

UNSTEADY THERMAL STRESSES IN OUTER SHIELDING WALL WITH DOME UNDER SOLAR RADIATION AND AMBIENT TEMPERATURE

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SUMMARY

The outer shielding wall with a hemispherical dome of varying thickness is designed for a PWR nuclear power plant. This configuration is planned to reduce top-heaviness of the tall outer shielding wall under severe design earthquake, to maintain sufficient shielding capability, and to keep the integrity of structure under non-axisymmetrical daily solar radiation. In particular we have much concern about thermal stresses of this structure due to non-axisymmetrical daily solar radiation. In thermal analysis of this structure, many difficult problems occur; one of them is to obtain the suitable computer program, and another is to select suitable properties and coefficients for computation. We developed computer programs to analyze:

- a) Direct solar radiation value,
- b) Three dimensional unsteady heat conduction,
- c) Shell stress due to non-axisymmetrical load from non-axisymmetrical daily solar radiation.

Referring to many published reports and from our experiences on thermal analyses, we assumed the properties and coefficients.

Two cases are analyzed assuming the average pattern of daily thermal cycles due to both solar radiation and outdoor temperature in midwinter (around 15th-February) and in midsummer (around 15th-August) respectively.

In this study the thermal conditions are assumed as follows;

- i) The maximum outdoor temperature and the minimum one in the seasons are assumed by investigating the average monthly records during the last thirty years from M. Meteorological observation point of JMA nearest to the site, and they are used as the maximum value at 3:00 PM and the minimum value at 3:00 AM of a daily temperature cycle in the form of a sinusoidal curve. The indoor temperature is assumed to be constant and equal to the average of the daily temperature.
- ii) In the analysis for solar radiation account is taken only of the direct solar radiation among other thermal coefficients.
- iii) Neglecting the fluctuation of properties and coefficients accompanied by temperature and stress variation, the analyses are carried out by the following steps:
 - (1) The effective normal direct solar radiation values at each outside nodal point of the model representing the outer shielding wall are computed every five minutes from sunrise to sunset, and it is converted to temperature multiplying it by the absorption factor.
 - (2) The temperature distributions in the structure are analyzed every fifteen minutes by the program of three-dimensional heat conduction.
 - (3) The thermal stresses of the structure at every fifteen degrees in the circumference of the outer shielding wall are computed every one hour under the above-mentioned temperature distributions by the program for analyzing shell stress due to non-axisymmetrical load. In this program, the temperatures are converted to the equivalent external loads such as axial forces and moments in the section of the wall at each nodal point.

Based on these analytical results, we confirmed the structural integrity subjected to solar radiation and evaluated the thermal analysis procedure. Final assessment of the behaviors of the outer shielding wall subjected to the solar radiation are considered to be ascertained by future experimental investigations on the real structure.

1. Introduction

The outer shielding wall of reinforced concrete with a hemispherical dome of varying thickness is designed for a PWR nuclear Power Plant. (Fig. 1)

This configuration is planned to reduce top-weight of the outer shielding wall considering design for severe earthquake and to provide sufficient shielding capacity. The configuration considered are derived from careful study on structural and shielding feasibility. However, we have much concern about thermal stresses of the structure under varying pattern of temperature conditions shown as follows;

- the temperature conditions (1) before plant operation
- (2) under normal plant operation,
- and (3) hypothetical accident.

We describe in this paper on the thermal stresses in the outer shielding wall before plant operation caused by average daily cycle of solar radiation and ambient temperature in midwinter and midsummer, not including irregular intermittent effects of them.

Unsteady temperature distributions are analyzed using the computer program for Direct Solar Radiation Value and Three Dimensional Unsteady Heat Conductions developed for this study.

From the temperature distributions in several hours around the time producing maximum temperature on the outside surface of the wall, the thermal stresses are analyzed using a computer program for Shell Stress due to Non-axisymmetrical Load.

We examined the structural integrity of the outer shielding wall by the analytical procedures described in this paper.

2. Average Pattern of Daily Thermal Cycle

Our country, Japan situated in the humid temperate zone. February is the coldest month having short daylight hours and August is the hottest month having long daytime period during a year.

The reference construction site considered has a latitude of 33 degrees 29 minutes and an east longitude of 133 degrees 19 minutes.

Investigating the observation records during the past 30 years from Matsuyama observatory of Japan Meteorological Agency (JMA), the nearest point to the site, the average patterns of daily thermal cycles of the above two months are defined in following paragraphs.

- 2.1 Based on these records the daily ambient temperature cycle is depicted to be a sinusoidal curve with the maximum value at 3:00 PM and the minimum value at 3:00 AM.
(Fig. 2)
- 2.2 The indoor temperature is assumed to be constant and equal to the average value of the day. (Fig. 2)
- 2.3 Though the heat transfer coefficient of the boundary layer over the outside surface of the wall are generally considered to be affected by wind-velocity and direction, the coefficient is assumed constant at light wind all day.
- 2.4 The solar radiation value is modified by introducing a modification coefficient to make the calculated amount of daily solar radiation value equal to the observed one for a whole day long applying the atmospheric transmittance. (Fig. 3)

3. Analytical Sequence

The analytical sequence is shown as the flow chart of Figure-6. The principal sequences with noted numerals in parentheses are explained as follows:

- (1) The structure is substituted to the analytical model which consists from the rectangular meshes shown in Fig. 4 considering convenience for the solar radiation and heat conduction analyses. This model is found to be adequate for our analysis by comparisons of the various conditions assuming one dimensional heat conduction, i.e.; (Fig. 7)
 - a. 3 unequal width mesh, time step of 15 min. (model in this analysis).
 - b. One third width mesh, time step of 6 min.
 - c. One sixth width mesh, time step of 6 min.
 - d. One twenty fourth width mesh, time step of 1.2 min.

- (2) The overall equivalent normal direct solar radiation values at each center of the surface of outside elements, are computed every five minutes from sunrise to sunset.

In order to set the initial temperature, time step, and running hours, one dimensional heat conductions are analyzed simultaneously. And those are established as shown in Table-II considering the mathematical convergence for the finite difference method, the step of solar radiation analyses, and the modeling above mentioned in (1).

- (3) The temperature distribution at each element of the model is analyzed by the computer program for Three Dimensional Unsteady Heat Conduction putting into the program the data of solar radiation value and the outdoor temperature.

- (4) The models for thermal and stress analyses are different from each other for the purpose of analyses required. The model for thermal stress analysis is shown in Fig. 1.

The results of the temperature distribution in the model used for the thermal analysis are altered for the stress analysis by means of linear interpolation in longitude and Fourier series in circumference.

- (5) The thermal stresses of the structure at every 15 degrees in circumference are computed every one hour 10:00 through 18:00 under the abovementioned temperature distributions by the computer program for Shell Stress due to Non-axisymmetrical Load.

This program is devised so that the temperature distributions through thickness corresponding to each nodal point are converted into the equivalent external forces at the nodal point as following manner. (Fig. 8)

- a. The uniform temperature rise from the average value of the daily outdoor temperature through thickness corresponding to nodal point is converted into the external axial force in longitude and equivalent pressure load in circumference.
- b. The non-uniform temperature gradient through thickness in each respective sections is converted to the external bending moment in both directions.

4. Assumed Properties and Results of Thermal Analyses

4.1 Solar Radiation Value;

The Properties used for analyses are shown in Table I. The assumptions adopted are as follow;

- a. Bouguer's equation is basically adopted in the program.

- b. The sun path is calculated depending on the geocentric latitude.
- c. Japan standard time is used in this study (AKASHI; east longitude of 135 degrees).
- d. Solar radiation values are not calculated on the shaded surface of the structure.

It can be seen in Table I that the modification coefficient are nearly 1.0 i.e, 0.95 in midwinter and 1.00 in midsummer. (Fig. 3)

4.2 Unsteady Heat Conduction;

The properties used for analyses are shown in Table II. The assumptions adopted are as follows;

- a. The absorption coefficient is assumed 0.65 considering the effect of direct solar radiation mainly, reflections and skylight on the new light gray concrete.
- b. The material properties are independent of temperature.
- c. The effect of reinforcing bars in the structure are ignored.
- d. The boundary conditions are assumed as follows;

The temperature of the outer shielding wall surface adjacent to rock formation, auxiliary building, and the foundation is taken equal to the daily average outdoor temperature. (Fig. 1, "A"- "A")

Consequently no thermal interactions are considered. In the same way, temperature on the inside surface of the wall is controlled equal to the daily average outdoor temperature for the convenience.

As shown in Fig. 6 the effect of the initial temperature is gradually reduced with three days as expected by one dimensional heat conduction analysis.

Among the analytical results of the temperature distribution, midwinter results analyzed is shown in Figures 9 and 10 which is severe in view of thermal stresses. During midwinter period the times of analyses are at 14:00, 15:00 and 16:00 and in circular plane including 4 and 16 nodal points respectively and in longitudinal planes of north-south and east-west Figures 9 and 10 show following items;

- 1) Unsteady heat conduction along outside surface accompanied with a little time lag to ambient condition.
- 2) Unsteady heat conduction through thickness with significant time lag to ambient condition.
- 3) The great difference between temperature distributions of sunny side and shady side of the structure.

The maximum temperatures of the outside surface are found on the dome as follows;

<u>Season</u>	<u>Temp.</u>	<u>Time</u>	<u>Angle of Elevation*</u>	<u>Azimuth</u>
Midwinter	35°C	15:00	40°	South-Southwest 15°
Midsummer	50°C	15:00	75°	South-Southwest 45°

Note: *mark is shown in Fig. 10.

5. Assumed Properties and Results of Stress Analyses

The properties are shown in Table III. The assumptions adopted are as follows;

- a. The Young's modulus, Poisson's ratio and the coefficient of linear expansion of the concrete are independent of temperature and stress.

b. Model of the outer shielding wall is fixed directly on the foundation. (Fig. 1)

The stresses and deformations of the structure are analyzed at every one hour from noon to 18:00, and at 0° (South), 15°, 30°, 45°, 90°, and 270° in circumference respectively.

From the analytical results of the thermal stresses and deformations, three cases are as shown in Fig. 11 are at the times,

14:00 midwinter

15:00 midwinter

and 15:00 midsummer respectively.

They show longitudinal moments, circumferential moments and longitudinal stresses of north-south and east-west. The maximum resultant deformations are found around the top of the dome as follows;

<u>Season</u>	<u>Max. Deformation</u>	<u>Time</u>	<u>Azimuth</u>
Midwinter	2.6 mm	15:00	South-Southwest 15°
Midsummer	2.5 mm	16:00	South-Southwest 30°

In these analyses, it might be said natural that bending moments govern the stresses of the structure in longitude and circumference.

Severe bending moments are found in the crown portion of the dome around south-southwest 30°~45 degrees at 15:00~16:00 in midsummer, and in the spring portion as well as cylindrical portion around south-southwest 15 degrees at 14:00~15:00 in midwinter taking the thickness into account.

The severe fibre stresses of the structure shown in Fig. 12 are calculated by superposing the stresses due to dead load of concrete structure and severe thermal stresses.

The equations are as follows, but not taking account of the effect of reinforcing bars in this calculation.

$$\sigma_1 = \frac{N}{A} + \frac{M}{Z} \text{ ----- (1)}$$

$$\sigma_2 = \frac{N}{A} - \frac{M}{Z} \text{ ----- (2)}$$

where:

σ_1, σ_2 ; Extreme fibre stress in circumference or longitude

A ; Sectional area of the concrete structure

Z ; Sectional modulus of the concrete structure

N ; Axial force in circumference or longitude

M ; Bending moment in circumference or longitude

The Fig. 12 reveals tensile fibre stresses, more or less, near the inside surface of the structure, and some of them exceed the stress leading to tensile cracking of concrete.

6. Conclusion

It is concluded from the present studies as follows;

- (1) Theoretically analyzed results of the daily amount of direct solar radiation on the horizontal plane coincide fairly well with the observed records during the past 30 years at M. observatory of JMA, the nearest point to the site.
- (2) In order to increase the accuracy of the analysis, we evaluated the results of one dimensional heat conduction of preparatory studies which consist of the finite element mesh, time step, running hours, and initial temperature in the various series.

The pattern of the resulted temperature distributions of three dimensional heat conduction are considered quite natural as expected from our experiences. Consequently one dimensional heat conduction model is alternative to three dimensional one for engineering practice as preparatory procedures.

- (3) We have found tensile stresses exceeding the stresses leading to initial tensile cracking of concrete to the inside surfaces of the structure.

In order to control tensile cracking, the following countermeasures are taking into consideration in the design, though those tensile stresses are expected to be relaxed due to the creep in early stage after the setting of the concrete and thereafter become milder than the resultant stresses computed in this study as a whole.

- a. As the steel decks are arranged along the inside surfaces of the concrete dome, they could be considered to be fully effective for preventing cracks and protecting cracks from being exposed to annulus.
 - b. As the inside surface of the cylinder portion is not provided with steel decks, the welded wire mesh shall be placed in the covering depth of concrete within the portion of the wall required control cracking of the concrete.
 - c. In addition to the countermeasures mentioned above, the annulus seal deck is desirable to maintain sufficient negative pressure in the annulus zone for the capture of the released radioactive air from penetrations.
 - d. As for strength of the structure, the amount of reinforcement required for analyzed stresses are well under the minimum requirement set by the standard of Architectural institute of Japan (AIJ).
- (4) Our results from this study are concerned only to an analytical study under the temperature conditions before plant operation.

We shall continue our study under normal plant operation and conduct experimental investigation on the actual structure through which we expect further understanding on the fundamental physical properties such as Young's modulus, creep behavior of concrete, heat transfer coefficient, absorption coefficient under various temperature conditions and at the same time evaluate the propriety of our analytical methods.

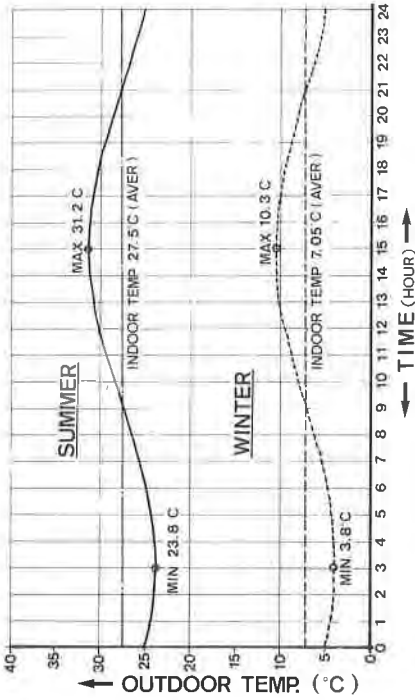


FIG. 2 THE VARIATION OF OUTDOOR TEMP. (SINUSOIDAL CURVE) AND INDOOR TEMP. (AVERAGE TEMP.)

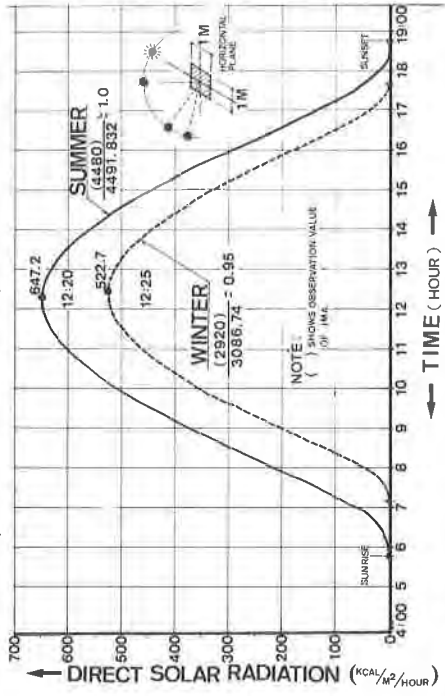


FIG. 3 THE AMOUNT OF DAILY DIRECT SOLAR RADIATION ON THE HORIZONTAL PLANE

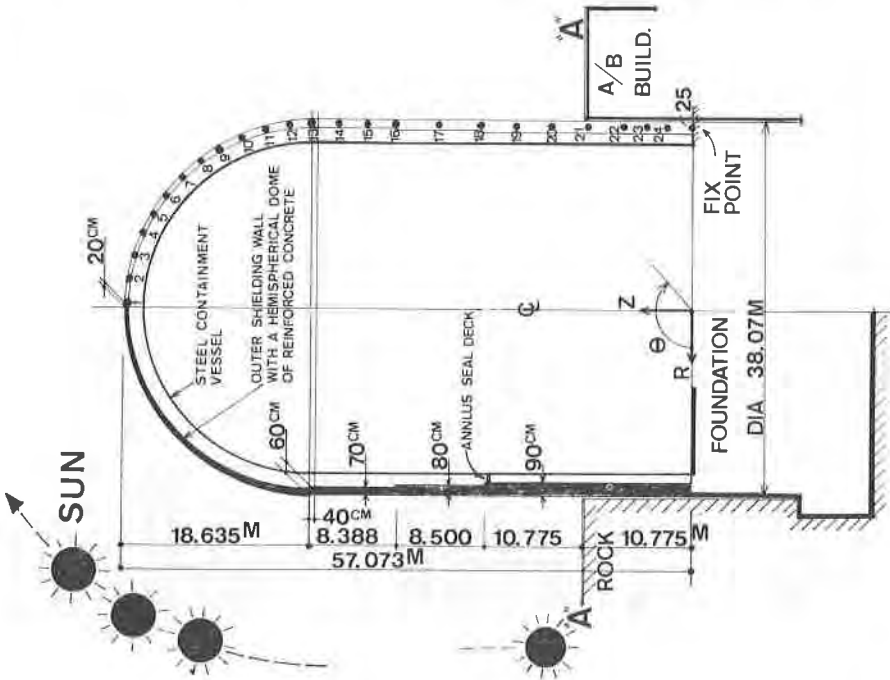


FIG. 1 THE CONFIGURATION OF OUTER SHIELDING WALL AND THE STRESS ANALYSIS MODEL

TABLE-I THE PROPERTIES FOR THEORETICAL SOLAR RADIATION ANALYSIS

ITEMS	PROPERTIES		REMARKS
	WINTER 15 TH - FEBRUARY	SUMMER 15 TH - AUGUST	
NUMBER OF NODAL POINT	SECTION : 19 N POINTS COMPASS DIRECTION : 36 EQ. PORTION TOTAL N. POINTS : 684 N. POINTS		SEE FIG 4
TIME STEP	5 MINUTES		
PLACE OF SITE	LATITUDE : 33 DEG 29 MIN EAST LONGITUDE : 133 DEG 19 MIN		GEOGRAPHICAL POSITION
DECLINATION	-12 DEG. 59 MIN 14 DEG. 19 MIN.		REPORTS OF JAPAN METEOROLOGICAL AGENCY (JMA)
EQUATION OF TIME	-14 MIN. 13 SEC. - 4 MIN. 39 SEC		
RADIUS VECTOR	0.98807		
SOLAR CONSTANT	1.164 KCAL/M ² /HOUR		
ATMOSPHERIC TRANSMITTANCE	0.73		TOSASHIMIZU
MODIFICATION COEFFICIENT	0.95		SEE FIG 3

TABLE-III THE PROPERTIES FOR STRESS ANALYSIS

ITEMS	PROPERTIES	REMARKS
YOUNG'S MODULUS	$2.1 \times 10^6 \text{ T/M}^2$	CONSTANT VALUE
POISSON'S RATIO	0.1667	*
COEFFICIENT OF LINEAR EXPANSION	$1.0 \times 10^{-5} \text{ 1/}^\circ\text{C}$	*
FOURIER SERIES	$T = A_0 + A_1 \cos \theta + \dots + A_4 \cos 4\theta + B_1 \sin \theta + \dots + B_4 \sin 4\theta$	4 - TERMS
NUMBER OF NODAL POINT	LONGITUDINAL DIRECTION : 25 N. POINTS	SEE FIG 1

TABLE-II THE PROPERTIES FOR THERMAL ANALYSIS

ITEMS	PROPERTIES		REMARKS
	WINTER 15 TH - FEBRUARY	SUMMER 15 TH - AUGUST	
MODEL MESH	1 BLOCK 79N POINTS COMPASS DIRECTION : 36 EQ. PORTION BOUNDARY OF CENTER : 4N POINTS TOTAL N POINT : 2 848 N POINTS TOTAL ELEMENT : 2 844 ELEMENTS		SEE FIG 4
TIME STEP	15 MINUTES CONVERGENT LIMIT BY FINITE DIFFERENCE METHOD IS 29MIN		
ABSORPTION COEFFICIENT	0.65 CONSTANT UNDER VARIOUS INCIDENCE ANGLE		CONSTANT UNDER VARIOUS TEMP
PHYSICAL PROPERTIES OF CONCRETE	THERMAL CONDUCTIVITY : 1.5 KCAL/MH ² C SPECIFIC HEAT : 0.23 KCAL/KG ² C SPECIFIC GRAVITY : 2.400 KG/M ³		
HEAT TRANSFER COEFFICIENT	15.8 KCAL/M ² H ² C BOTH CONVECTION AND RADIATION OF HEAT TRANSFER ARE CONSIDERED IN THIS VALUE		2.0 M/SEC WIND VELOCITY
DATA OF OUTDOOR TEMP.	(MAX) 10.3 °C (MIN) 3.8 °C	(MAX) 31.2 °C (MIN) 23.8 °C	SEE FIG 2
INITIAL TEMPERATURE	9.55 °C		30.00 °C
RUNNING HOURS	72 HOURS + 24 HOURS = 96 HOURS		* DURATION USED IN ANALYSIS

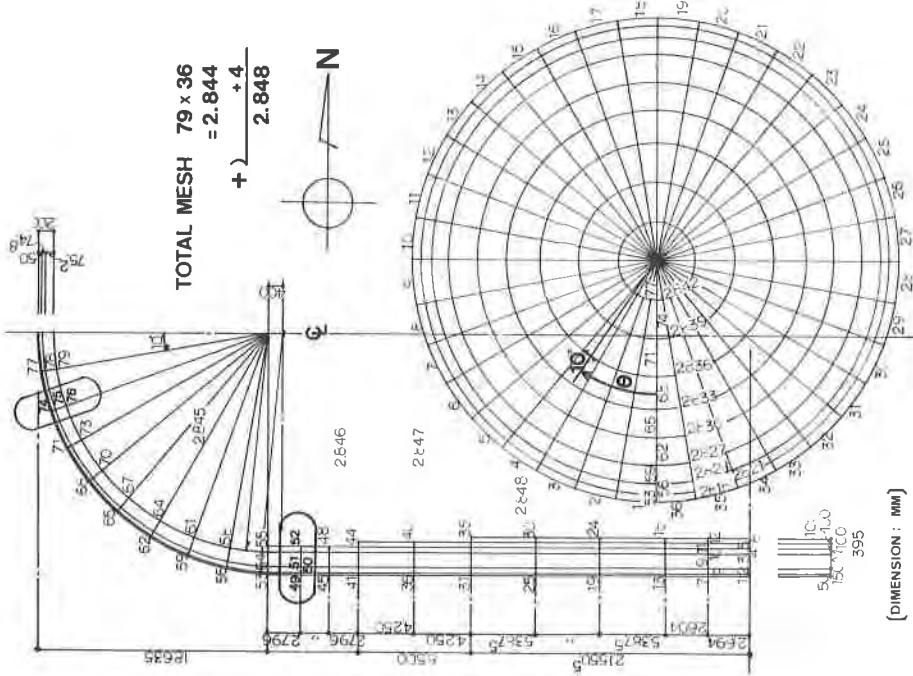


FIG. 4 THE THERMAL ANALYSIS MODEL

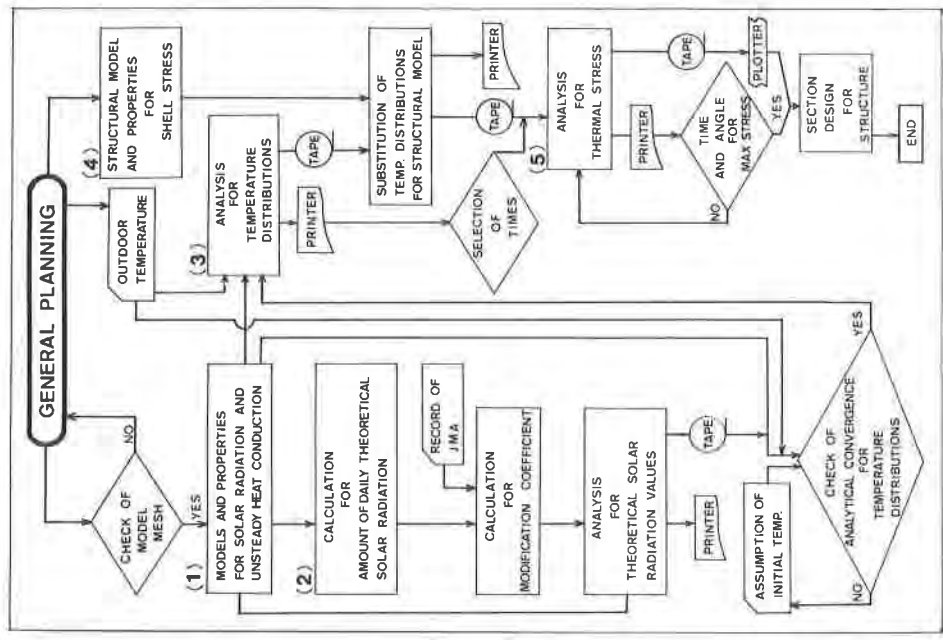


FIG. 5 THE ANALYTICAL SEQUENCE (FLOW CHART)

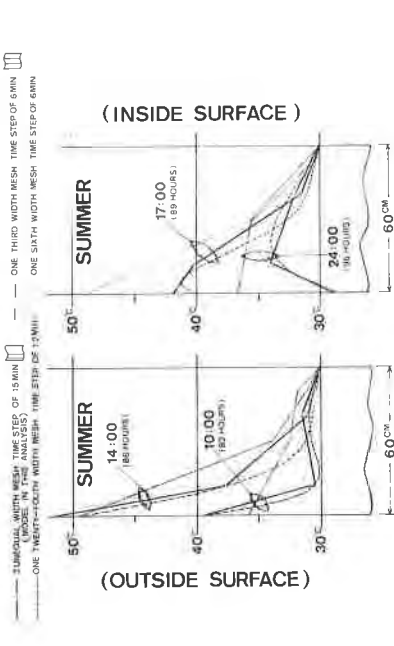


FIG. 7 THE TEMP. DISTRIBUTIONS THROUGH THICKNESS UNDER VARIOUS CONDITION I.E.; (MODEL MESH, TIME STEP)

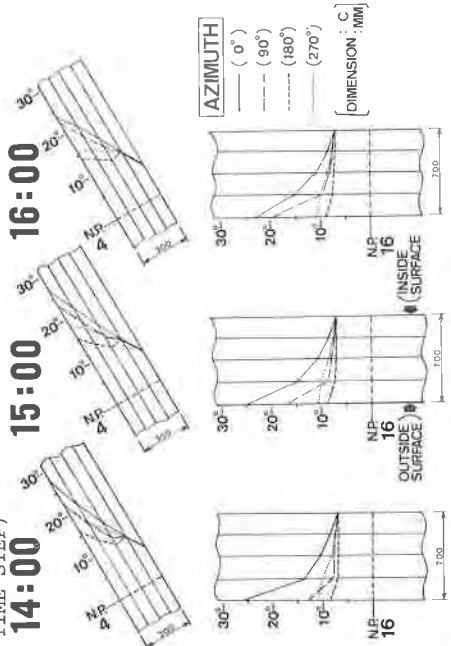


FIG. 8 THE TEMP. DISTRIBUTIONS THROUGH WALL THICKNESS AND NODAL POINTS OF 4, 16 (WINTER) (°C)

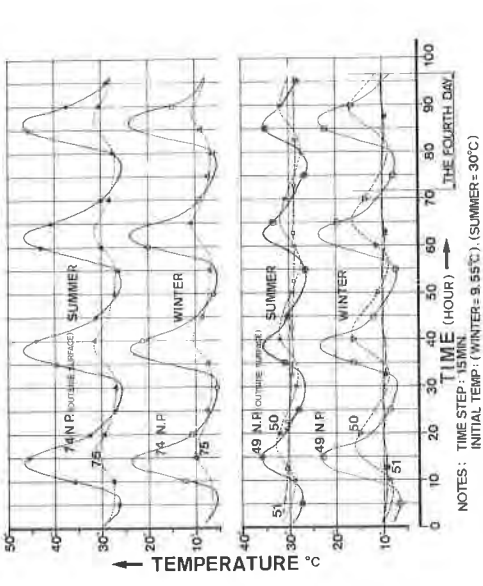


FIG. 6 THE TEMP. DISTRIBUTIONS AT N. POINTS (74, 75) (45, 50, 51) DUE TO THREE DIMENSIONAL THERMAL ANALYSIS

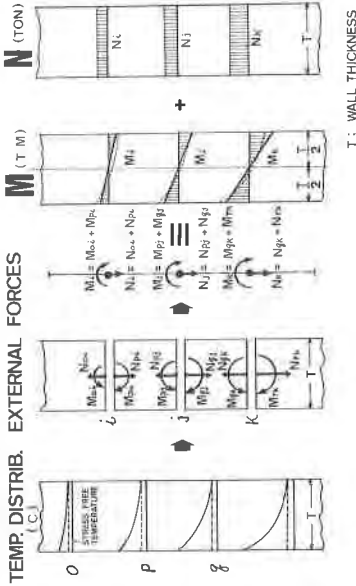


FIG. 8 THE CONVERSION FROM TEMP. DISTRIBUTIONS TO EQUIVALENT EXTERNAL FORCES.

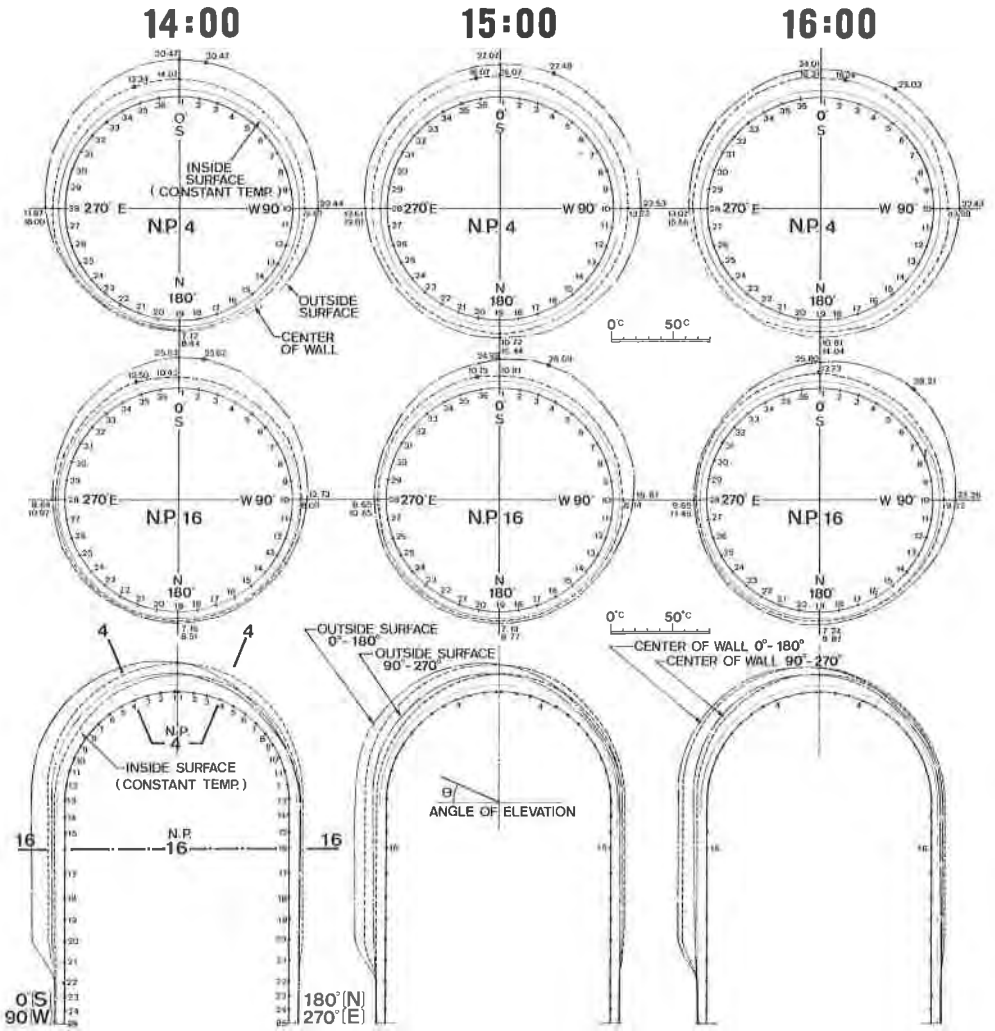


FIG.10 THE TEMP. DISTRIBUTIONS AT NODAL POINTS OF 4, 16 (WINTER)

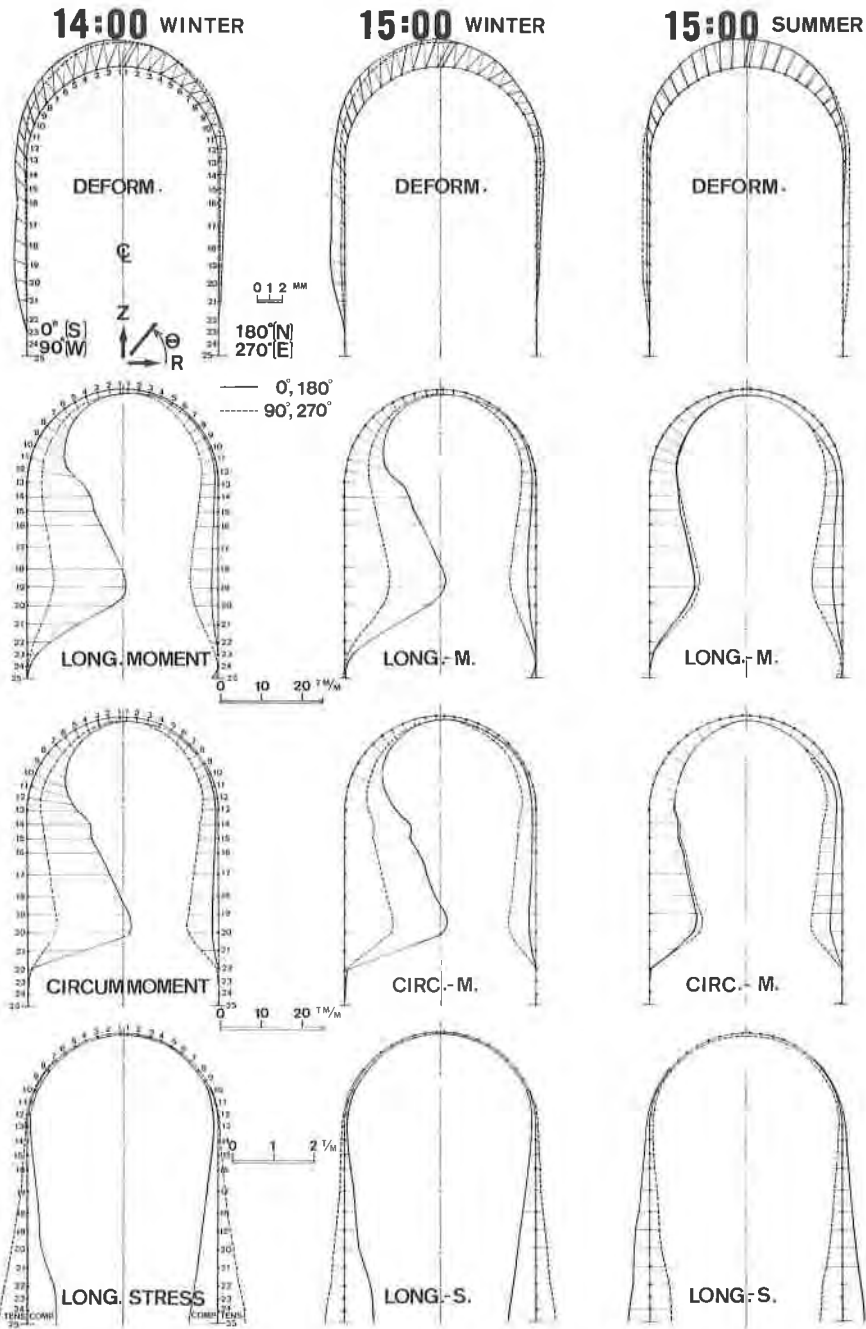


FIG. 11 THE DEFORMATIONS AND STRESSES: (14:00 WINTER), (15:00 WINTER) AND (15:00 SUMMER)

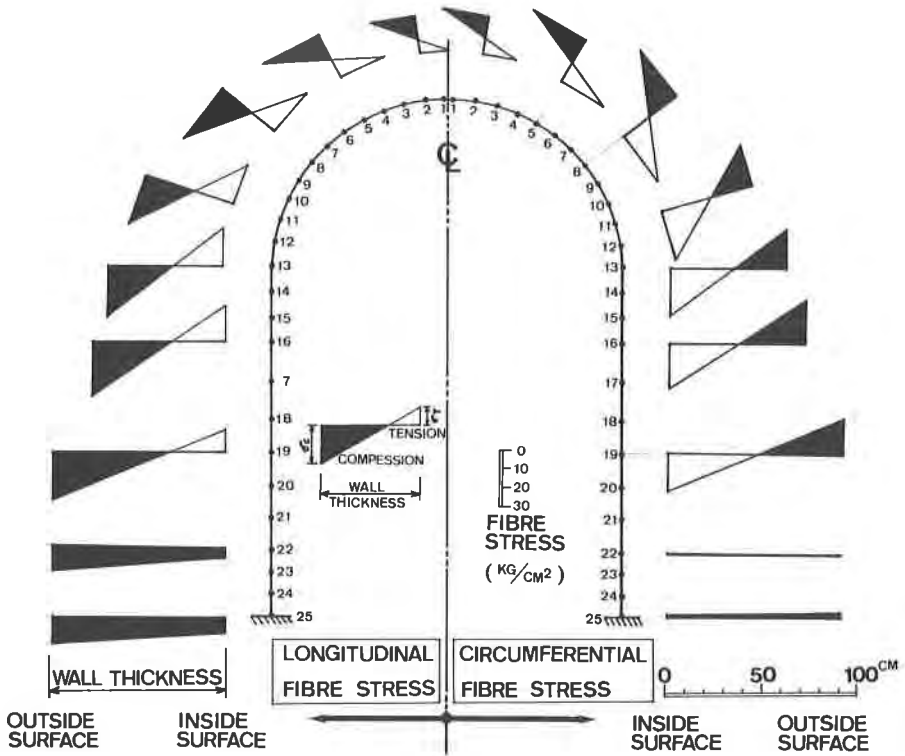


FIG.12 THE SEVERE FIBRE STRESS (DEAD LOAD + THERMAL LOAD)

Reference

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