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OLD DOMINION UNIVERSITY RESEARCH FOUNDATION

DEPARTMENT OF MECHANICAL ENGINEERING AND MECHANICS
SCHOOL OF ENGINEERING
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA

SELF-SHADOWING OF ORBITING TRUSSES

By

Jack Mahaney

and

Earl A. Thornton, Principal Investigator

Progress Report
For the period ending May 15, 1983

Prepared for the
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

Under
Research Grant NAG1-257
L. Bernard Garrett, Technical Monitor
Space Systems Division

August 1983

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P.O. Box 6369
Norfolk, Virginia 23508

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SELF-SHADOWING OF ORBITING TRUSSES

By

Jack Mahaney[1] and Earl Thornton[2]

SUMMARY

Purpose -- Determine shadowing reductions on heating of orbiting trusses

Scope -- Determination of heating rates with slender member shadowing effects included

-- Thermal response of shadowed member

Analysis Approach

1. Determine shadowing
2. Heating analysis
3. Thermal analysis
4. Structural analysis

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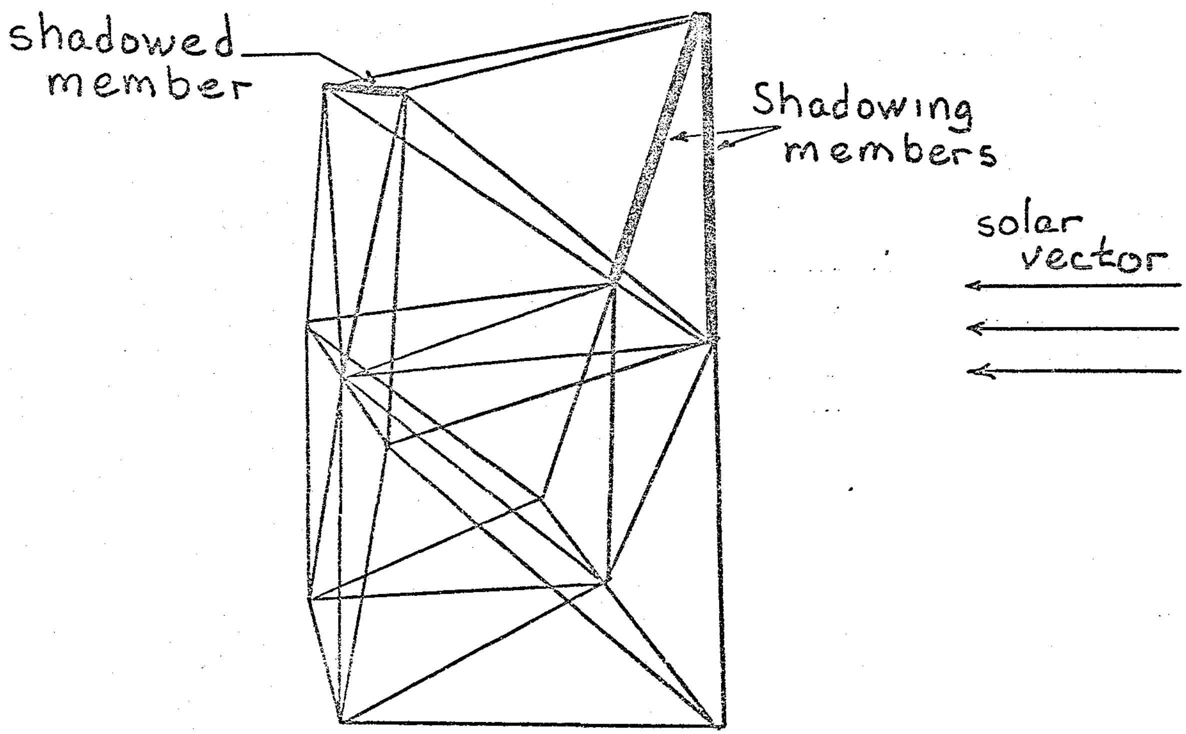
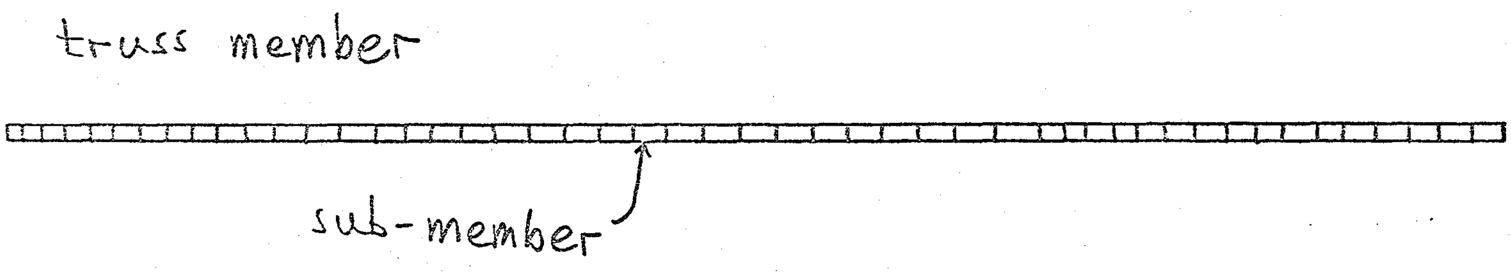
TYPICAL TRUSS SHADOWING



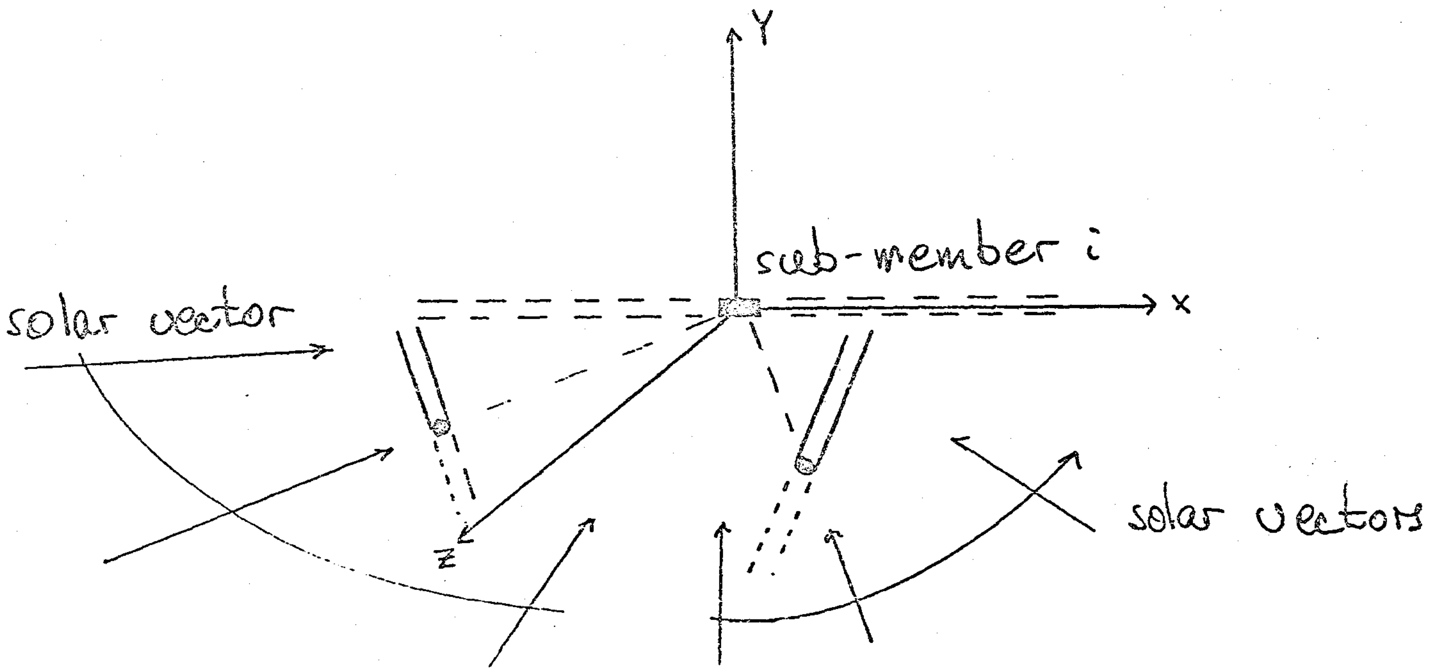
APPROACH

1. Subdivide shadowed member



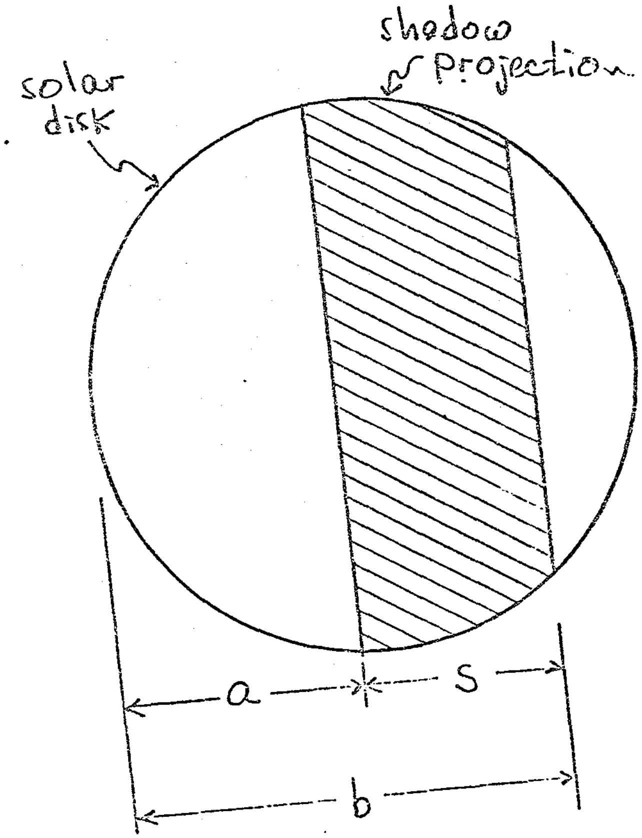
Approach

2. Calculate centroid of sub-member i.
3. Translate nodal co-ordinates
4. Identify shadowers
5. Determine where shadowing occurs.



APPROACH

6. Calculate shadow intensity (SHAD)



$$SHAD = f(a, b, s, R_s)$$

R_s = Radius of Sun

SHAD is a measure of shadow intensity.

= 1, no shadow

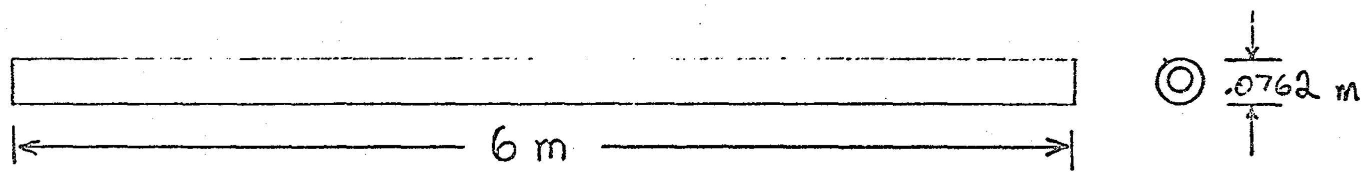
= 0, full shadow

incident solar heat = solar flux × SHAD

APPROACH

1. Subdivide truss member
2. Calculate centroid of sub-member i.
3. Translate nodal co-ordinates to i-centered system
4. Identify shadowers
5. Find locations where shadowing occurs
6. Calculate shadow intensity (SHAD)

Typical Truss Member

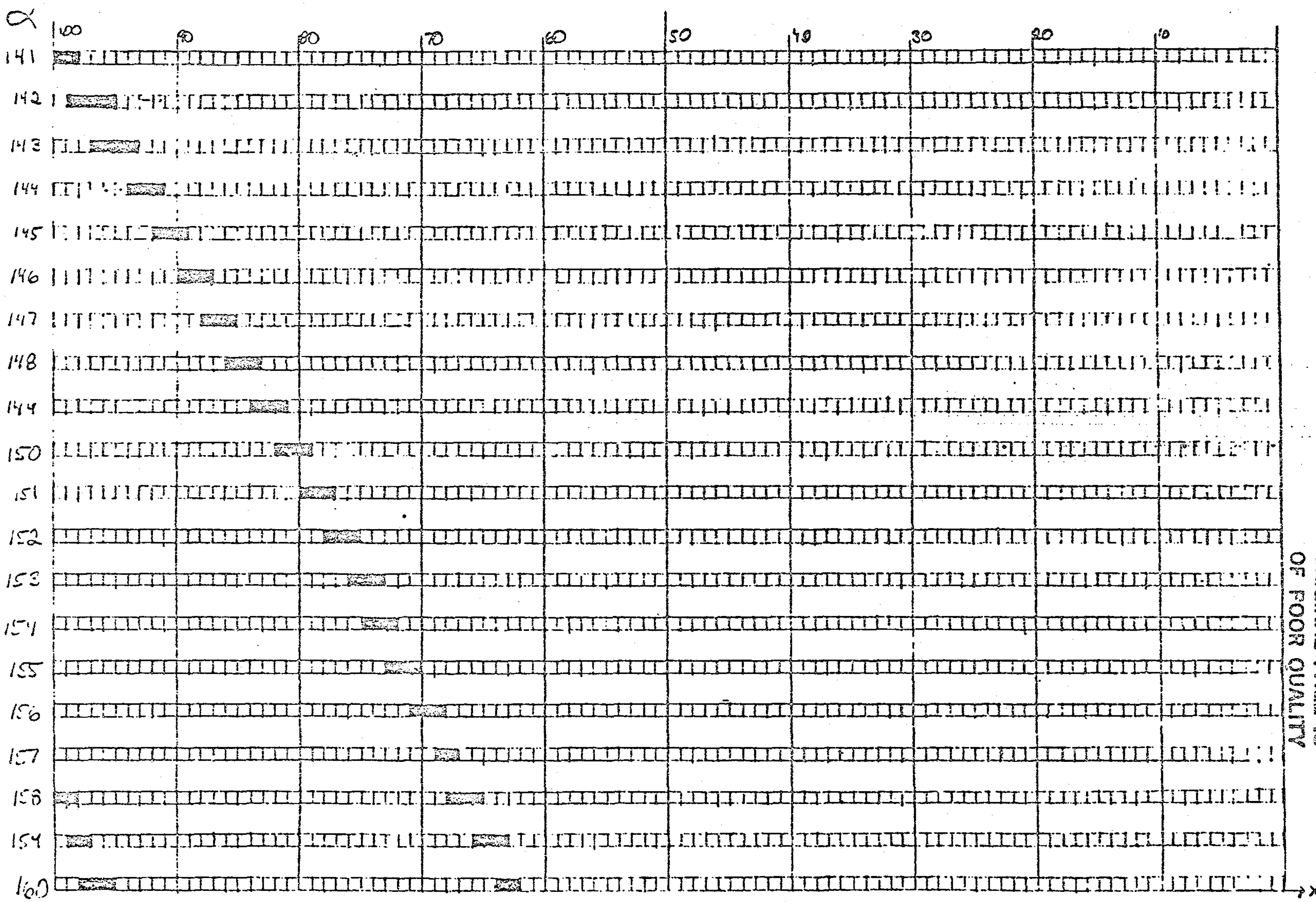


Cross-Sectional Area $.171E{-3}\ m^2$

Radiating Perimeter $.2395\ m$

K	$1.7307\ W/m \cdot K$
ϵ	$.84$
σ	$.56697\ \frac{W}{m^2 \cdot K^4}$
C_p	$1044\ J/kg \cdot K$
ρ	$1576\ kg/m^3$

MOVEMENT OF SHADOWS ON TRUSS MEMBER



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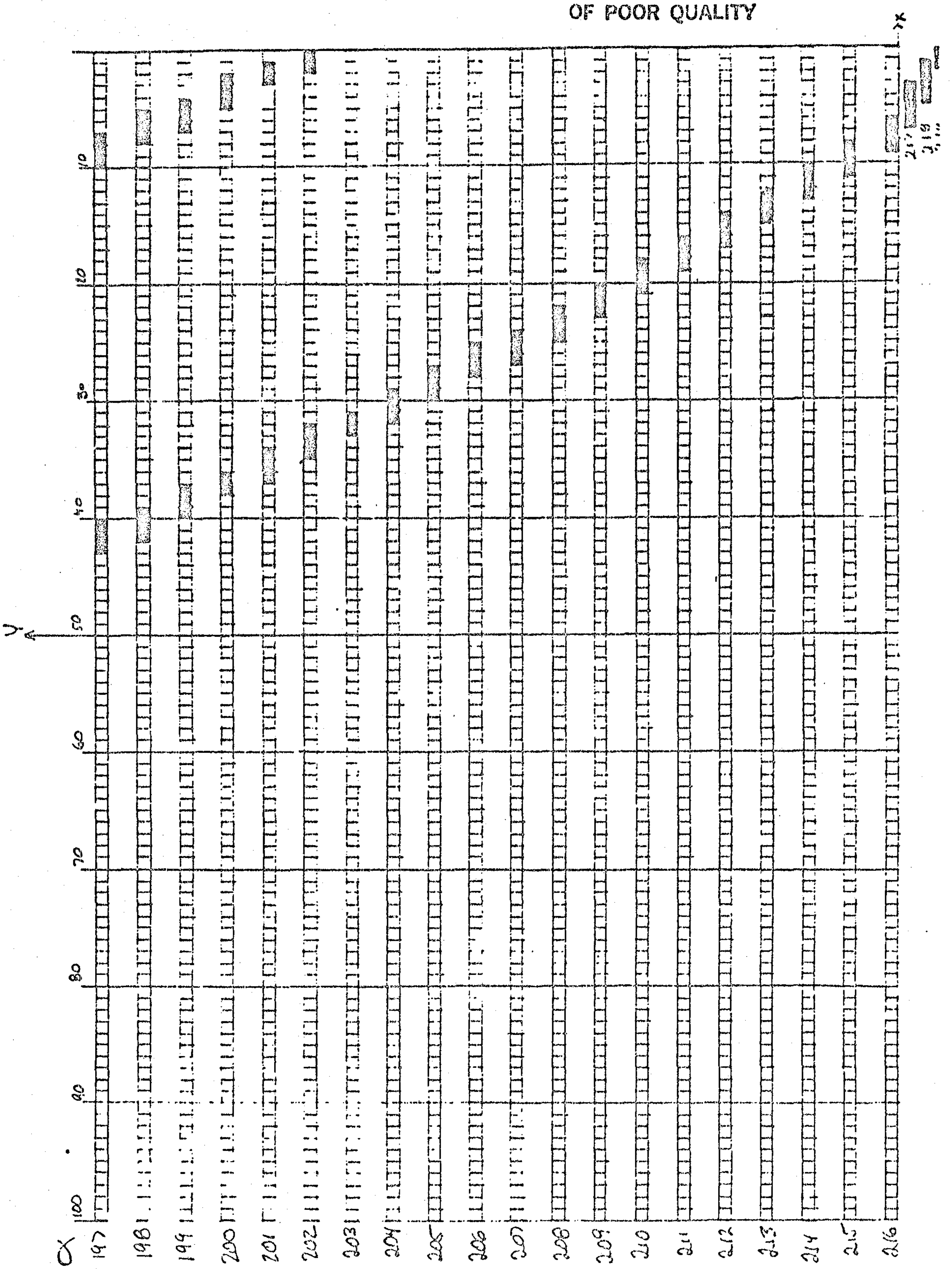

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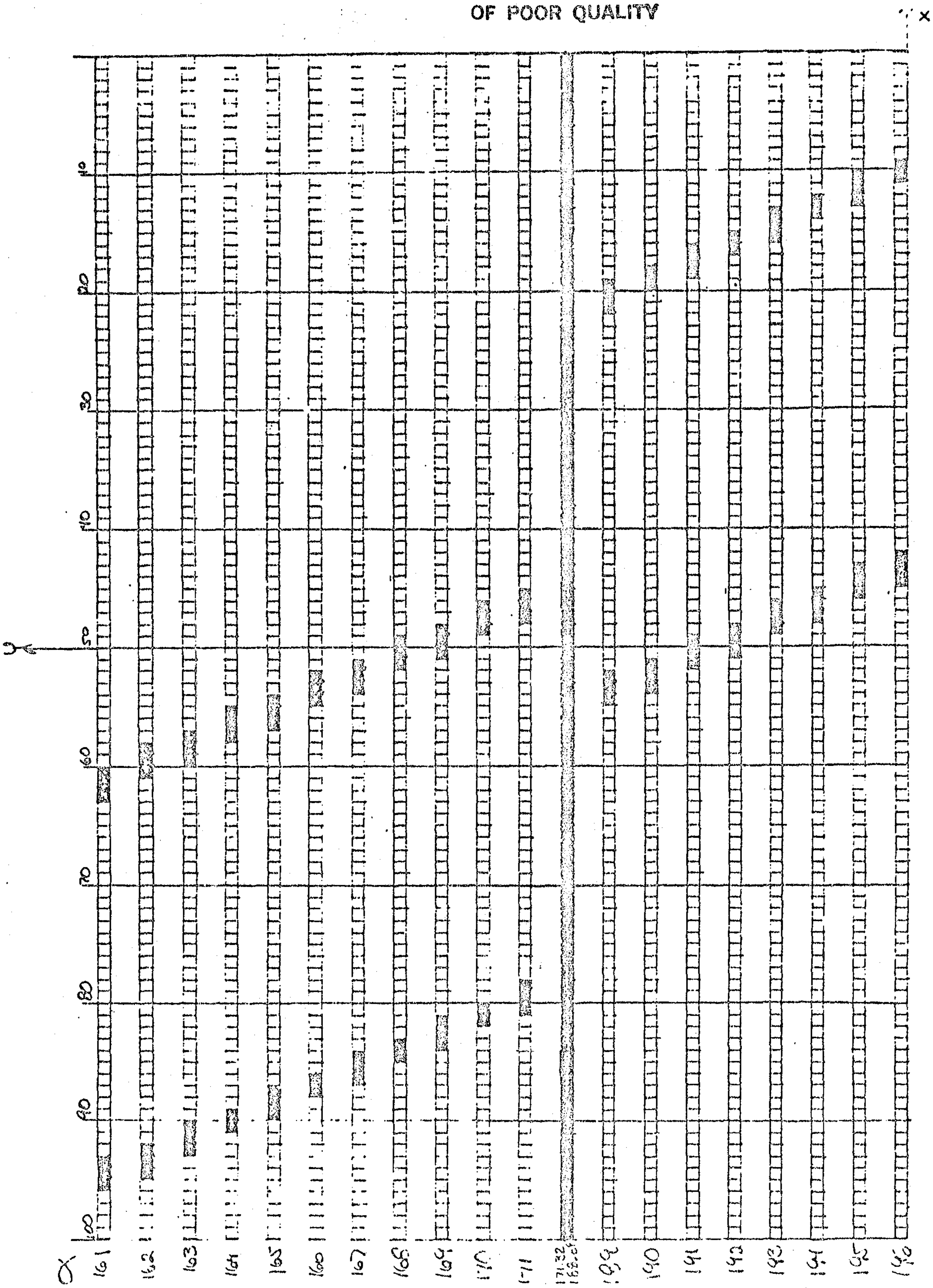
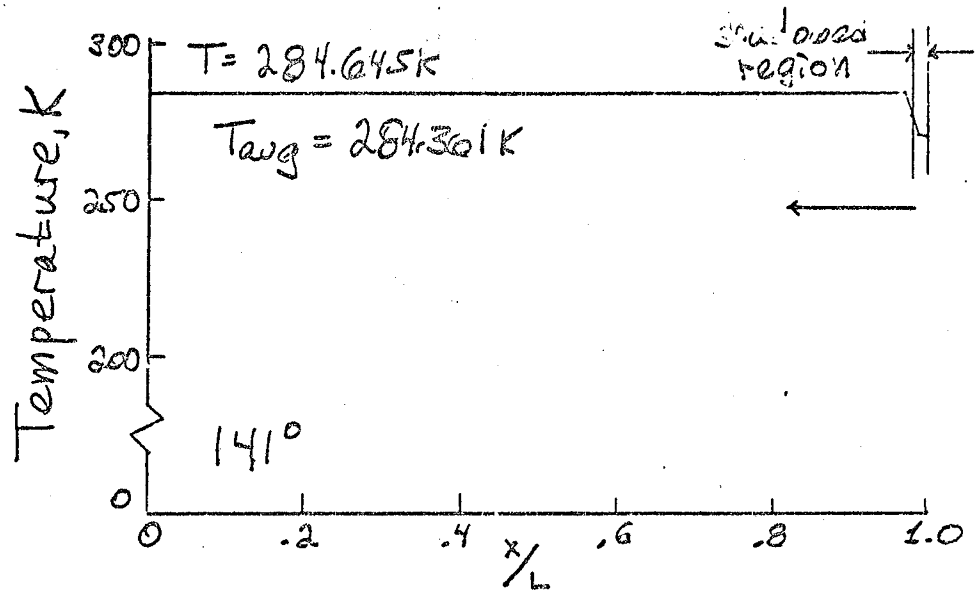
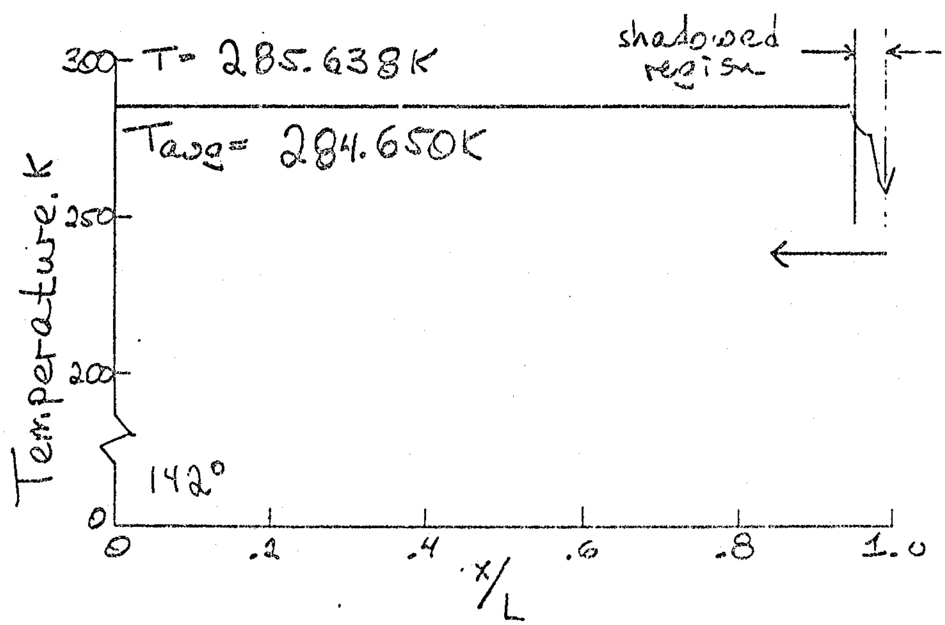


TEMPERATURE DISTRIBUTION OF SHADOWED TRUSS MEMBER





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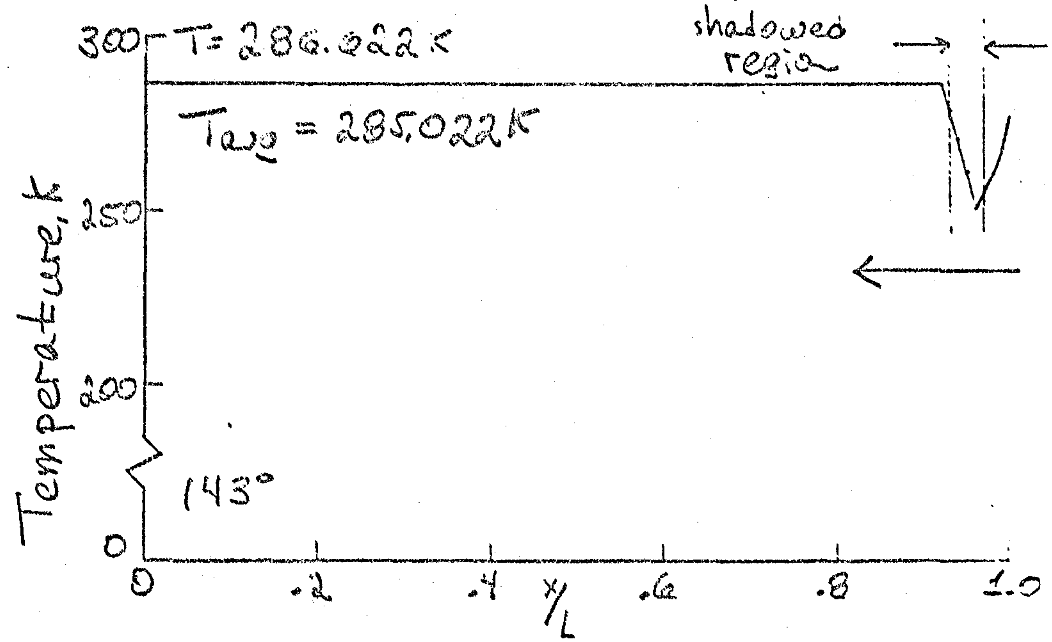
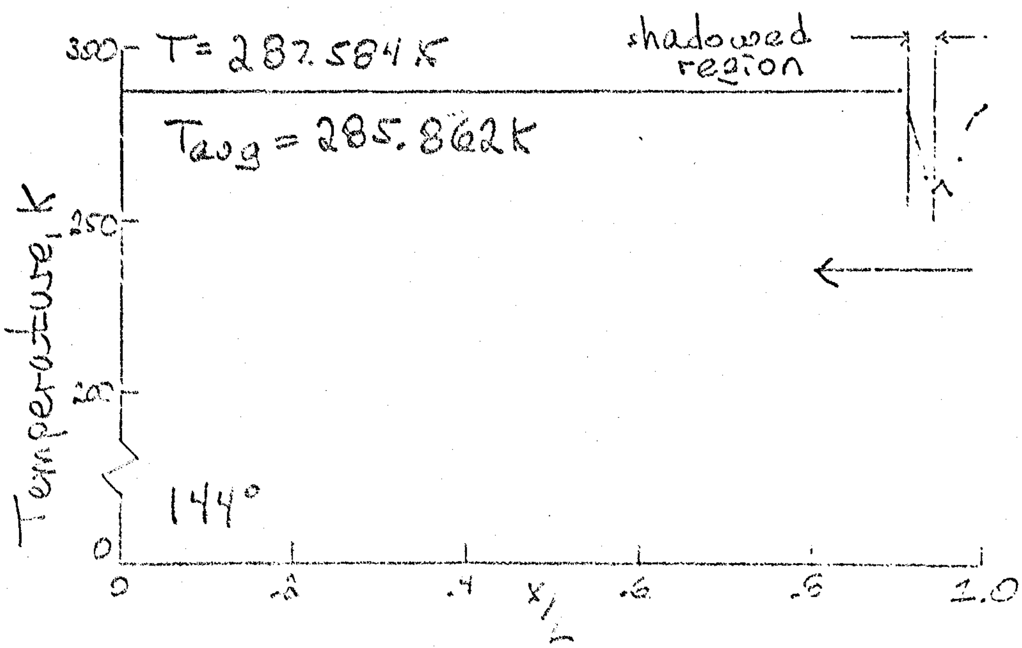
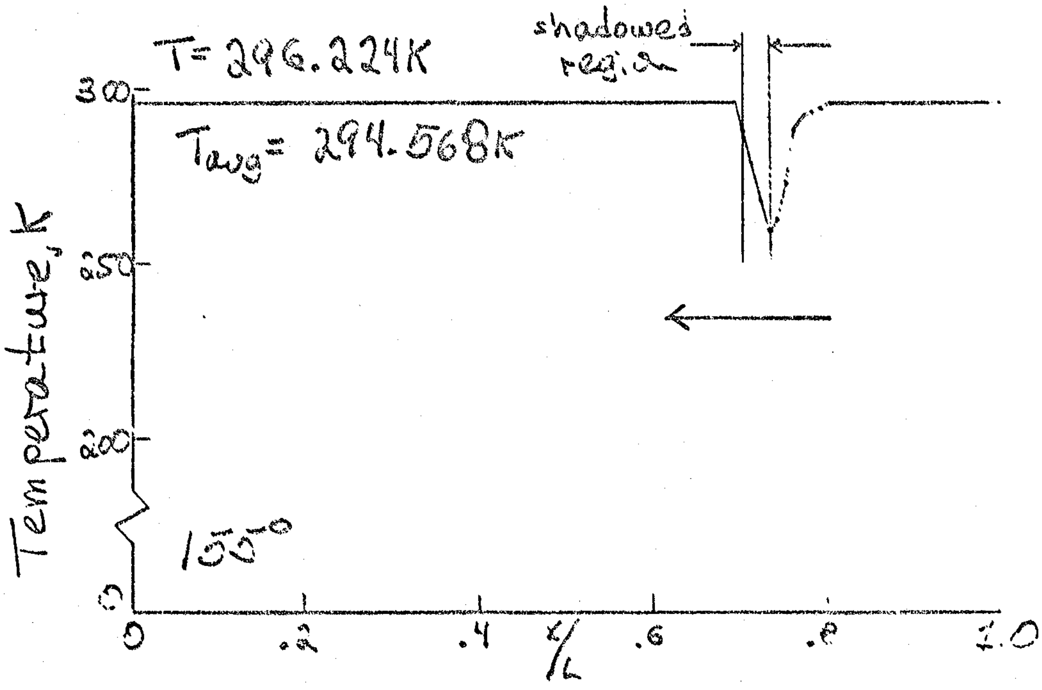
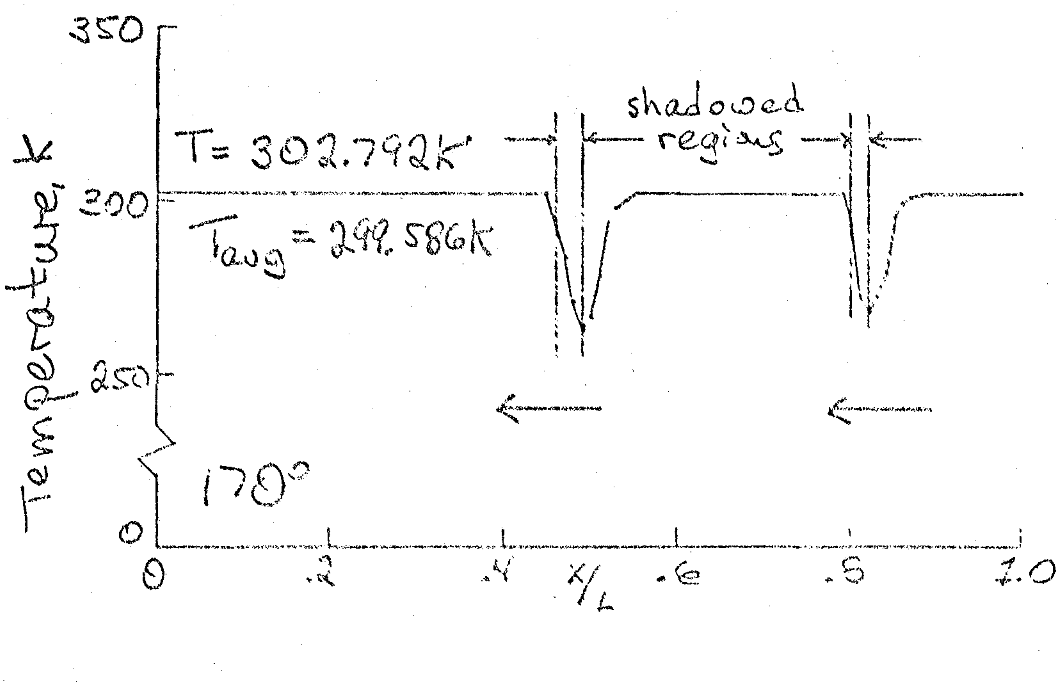
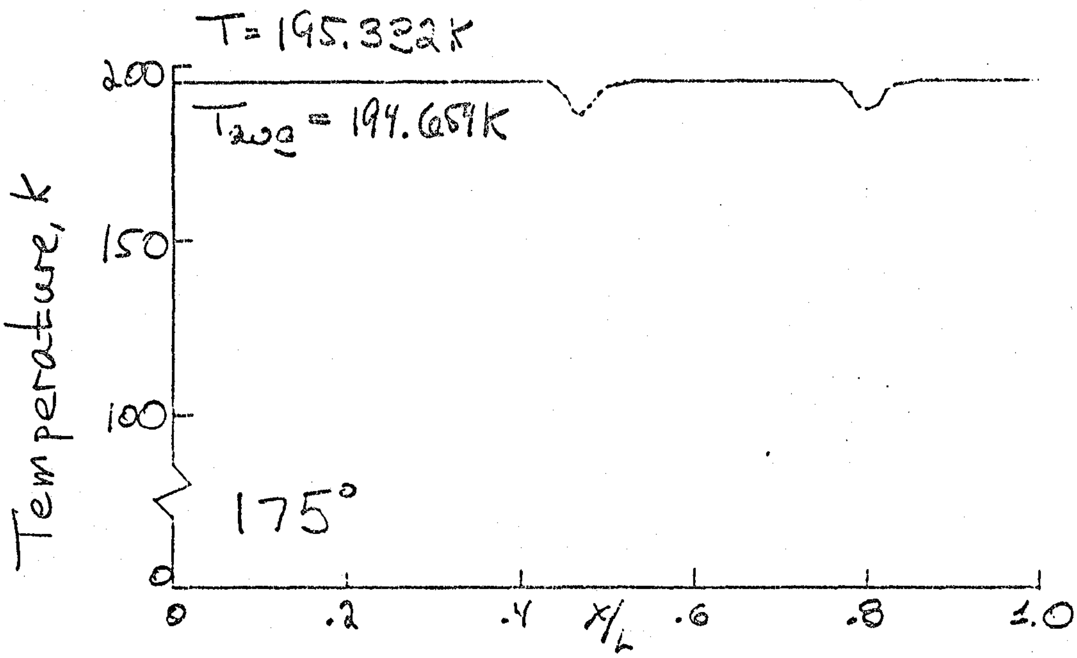
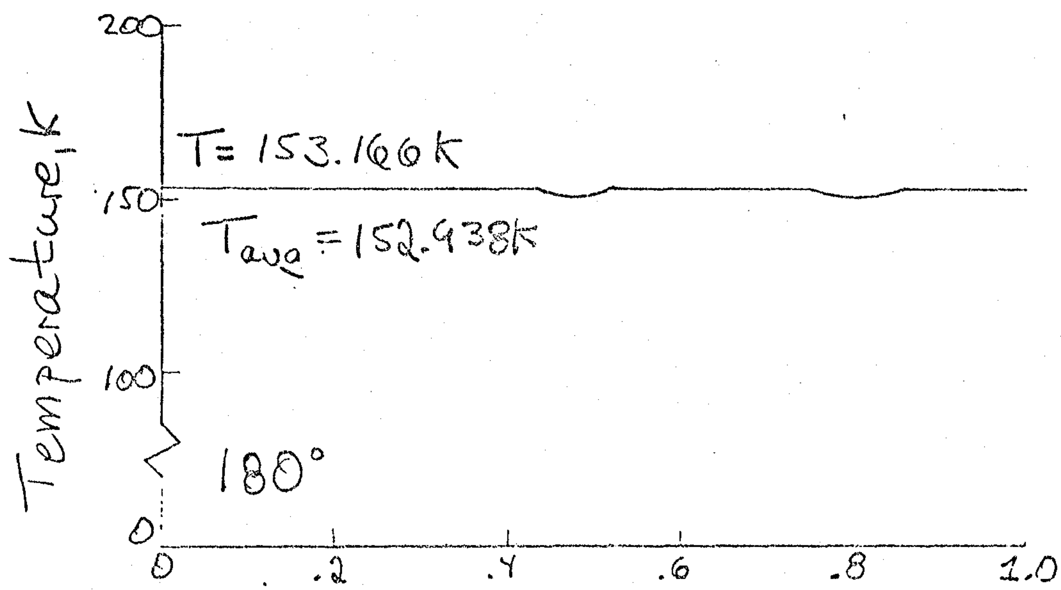


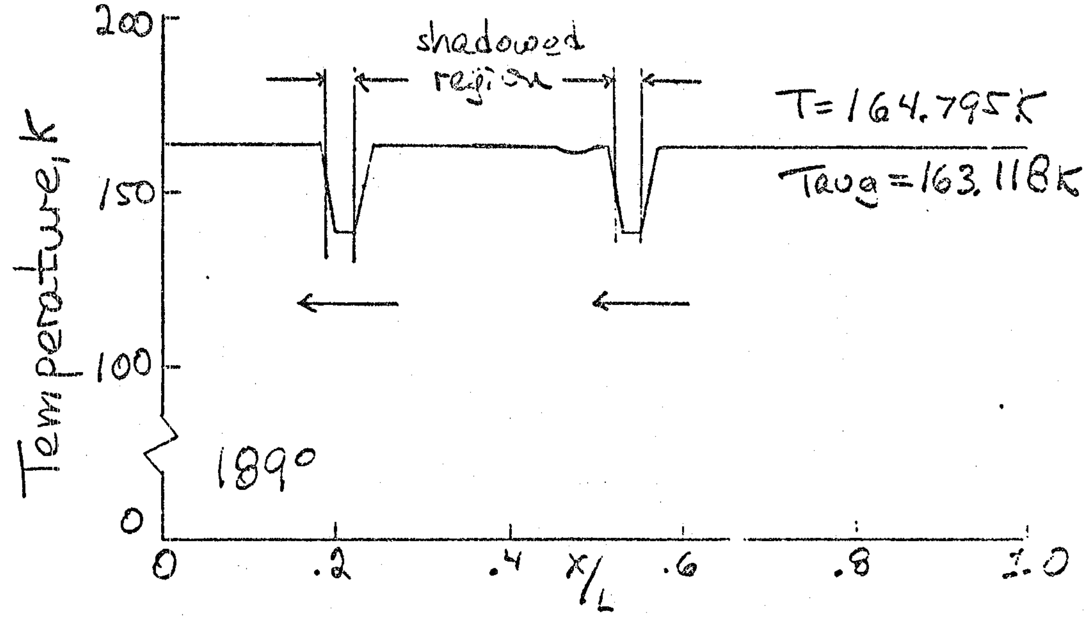


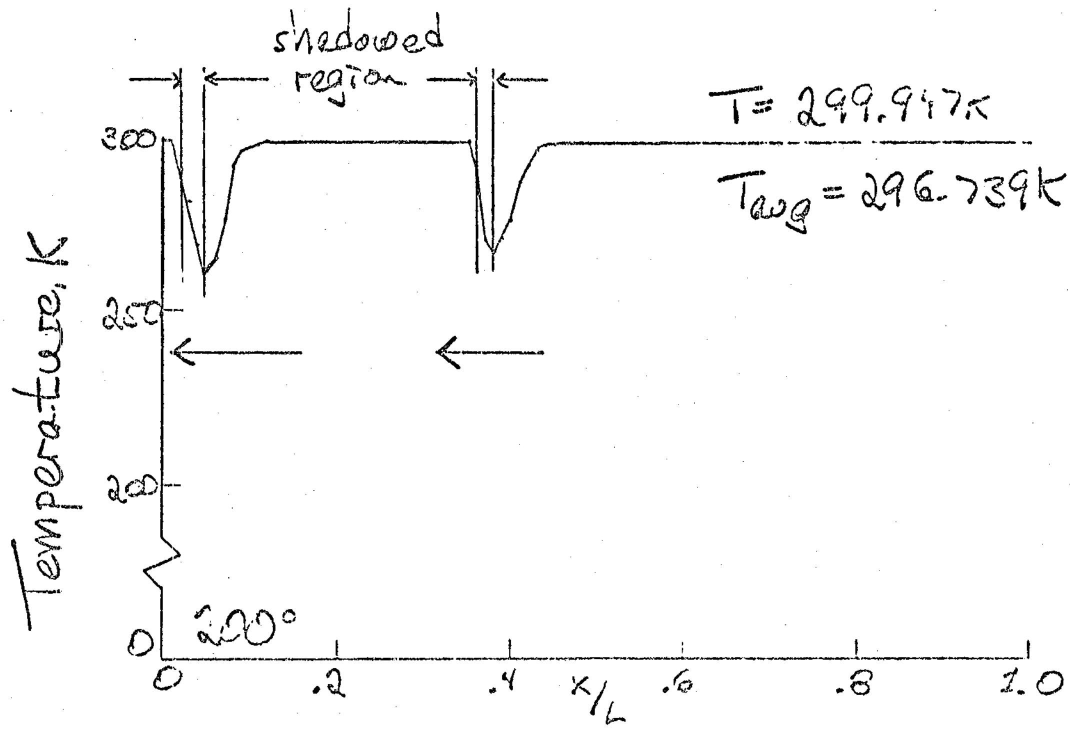

T= 296.224K
shadowed region
Tavg= 294.568K
Temperature, K
300
250
200
0
150°
0
.2
.4
x/L
.6
.8
1.0


350
shadowed regions
T= 302.792K
300
Tavg= 299.586K
Temperature, K
250
170°
0
0
.2
.4
x/L
.6
.8
1.0


T= 195.322 K
T_{avg} = 194.659 K
Temperature, K
200
150
100
0
175°
0
.2
.4
X/L
.6
.8
1.0


T= 153.166 K
T_{avg} = 152.938 K
Temperature, K
200
150
100
0
180°
0
.2
.4
.6
.8
1.0


shadowed
region
T=164.795K
Tavg=163.118K
189°
Temperature, K
200
150
100
0
0
.2
.4
x/L
.6
.8
1.0


shadowed
region
T= 299.947K
Tavg = 296.739K
220°
Temperature, K
300
250
200
0
0
.2
.4
x/L
.6
.8
1.0

FINITE ELEMENT THERMAL-STRUCTURAL ANALYSIS OF CABLE SPACE STRUCTURES

- ANALYSIS INCLUDES :

  (a) CABLE PRESTRESS

  (b) APPLIED SURFACE HEATING

  (c) NONLINEAR TRANSIENT THERMAL ANALYSIS

  (d) NONLINEAR LARGE DEFORMATION STRUCTURAL ANALYSIS

- HOOP COLUMN EXAMPLE IS USED TO DEMONSTRATE THE ANALYSIS.

OBJECTIVE: INVESTIGATE THREE APPROACHES FOR THERMAL-STRUCTURAL ANALYSIS OF CABLE STIFFENED SPACE STRUCTURES.

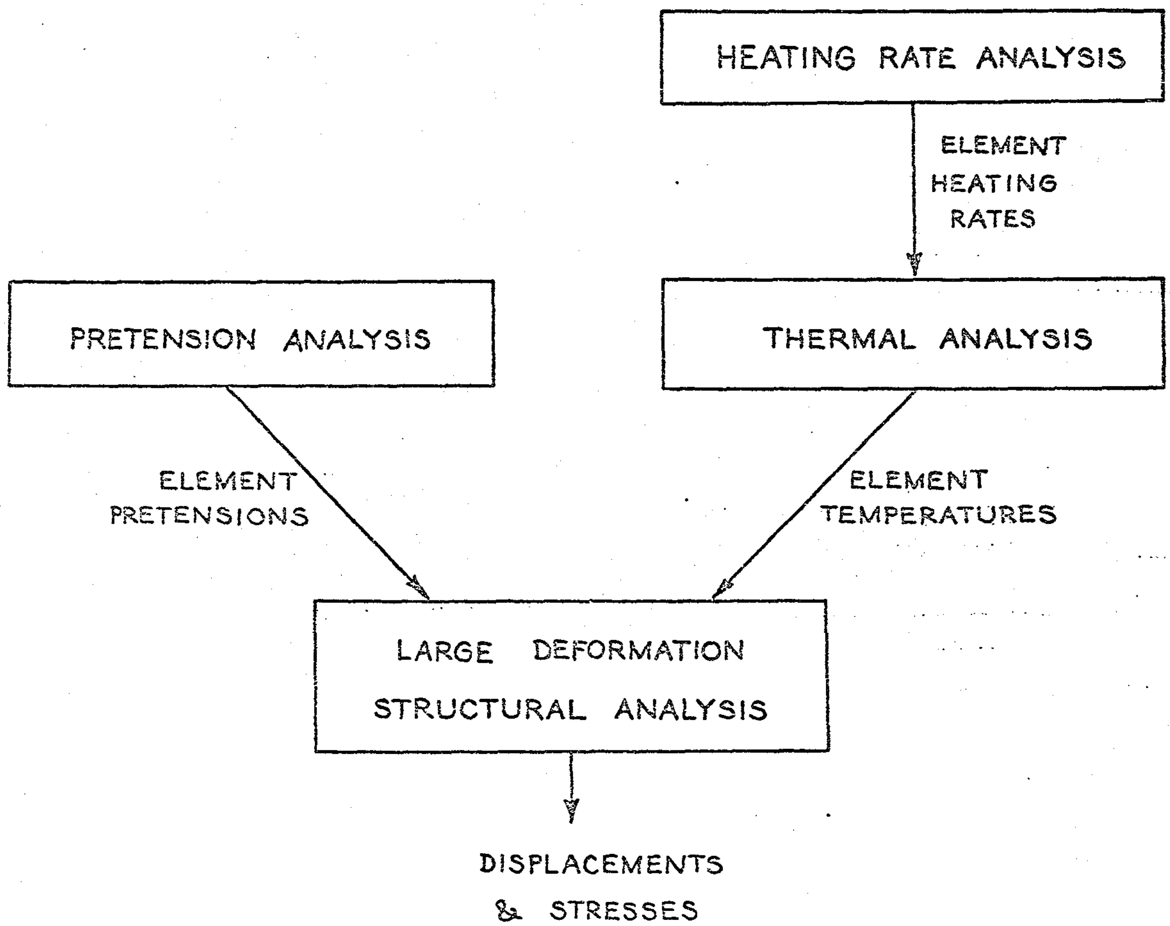
APPROACHES:

(1) LINEAR SMALL DISPLACEMENT STRUCTURAL ANALYSIS WITH PRETENSION.

(2) LINEAR "STRESS-STIFFENING" SMALL DISPLACEMENT STRUCTURAL ANALYSIS.

✓ (3) NON-LINEAR LARGE DISPLACEMENT STRUCTURAL ANALYSIS WITH PRETENSION.

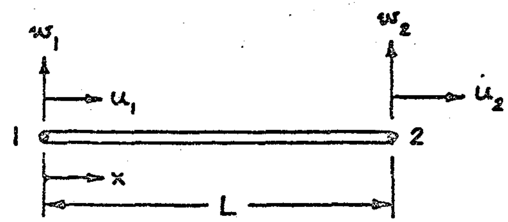
ANALYSIS PROCEDURES



LARGE DEFORMATION CABLE ANALYSIS

- STRAIN - DISPLACEMENT RELATION,

$$\epsilon = \frac{\partial u}{\partial x} + \underbrace{\frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2}_{\text{NONLINEAR TERM}}$$



- FINITE ELEMENT FORMULATION;

  — ESTABLISH ELASTIC STRAIN ENERGY EXPRESSION

  — PERFORM MINIMIZATION WRT. NODAL DISPLACEMENTS TO OBTAIN F.E. EQS. IN THE FORM:

LARGE DEFORMATION CABLE ANALYSIS

$$\Big[\underbrace{[K_L]}_{\text{LINEAR}} + \underbrace{[K_{NL}(\delta)]}_{\text{NONLINEAR}} \Big] \{\delta\} = \underbrace{\{F\}}_{\text{LOADS}}$$

LOADS
- THERMAL EFFECT
- PRETENSION EFFECT
- CONCENTRATED & DISTRIBUTED LOADS

— SOLVE THE ABOVE NONLINEAR EQS. USING ITERATIVE TECHNIQUE (NEWTON - RAPHSON ITERATION).

CABLE ELEMENTS WITH THERMAL STRAIN AND PRESTRESS

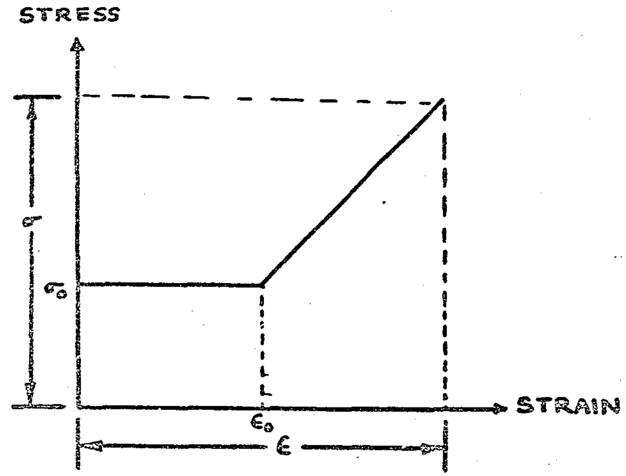
- STRESS-STRAIN RELATION:

$$\sigma = E(\epsilon - \epsilon_0) + \sigma_0$$

WHERE

$\epsilon_0 \rightarrow$ THERMAL STRAIN

$\sigma_0 \rightarrow$ PRE-STRESS



- DERIVATION OF F.E. EQS.;

— ESTABLISH ELASTIC STRAIN ENERGY

$$U = \frac{1}{2}\int_V (\sigma - \sigma_0)(\epsilon - \epsilon_0)\,dv + \int_V \sigma_0 \epsilon \, dv$$

CABLE ELEMENT WITH THERMAL STRAIN AND PRESTRESS

– EXPRESS STRAIN ϵ IN TERMS OF DISPLACEMENTS

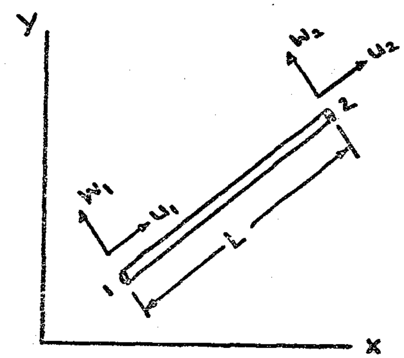
$$\epsilon = \frac{\partial u}{\partial x} + \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2$$

$$\epsilon = e + \frac{1}{2}\theta^2$$

WHERE

$e = \text{STRAIN} = \dfrac{u_2 - u_1}{L}$

$\theta = \text{ROTATION} = \dfrac{W_2 - W_1}{L}$



– MINIMIZE STRAIN ENERGY W.R.T. NODAL DISPLACEMENTS $\{u\}$

TO OBTAIN F.E. EQS.;

$$\Big[\underbrace{[K_L]}_{\text{LINEAR}} + \underbrace{[K_{NL}]}_{\text{NONLINEAR}}\Big]\{u\} = \underbrace{\underbrace{\{F\}_{\epsilon_0}}_{\text{THERMAL STRAIN}} - \underbrace{\{F\}_{\sigma_0}}_{\text{PRESTRESS}}}_{\text{NODAL LOADS}}$$

CABLE ELEMENT WITH THERMAL STRAIN AND PRESTRESS

- SOLUTION METHOD

  – APPLY NEWTON-RAPHSON ALGORITHM TO OBTAIN EQS. IN THE FOLLOWING FORM

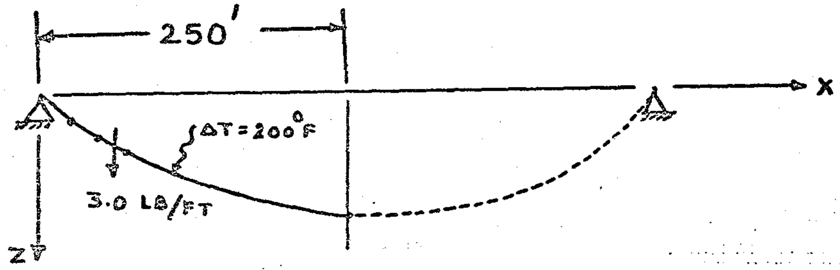
$$\left[\bar{K}(u)\right]^{m}\left\{\Delta u\right\}^{m+1} = \left\{\bar{R}\right\}^{m}$$

WITH

$$\left\{u\right\}^{m+1} = \left\{u\right\}^{m} + \left\{\Delta u\right\}^{m+1}$$

TEST CASES

CABLE WITH ITS OWN WEIGHT AND TEMPERATURE

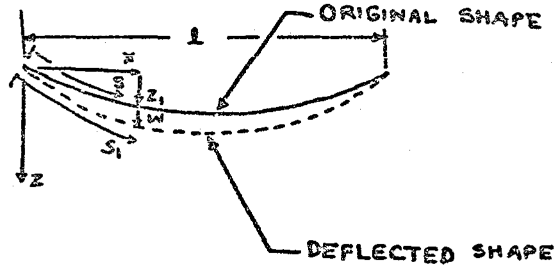


- 25 ELEMENTS ARE TAKEN AND SYMMETRY UTILIZED
- NUMBER OF ITERATION = 5 WITH TOL = 0.001%
- AVERAGE ERROR = 0.02% IN DISPLACEMENTS

EXACT SOLUTION OF CATENARY PROBLEM

- DEFLECTION DUE TO OWN WEIGHT:

"INEXTENSIBLE"



— x, z AND S FOR ORIGINAL SHAPE ARE

$$Z = Z_1 = \frac{H}{mg}\left[\operatorname{Cosh}\left(\frac{mgl}{2H}\right) - \operatorname{Cosh}\frac{mg}{H}\left(\frac{l}{2} - x\right)\right]$$

$$S = \frac{H}{mg}\left\{\operatorname{Sinh}\left(\frac{mgl}{2H}\right) - \sinh\frac{mg}{H}\left(\frac{l}{2} - x\right)\right\}$$

H IS SOLVED FROM $\quad \mathrm{SIN}\left(\frac{mgl}{2H}\right) = \frac{mgL_o}{2H}$

"EXTENSIBLE"

— FOR DEFLECTED SHAPE, H IS SOLVED FROM EQS.

$$\operatorname{Sin}\left(\frac{Wl}{2HL_o} - \frac{W}{2EA_o}\right) = \frac{W}{2H}$$

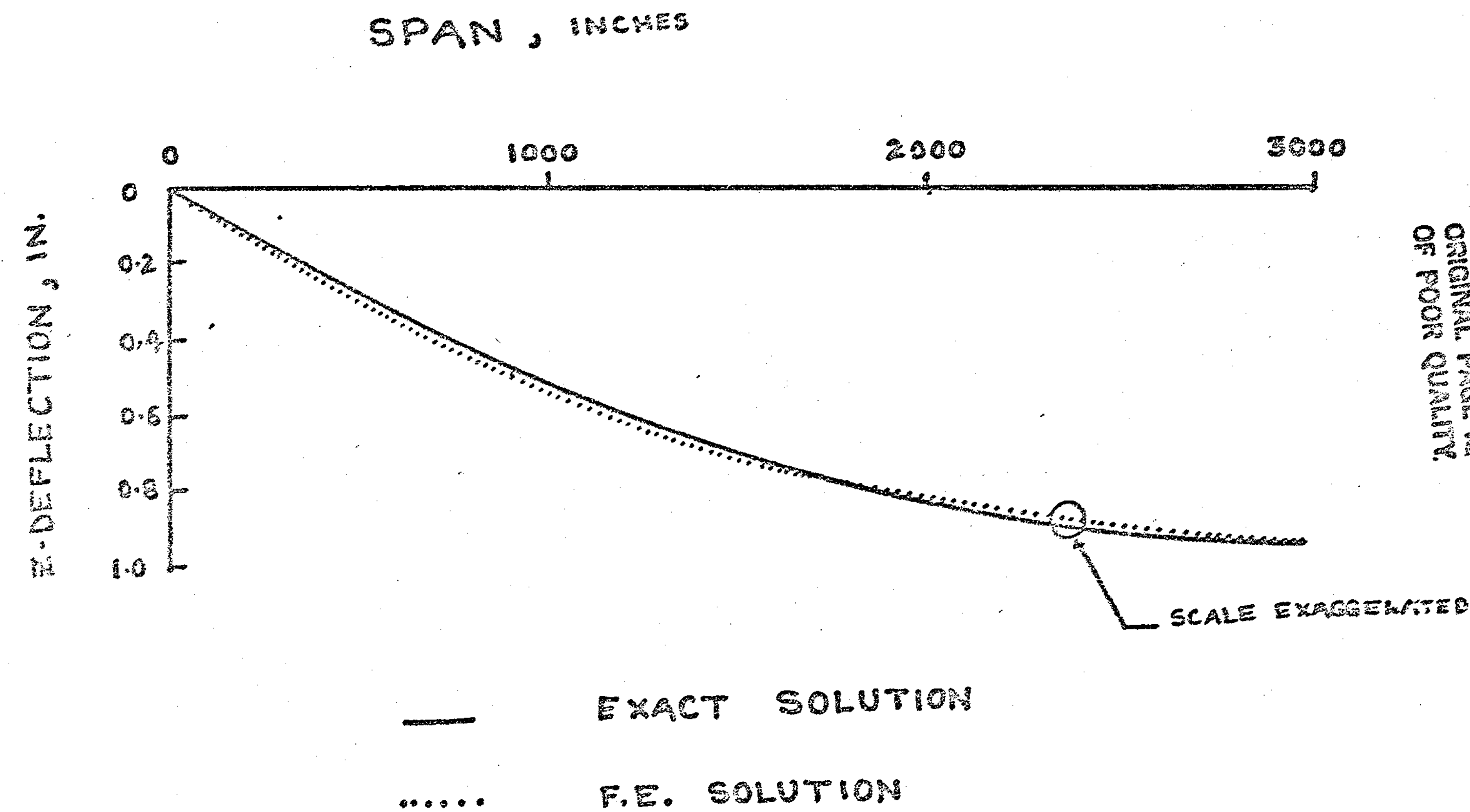
CO-ORDINATES OF DEFLECTED POINTS ARE GIVEN BY

$$x = \frac{HS}{EA_o} + \frac{HL_o}{W}\left[\sin^{-1}\left(\frac{W}{2H}\right) - \sin^{-1}\left\{\frac{W\left(\frac{1}{2} - \frac{S}{L_o}\right)}{H}\right\}\right]$$

$$Z = Z_2 = \frac{WS}{EA_o}\left(\frac{1}{2} - \frac{S}{L_o}\right) + \frac{HL_o}{W}\left[\left\{1 + \left(\frac{W}{2H}\right)^2\right\}^{1/2} - \left\{1 + \frac{W^2}{H^2}\left(\frac{1}{2} - \frac{S}{L_o}\right)^2\right\}^{1/2}\right]$$

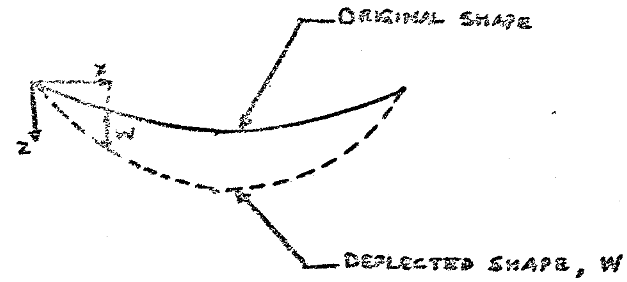
DEFLECTION IN Z-DIRN IS $W = Z_2 - Z_1$

DEFLECTION OF CATENARY DUE TO WEIGHT



EXACT SOLUTIOIN OF CATENARY PROBLEM

• DEFLECTION DUE TO OWN WEIGHT AND TEMPERATURE RISE:



$$W = \left(\frac{mgl^2}{2H}\right)\left[\frac{\bar{h}}{(1-\bar{h})}\,\frac{x}{l}\left(1-\frac{x}{l}\right)\right]$$

$\bar{h}$ IS ROOT (POSITIVE) OF EQS.

$$\bar{h}^3 - \left(2+\theta+\frac{\lambda^2}{24}\right)\bar{h}^2 + \left(1+2\theta+\frac{\lambda^2}{12}\right)\bar{h} - \theta = 0$$

WHERE

$$\theta = \alpha\,|\Delta T|\,L_t \Big/ (HL_c/EA)$$

$$L_t = l\left[1+\left(\frac{mgl}{H}\right)^2\Big/12\right]$$

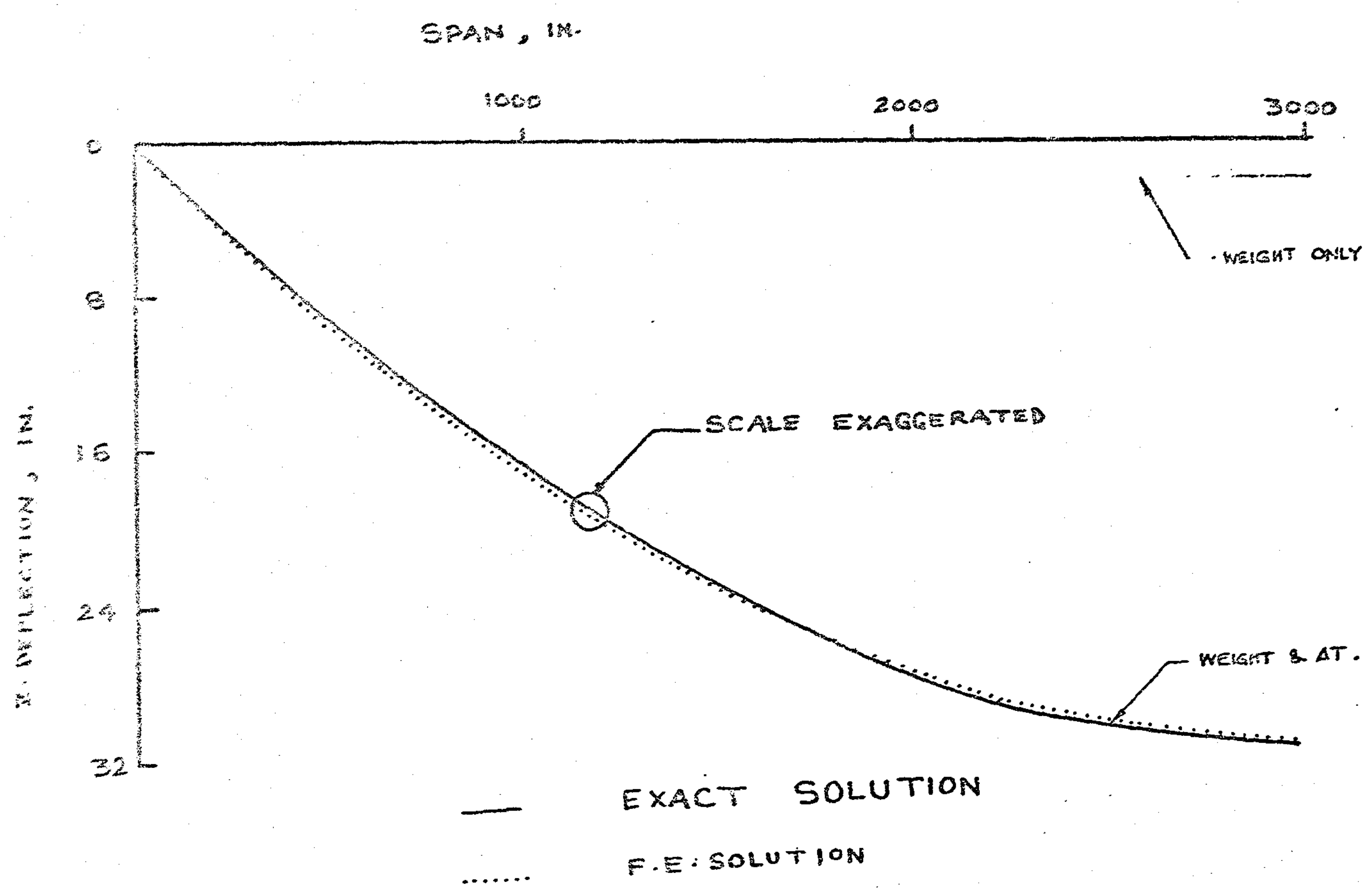
$$L_c = l\left[1+8\left(\frac{f}{l}\right)^2\right]$$

$$\lambda^2 = \left(\frac{mgl}{H}\right)^2 l \Big/ (HL_c/EA)$$

α = COEFF. OF THERMAL EXPANSION

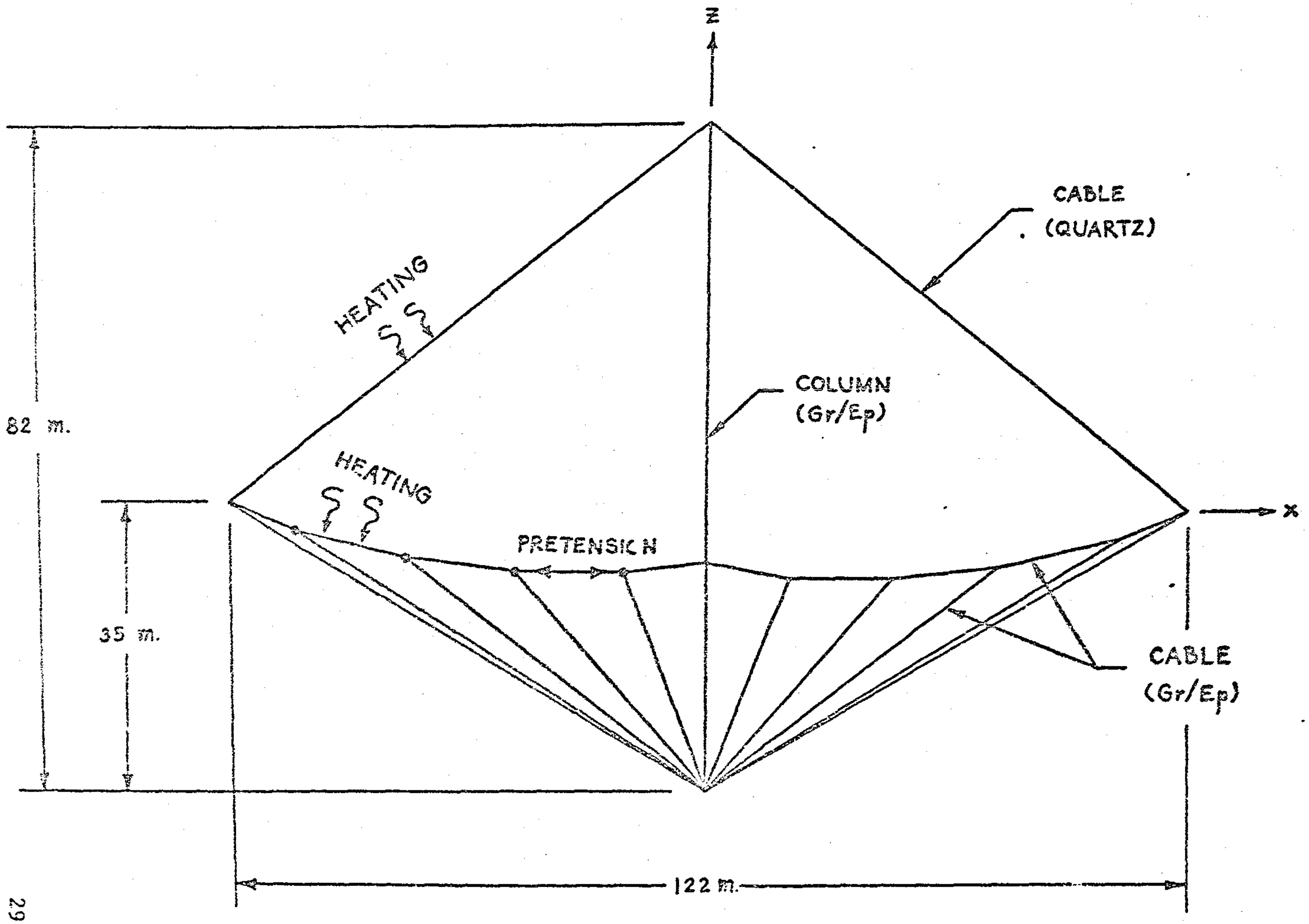
ΔT = RISE IN TEMPERATURE.

DEFLECTION OF CATENARY DUE TO WEIGHT AND TEMPERATURE

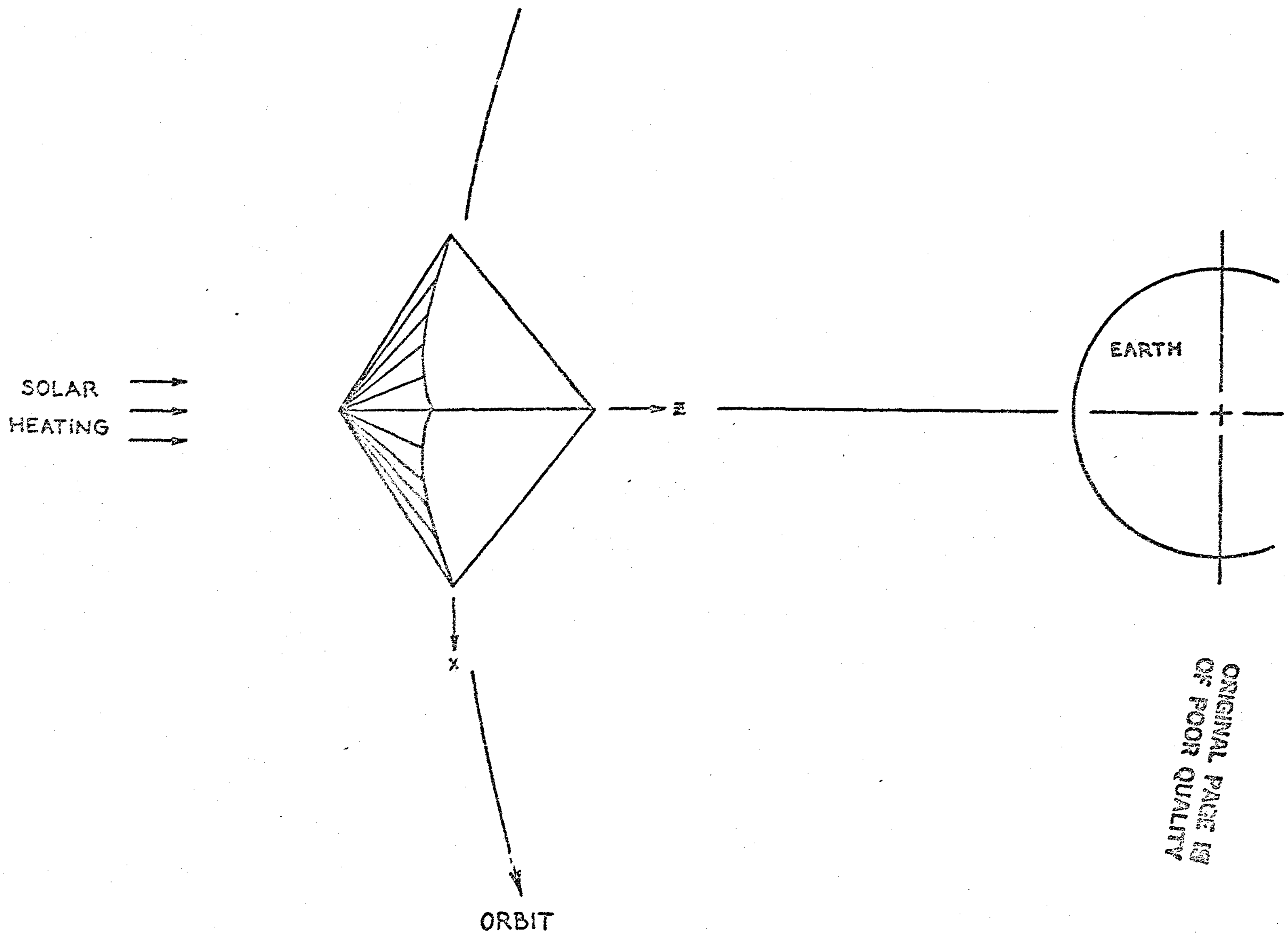


THERMAL-STRUCTURAL ANALYSIS OF HOOP COLUMN

(IDEALIZED 2-D MODEL)

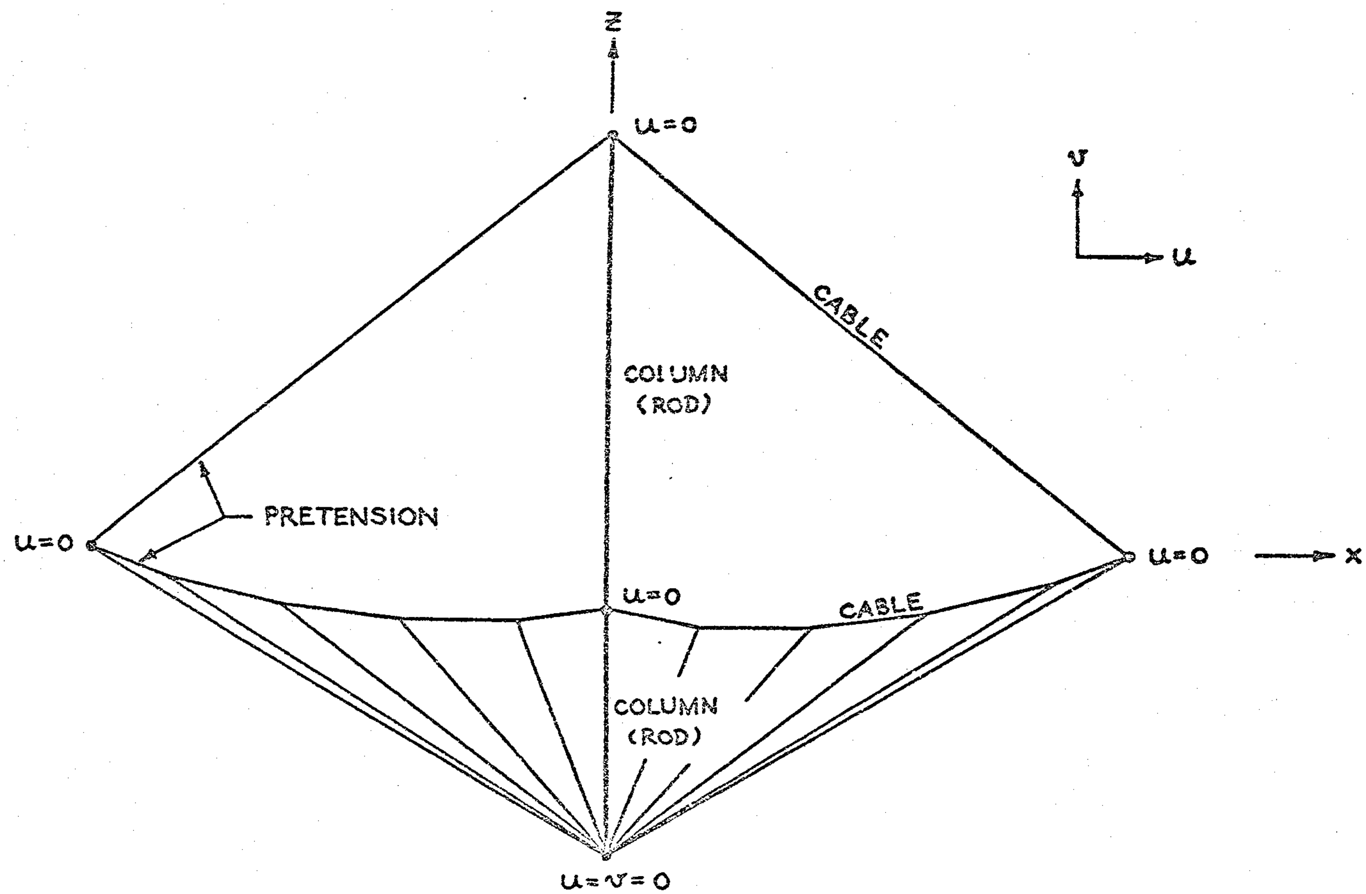


THERMAL-STRUCTURAL ANALYSIS OF HOOP COLUMN



HOOP COLUMN BOUNDARY CONDITIONS

(IDEALIZED 2-D MODEL)



PRETENSION ANALYSIS

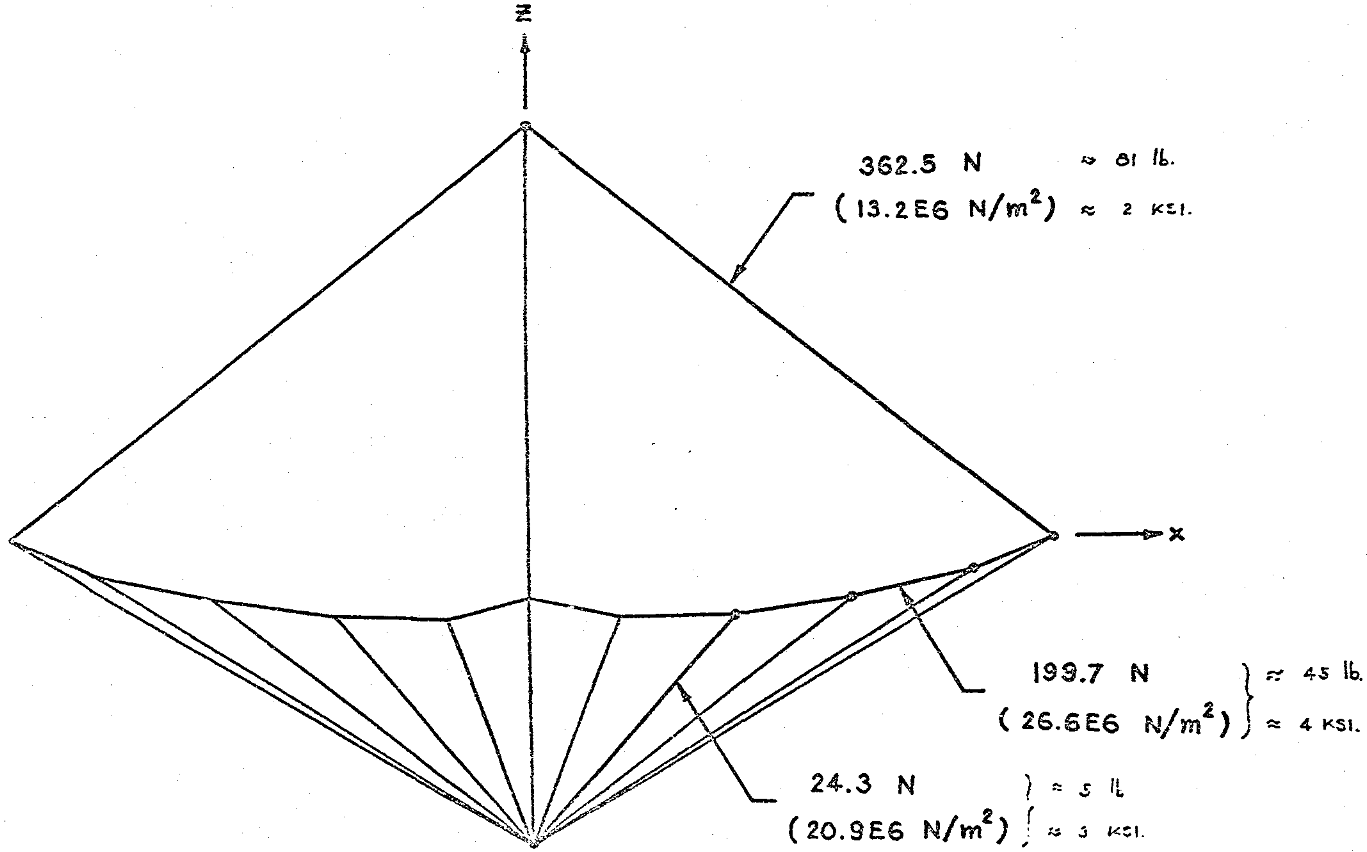
- USING A COMPUTER CODE DEVELOPED, CABLE PRETENSIONS ARE COMPUTED SUCH THAT THE STRUCTURE IS IN:

  — REQUIRED GEOMETRY

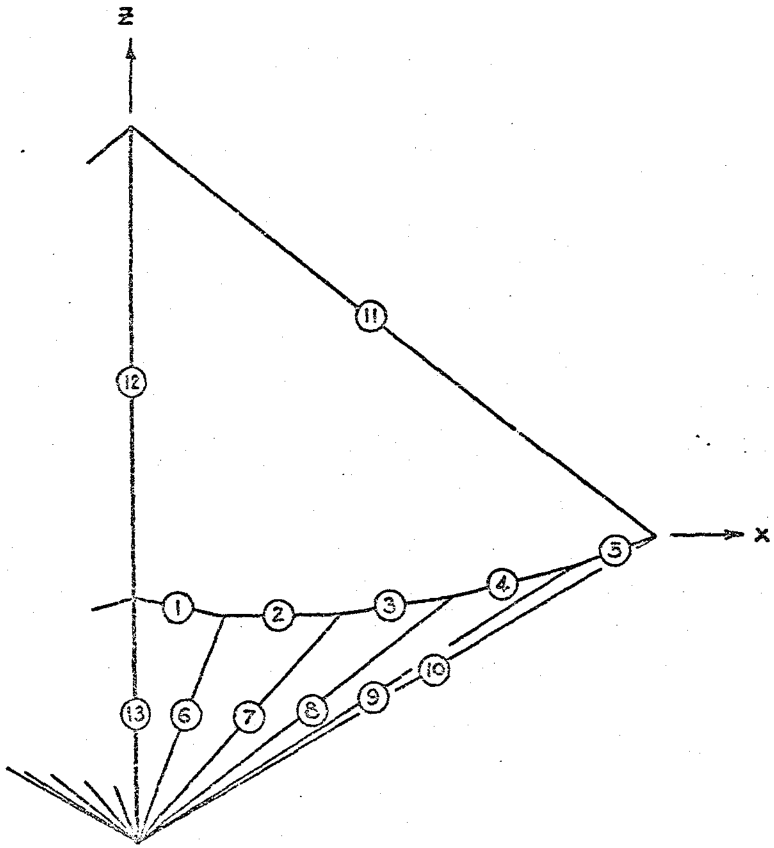
  — EQUILIBRIUM

- CABLE PRETENSIONS OBTAINED ARE TRANSFERRED DIRECTLY TO THE LARGE DEFORMATION STRUCTURAL ANALYSIS PROGRAM (AS PRETENSION EFFECT) WHICH WILL BE INCLUDED IN THE FINAL DISPLACEMENT AND STRESS COMPUTATIONS.

TYPICAL RESULT OF CABLE PRETENSIONS



RESULT OF CABLE PRETENSIONS



ELEMENT No.	FORCE (N)	STRESS (N/m^2)
1	141	19.E6
2	152	20.E6
3	170	23.E6
4	200	27.E6
5	452	60.E6
6	43	37.E6
7	24	21.E6
8	33	[illegible]
9	258	222.E6
10	140	140.E6
11	363	13.E6
12	-511	-2.E6
13	-580	-2.E6

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HEATING RATE ANALYSIS

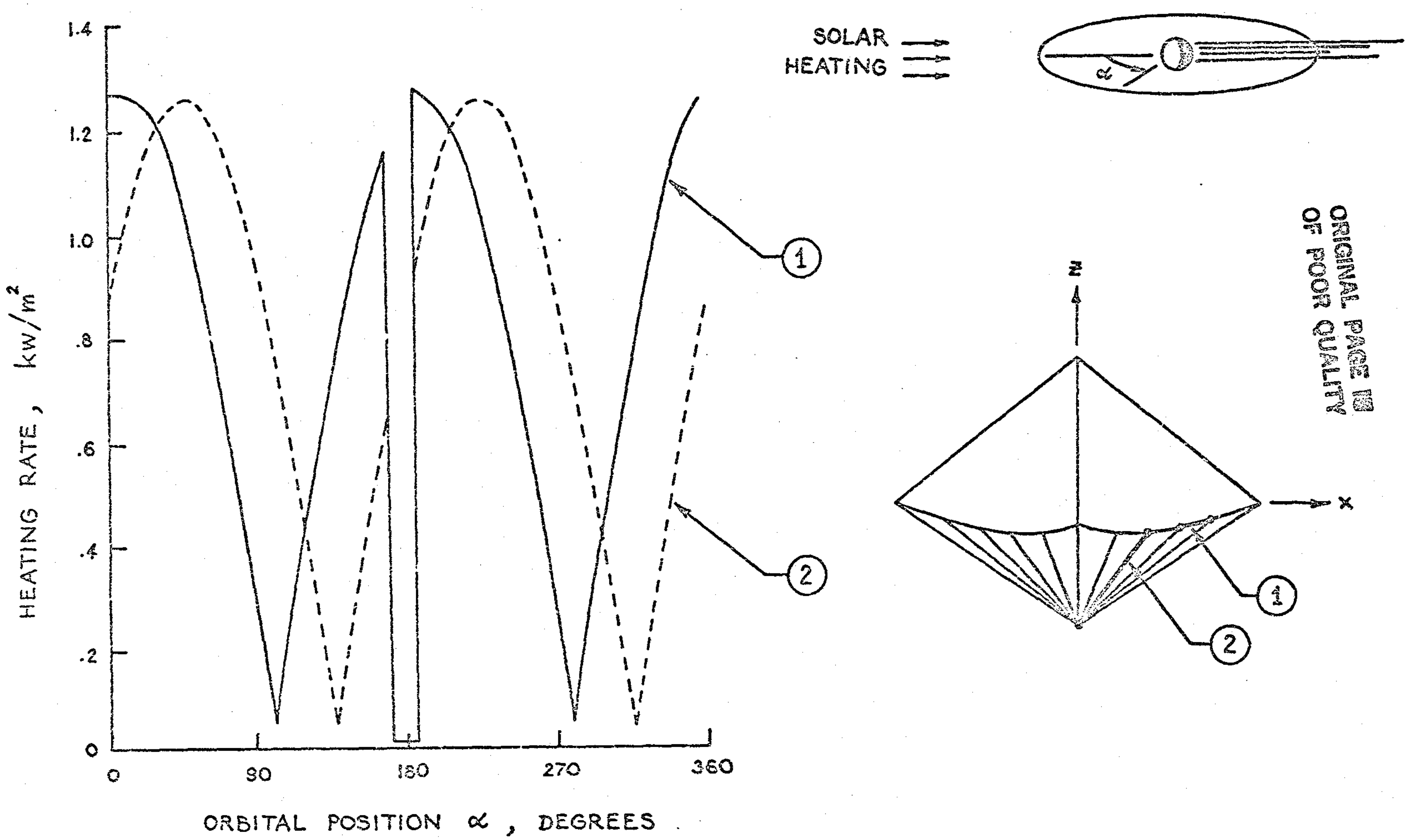
- HEAT SOURCES INCLUDE;

  - SOLAR
  - EARTH EMISSION
  - EARTH ALBEDO

- ELEMENT HEATING RATES ARE COMPUTED AT DIFFERENT ORBITAL POSITIONS FOR AN ORBIT.

- THESE ELEMENT HEATING RATES ARE TRANSFERRED DIRECTLY TO THE THERMAL ANALYSIS PROGRAM FOR COMPUTATION OF ELEMENT TEMPERATURE RESPONSES.

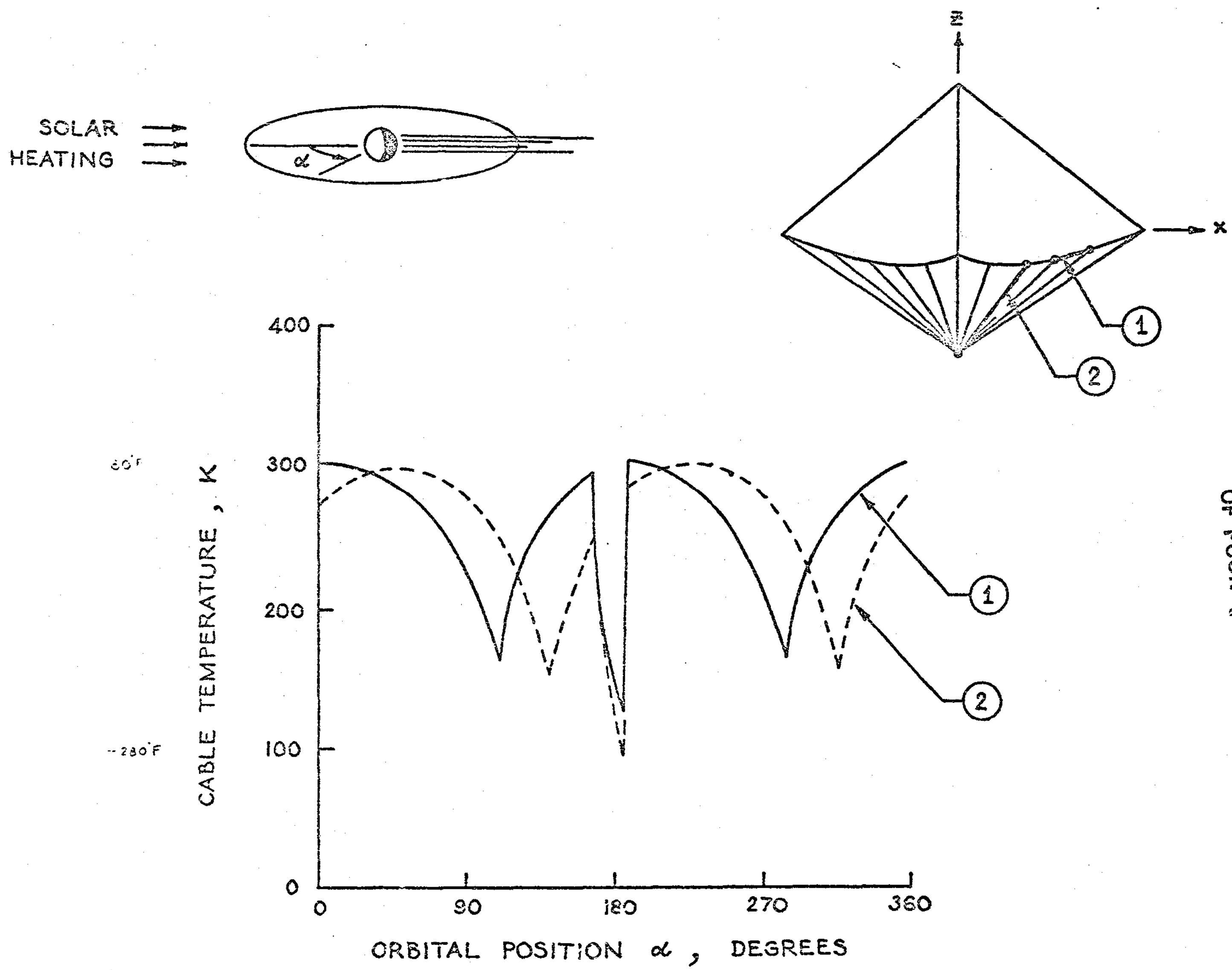
TYPICAL CABLE SURFACE HEATING RATES



THERMAL ANALYSIS

- ASSUME ISOTHERMAL ELEMENT TEMPERATURES.
- ANALYSIS (NONLINEAR TRANSIENT) INCLUDES:
  - APPLIED SURFACE HEATING
  - SURFACE RADIATION TO SPACE
- ELEMENT TEMPERATURES ARE COMPUTED AT DIFFERENT ORBITAL POSITIONS FOR AN ORBIT.
- ELEMENT TEMPERATURES ARE TRANSFERRED TO THE LARGE DEFORMATION STRUCTURAL ANALYSIS PROGRAM (AS THERMAL EFFECT) FOR DISPLACEMENT AND STRESS COMPUTATIONS.

TYPICAL CABLE TEMPERATURE RESPONSE

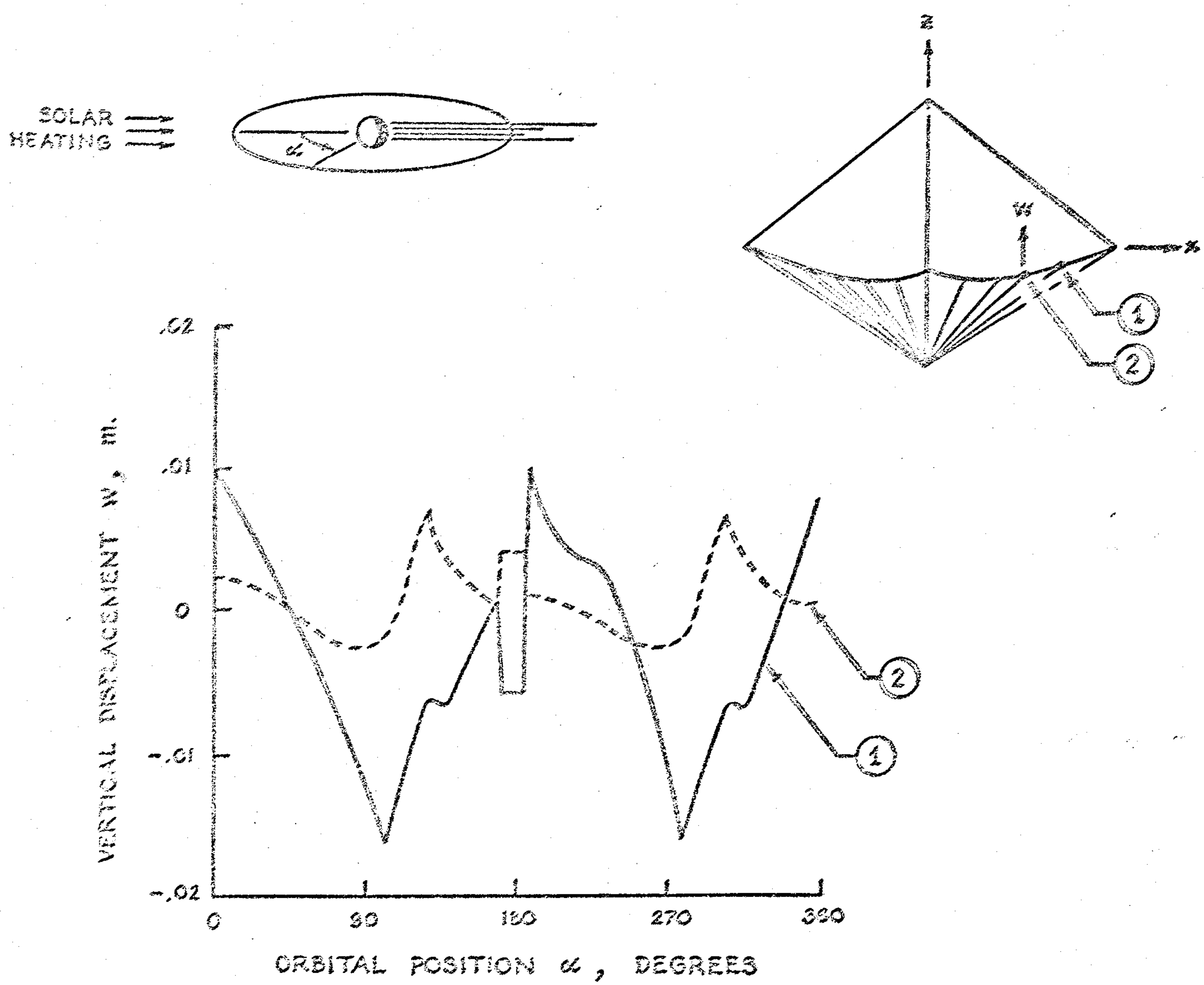


STRUCTURAL ANALYSIS

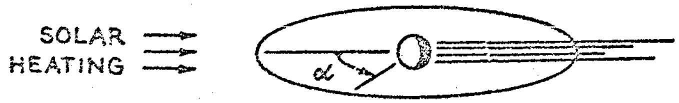
- ANALYSIS INCLUDES :
  - LARGE DEFORMATION (NONLINEAR)
  - THERMAL EFFECT
  - PRETENSION EFFECT

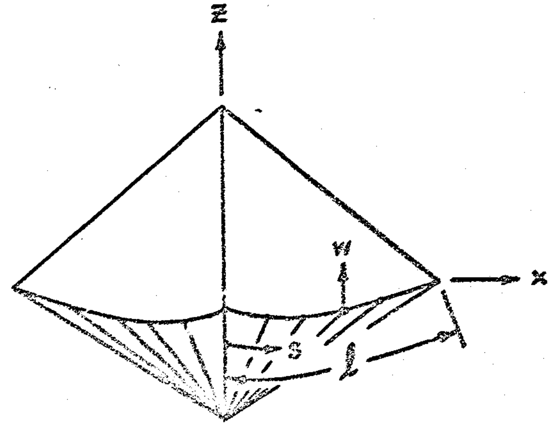
- DISPLACEMENTS AND STRESSES ARE COMPUTED AT DIFFERENT ORBITAL POSITIONS FOR AN ORBIT (QUASI-STATIC)

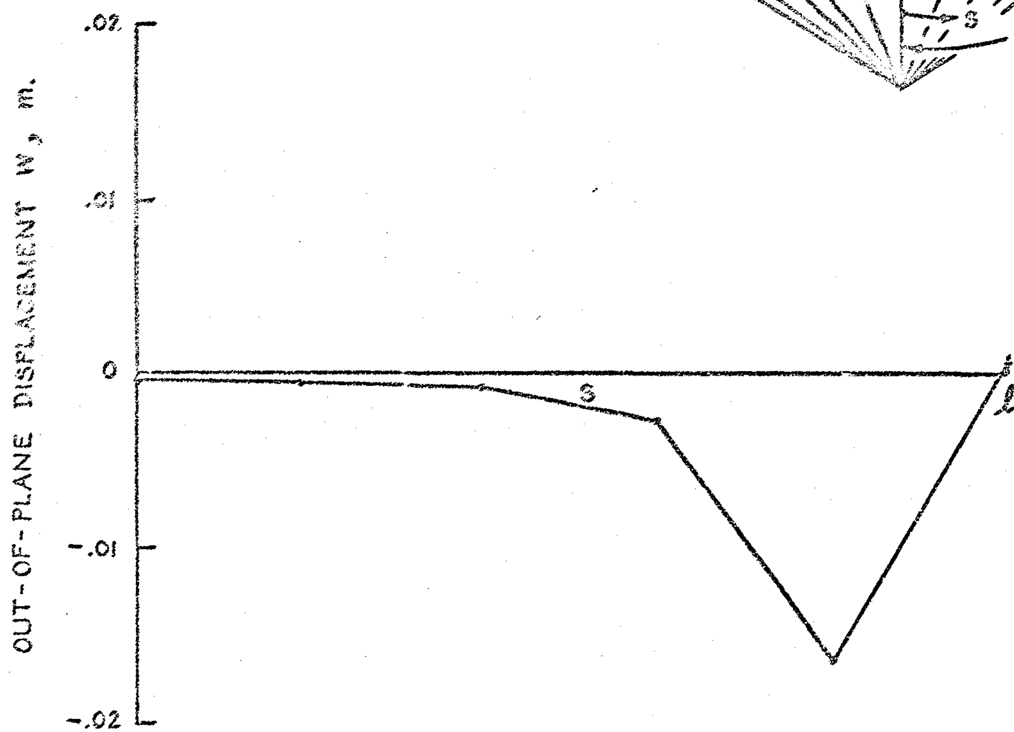
TYPICAL NODAL DISPLACEMENT HISTORIES



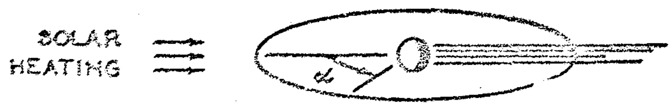
OUT-OF-PLANE DISPLACEMENT DISTRIBUTION AT $\alpha = 100^\circ$

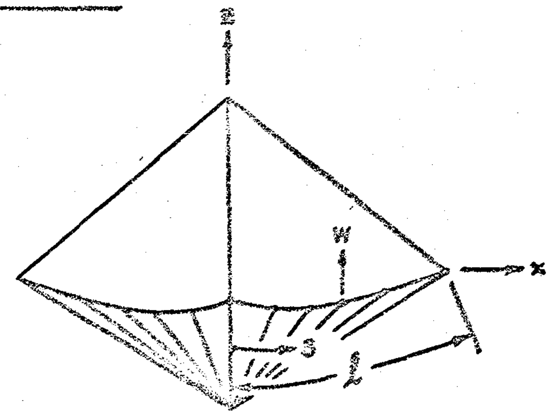


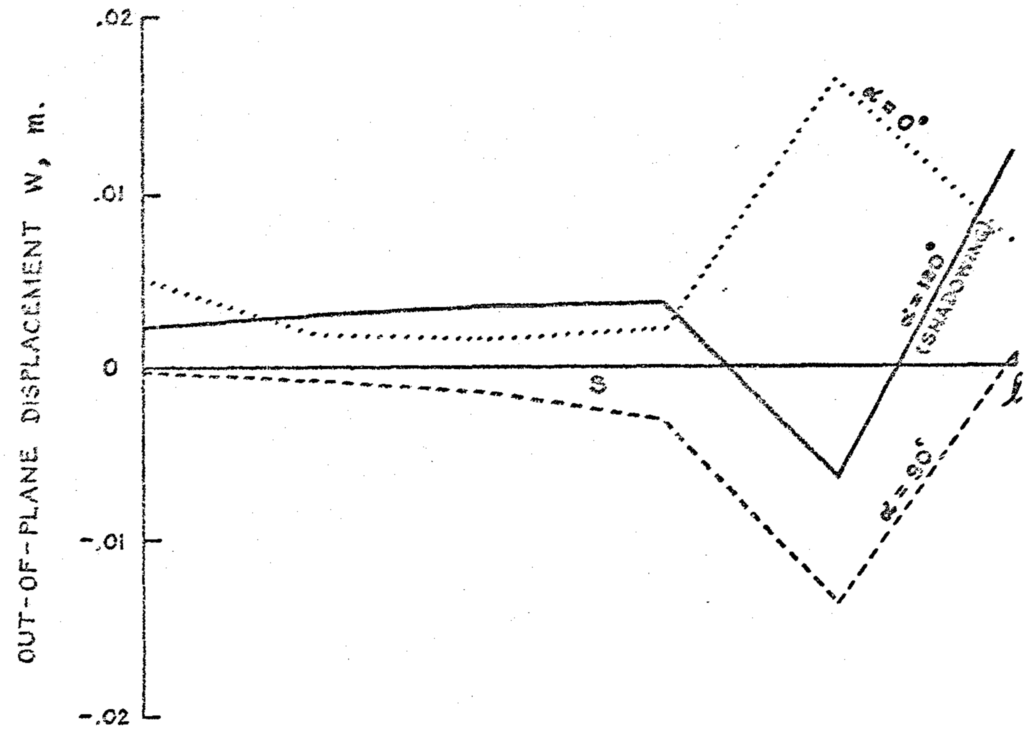




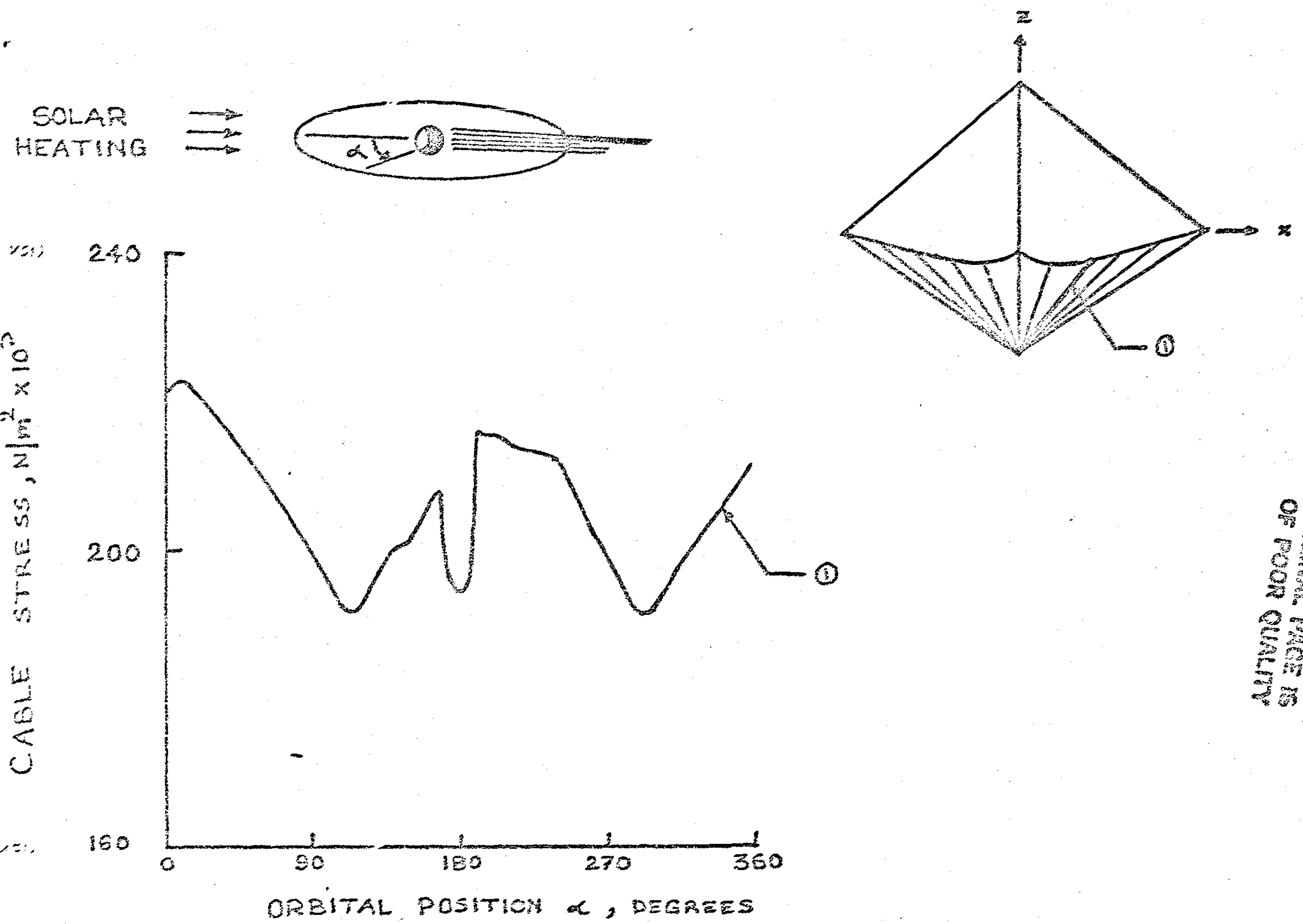
OUT-OF-PLANE DISPLACEMENT DISTRIBUTIONS AT DIFFERENT ORBITAL POSITIONS



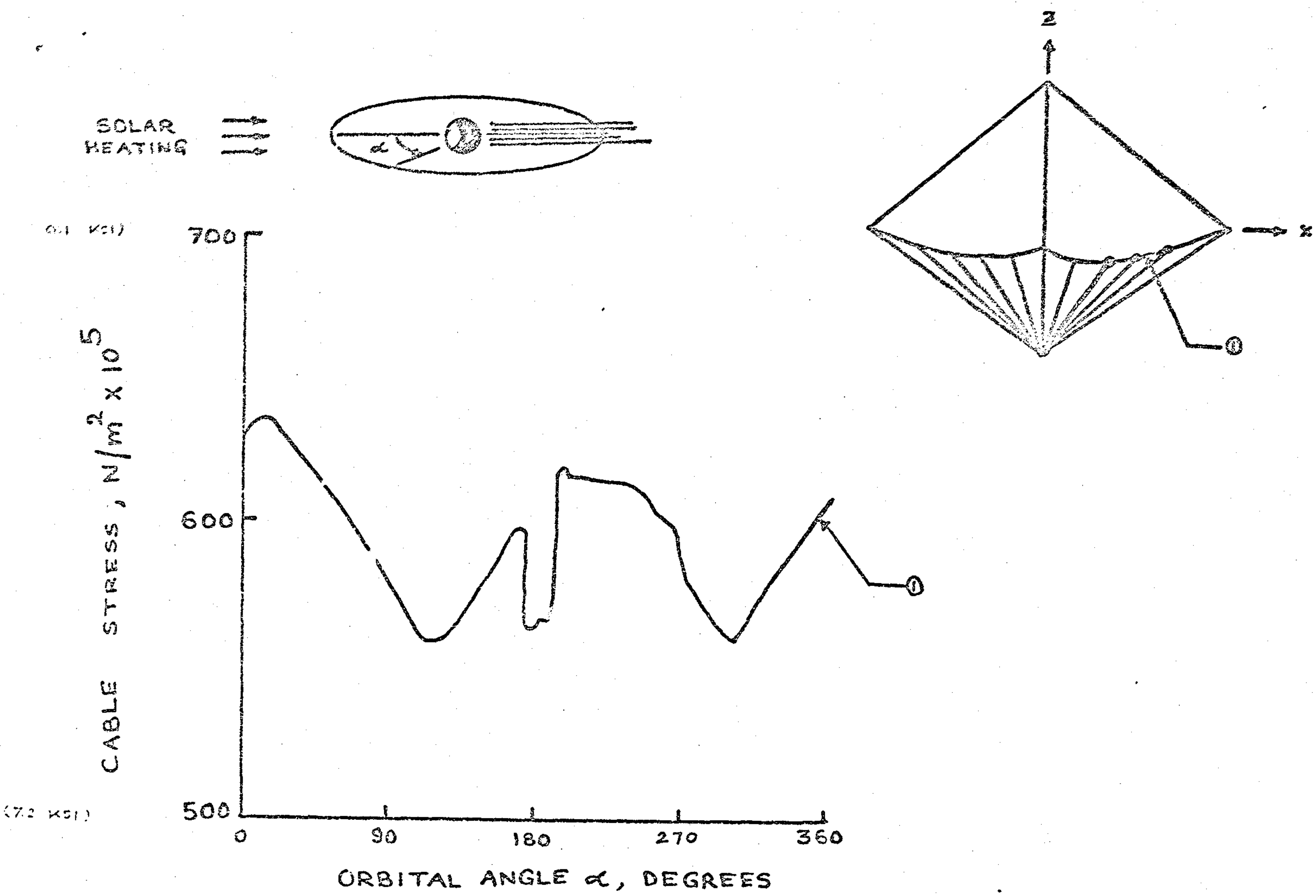




TYPICAL CABLE STRESS RESPONSE

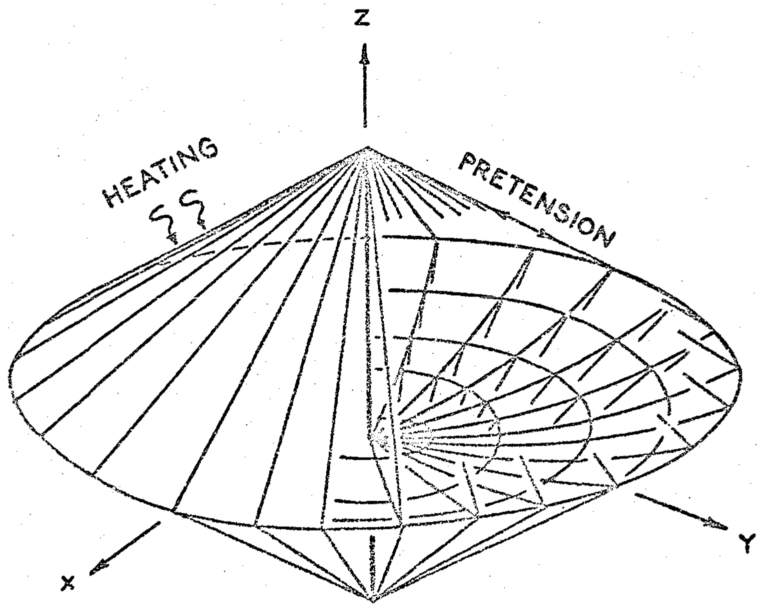


TYPICAL CABLE STRESS RESPONSE



ORIGINAL PAGE IS OF POOR QUALITY

3-D HOOP COLUMN MODEL



(123 NODES, 386 ELEMENTS)

PLANS:

- COMPLETE DEVELOPMENT OF PRETENSION PROGRAM.

- PERFORM 2-D HOOP COLUMN MODEL WITH:

  (1) LINEAR ANALYSIS

  (2) LINEAR "STRESS-STIFFENING" ANALYSIS (ANSYS)

- PERFORM 3-D HOOP COLUMN MODEL WITH:

  (1) LINEAR ANALYSIS

  (2) LINEAR "STRESS-STIFFENING" ANALYSIS

  (3) NON-LINEAR ANALYSIS

- MEMBRANE EFFECTS (?)

  — THERMAL ANALYSIS

  — STRUCTURAL ANALYSIS

End of Document