Structural/Thermal Considerations For Design Of Large Space Platform Structures

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STRUCTURAL/THERMAL CONSIDERATIONS FOR DESIGN OF LARGE SPACE PLATFORM STRUCTURES

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INTRODUCTION

PLACING A LARGE, STS-COMPATIBLE PLATFORM ON ORBIT CAN BE ACCOMPLISHED WITH A CONSTRUCTION METHOD EMPLOYING BOTH DEPLOYABLE AND ERECTABLE STRUCTURES. THIS PAPER DISCUSSES SUCH A PLATFORM, A MULTIFUNCTIONAL MECHANISM FOR DEPLOYABLE STRUCTURES, AND AN ON-ORBIT ASSEMBLY TECHNIQUE FOR ERECTABLE STRUCTURES.

CONFIGURATION CONTROL OF LARGE ON-ORBIT STRUCTURES IS DEPENDENT IN PART ON THE RESPONSE OF THE STRUCTURE TO THE NATURAL THERMAL RADIATION AND TO ON-BOARD HEATING. THIS PAPER DISCUSSES ANALYSES WHICH ASSESS THE THERMAL DISTORTION OF A SIMPLE OPEN TRUSS AND A MORE COMPLEX TRUSS.

STRUCTURAL/THERMAL CONSIDERATIONS (Figure 1)

DEPLOYABLE AND ERECTABLE LARGE TRUSS STRUCTURES WERE INVESTIGATED. A SCENARIO WAS DEVELOPED WHICH WOULD ENABLE THE PLACING OF A 300 M x 300 M PLATFORM IN LOW EARTH ORBIT USING THE STS. THE PLATFORM IS ASSEMBLED USING 7 DEPLOYABLE TETRAHEDRAL MODULES, 120 M x 104 M IN SIZE, MOUNTED (3 POINT SUSPENSION) TO AN ERECTABLE TRUSS STRUCTURE CONSISTING OF 102 COLUMNS.

A KNEE JOINT CONCEPT, APPLICABLE TO TYPICAL DEPLOYABLE TRUSS STRUCTURES AND CONTAINING A DEPLOYMENT, LATCHING, AND DAMPING MECHANISM SYSTEM, WAS SELECTED FOR DETAIL INVESTIGATION.

AN ON-ORBIT ASSEMBLY PROCEDURE WAS IDENTIFIED FOR ERECTABLE STRUCTURES ALONG WITH COMPATIBLE ASSEMBLY JOINTS.

THE STRUCTURAL RESPONSE WAS DETERMINED FOR (1) A SIMPLE OPEN TRUSS SUBJECTED TO THE NATURAL THERMAL RADIATION AND (2) A MORE COMPLEX TRUSS SUBJECTED TO ON-BOARD HEATING AS WELL AS THE NATURAL THERMAL RADIATION.

Structural/Thermal Considerations

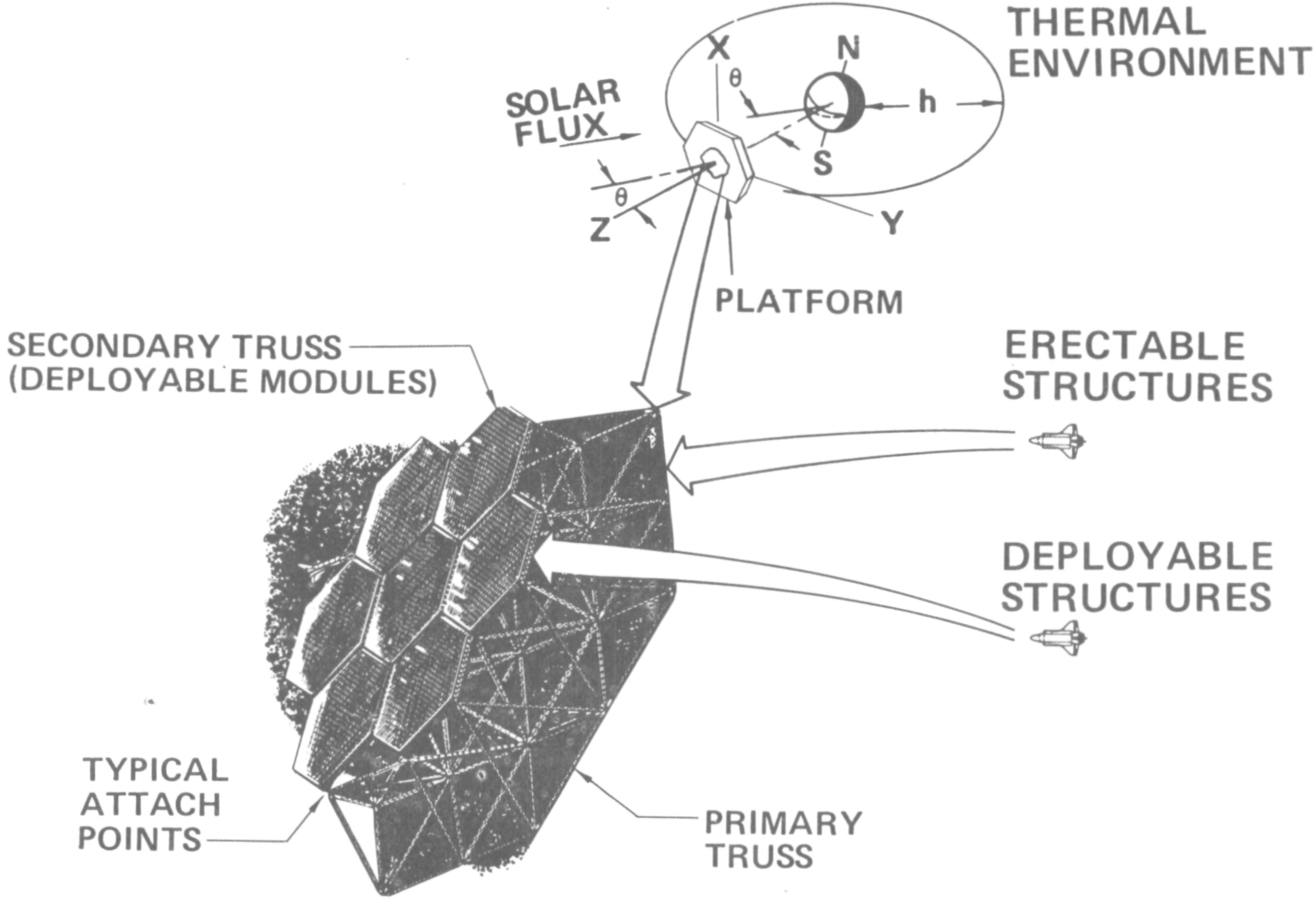


Figure 1

DEPLOYABLE STRUCTURE JOINTS (Figure 2)

THE USE OF STORED INTERNAL ENERGY FOR TRUSS DEPLOYMENT WAS SELECTED OVER OTHER OPTIONS, E.G., SPIN ABOUT Z AXIS, INFLATION/PNEUMATIC TECHNIQUES, EXPANSION BY RADIAL THRUSTER, TENSION CABLES WITH PULLEYS. MODELS WERE FABRICATED TO DEMONSTRATE DEPLOYMENT/PACKAGING TECHNIQUES. A CLUSTER FITTING JOINT DESIGN WAS SELECTED. AN EVALUATION OF KNEE JOINT CONCEPTS WHICH CONTAIN STORED INTERNAL ENERGY WAS MADE AND A CANDIDATE SELECTED FOR DETAIL INVESTIGATION.

Deployable Structure Joints

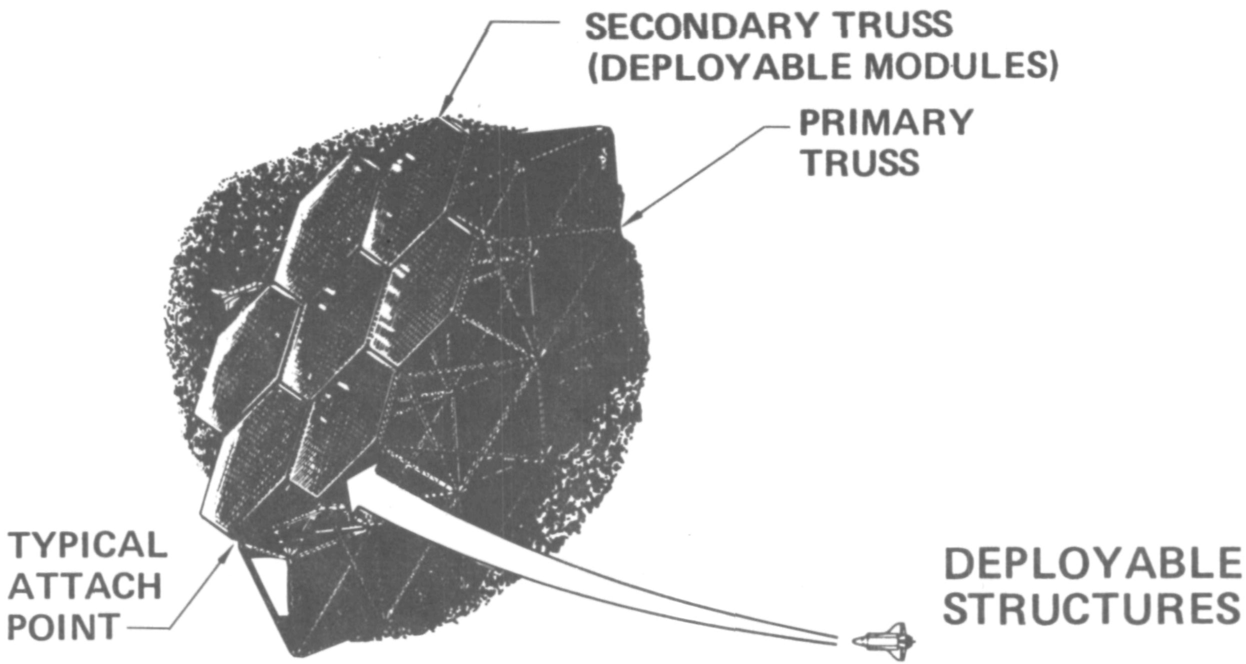
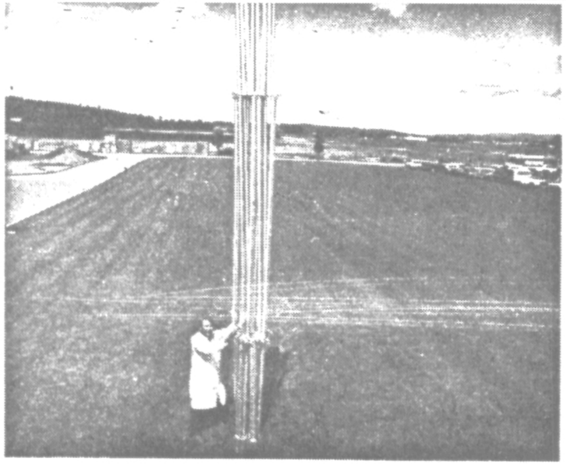


Figure 2

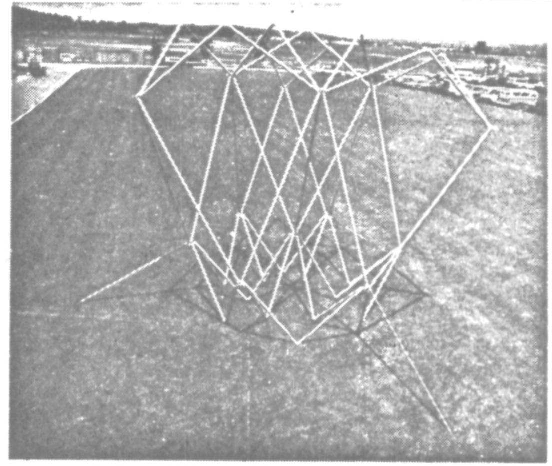
TYPICAL DEPLOYABLE TRUSS MODULE (Figure 3)

A 36-ELEMENT TETRAHEDRAL TRUSS MODULE WAS FABRICATED TO SERVE AS (1) A MODEL FOR DEMONSTRATING THE PACKAGING AND DEPLOYMENT CONCEPT AND (2) A MOCKUP TO EVALUATE JOINT CONCEPTS. THE 50 MM DIAMETER ALUMINUM ALLOY STRUT MEMBERS ARE 3 M LONG. PACKAGED LENGTH OF THE TRUSS IS 6 M. WHEN DEPLOYED, THE MAIN SURFACE DIMENSION OF THE TRUSS IS 6 M AND THE DEPTH IS 2.5 M.

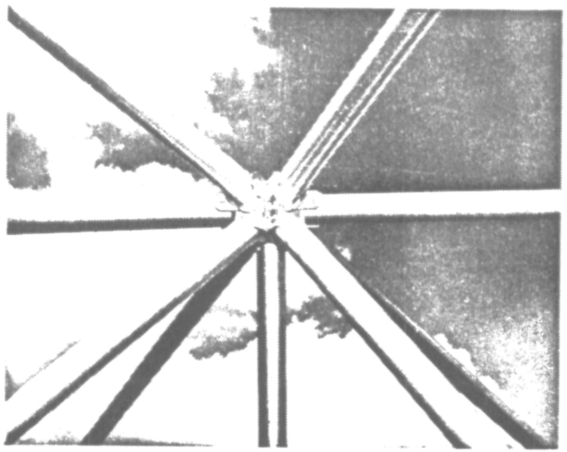
Typical Deployable Truss Module



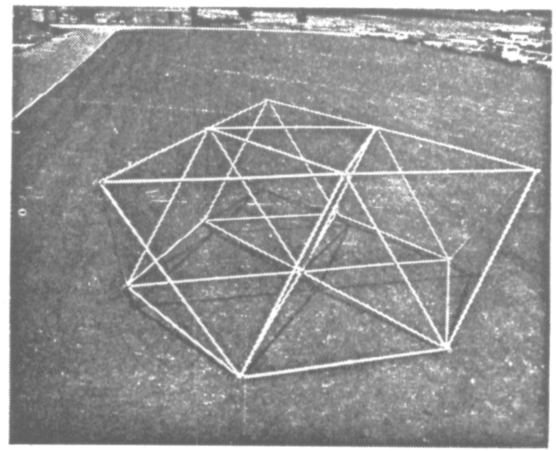
a) PACKAGED



b) PARTIALLY DEPLOYED



c) CLUSTER FITTING



d) DEPLOYED

Figure 3

CLUSTER FITTING JOINT (Figure 4)

CONCEPTS FOR THE CLUSTER FITTINGS WHICH JOIN THE SURFACE AND THE INTERSURFACE MEMBERS WERE EVALUATED. FITTINGS WITH SINGLE LUGS FOR THE PIN JOINT CONNECTIONS WERE FOUND TO HAVE CONSIDERABLE JOINT FREE PLAY WHEN THE ATTACHING MEMBERS WERE IN THE PACKAGED CONDITION OR ARTICULATING FOR DEPLOYMENT. A QUALITATIVE EVALUATION SUGGESTED THAT THIS FREE PLAY WOULD DETRACT SUBSTANTIALLY FROM THE CAPABILITY OF THE TRUSS TO DEPLOY UNIFORMLY, IN A SMOOTH FASHION, AND WITHOUT EXCESSIVE BINDING AT THE JOINTS. NON-UNIFORM DEPLOYMENT AND BINDING AT THE PIN JOINT CONNECTIONS COULD RESULT IN HIGH MEMBER LOADS AND REQUIRE AN INCREASE IN STORED DEPLOYMENT ENERGY. FITTINGS WITH DOUBLE LUGS FOR THE PIN JOINT CONNECTIONS HAVE MUCH LESS JOINT FREE PLAY THAN THE SINGLE LUG FITTINGS AND THEREFORE WERE SELECTED.

Cluster Fitting Joint

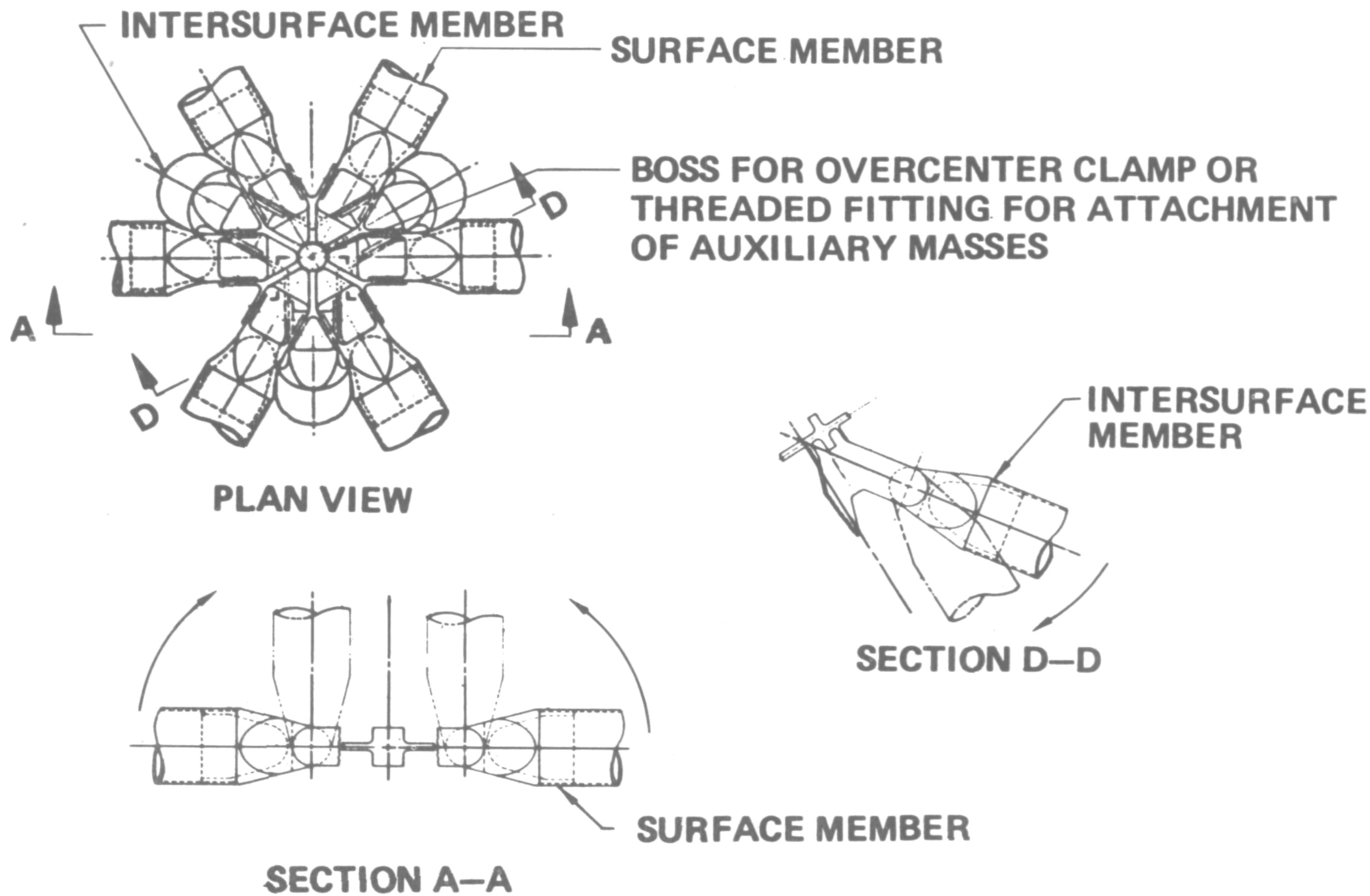


Figure 4

KNEE JOINT CONCEPT EVALUATION (Figure 5)

THREE KNEE JOINT CONCEPTS WHICH STORE INTERNAL ENERGY FOR TRUSS DEPLOYMENT WERE EVALUATED. THE EVALUATION CRITERIA INCLUDED (1) THE CAPABILITY TO ADJUST THE AMOUNT OF STORED ENERGY SO THAT THE ENERGY VALUES AT EACH TRUSS JOINT CAN BE TAILORED AS REQUIRED FOR A RELIABLE DEPLOYMENT CYCLE WITH MINIMUM LOADS ON THE MEMBERS, (2) ZERO FREE PLAY IN THE JOINT OR A MECHANISM TO REDUCE FREE PLAY, (3) A MECHANISM TO ABSORB THE SYSTEM'S ENERGY DURING THE FINAL STAGES OF DEPLOYMENT, AND (4) A CONVENIENT METHOD FOR RELEASING THE LOCKING MECHANISM OF THE DEPLOYED JOINT TO PERMIT REPACKAGING OF THE TRUSS. THE CAPABILITY TO CONVENIENTLY REPACKAGE A DEPLOYED TRUSS IS NECESSARY DURING THE GROUND TEST PHASE OF A DEVELOPMENT TEST PROGRAM AT WHICH TIME NUMEROUS DEPLOYMENT TESTS WILL BE CONDUCTED ON THE TRUSS. IN THE EVALUATION, THE TORQUE SPRING/CAM LATCH CONCEPT WAS RATED THE HIGHEST.

Knee Joint Concept Evaluation

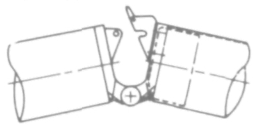
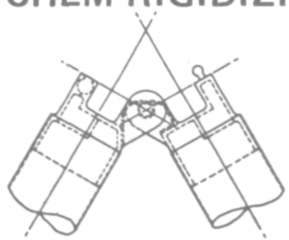
CONCEPT	EVALUATION CRITERIA				
	DEPLOYMENT ENERGY	ADJUSTABLE DEPLOYMENT ENERGY	FREE-PLAY REDUCING MECHANISM	DAMPING MECHANISM	CONVENIENT RELEASE METHOD
a) TORQUE SPRING/ CAM LATCH 	√	√	√	√	√
b) TORQUE SPRING/ CHEM RIGIDIZING 	√	√	√	√	
c) ELASTIC RECOVERY 	√		√		

Figure 5

FEATURES OF TORQUE SPRING/CAM LATCH CONCEPT (Figure 6)

THIS CONCEPT CONTAINS TWO DEPLOYMENT SPRINGS. THESE SPRINGS COUPLED WITH ALL THE OTHER KNEE JOINT SPRINGS PROVIDE THE ENERGY FOR TRUSS DEPLOYMENT. BUT AS WELL, THESE SPRINGS PROVIDE LOCAL ENERGY TO DRIVE THE LATCH PIN AGAINST THE CAM, PUSHING IT INTO THE "LATCHED" POSITION. THE USE OF TWO SPRINGS AT EACH JOINT MINIMIZES TORSION IN THE TUBULAR MEMBERS AND PROVIDES DEPLOYMENT/LATCHING RELIABILITY IN CASE ONE SPRING FAILS. THE CAM SURFACE IS SHAPED AND ARRANGED WITH ITS FULCRUM AND COMPRESSION SPRING SUCH THAT IN THE "LATCHED" POSITION, IF THERE IS FREE-PLAY OF THE LATCH PIN IN THE SLOT, ANY JOINT VIBRATION WILL DRIVE THE CAM AGAINST THE PIN, FORCING THE PIN AGAINST THE SLOT.

TO REPACKAGE THE TRUSS, THE CAM LEVER IS PUSHED IN A DIRECTION AWAY FROM THE MEMBER ON WHICH THE CAM BRACKET IS MOUNTED. THIS ACTION MOVES THE CAM SURFACE PAST THE LATCH PIN (FURTHER COMPRESSING THE LATCH SPRING). A HOLDING PIN IS THEN INSERTED WHICH KEEPS THE CAM IN THE "RELEASED LATCH" POSITION. THE NEXT STEP IS TO RELEASE THE TORSION IN THE SPRINGS BY REMOVING THE SPRING LEG RETAINING SCREW. THIS CAUSES THE SPRING TO UNWIND 360^{o}. THEN THERE IS A MINIMUM RESISTANCE AGAINST ARTICULATING THE SURFACE MEMBER INTO THE PACKAGED CONDITION.

Features of Torque Spring/ Cam Latch Concept

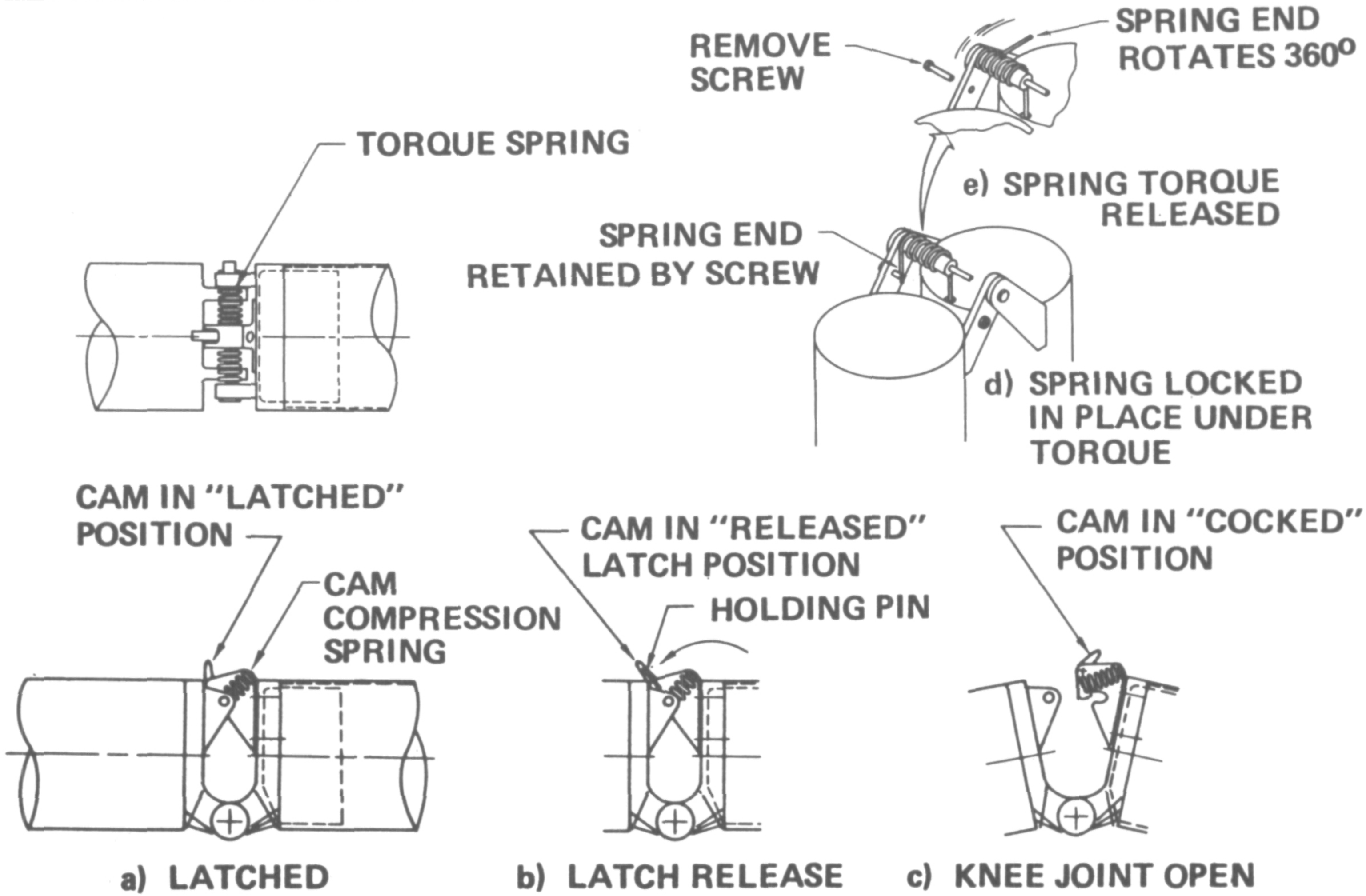


Figure 6

JOINT AND ASSEMBLY CONCEPTS FOR ERECTABLE SPACE STRUCTURES (Figure 7)

THE ASSEMBLY SCENARIO FOR THE TWO-TIER PLATFORM ILLUSTRATED IN THE "ERECTABLE STRUCTURE" CHART IS INITIATED WITH THE SHIPPING TO ORBIT, DEPLOYMENT, AND DOCKING OF THE SECONDARY TRUSS UNITS. THE SECONDARY TRUSS IS THEN USED AS A COLUMN ASSEMBLY PLATFORM. STRUT ASSEMBLY MACHINES ARE MOUNTED TO THE PLATFORM, RECEIVE STRUT MAGAZINES, AND ASSEMBLE THE 10-METER-LONG STRUTS. BY MEANS OF MANIPULATORS AND EVA ACTIVITY THE 130-METER-LONG PRIMARY TRUSS COLUMNS ARE FABRICATED FROM THE STRUTS. THE COMPLETED COLUMNS ARE ASSEMBLED TOGETHER TO FORM THE PRIMARY TRUSS AND CONNECTED AT THE APPROPRIATE POINTS TO THE SECONDARY TRUSS UNITS. THE FINAL TWO-TIER PLATFORM ASSEMBLY OPERATION IS TO DISENGAGE THE DOCKING DEVICES CONNECTING THE SECONDARY TRUSS UNITS. THIS ALLOWS FOR LEVELLING ADJUSTMENT OF THE SECONDARY TRUSS STRUCTURE MODULES.

Joint and Assembly Concepts for Erectable Space Structures

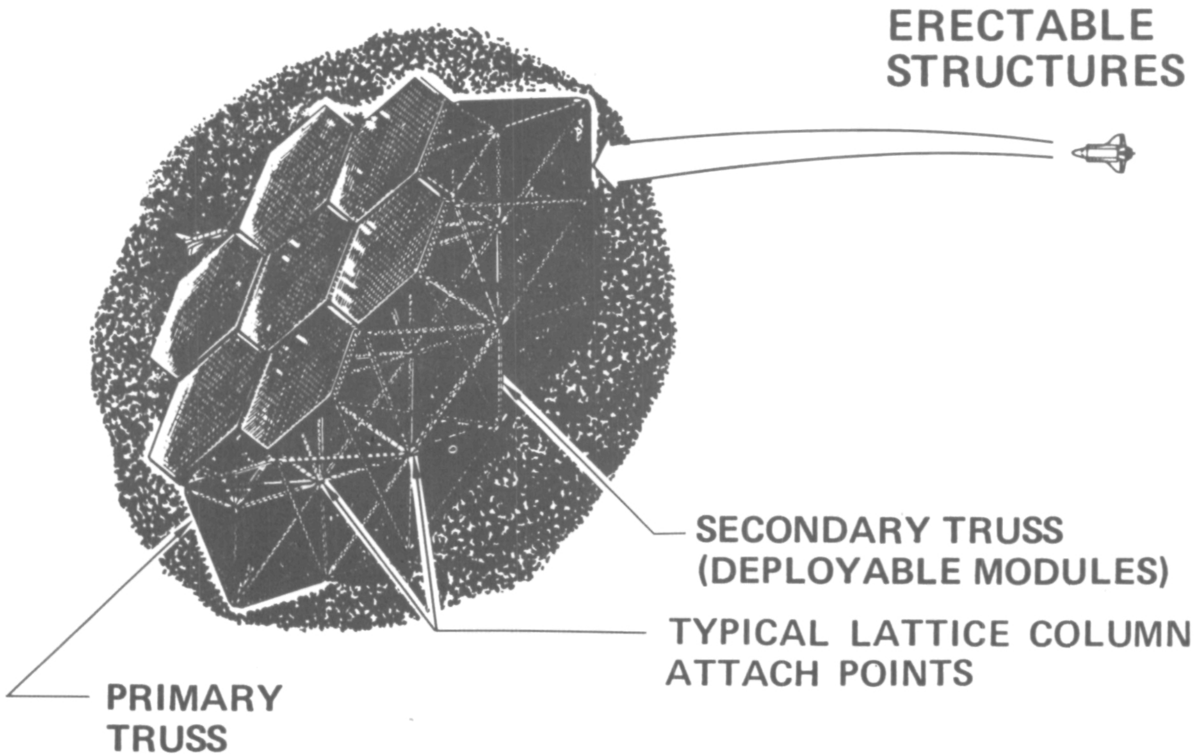


Figure 7

PRIMARY STRUCTURE - ERECTABLE LATTICE COLUMNS (Figure 8)

THE PRIMARY STRUCTURE SHOWN IN THE "ERECTABLE STRUCTURE" CHART CONSISTS OF 102 LATTICE COLUMNS, 130 METERS LONG. TO BE SHUTTLE COMPATIBLE, THESE COLUMNS ARE CONSTRUCTED FROM 111 REPEATING TAPERED COLUMN ELEMENTS, EACH 10 METERS LONG.

A BALL JOINT CONNECTION WHICH ALLOWS MULTIPLE COLUMNS TO BE FITTED AT THE NODAL POINTS WAS ASSUMED AS THE MAIN JOINING METHOD.

Primary Structure – Erectable Lattice Columns

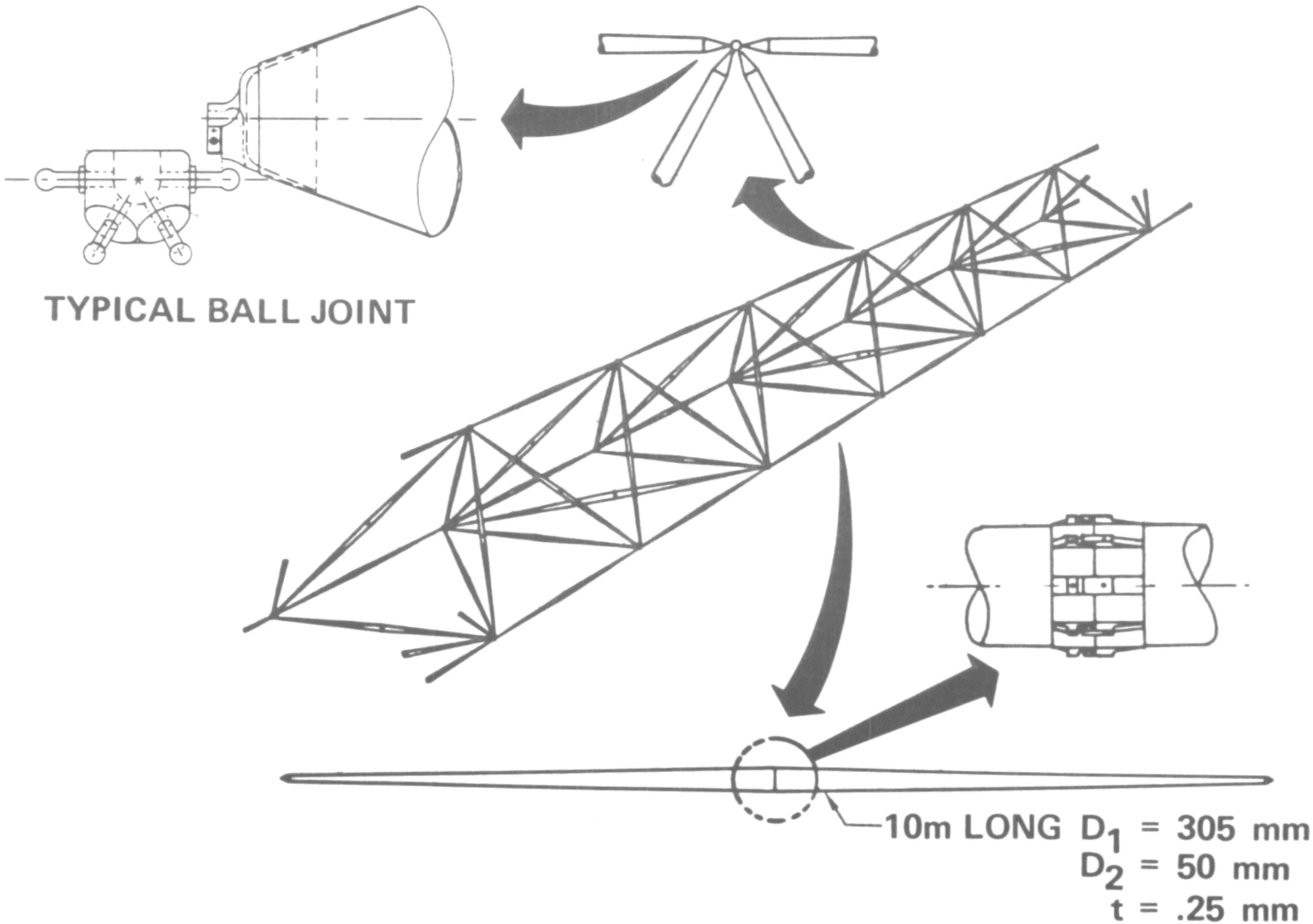


Figure 8

THERMAL DISTORTION ANALYSES OF LARGE TRUSS STRUCTURES (Figure 9)

TEMPERATURE DISTRIBUTIONS FOR A SIMPLE OPEN TRUSS SUBJECTED TO NATURAL THERMAL RADIATION ONLY AND FOR A MORE COMPLEX TWO-TIER CONFIGURATION WITH REFLECTING SURFACES, AND SOLAR PLUS ON-BOARD HEATING WERE COMPUTED AND USED TO PREDICT GEOMETRIC DISTORTIONS FOR THE PLATFORM.

Thermal Distortion Analyses of Large Truss Structures

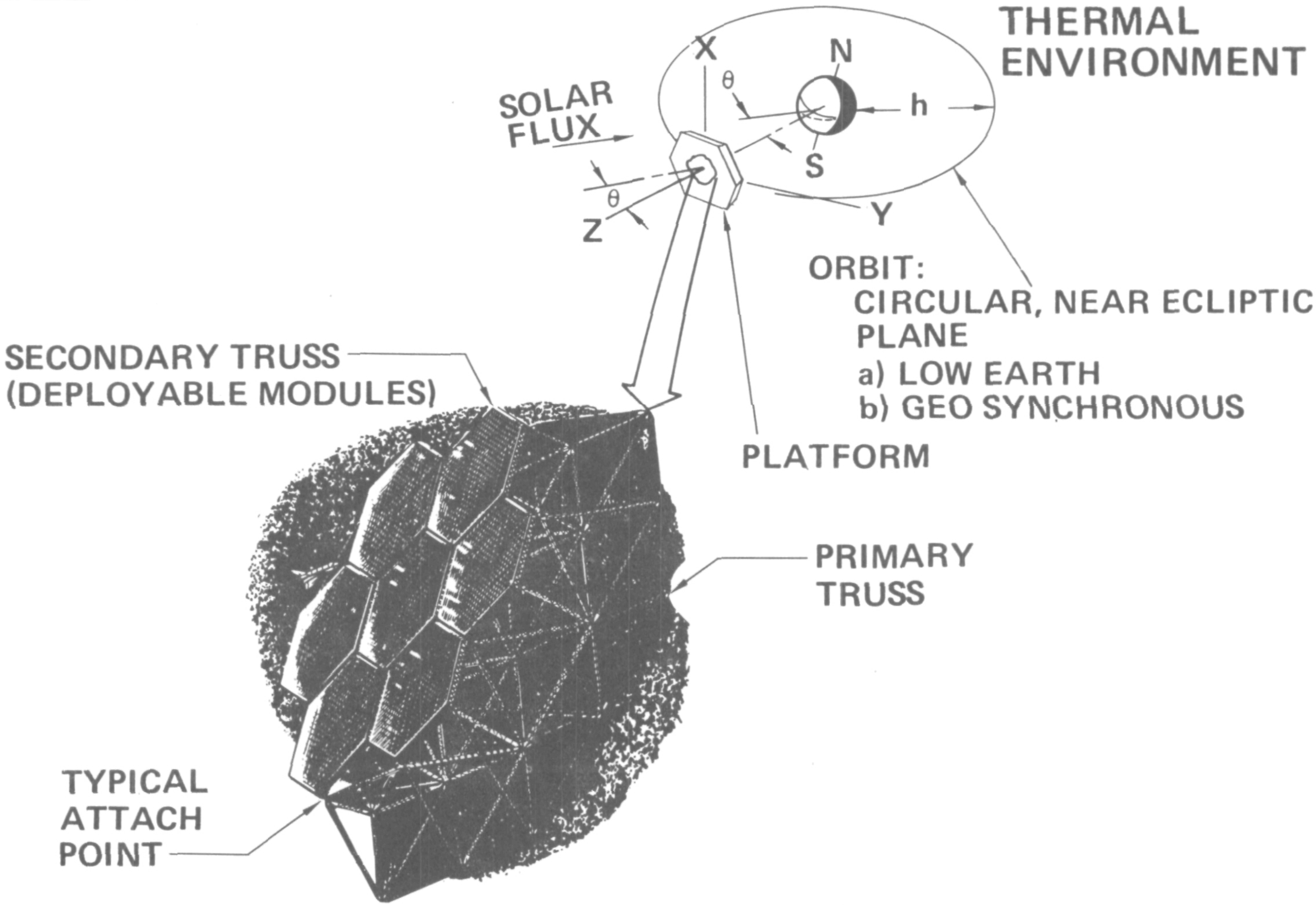
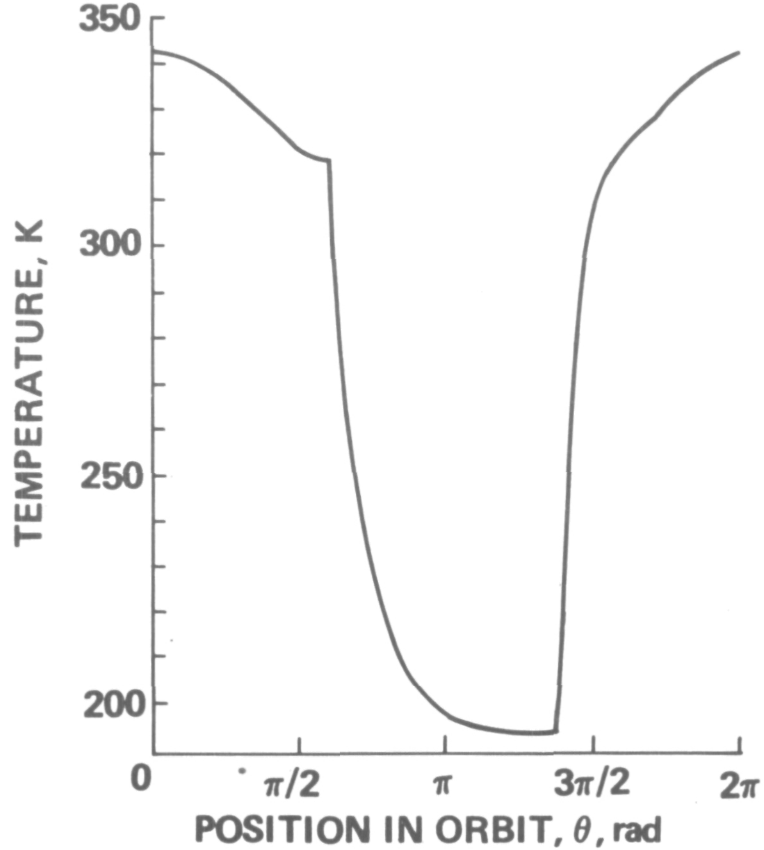


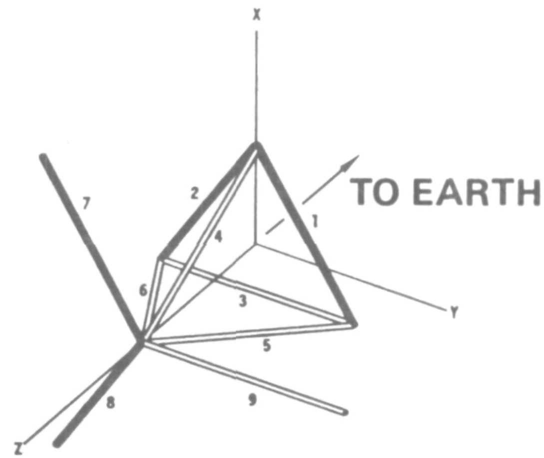
Figure 9

SAMPLE TEMPERATURES - TETRAHEDRAL MODULE (Figure 10)

A HEXAGONAL PLATFORM CONSTRUCTED FROM REPEATING TETRAHEDRAL MODULES WAS ANALYZED FOR TEMPERATURES AND THERMAL DISTORTIONS WHILE IN LOW EARTH ORBIT. THE THERMAL ENVIRONMENT CONSISTED OF SOLAR, EARTH-EMITTED, AND EARTH-REFLECTED RADIATION. TRANSIENT RESPONSE, I.E., THERMAL CAPACITANCE, OF THE MEMBERS WAS CONSIDERED BUT CONDUCTION THROUGH JOINTS AND RADIANT INTERCHANGE BETWEEN MEMBERS WERE IGNORED. A SEPARATE STUDY SHOWED JOINT CONDUCTANCE TO BE INSIGNIFICANT TO THE TEMPERATURES OF THE 50 MM DIAMETER GRAPHITE-EPOXY TUBES FOR ALL LENGTHS GREATER THAN ABOUT 3 METERS. CONFIGURATION SYMMETRY AND ORIENTATION IN ORBIT RESULTED IN CERTAIN MEMBERS, SUCH AS THOSE INDICATED IN THE SAMPLE PLOT, HAVING COMMON TEMPERATURE HISTORIES. THE PLOT SHOWS TEMPERATURES FOR ONE COMPLETE ORBIT, WITH THE EFFECT OF PASSAGE THROUGH THE EARTH'S SHADOW VERY EVIDENT.

Sample Temperatures - Tetrahedral Module





TETRAHEDRAL MODULE

TEMPERATURES SHOWN FOR MEMBERS 1, 2, 7, & 8

MEMBERS: GRAPHITE-EPOXY TUBES, d/t = 100

ORBIT: CIRCULAR, NEAR-ECLIPTIC PLANE, 463 km

Figure 10

TEMPERATURES OF SECONDARY TRUSS MEMBERS (Figure 11)

A TWO-TIER STRUCTURE, CONSISTING OF A HEXAGONAL PRIMARY TRUSS COMPOSED OF TWO RINGS OF TETRAHEDRAL MODULES, SUPPORTING 7 SECONDARY HEXAGONAL TRUSSES, WAS ANALYZED FOR THERMAL DISTORTIONS. EACH SECONDARY TRUSS CONSISTED OF SEVEN RINGS OF TETRAHEDRAL MODULES AND SUPPORTED ON ITS EARTH-FACING SIDE A CONTINUOUS ARRAY OF OPAQUE NON-STRUCTURAL PANELS. THESE PANELS WERE ASSUMED TO EMIT THERMAL RADIATION AT 3 DIFFERENT INTENSITIES (POWER LEVEL STEPS 1, 2, AND 3 ON THE DIAGRAM). THE STRUCTURE WAS ANALYZED IN A CIRCULAR, ECLIPTIC-PLANE GEOSYNCHRONOUS ORBIT AND TEMPERATURES WERE COMPUTED AT FIVE CONDITIONS: $\Theta = 0$, $\Theta = \pi/2$ RAD, $\Theta = \pi$ RAD WITH NO ECLIPSE, $\Theta = \pi$ RAD WITH FULL ECLIPSE, AND $\Theta = 3\pi/2$ RAD. THE CASE OF $\Theta = \pi$ RAD WITH FULL ECLIPSE, WHEN THE RADIALLY-VARYING ON-BOARD HEATING TOTALLY DOMINATED THE TEMPERATURE DISTRIBUTIONS AND WAS FOUND TO BE THE MOST CRITICAL CASE FOR THERMAL DISTORTIONS. THE CHART SHOWS TEMPERATURES OF SECONDARY TRUSS MEMBERS FOR THIS CASE, FOR TETRAHEDRAL MODULES LOCATED WHOLLY WITHIN EACH OF THE 3 LEVELS OF ON-BOARD HEATING. THE PEAK ON-BOARD HEATING (STEP 1 REGION) WAS 3.5 kW/m^2 AT THE RADIATING PANELS. THE POWER STEP LEVELS USED WERE THE FIRST THREE STEPS OF A 10-STEP APPROXIMATION OF A 10 DB GAUSSIAN TAPER APPLIED TO THE STRUCTURE EXTENDED TO 1 KM DIAMETER.

Temperatures of Secondary Truss Members

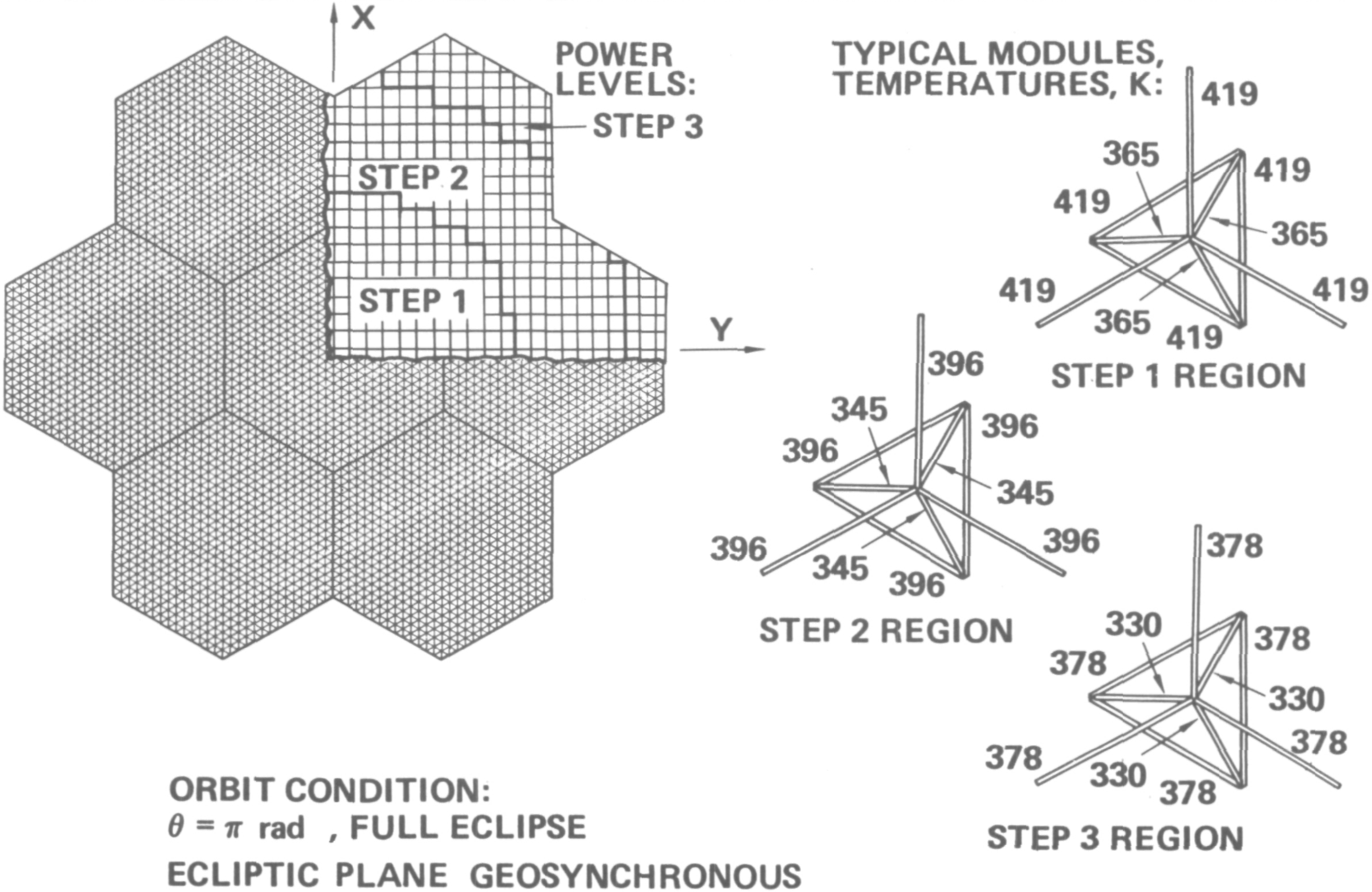


Figure 11

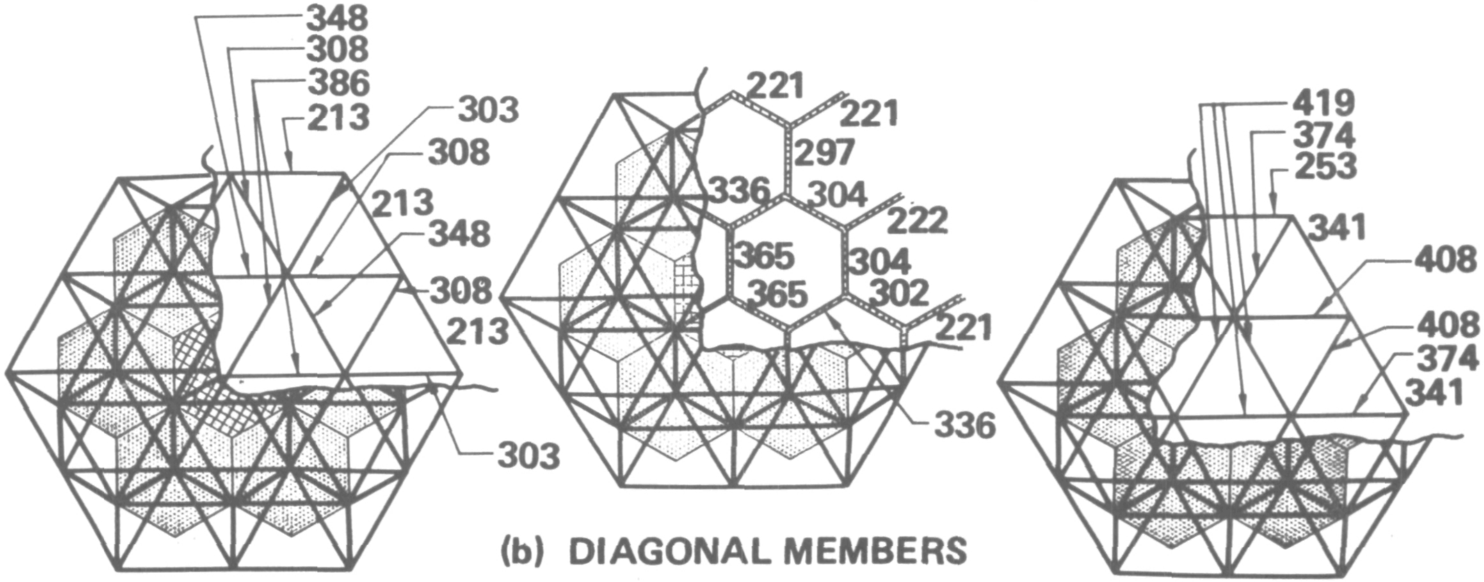
TEMPERATURES OF PRIMARY TRUSS MEMBERS (Figure 12)

THE CHART SHOWS SAMPLE TEMPERATURES FOR THE PRIMARY STRUCTURE OF THE TWO-TIER PLATFORM. AS FOR THE SECONDARY TRUSS MEMBERS, THE CASE OF $\Theta = \pi$ RAD WITH FULL ECLIPSE RESULTED IN THE GREATEST TEMPERATURE DIFFERENTIALS AND THE MAXIMUM DISTORTIONS. FOR THIS CONDITION, THE ON-BOARD HEATING IS THE ONLY THERMAL INFLUENCE. THIS FACT, PLUS THE NEAR-CONCENTRIC BOUNDARIES OF POWER LEVEL STEPS, RESULTS IN TEMPERATURE DISTRIBUTIONS WITH AXIAL SYMMETRY ABOUT THE Z-AXIS. TEMPERATURES FOR THE TWO-TIER PLATFORM, LIKE THOSE FOR THE STRUCTURE OF "SAMPLE TEMPERATURES - TETRAHEDRAL MODULE" WERE COMPUTED ASSUMING NO THERMAL CONDUCTION THROUGH JOINTS NOR RADIANT INTERCHANGE BETWEEN TRUSS MEMBERS. RADIANT INTERCHANGE BETWEEN THE OPAQUE PANELS AND PRIMARY AND SECONDARY TRUSS MEMBERS WAS ACCOUNTED FOR.

Temperatures of Primary Truss Members

TEMPERATURES IN K

ORBIT CONDITION: $\theta = \pi$ rad, FULL ECLIPSE
ECLIPTIC PLANE, GEOSYNCHRONOUS



(a) OUTER FACE MEMBERS

(b) DIAGONAL MEMBERS

(c) INNER FACE MEMBERS

Figure 12

SLOPES DUE TO THERMAL DISTORTIONS (Figure 13)

PLATFORM SLOPES DUE TO THERMAL DEFLECTIONS WERE CALCULATED USING FINITE-ELEMENT MODELS OF THE PRIMARY AND SECONDARY TRUSSES. FIRST, THERMAL DEFLECTIONS OF THE ATTACHMENT POINTS ON THE PRIMARY TRUSS WERE DETERMINED USING AN EQUIVALENT PLATE ELEMENT MODEL OF THE SECONDARY TRUSS UNITS. THEN A DETAILED FINITE-ELEMENT MODEL OF ONE ARBITRARILY SELECTED SECONDARY TRUSS WAS CONSTRUCTED AND SUBJECTED TO ITS TEMPERATURE DISTRIBUTION AND THE IMPOSED DEFLECTIONS OF ITS THREE ATTACHMENT POINTS DETERMINED FROM THE PRIMARY TRUSS THERMAL DEFLECTION ANALYSIS. THE SLOPES FOR ONE SECONDARY TRUSS AND THE UNDERLYING PRIMARY TRUSS SLOPES ARE SHOWN IN THE FIGURE ALONG THE SECTIONS INDICATED. THE PRIMARY TRUSS SLOPES ARE CONSTANT OVER EACH SECONDARY TRUSS SINCE THE PRIMARY SLOPES ARE DEFINED BY THE LOCATIONS OF THE 3 SUPPORT POINTS FOR EACH SECONDARY TRUSS. EACH SECONDARY TRUSS WILL HAVE SLOPE DISTRIBUTIONS DEPENDENT UPON ITS THERMAL ENVIRONMENT AND THE IMPOSED DEFLECTIONS OF ITS ATTACHMENT POINTS AND IS INDEPENDENT OF THE SLOPE DISTRIBUTION OF THE NEIGHBORING SECONDARY TRUSS. IN GENERAL, THE SLOPES AT THE PERIMETER OF THE TOTAL PLATFORM WILL BE GREATER THAN THOSE IN THE CENTRAL REGION DUE TO GREATER PRIMARY TRUSS DEFLECTIONS AROUND THE PERIMETER.

Slopes Due to Thermal Distortions

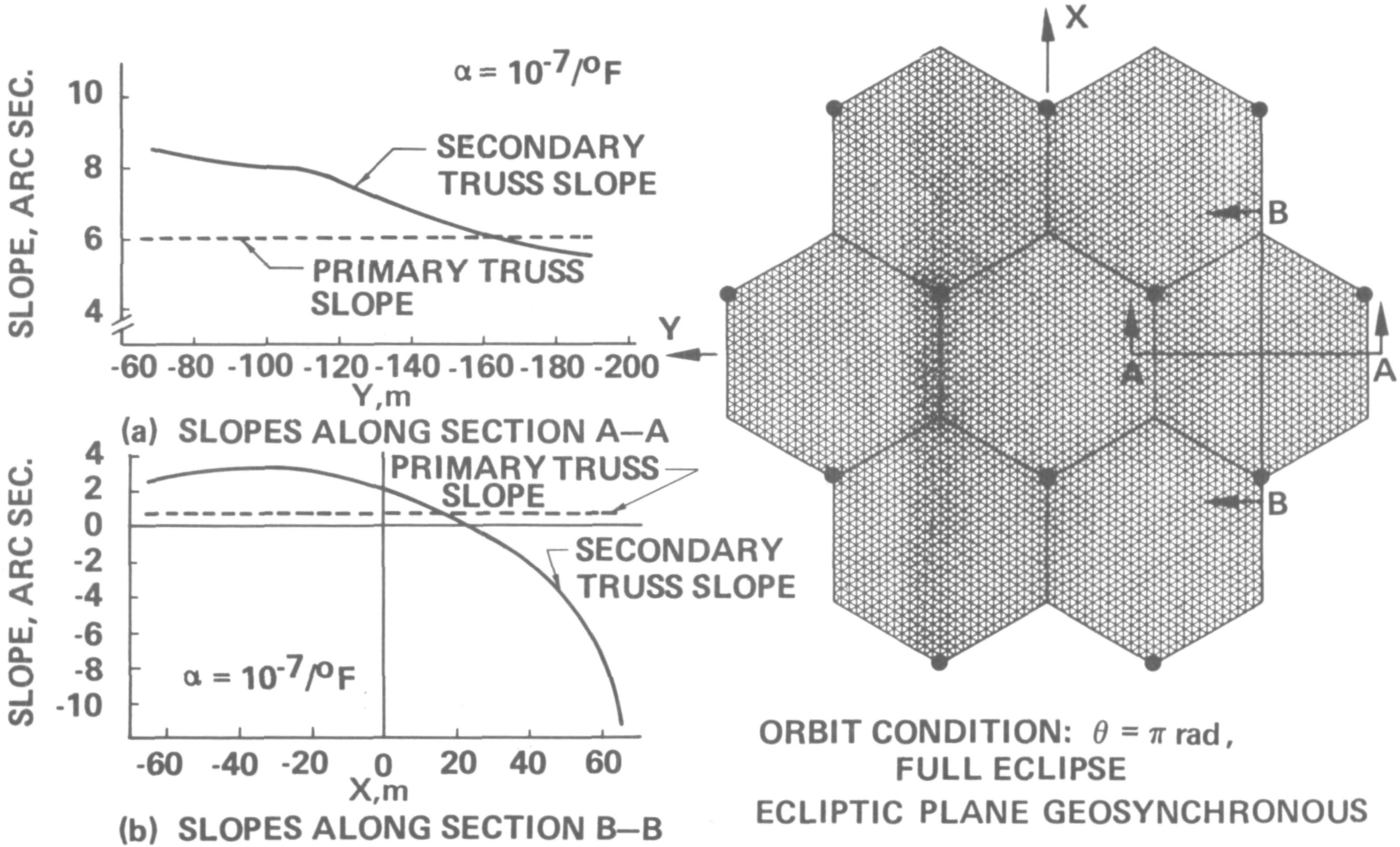


Figure 13

Summary

- 300m x 300m PLATFORM IS COMPATIBLE WITH STS
  - MULTIFUNCTIONAL MECHANISM OFFERS ADVANTAGES FOR DEPLOYABLE STRUCTURES DESIGN AND TEST PROCEDURES
  - LONG LATTICE COLUMNS ($\geqslant$ 130m) ARE COMPATIBLE WITH STS AND ON-ORBIT ASSEMBLY
- LOW THERMAL DISTORTION OF GRAPHITE COMPOSITE REPEATING MODULE TRUSS STRUCTURE
  - WITHOUT ON-BOARD HEATING - NO APPRECIABLE CURVATURE
  - WITH ON-BOARD HEATING ($\approx$ 3.5 kw/m^2) - LESS THAN ONE ARC MINUTE OF SURFACE DISTORTION

Figure 14