRATEGIES FOR LARGE SPACE STRUCTURES

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INTRODUCTION

As space missions become increasingly ambitious, requirements for larger and more precise structures have collided with demands for greater cost effectiveness and more routine operations. This has led to a search for alternate methods of verifying that key design/performance requirements have been met. This search has resulted in increasing reliance on analysis with less experimental verification. If this is to be done without a large increase in technical risk, it is necessary to integrate testing and analysis, looking at them as alternate means of reaching the same end, each with its own peculiar advantages and disadvantages.

The substitution of analysis for test has been enthusiastically pursued in the area of large space structures due to the difficulty of accurately simulating the flight environment of the very large structures under consideration. This applies to two principal areas: thermoelastic behavior and dynamic performance. This paper examines methods of verifying thermal and thermoelastic performance. The options available for ground thermal testing are summarized, and corresponding analytical methods are enumerated. Finally, alternate paths which combine test and analysis to arrive at a verified thermal/structural design are traced. Options for reducing test requirements by testing smaller assemblies and/or testing in simplified environments are outlined. A generic large deployable structure is examined in light of these considerations.

GROUND THERMAL TESTING OPTIONS

Common thermal testing options are listed in Table I. Thermal test environments are selected with one of three goals in mind. One goal is to simulate the operational environment as closely as possible. Alternatively, the goal can be to impose appropriate environmental conditions which facilitate correlation of analytical models against test results. Both of these serve to verify the thermal design of the system under test. A third goal is to demonstrate the ability of a design ("qualification testing") or a particular item ("acceptance testing") to withstand expected temperature extremes. This last goal is often combined with an attempt to verify the thermal/structural design. Thermal/structural design of space structures must control the thermoelastic behavior of the structure. The design parameters include conductive heat paths, radiative exchange properties, active heater control, and structural design parameters. Generally, structural parameters are driven by nonthermal design requirements. The flight thermal environment includes direct solar radiation, planetary reflected solar radiation ("albedo"), planetary emitted IR radiation, and on-board heat loads.

Thermal testing goals are determined by the thermal/structural design verification approach. With one approach, the design is verified if the test article does not respond with unacceptable temperatures or distortions. Ideally, this approach requires very little analysis. However, the results are valid only insofar as the test environment is an accurate simulation of the flight environment and the test article conforms to the flight hardware. The alternate approach does not require an accurate simulation of the flight environment or precise duplication of the flight hardware configuration. In this approach an analytical model of the test article in the test environment is correlated against actual test results. The resulting "test-validated model" is then modified to reflect the operational environment. This modified analytical model is then used to generate predictions of flight performance. In this case, the test environment is generally defined to bound "worst case" conditions of maximum temperature, minimum temperature, and/or temperature gradients predicted for flight. This relatively simple test environment is typically much easier to create on the ground than is a full simulation of the flight environment.

The test environment consists of heat sources and sinks. These can be convective, conductive, or radiative. A convective source or sink is simply temperature-controlled gas (dry air, N_2, etc.) in a (non-vacuum) thermal chamber. They cannot usually be used to generate large gradients. Conductive sources and sinks include temperature-controlled fluid loops, heaters contacting the test article, test article internal dissipation, and any supporting fixtures attached to the test article. Usually conductive heat leaks are minimized by test fixture design. Radiative sinks and sources are important in a vacuum environment since there is no convective heat transfer. Radiative sinks include shrouds which view but do not contact the test article. The shrouds themselves are temperature controlled by heaters and/or fluid loops. Shrouds become sources by definition whenever their temperature exceeds the temperature of the test article. Other radiative sources are IR lamps and solar simulation lamps. When shrouds alone are used, the flight environment is reduced to an "equivalent sink temperature" for the shroud. When IR lamps are available, or heaters can be attached directly to the exterior of the test article, an "equivalent sink heat rate" flux is used. In both cases accounting for solar radiation requires accurate knowledge for the test article's thermo-optical properties. Solar simulation lamps are used to directly simulate solar fluxes. These are commonly employed for geometrically complex test items where considerable doubt exists as to the solar flux levels resulting from reflections and shadowing between different parts of the test article. Internal electrical dissipation can be simulated by heaters if the actual electronics are not in place.

Costs increase rapidly with greater fidelity of the text environment to the actual flight environment. Nonvacuum thermal tests are the least expensive, but are incapable of creating realistic gradients because of high convective heat transfer rates. Thermal vacuum tests cannot simulate the spectral and reflecting/shadowing characteristics of the radiative flight environment without solar simulation lamps which greatly increase cost. At any given level of test fidelity, increasing the test article's size results in increased cost.

Data collected during thermal tests includes temperature, strain, displacement, heat fluxes and power usage, and test article function/performance data. Function/performance data requirements are specific to each test article and can include both electrical and mechanical function data. Radiative heat flux is measured with radiometers. With heaters or electronic equipment, current flow is measured to determine heat rates. Temperatures are measured with thermocouples or thermistors. Strain gauges are used to measure local thermoelastic strain. Thermoelastic deformations are measured by mechanical or optical means. Depending upon the resolution required, photogrametry or interferometric optical methods can be used. In some cases large-scale thermoelastic deformations can be inferred from local strain measurements.

COMBINING TEST WITH ANALYSIS

Both thermal tests and analytical models can be considered in terms of input and output, as illustrated in Figure 1. Ideally, the relationship between input and output is the same for test and analysis. If this is true for the range of inputs seen during flight, analysis and test are interchangeable for use in predicting flight performance. In reality, there can be a significant discrepancy between analytical and empirical (test) performance. Analysis is generally less expensive and time consuming. Test is usually more representative of actual flight performance. Thus, the trade-off is between lower cost (analysis) and lower risk (test), keeping in mind that perfect tests are as impossible as perfect analyses.

Thermal analysis of a space structure actually involves a number of interrelated analyses, listed in Table II. A typical analysis flow is shown in Figure 2. Listed in Table III are types of thermal tests which have inputs and outputs corresponding to various analyses. If analysis alone is used for thermal/structural design performance verification, thermal testing is required only to qualify the structure and its components to the appropriate temperature and vacuum conditions.

It is often useful to test large structures as subassemblies, using analysis to extrapolate the performance of the total system. This is especially attractive if the heat flows between subassemblies are small or well defined. Some structures are periodic assemblies of identical subassemblies, allowing a single subassembly test to be readily extrapolated to the entire structure.

DESIGN VERIFICATION OF A LARGE DEPLOYABLE TRUSS BEAM

A deployable truss beam which is representative of future large space structures provides an instructive example.

GENERIC DEPLOYABLE TRUSS BEAM

A number of deployable truss beam structures have been described in References 1 and 2. These structures consist of a series of collapsible bays. Generally, these beams have a slenderness ratio (deployed length/ deployed diameter) between 30 and 50 and an extension ratio (deployed length/stowed length) of about 20. The are deployed by a mechanism which extends each bay in turn and latches the joints. Reversing the process retracts the beam. For the purposes of this example, a 100 meter beam can be postulated, as shown in Figure 3. This structure could be used to deploy an experiment package from the Space Station. The beam and deployment mechanism can be easily designed to deploy a single bay vertically in a one gravity environment.

The thermal design must accommodate the requirements of the experiment on the truss beam tip. Thermal control of the truss beam structure is achieved passively with coatings. The deployment mechanism uses heaters plus insulation and coatings. This thermal/structural design is driven by three requirements. The first requirement is to survive the thermal environment without unacceptable degradation. The second is to reliably deploy and retract the truss beam in the flight thermal environment. Finally, thermal distortions must be minimized to avoid compromising the experimental data.

THERMAL/STRUCTURAL DESIGN VERIFICATION APPROACH

Verification of the thermal/structural design requires a combination of analysis and test due to the size of the deployed structure. The verification approach is summarized in Figure 4. Flight temperature predictions can be made from analytical models for both stowed and deployed configurations. A structural model can then be used to predict component stress levels due to thermal loads, as well as structural distortions. These analyses rely upon testing of individual elements (such as tubes and joints) and material samples for properties data. Key structural assemblies are proofloaded to levels incorporating the thermal loads. A single bay is cycled to the predicted extremes of temperature and stress. Because of the periodic nature of the beam structure, the behavior of a single bay is representative of the entire beam. Combined with thermal qualification testing of the materials and mechanisms, this test verifies that the structure will not degrade unacceptably in the flight thermal environment.

Verification of the deployment kinematics under flight thermal conditions involves the effects of both local and global thermal distortions. To evaluate local thermal effects, representative joints and mechanism devices are cycled through their full range of motion at predicted temperature extremes plus margin. This verifies performance of truss beam joints and the deployment devices. To verify deployment and retraction under global thermal loads, the entire assembly undergoes a thermal-vacuum deployment and retraction test as shown in Figure 5. This adds confidence to the analytically predicted performance of the beam and the deployment mechanism. Although this test is relatively expensive, failure of the beam to deploy would be a costly failure. In addition, the heat exchange within a complex collection of devices such as the deployment mechanism is difficult to predict accurately. Because of the periodic nature of the beam structure, deployment of a single bay is sufficient to verify the kinematics. The beam is deployed in worst-case hot and cold environments, then the worst side-to-side gradient is imposed by adjusting shroud temperatures on opposite sides of the beam. These worst-case temperatures are those predicted by analysis.

Thermoelastic distortion predictions for the deployed beam cannot be directly verified by ground test because of vacuum chamber size limitations and gravity effects. Reliance is placed upon analysis plus measurements of the coefficient of thermal expansion of individual structural elements. Additionally, predicted temperature extremes and thermoelastic stress levels are used to cycle individual structural elements to determine the change in the thermoelastic properties of the elements after exposure to flight environment.

CONCLUSIONS

Requirements for space structures of increasing size, complexity, and precision have engendered a search for thermal design verification methods that do not impose unreasonable costs, that fit within the capabilities of existing facilities, and that still adequately reduce technical risk. This requires a combination of analytical and testing methods. This results in two approaches. The first is to limit thermal testing to subelements of the total system or to test the system only in a compact configuration (i.e., not fully deployed). The second approach is to use a simplified environment to correlate analytical models with test results. These models can then be used to predict flight performance. In practice, a combination of these approaches is needed to verify the thermal/structural design of future very large space systems.

REFERENCES

1. Mikulas, Martin M. Jr. and Harold G. Bush: "Advances in Structural Concepts" Large Space Antenna Systems Technology, 30 Nov - 3 Dec 1982, NASA CP-2269

2. Rhodes, Marvin D: "New Concepts in Deployable Beam Structures", Large Antenna Systems Technology, 4-6 Dec 1984, NASA CP-2368

TABLE I - TERMINOLOGY AND INPUT/OUTPUT DATA FOR TYPICAL THERMAL TESTS

Type of Test	Input Variables	Output Data
THERMAL (THERMAL CYCLE) - Test article immersed in a temperature-controlled dry gas bath	Test article bulk temperature(s)	Functional and survival data
THERMAL VACUUM - Test article in a vacuum environment with spatially uniform heat sources and sinks	Temperature(s) of the sink and/or test article	Functional and survival data
THERMAL BALANCE - Test article in a vacuum environment with spatially and temporally non-uniform heat sources and sinks	External heat fluxes ("Q -test") or sink temperatures ("T-test")	Test article temperature(s), especially gradients
SOLAR THERMAL VACUUM - Test article in a vacuum environment with spatially and temporally non-uniform heat sources including simulated solar flux and heat sinks	External sink temperatures and solar fluxes	Test article temperature(s) and incident fluxes

TABLE II - ANALYTICAL THERMAL MODELS OF SPACE STRUCTURES

Type of Model	Input Data	Output Data	Typical General Purpose Program
Radiation Exchange	• Geometry •Surface properties	•Internal radiation exchange factors	TRASYS
Heat Rate	•Exterior geometry •Exterior surface properties •External environment •Radiation exchange factors	•Nodal heat fluxes and boundary conditions (BCs)	TRASYS
Thermal Balance	•Internodal conductances •Nodal heat fluxes and BCs •Radiative exchange factors •Internal heat sources • Nodal heat capacities	•Steady-state nodal temperatures •Transient nodal temperatures	SINDA MITAS
Thermoelastic	•Structural BCs •Element temperatures •Element pre-loads •Element stiffness •Element coefficient of	•Displacements •Rotations	NASTRAN

TABLE III - CORRESPONDENCE BETWEEN TEST AND ANALYSIS

Type of Test	Input Data	Output Data	Corresponding Analytical Model(s)
Thermal - Vacuum (Uniform heat sinks and sources)	External (uniform) sink temperature or test article temperature	Functional and survival data	Thermal balance (with simplified heat fluxes and BCs) + radiation exchange
Thermal Balance (Non-uniform heat sinks and sources)	External (non-uniform) sink temperatures and BCs	Test article temperatures (transient and/or steady-state	Thermal balance + radiation exchange
Solar Thermal-Vacuum	External sink temperatures and solar fluxes	Test article temperature (transient and/or steady-state)	Thermal balance + radiation exchange + heat rate

If temperature-induced distortions are measured, then the thermoelastic analytical model is included among the corresponding analytical models

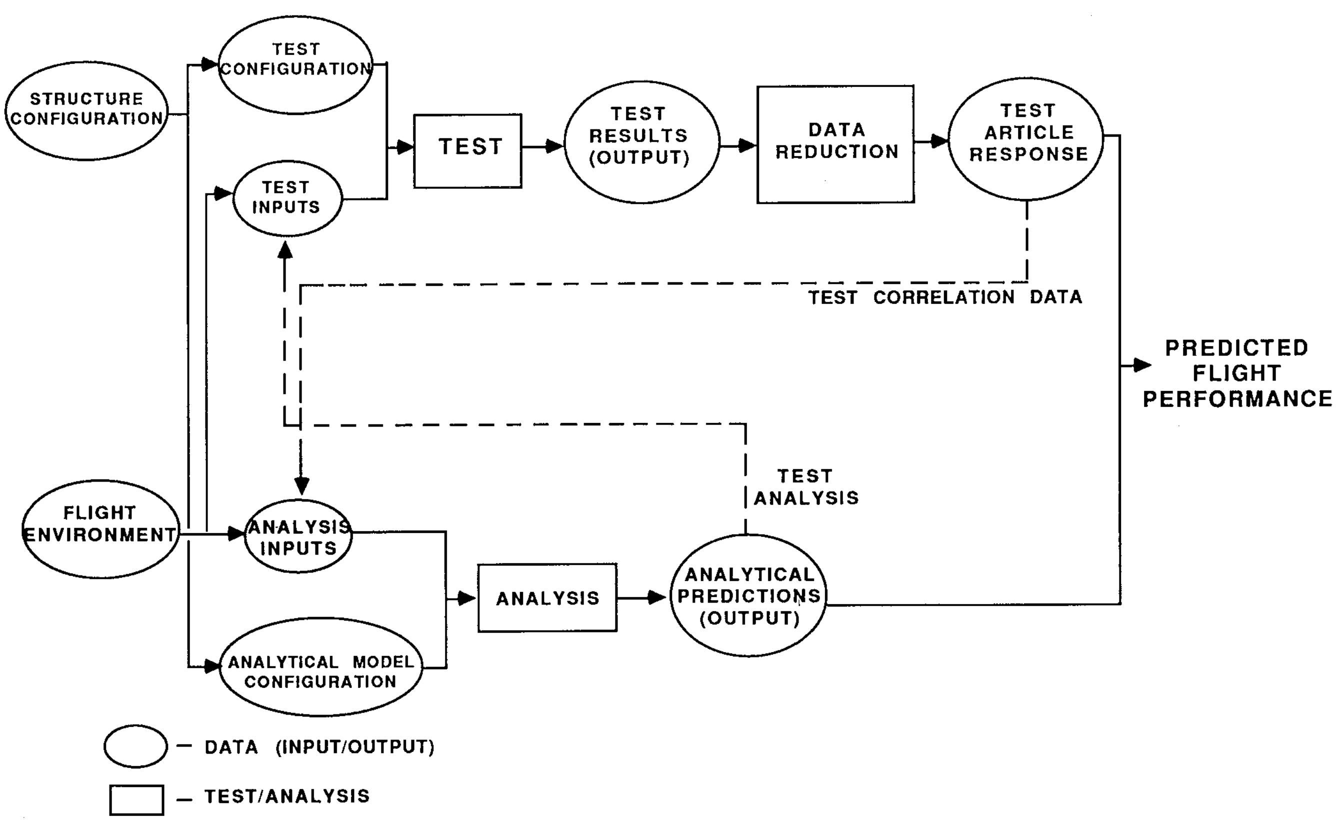

FIGURE 1. INPUT/OUTPUT RELATIONSHIP BETWEEN ANALYSIS AND TEST

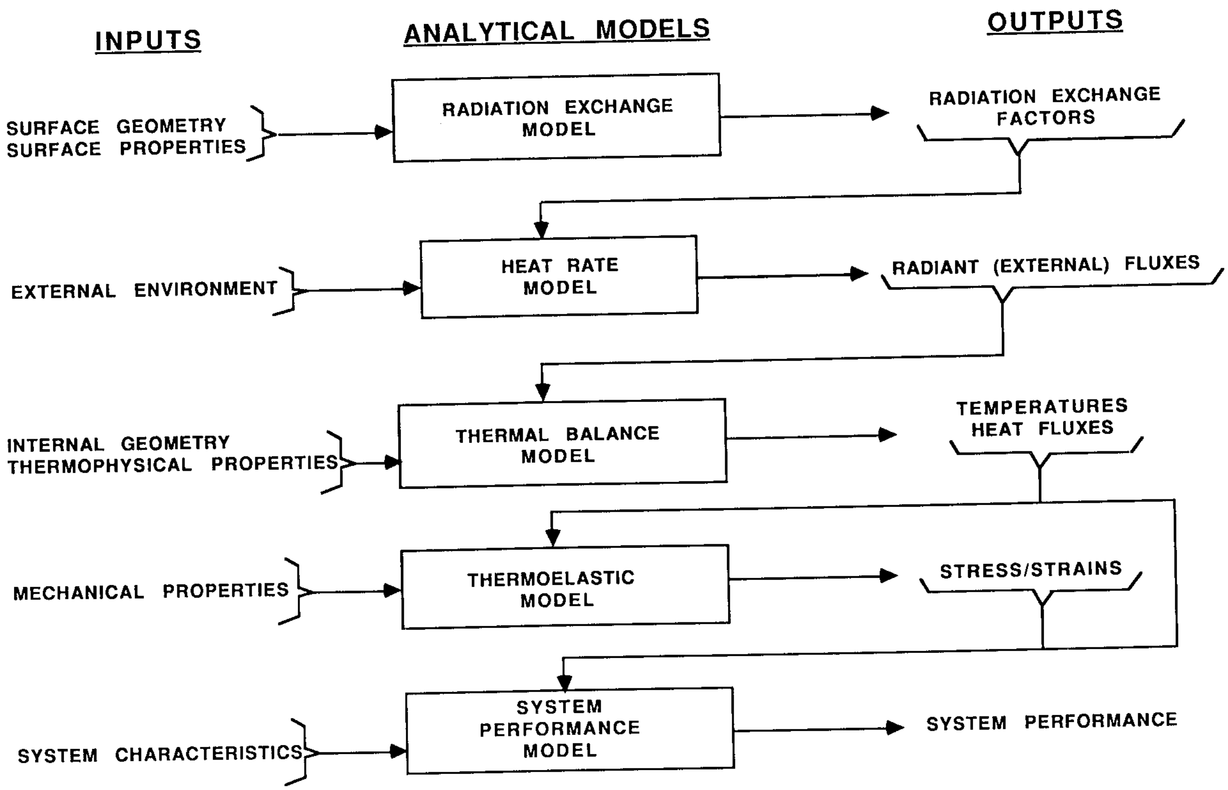

FIGURE 2. THERMAL ANALYSIS INPUTS, OUTPUTS, AND MODELS

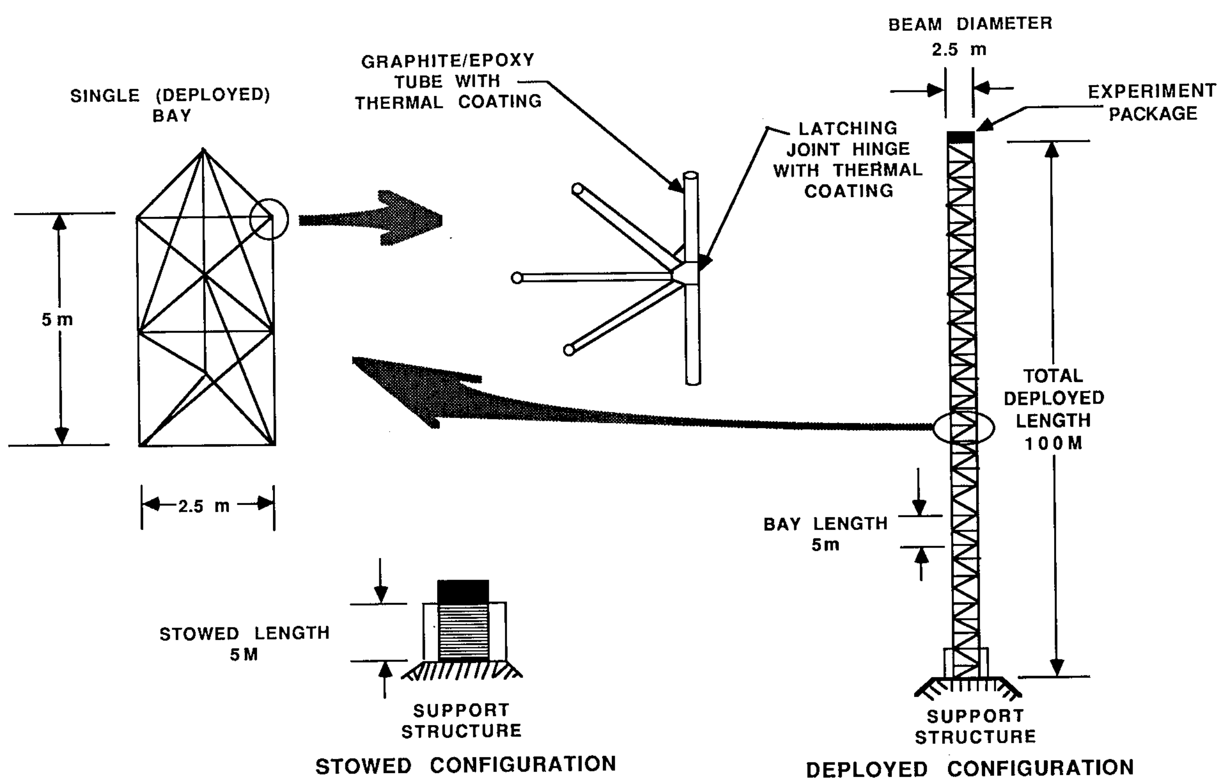

FIGURE 3. GENERIC DEPLOYABLE/RETRACTIBLE TRUSS BEAM

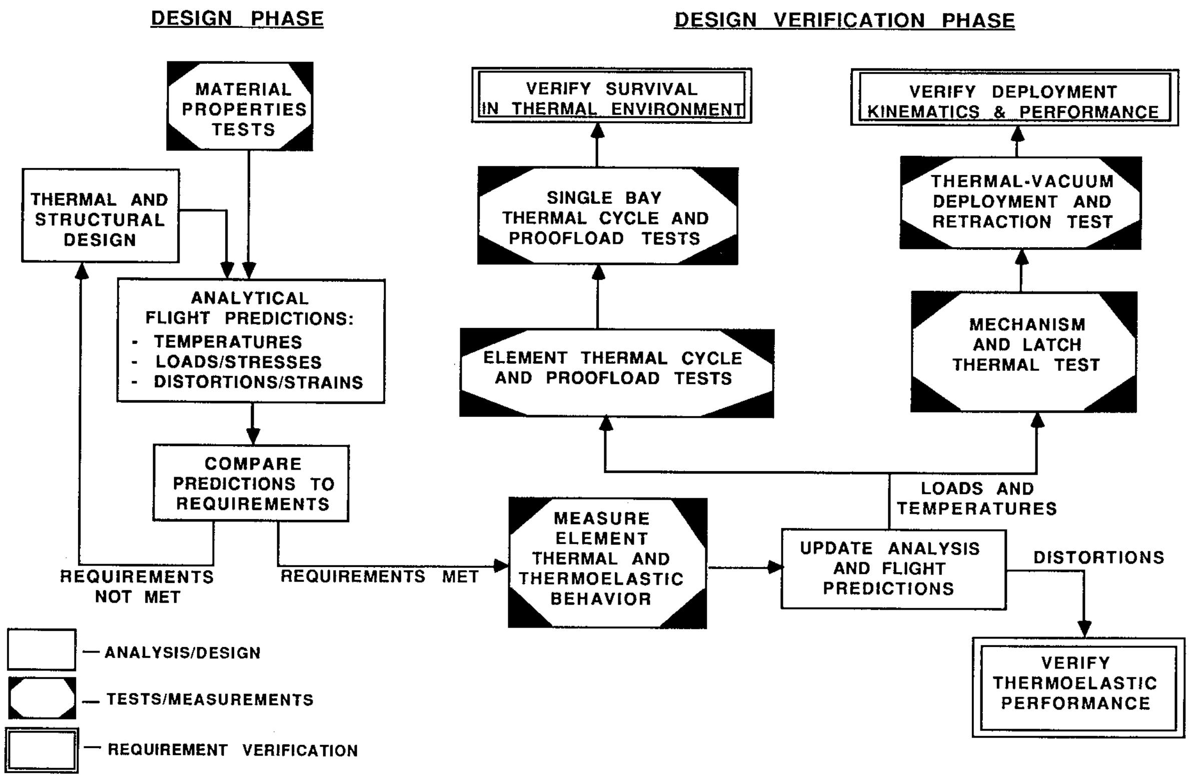

FIGURE 4. DESIGN VERIFICATION STRATEGY FOR GENERIC DEPLOYABLE TRUSS BEAM

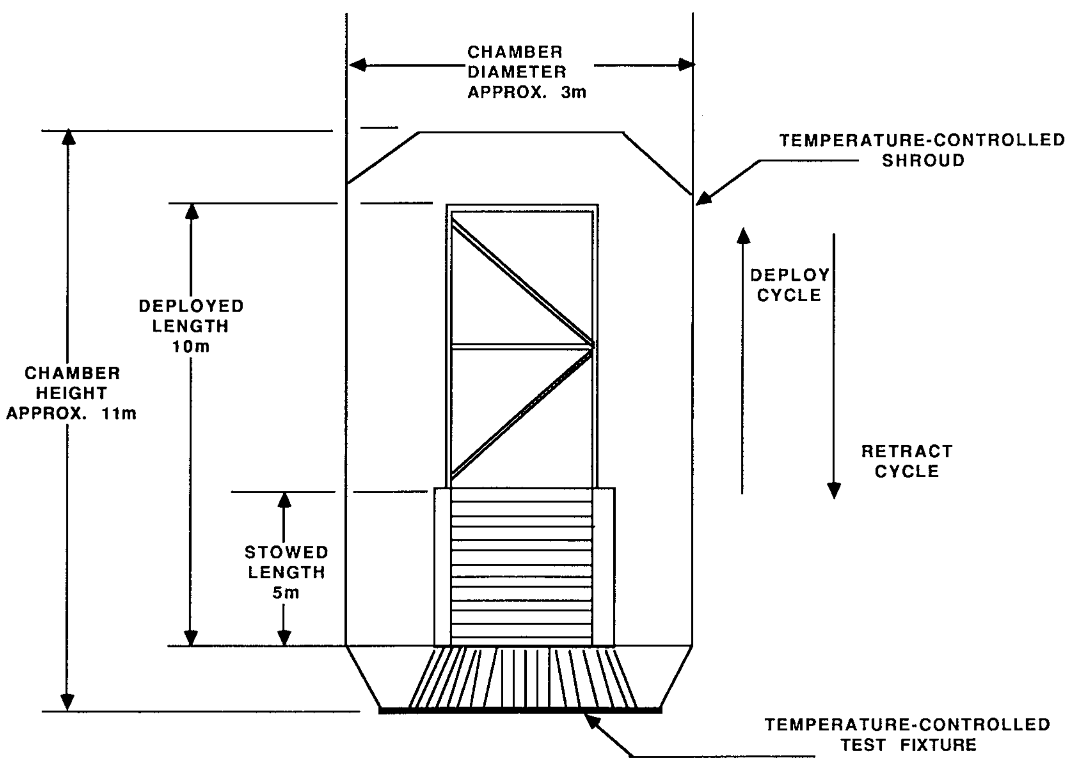

FIGURE 5. DEPLOYMENT/REFRACTION TEST CONFIGURATION IN VACUUM CHAMBER