APAE-112(Vol. II)

30 MEGAWATT HEAT EXCHANGER AND STEAM GENERATOR FOR SODIUM COOLED REACTOR SYSTEM

Volume II. Chemical and Stress Analysis

February 28, 1962

Alco Products, Inc.
Schenectady, New York

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APAE-112(Vol. II)

REACTOR TECHNOLOGY

30 MEGAWATT
HEAT EXCHANGER AND STEAM GENERATOR FOR SODIUM COOLED REACTOR SYSTEM

Volume I	Thermal & Mechanical Final Design
Volume II	Chemical and Stress Analysis
Volume III	Material and Welding Specifications
Volume IV	Operation and Maintenance Procedures

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ALCO PRODUCTS, INC.
Research & Development
Schenectady, New York

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INTRODUCTION

This volume presents the chemical engineering analysis and stress analysis for design of the 30 megawatt intermediate heat exchanger and steam generator for service with a liquid sodium heat transfer fluid.

The chemical engineering analysis includes the inert cover gas system, liquid level control, and design provisions for system pressure relief. Consideration is given to possible hazards resulting from a steam-to-sodium leak. Supplemental information is presented in Volume IV, Operation and Maintenance Procedures.

The stress analysis section covers those thermal transients which would be physically possible with this intermediate heat exchanger and steam generator design. Attention has been given to methods of operation which would minimize the magnitude and frequency of thermal shocks. Certain areas have been studied in detail where thermal stresses appear high. This report also includes a structural design basis for handling stress analysis of combined mechanical, hydrostatic, and thermal stresses and conditions for using creep and stress rupture properties .

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SECTION 2

CHEMICAL ENGINEERING ANALYSIS

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CHEMICAL ENGINEERING ANALYSIS

INTERMEDIATE HEAT EXCHANGER

The intermediate heat exchanger serves to avoid the hazard of chemical reaction between water and radioactive sodium in the event of an internal boiler leak, and to assure containment of all radioactivity in the reactor building. It is thus imperative to insure that there is no undetected radioactive contamination of the secondary sodium in the event of an internal intermediate heat exchanger leak. It is recommended that the secondary coolant system be maintained at a higher pressure than the primary coolant system at all adjacent locations in the intermediate heat exchanger to assure that any leakage in the intermediate heat exchanger will be from the secondary system to the primary system. The secondary sodium system should be continuously monitored for gamma radiation as an added precaution.

The only operating malfunction which could result in a dangerous primary system pressure rise would be a water leak in the steam generator with transmission of the pressure surge to the intermediate heat exchanger, where a leak between the secondary and primary systems could result. Although this possibility is remote because of secondary relief provision, it is recommended that a relief device be provided on the primary system piping near the intermediate heat exchanger vessel with no valves between the relief device and vessel. This relief device should be designed to preclude any possibility of intermediate heat exchanger equipment rupture because of over pressure.

COVER GAS SYSTEM

Argon or helium will be satisfactory as a cover gas for the primary sodium system. Nitrogen is not recommended, because of the nitriding effect on stainless steel at high temperature.(R-1) Nitriding will reduce the strain fatigue strength of stainless steel at high strains.(R-2) Argon is recommended as the preferable choice, because it has a greater density than air, and will form a cover over sodium in the presence of air. This will allow internal access to equipment containing sodium with a minimum of oxygen contamination to the system. However, some radioactivity will be induced in the primary argon and facilities for safe handling of the radioactive gas must be made available. All cover gas must be passed through sodium-potassium bubblers for removal of water vapor and oxygen prior to use over sodium.

(R-1) - KAPL-1618, S1G/S2G Program Progress Report, pp 89-90, August and September 1956.

(R-2) - KAPL-1654, S1G/S2G Program Progress Report, pp 75, October and November 1956.

The intermediate heat exchanger is designed to operate full of sodium without a gas blanket. It is anticipated that liquid level for the primary sodium loop will be established in an expansion tank external to the intermediate heat exchanger unit. A level detector on the intermediate heat exchanger will thus be unnecessary. One of the vent holes through the top tubesheet can serve as a bleed point to insure that no gas is accumulated beneath the upper tubesheet.

Epstein (R-3) reports the solubility of helium in liquid sodium to be 1.63×10^{-14} and 1.48×10^{-10} mole fraction at 450°F and 900°F, respectively. Assuming that argon has the same behavior in sodium of greater solubility at higher temperatures, there is a possibility of solubility induced mass transfer of the cover gas from the reactor to the heat exchanger vessel. If this occurs, the cover gas will tend to collect around the top tubesheet, since the primary sodium temperature is reduced in the intermediate heat exchanger. The magnitude of this effect will be determined by the temperature difference in solubilities from the cover gas location to the primary coolant exit from the intermediate heat exchanger, the sodium mass flow rate, and the degree of solubility of the cover gas in relation to completeness of mixing in the system. The quantity of gas mass transfer cannot be calculated without experimental observation, because of the dependence on degree of gas-sodium contact for the sodium to become saturated.

One of the outer tubes in the intermediate heat exchanger bundle is open to the primary sodium to allow automatic removal of any gas which collects around the top tubesheet. The tubesheet is undercut and the tube is flush with the lower tubesheet surface at that point. The lower end of the vent tube is open at a point near the primary sodium exit nozzle. When the pressure drop, due to friction losses from the top of the unit to the exit nozzle, exceeds the sodium head between those two points, a continuous flow of sodium will be forced through the vent tube. Any gas which is trapped beneath the upper tubesheet will then pass through this vent tube and be entrained in the exit sodium.

Design calculations indicate that the primary sodium loop must operate at or near full flow conditions to attain a friction pressure drop sufficient for satisfactory operation of the vent tube. An alternate method of preventing gas collection below the tubesheet will be necessary if the operating pressure drop should be substantially less than calculated. The gas must then be bled through one of the tubesheet vent holes and piped externally to a gas blanket chamber of the primary loop. If the piping layout is such that a suitable downstream discharge point of lower pressure does not exist because of sodium head, a small pump will be needed in the pipe line. Natural circulation may be employed, if feasible. The external bleed line must be kept hot, since liquid sodium will normally flow through it.

(R-3) - Epstein, L. F., "The Solubility of Helium Gas in Liquid Sodium" Report No. Memo LFE-10, KAPL, January 9, 1952.

It is recommended that no external bleed line be employed, unless test operation indicates that internal venting does not satisfactorily prevent collection of gas below the tubesheet. Internal venting should be satisfactory even under partial flow conditions, if gas collection is slow enough so that gas is removed in bubbles, thus allowing a balancing sodium head to exist on the inside of the vent tube. If an appreciable blanket of gas is present, the aforementioned difficulty of overcoming the sodium head may prevent removal of the gas at partial flow. The unit should then be operated at full flow until the gas is removed. This problem should be studied during test operation.

Vent holes provided in the tubesheet from the shell-side to the exterior will facilitate filling and draining operations. These can also serve as pressure taps and for bleeding to determine if the unit is free of gas.

LIQUID LEVEL CONTROL FOR STEAM GENERATOR

A gas blanket is provided in the steam generator to act as a surge volume. The cushioning effect of the surge volume will allow more time for pressure relief mechanism to function and relieve pressure smoothly, in the event of a sodium-to-water leak.

A liquid level indicator is required to allow regulation of the sodium level to give the desired gas blanket volume, and to insure full coverage of the effective heat transfer area.. An external liquid level measurement system is recommended for this purpose, in order to avoid stress problems which arise from differential thermal expansion of the stand pipe needed for more common level detectors.

Components of the recommended level detection system include:

1. A "Source Unit", which contains source material to provide gamma rays.
2. A "Detector Unit", which detects radiation from the source unit.
3. An "Amplifier", which converts a signal from the detector unit into a direct current signal.
4. A "Panel Meter" and "Electronic Recorder", which accept the signal from the amplifier, and provide readout of the level measurement.

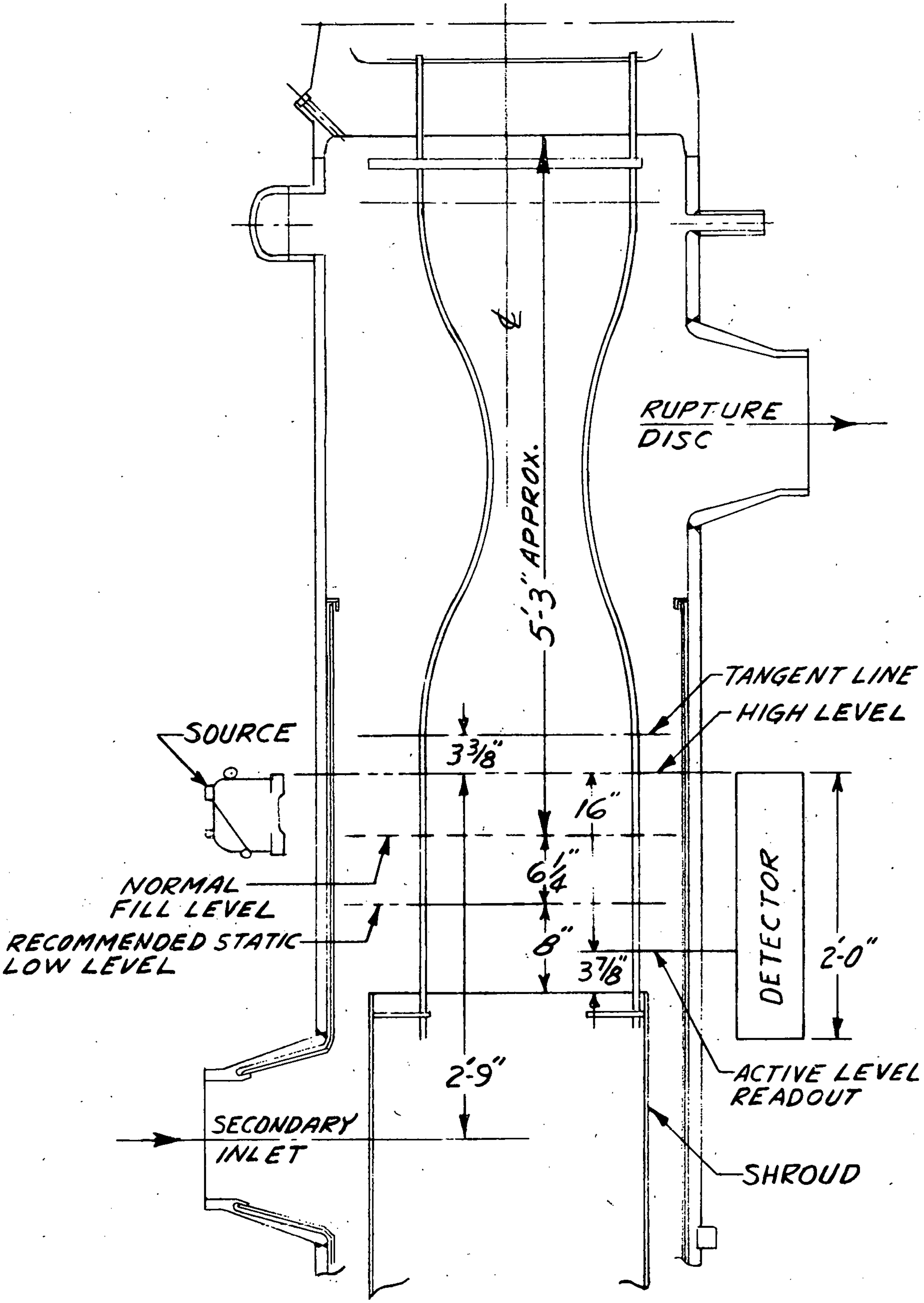
All units of the system are mounted externally to the insulation around the vessel, and do not contact the sodium at any time.

The radiation leaving the source unit is directed horizontally across the vessel and in a downward direction with a maximum angle from the horizontal of sixty degrees. Sodium level rise into the path of the gamma ray beam attenuates the calibrated signal from the detector.

The source and detector units must be located very precisely in relation to the vessel, both in elevation and circumferentially. The elevation location and active detector readout are indicated in Figure 2.1. The steam generator tube bundle is aligned so that there are six paths, one half inch in width, diametrically across the vessel with no obstruction by tubes. The gamma beam will be directed through one of these paths, which is perpendicular to the vertical plane of the sodium inlet nozzle. The circumferential location will be marked when the steam generator is assembled, and can be determined precisely by noting the point of maximum gamma penetration through the empty vessel. One-half inch tubing outlets will be provided in the vessel at points corresponding to the low level limit, the high level limit, and midway between the limits to allow calibration of the detector unit. These outlets may be sealed after calibration.

Design considerations for the liquid level detection system are based on the presumed use of the Accu Ray level measurement system supplied by Industrial Nucleonics. Industrial Nucleonics engineers have given assurance that the one-half inch path width for the gamma ray beam will allow satisfactory operation of their unit. However, if tubes are distorted into the beam path during operation, some error will be introduced in level readings from the detector, since it will be calibrated with no tubes in the path. Design precautions have been taken to minimize the possibility of movement of the tubes into the gamma ray path. Detector operation should be watched closely in initial service to ascertain that such an error is not introduced.

During operation, the sodium liquid level will be at a high point on the outer circumference where the incoming sodium rises over the shroud, and then will funnel down into the central hole of the top baffle. The detector will indicate the peak level, rather than a mean level. This peak level must be about eight inches above the top baffle to provide sufficient head for full flow. The suggested minimum static fill level is, therefore, eight inches above the top baffle. A further drop in level could not be detected under flow conditions, since a funnel will be formed with an eight inch detectable peak to overcome cross flow pressure drop. If the static level is dropped to about two inches above the top baffle, the space beneath the baffle will not be full of sodium, and performance will drop. Such operation will also create danger of gas entrainment with the sodium. Recommended operational levels are indicated in Figure 2.1. High and low level alarms, and continuous recording may be included in the liquid level detection system, if desired.



STEAM GENERATOR LIQUID LEVEL ANALYSIS

FIG. 2·1

STEAM GENERATOR PRESSURE RELIEF

Although considerable data are available on study of the sodium-water reaction, it is not possible to accurately predict exactly what reaction will occur in the event of a leak. Data are somewhat conflicting, and the degree of completion of the reaction and the portion of reactants entering into the reaction are highly dependent on conditions of contact, which will vary with size and location of the leak. Consequently, the worst possible conditions have been considered in design of relief provisions. These conditions are as follow:

Maximum Pressure Rise

$$Na(1) + H_2O(g) \rightarrow Na(1) + H_2O(g) \qquad (1)$$

(Little, or no, reaction, because of inadequate contact of the steam with sodium)

$$2Na(1) + H_2O(g) \rightarrow Na_2O(s) + H_2(g) \qquad (2)$$

(Actually occurs with NaOH as an intermediate reaction product.)

Maximum Temperature Rise

$$Na(1) + H_2O(g) \rightarrow NaOH(s) + 1/2H_2(g) \quad \Delta H^o 298 = -45.7 \frac{Kcal}{gm\ mole} \qquad (3)$$

(Assuming that oxygen is excluded from the system.)

Nothing can be done to alleviate any hazards due to temperature rise, except to keep circulating the system sodium so that the heat is distributed, rather than localized. A localized concentration of heat from a steam reaction with sodium could cause additional tube failures, due to excessive temperature in the leakage area. Design precautions have been taken to reduce the probability of such an occurrence, especially if the sodium is kept circulating.

Equations (1) and (2) would result in approximately equivalent pressure rise, since the volume of unreacted superheated steam would be roughly equivalent to the volume of the same number of moles of hydrogen gas. One mole of gas would be present in the sodium for every mole of water leakage in either case.

The major objective of sodium-side pressure relief is to exclude the possibility of shell rupture from any rapid pressure rise which may result from a large steam leak. This is done by incorporating a rupture disc in a twelve inch relief line from the surge gas volume. The relief area must be large to allow rapid exit flow of liquid sodium after the surge gas is exhausted. The disc is located in the gas blanket to minimize corrosion, and to allow initial rapid expulsion of the surge gas before liquid sodium is forced out. This will also allow direct relief of steam entering through a leak in the upper tubesheet, so that much of the steam may not contact the sodium. The twelve inch size was selected to make the relief nozzle identical with the sodium inlet and outlet nozzle designs, since this size will be adequate for discharge of sodium displaced by steam entering through any conceivable leak.

A relief valve located high in the gas blanket will exhaust gas to keep the pressure low enough, so that the rupture disc does not burst for small leaks. The function of this valve is to avoid uncontrolled ejection of sodium and steam mixtures through the rupture disc line for small leaks which present no immediate hazard. Uncontrolled ejection of sodium and reaction products can complicate damage to the steam generator, and may be hazardous, depending on the adequacy of exhaust and containment equipment. It is, therefore, desirable to contain the reaction in the steam generator until a controlled shutdown can be accomplished, if this can be done safely. The relief valve will be effective only when exhausting steam or gas, since the relief line will be too small to discharge liquid sodium at a rate which would prevent pressure buildup during a leak. It will also be more effective for a leak into the gas blanket or near the sodium surface, since a large leak far below the surface will tend to displace the liquid sodium to cause a liquid level rise, forcing sodium into the relief line. Steam or gaseous reaction products which bleed into the gas blanket before the cover gas is exhausted will allow the valve to operate for an indefinite period of time to limit the pressure in the steam generator, so long as the leakage gas volume does not exceed the volume of gases being exhausted.

Assumptions have been made on various leakage conditions, in order to size the relief valve. It has been concluded that a valve with relief capacity for two cubic feet of cover gas per second at maximum operating temperature and valve set pressure will satisfy a broad range of leakage conditions. Most relief valves of this approximate relief capacity have 1 1/2 inch standard pipe size inlets. Consequently, a 1 1/2 inch pipe relief line has been incorporated in the steam generator shell to accommodate installation of the relief valve. A set pressure of 140 psig is recommended for the valve. A pressure rise of 40 psi will then be required in the gas blanket, operating at a nominal 100 psig, before the relief valve opens. There is also a margin of approximately 25 psi for pressure surge after the relief valve opens before the rupture disc will burst. The rupture disc should be rated for 165 psig at 1200°F.

A safety valve set for 2500 psig is to be located off the steam exit line of the steam generator, in accordance with the ASME Boiler and Pressure Vessel Code, Section VIII.

RECOMMENDATIONS ON SODIUM PURITY CONTROL AND FEEDWATER CHEMISTRY

Specifications on feedwater chemistry, and recommendations concerning the purity of the sodium heat transfer fluid are given in the Appendix of Volume IV, "Operation and Maintenance Procedures".

SECTION 3

STRESS ANALYSIS

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STRESS ANALYSIS

SUMMARY

This report includes all stress calculations deemed necessary for a complete analysis of a 30 megawatt intermediate heat exchanger and steam generator based on some necessary assumptions as to heat source and sink which are not yet specified. Particular attention is directed to a discussion of the thermal transients -- the temperature changes with the resulting stresses and the corrective action which should be taken to reduce the stress intensities. While all calculated thermal stresses are within the allowable limit, action should be taken to reduce stress levels whenever possible.

The 30 megawatt intermediate heat exchanger is identical in many respects to the 70 megawatt unit described in APAE-78. Except for being a smaller unit, the only change of any significance is the reduction of the riser height to 1/8 in. for tube-to-tube sheet joints.

The steam generator is now a once-thru unit, as opposed to the design of the 70 megawatt unit which was a recirculation type. The problems encountered with this type of unit, and the methods of operation under various transient and casualty conditions are discussed along with the specifications of the unit.

STRUCTURAL DESIGN BASIS

The United States Navy Code "Tentative Structural Design Basis for Reactor Pressure Vessels and Directly Associated Components," December 1, 1958 Revision, has been selected as a method for handling stress analysis of combined mechanical, hydrostatic, and thermal stresses and conditions for using creep and stress rupture properties.

The structural material used is Type 316 stainless steel for both the intermediate heat exchanger and steam generator. The tubes of the steam generator are metallurgically bonded stainless steel and Inconel, and the interior of both heads of the steam generator is overlaid with Inconel (this also includes the tube side surface of the tubesheet).

A table of allowable stresses for stainless steel up to 1200°F is attached. Membrane stresses, and stresses due to gross discontinuities, are based upon figures given in the latest revisions of the ASME Unfired Pressure Vessel Code, as modified by Case Ruling 1270N. Values of yield and ultimate strengths are based upon the best available data.

The allowable values for pipe reaction stresses, plus membrane and gross discontinuity stresses, are taken as 90 per cent of the yield strength. Values for thermal stress and stress concentrations were taken from the Navy Code up to 700°F, which is as far as it goes. Beyond 700°F, the allowable stresses were first assumed to vary with ultimate strength, and these values were revised after extenstive cyclic testing of sinewave tubes at all temperatures up to 1200°F.

Thermal stresses are treated as governed by Paragraph 5.1.4 of the Navy Code, "No stress limitation need be considered with regard to steady-state thermal stresses. All thermal stresses shall be considered as transient conditions and treated in accordance with Paragraph 5.2".

TRANSIENT THERMAL STRESSES

Temperatures resulting from transients were calculated with the use of tables developed by ALCO. These tables are based on the finite difference method of Schmidt, but modified to provide for the temperature differential between the face of a plate and the body of a liquid. Covering a wide range of Biot and Fourier numbers, the tables give the resulting transient temperatures at various points throughout the thickness of a plate of finite thickness. Properly handled, these tables can also be used to apply to shielded plates and to linear changes in temperature followed by a dwell. For simpler cases, the six charts (Figures 3.1 thru 3.6) included herewith are useful. Three of these charts deal with the temperatures at outer and inner face, and mean temperature, in plates of various thicknesses, at various intervals of time following a sudden change, T_f, in the temperature of the fluid flowing past the plate. The other three deal with the same three temperatures in a plate, during the period while the fluid flowing past this plateis changing in temperature at a uniform rate. The intermediate case of a linear change followed by a dwell may be handled by approximating between these two cases. Derivations connected with these charts are given in an ALCO supplement to the 70 megawatt report APAE 78, September 30, 1960.

Two of the three charts last mentioned correspond to Figures A. 3-5 and A. 3-6 in the Navy Code, considerably extended and revised.

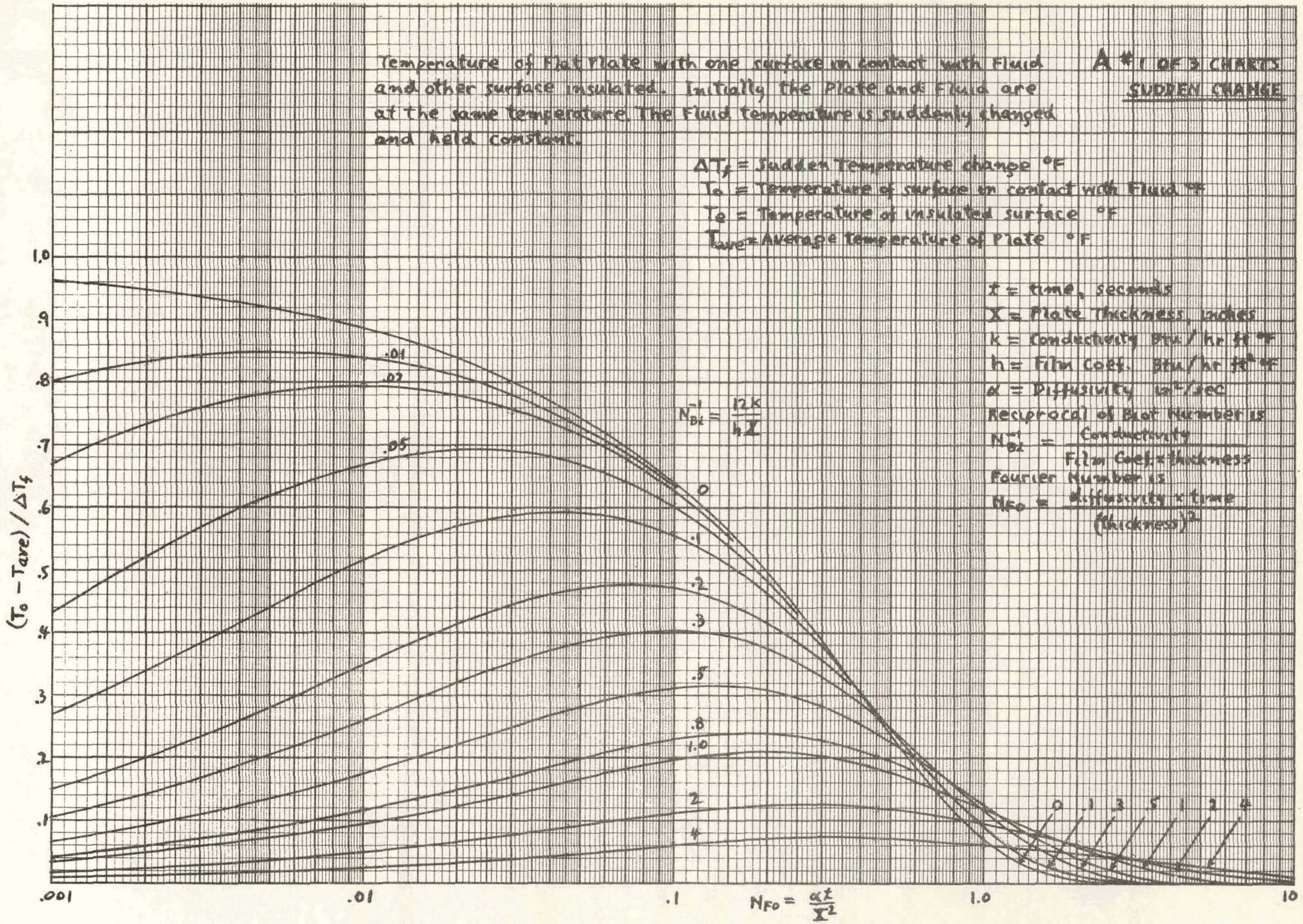
To obtain a true picture of thermal stresses, it has been necessary to study temperature changes and their effect upon stresses under the following conditions:

1. Normal start-up and shut-down.

2. Normal ramp and step changes in load during operation.

TABLE 3.1
MAXIMUM ALLOWABLE STRESS INTENSITIES
TYPE 316 STAINLESS

						Thermal Stress + Stress Concentrations				
	UFPV	Sp		Sy Yield Stress	Su Ultimate Strength	S_s Steady State Component	S_o Endurance Limit	Sa I 100, 000	Sa II 2, 500	Sa III 500
Metal Temp ^oF	Plate or Tubing & Forgings	Membrane + Discontinuities	+ Pipe Reactions							
RT	18750	50% above UFPV Code	90% of Yield Strength 27000	30000	75000	52000	24000	24000	45000	66000
400	17500		24750	27500			24000	24000	45000	66000
600	17100		22500	25000			24000	24000	45000	66000
700	17000		21600	24000	72000	45000	24000	24000	45000	66000
750	16900									
800	16750		20700	23000	72000	43000	23000	23000	43000	61000
850	16500						23000	23000		
900	16000		19800	22000	70000	41500	22000	21000	40000	56000
950	15100									
1000	14000		18900	21000	68000	40000	21000	19000	36000	51000
1050	12200									
1100	10400		18500	20500	62000	37000	20000	17000	32000	45000
1150	8500									
1200	6800		18000	20000	55000	34000	18000	15000	28000	39000
1250	5300			19500		-	-	-	-	-
1300	4000		17100	19000		-	-	-	-	-



Temperature of Flat Plate with one surface in contact with Fluid and other surface insulated. Initially the Plate and Fluid are at the same temperature. The Fluid temperature is suddenly changed and held constant.

A #1 OF 3 CHARTS

SUDDEN CHANGE

ΔT_f = Sudden Temperature change °F

T_o = Temperature of surface in contact with Fluid °F

T_e = Temperature of insulated surface °F

T_{ave} = Average temperature of Plate °F

t = time, seconds

X = Plate Thickness, inches

k = Conductivity Btu / hr ft °F

h = Film Coef. Btu/hr ft² °F

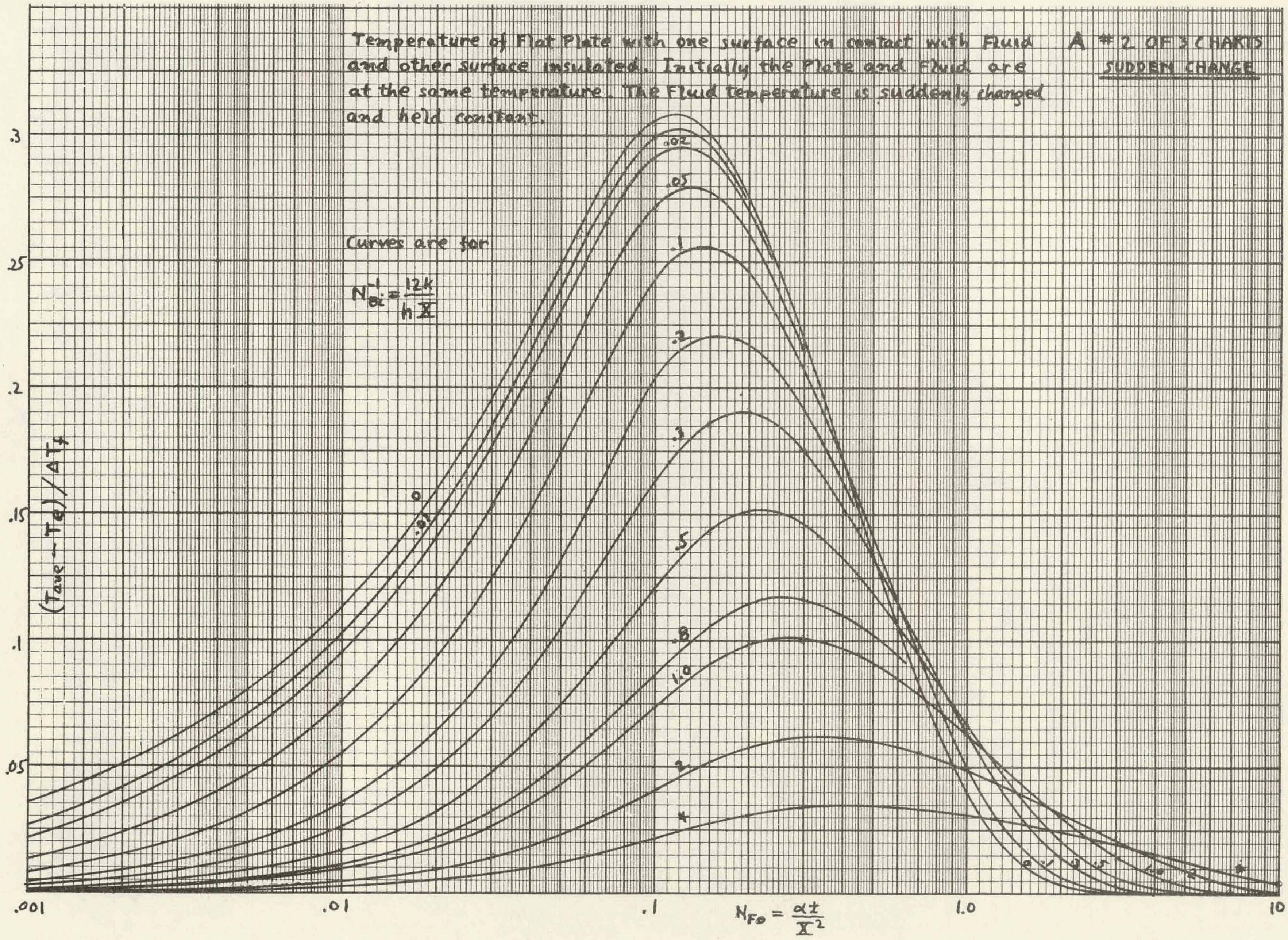
α = Diffusivity in²/sec

Reciprocal of Biot Number is

$$N_{Bi}^{-1} = \frac{\text{Conductivity}}{\text{Film Coef.} \times \text{thickness}}$$

Fourier Number is

$$N_{Fo} = \frac{\text{diffusivity} \times \text{time}}{(\text{thickness})^2}$$



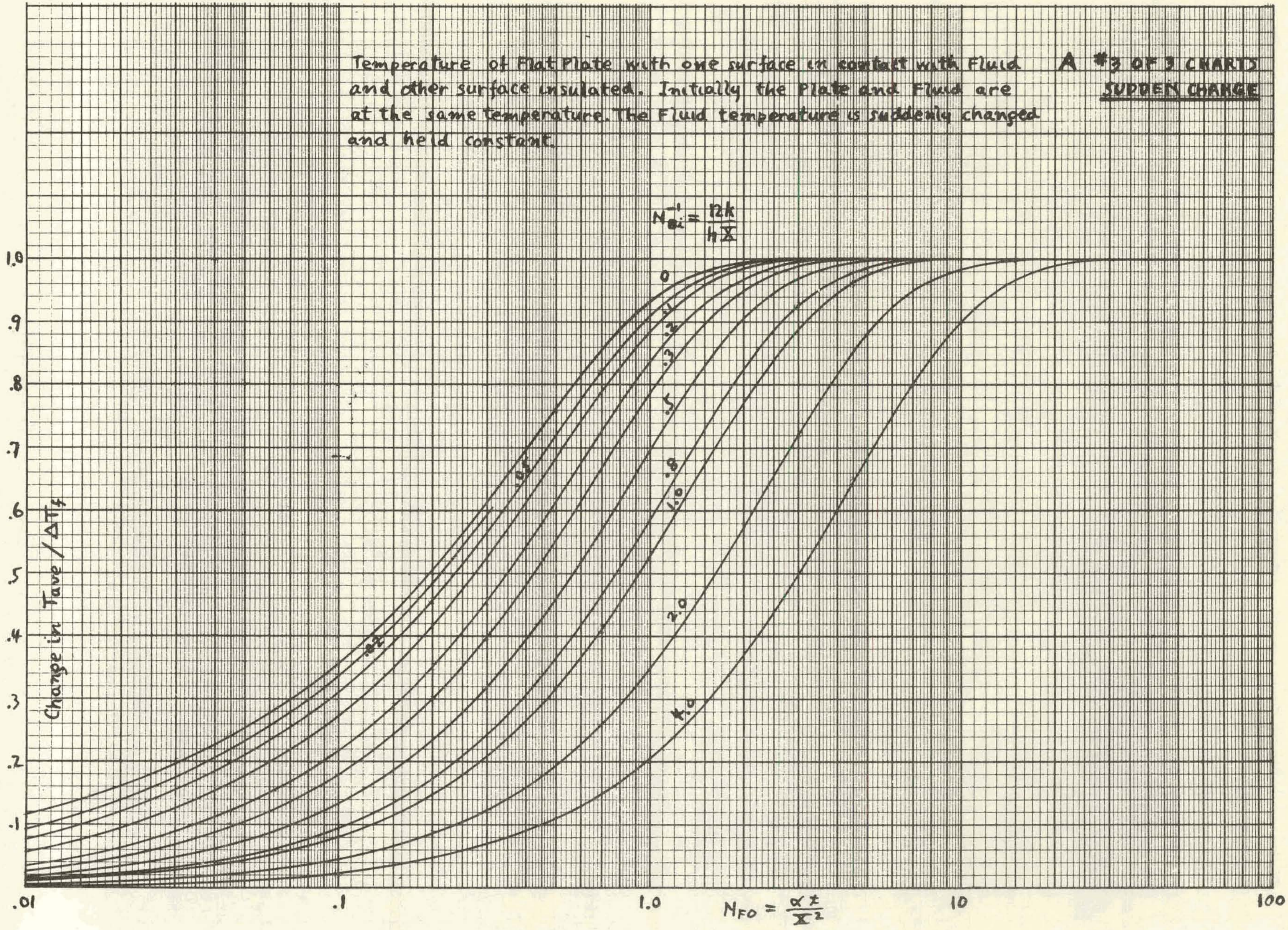
Temperature of Flat Plate with one surface in contact with Fluid and other surface insulated. Initially the Plate and Fluid are at the same temperature. The Fluid temperature is suddenly changed and held constant.

A # 2 OF 3 CHARTS

SUDDEN CHANGE

Curves are for

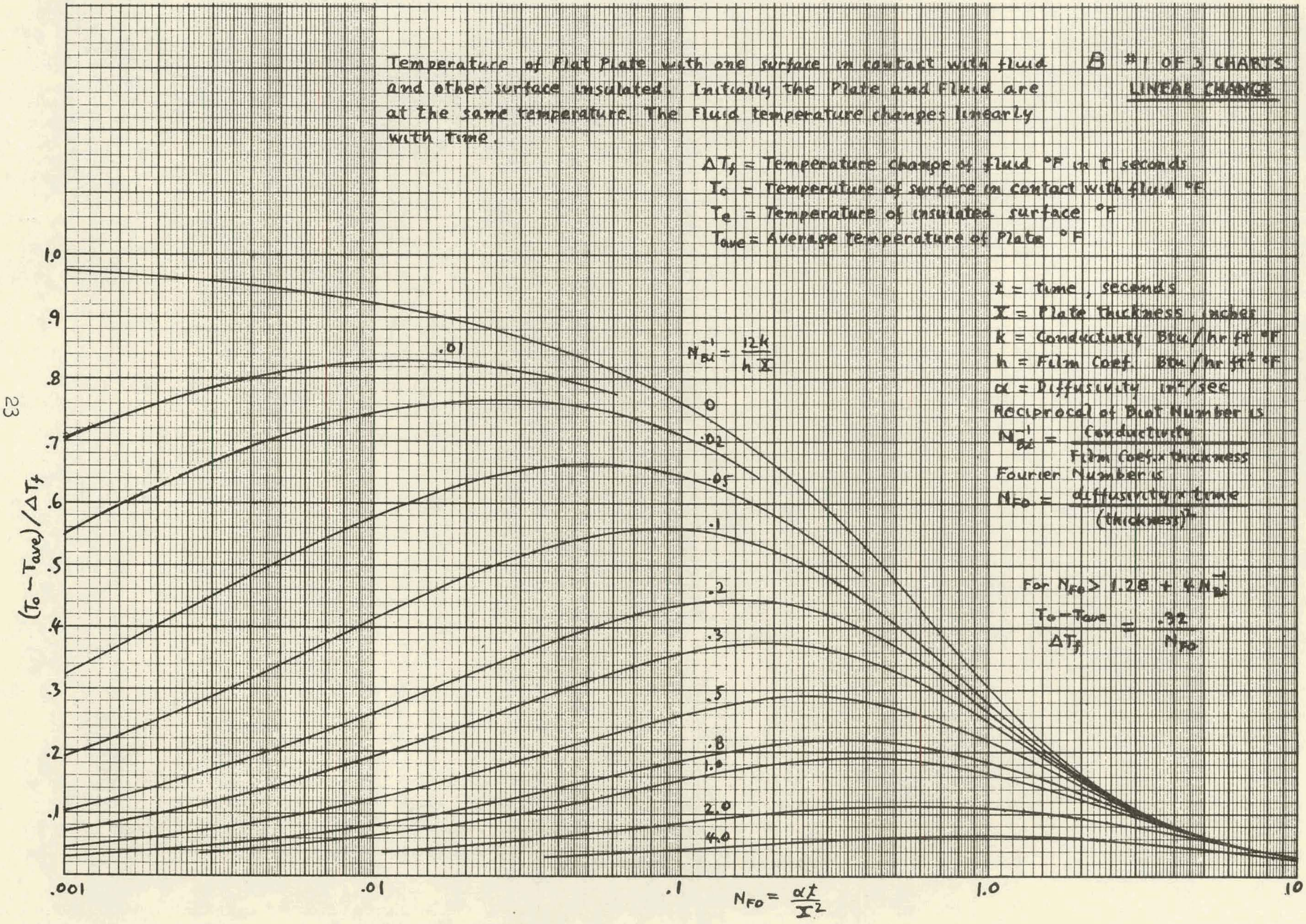
$N_{Bi}^{-1} = \frac{12k}{h X}$



Temperature of Flat Plate with one surface in contact with Fluid and other surface insulated. Initially the Plate and Fluid are at the same temperature. The Fluid temperature is suddenly changed and held constant.

A #3 OF 3 CHARTS

SUDDEN CHANGE



Temperature of Flat Plate with one surface in contact with fluid and other surface insulated. Initially the Plate and Fluid are at the same temperature. The Fluid temperature changes linearly with time.

B #1 OF 3 CHARTS

LINEAR CHANGE

ΔT_f = Temperature change of fluid °F in t seconds

T_o = Temperature of surface in contact with fluid °F

T_e = Temperature of insulated surface °F

T_{ave} = Average temperature of Plate °F

t = time, seconds

X = Plate thickness, inches

k = Conductivity Btu/hr ft °F

h = Film Coef. Btu/hr ft² °F

α = Diffusivity in²/sec

Reciprocal of Biot Number is

$$N_{Bi}^{-1} = \frac{\text{Conductivity}}{\text{Film Coef.} \times \text{thickness}}$$

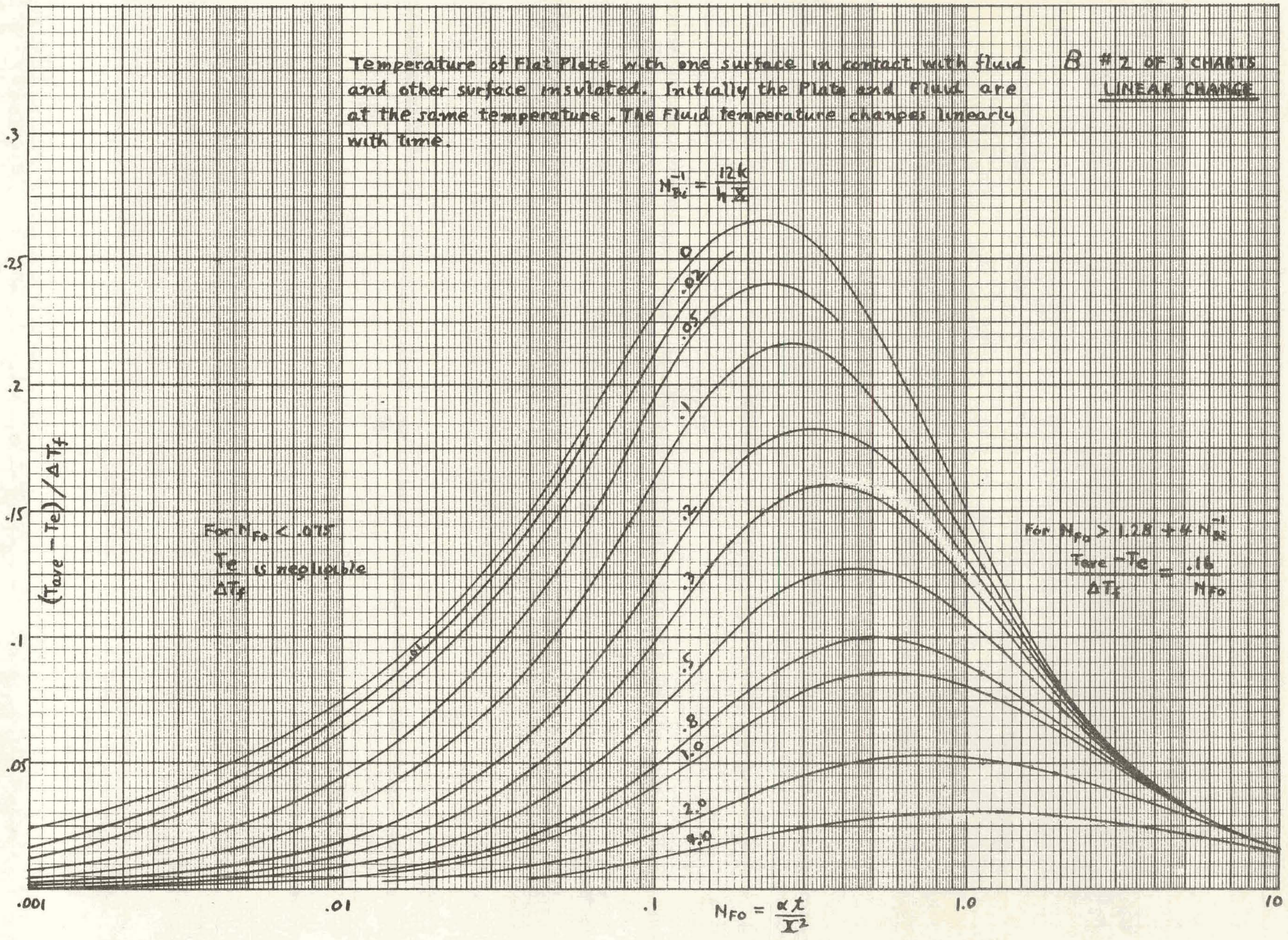
Fourier Number is

$$N_{Fo} = \frac{\text{diffusivity} \times \text{time}}{(\text{thickness})^2}$$

For $N_{Fo} > 1.28 + 4 N_{Bi}^{-1}$

$$\frac{T_o - T_{ave}}{\Delta T_f} = \frac{.32}{N_{Fo}}$$

$$N_{Bi}^{-1} = \frac{12k}{h X}$$



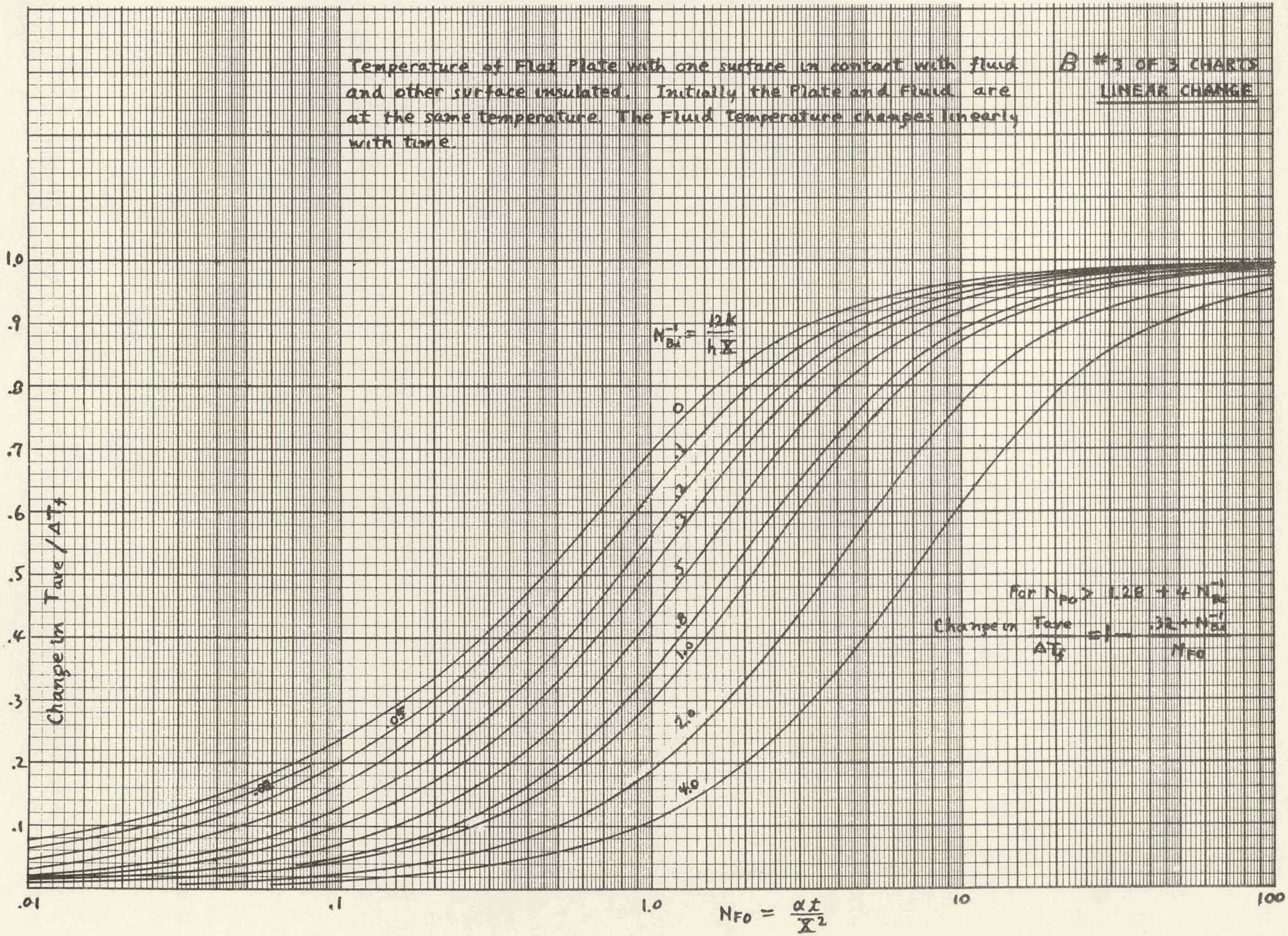
Temperature of Flat Plate with one surface in contact with fluid and other surface insulated. Initially the Plate and Fluid are at the same temperature. The Fluid temperature changes linearly with time.

B #2 OF 3 CHARTS

LINEAR CHANGE

For $N_{Fo} < .075$ $\frac{T_e}{\Delta T_f}$ is negligible

For $N_{Fo} > 1.28 + 4 N_{Bi}^{-1}$ $\frac{T_{ave} - T_e}{\Delta T_f} = \frac{.16}{N_{Fo}}$



Temperature of Flat Plate with one surface in contact with fluid and other surface insulated. Initially the Plate and Fluid are at the same temperature. The Fluid Temperature changes linearly with time.

B #3 OF 3 CHARTS

LINEAR CHANGE

For $N_{FO} > 1.28 + 4\,N_{Bi}^{-1}$

$$\text{Change in } \frac{T_{ave}}{\Delta T_f} = 1 - \frac{.32 + N_{Bi}^{-1}}{N_{FO}}$$

3. Stoppage of primary sodium pump while the secondary sodium pump continues to operate. –

4. Stoppage of secondary sodium pump while the primary sodium pump continues to operate.

5. Stoppage of feedwater pump while the two sodium pumps may or may not continue to operate.

6. A steam or water leak into the sodium, which would compel decreasing the steam pressure as rapidly as feasible.

7. A power failure, which would result in a simultaneous stoppage of the feedwater pump and of both sodium pumps.

8. A reactor scram while all pumps continue to operate at full or partial speed.

In the present design, the mass of sodium, thin metal, and of water and steam in the intermediate heat exchanger and the steam generator is large enough to give a relatively high heat storage in comparison to the throughput of heat in BTU per second. As a result, most of the transient temperatures can be computed without regard to the dimensions or properties of the reactor, which are not yet determined. An exception is the primary sodium inlet nozzle in the intermediate heat exchanger, with the adjacent portions of the shell. In this design, as with the 70 megawatt unit, the thermal transients were based upon an assumed drop in temperature of 490°F in fourteen seconds, which is similar to, but more severe than, that listed under reactor scrams in the contract.

Certain assumptions have necessarily been made. As stated in the specifications, the temperature of primary sodium entering the intermediate heat exchanger has been assumed not to rise above 1200°F. Similarly, the normal minimum temperature during casualties has been taken as 650°F. This involves the requirement that, insofar as possible, during operation and during casualties, the steam pressure shall be maintained at 2200 psi. A trip valve between steam generator and turbine would close, in order to maintain pressure and in order to prevent sudden cooling of the turbine, and excess steam would be released through safety valves. Except where imperatively needed, in order to stop leakage of water into the sodium, or in the event of feedwater flow stoppage when the water in the lower drum is needed to cool the sodium, the steam pressure would be decreased below 2200 psi only gradually and under controlled conditions.

Conditions 1 and 2

The permissible rate of temperature change under normal start-up and shutdown procedure is discussed elsewhere. Normal ramp and step changes in load during operation cause relatively small temperature fluctuations. Their effect is also discussed elsewhere.

Conditions 3

Stoppage of the primary sodium pump while the secondary sodium pump continues to operate will cause heat to be drawn away from the heat exchanger at a rate equal to the weight of secondary sodium per second times specific heat times difference between outlet and inlet temperatures of the secondary sodium. Initially, at full load operation of the pump, this will equal 29,350 BTU per second, but as the intermediate heat exchanger cools, the outlet temperature of the sodium will drop, and with it this rate of heat loss. This results in the temperature in the heat exchanger dropping at a logarithmically decreasing rate, as the heat initially stored up in the sodium and the metal of the heat exchanger is gradually drawn away.

For a secondary sodium flow of W pounds per second, entering at a constant temperature T_1, and leaving at a decreasing temperature T, the heat withdrawn in time dt will be $dQ = 0.3W\ (T-T_1)\ dt$.

Let Q_o be the initial available heat storage above temperature T_1, and T_o the corresponding initial temperature of the outgoing secondary sodium. Under the assumption that the mean temperature of the heat exchanger maintains a reasonably constant relation to the outgoing secondary sodium temperature,

$$dQ = \frac{Q_o\ dT}{T_o-T_1} = 0.3W\ (T-T_1)\ dt$$

Rearranging:

$$\int_0^t dt = \frac{-Q_o}{0.3W\ (T_o-T_1)} \int_{T_o}^{T} \frac{dT}{T-T_1}$$

Integrating:

$$\text{Time} = \frac{Q_o}{0.3W\ (T_o-T_1)}\ \ln \frac{T_o-T_1}{T-T_1}$$

As already stated, at full load pump operation, $0.3W(T_o-T_1)$ will equal 29,350 BTU per second.

Q_o is the total amount of available heat above temperature T_1. It will include the total sensible heat in the sodium, plus that part of the sensible heat in the metal which may be given up to the sodium during the period while the transient is occurring. Thus, it will include virtually all the heat in the tube metal and in the thin baffles and shield, and a percentage of the heat in the shell and barrel walls; this percentage increasing as the time of cooling becomes longer. For stoppage of the primary pump, the heat will be that in the heat exchanger itself, plus such as may be received from the reactor due to natural circulation following pump stoppage. In the event of a reactor scram, with both pumps continuing to run, Q_o will include the heat stored in the reactor as well. By slowing down the pumps, W can be reduced, and so the time prolonged, down to the minimum practicable speed at which the pumps can be operated.

If the pressure in the steam generator is maintained at 2200 psi, the secondary sodium temperature leaving the steam generator and entering the lower end of the intermediate heat exchanger will remain at 777°F for about forty to fifty seconds. The rated temperature for the primary sodium at top is 1200°F and at bottom 900°F, indicating an average temperature of 1050°F. The unit holds 7060 pounds of primary sodium. In addition, there is a total of 7900 pounds of easily cooled metal. This indicates a total available stored heat of

$$(7060 \times 0.30 + 7900 \times 0.16)(1050-777) = 923,000 \text{ BTU}$$

The heat in the thicker metal will be drawn upon more slowly. Using these figures, and assuming full load speed of secondary pump and of feedwater pump and no flow from the reactor,

$$t = \frac{923000}{29350} \text{ Ln } \frac{1175-777}{T-777}$$

$$= 31.5 \text{ Ln } \frac{398}{T-777}$$

Following a scram, both pumps would normally continue to be operated for a time, in order to withdraw decay heat from the reactor. On an arbitrary assumption as to the capacity of the reactor and of the connecting piping, the available heat would be 80 to 100 per cent greater than for the intermediate heat exchanger only, and say $t = 60 \text{ Ln } \frac{398}{T-777}$ seconds.

The first of the above equations assumes no heat input to the intermediate heat exchanger, that is, the primary circulation is stopped. The second is with both pumps operating under the assumptions given. Neither equation is valid beyond approximately fifty seconds, as this is the time for exiting secondary sodium to return to the intermediate heat exchanger at the inlet. A plot of these two curves is given in the accompanying figure and compared with the ten degree per second rate. As is shown in this figure, the ten degree rate is more severe,

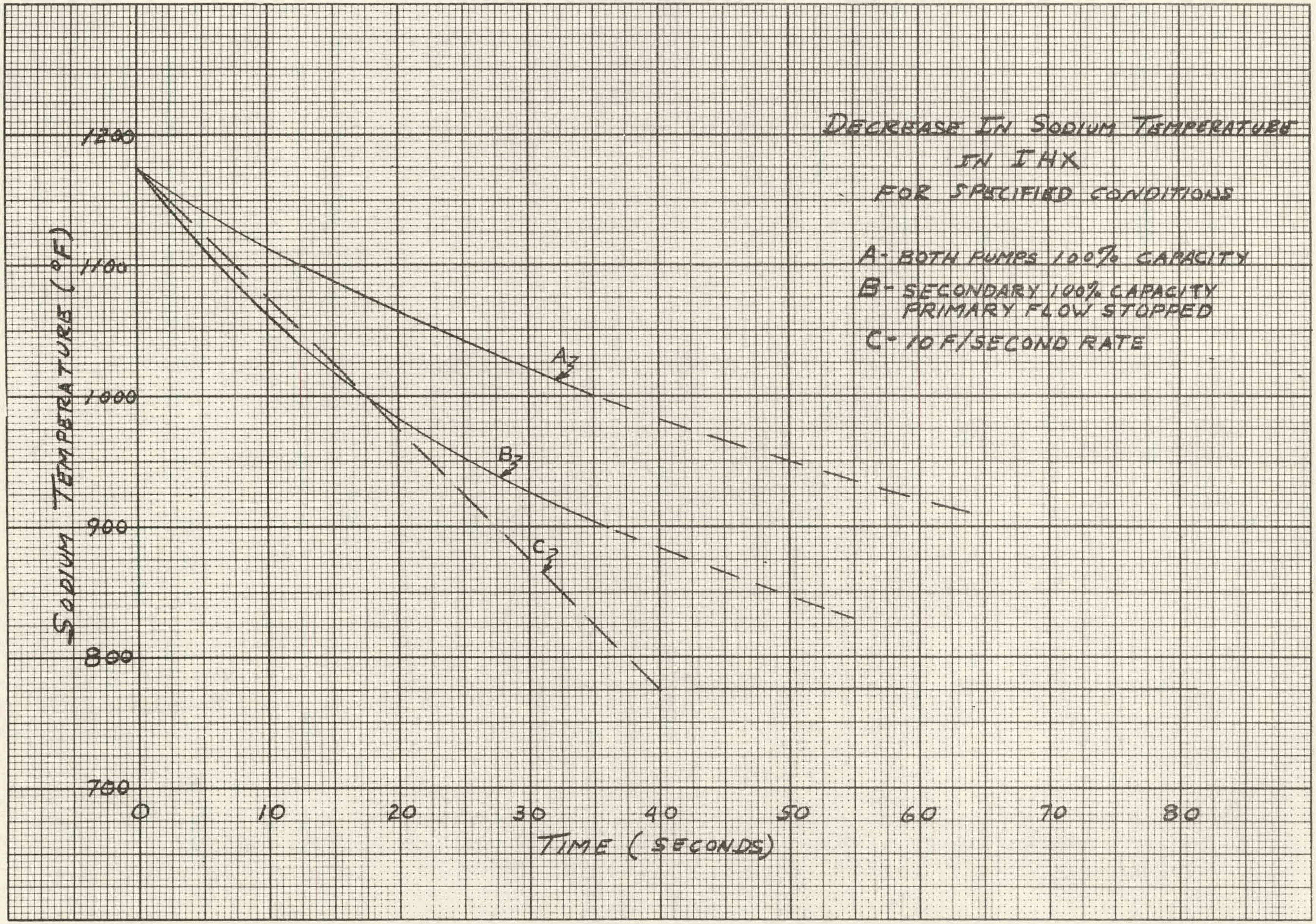

DECREASE IN SODIUM TEMPERATURE
IN IHX
FOR SPECIFIED CONDITIONS
A- BOTH PUMPS 100% CAPACITY
B- SECONDARY 100% CAPACITY
PRIMARY FLOW STOPPED
C- 10 F/SECOND RATE
A
B
C
SODIUM TEMPERATURE (°F)
1200
1100
1000
900
800
700
0
10
20
30
40
50
60
70
80
TIME (SECONDS)

FIGURE 3.7

and has been selected as the sodium temperature change rate to be used for the transient analysis after a primary pump failure. It has also been used as the basis for calculation of a reactor scram.

Should the sodium pumps and feedwater pump be slowed, the rate of cooling would be decreased considerably; as much as by a factor of five, if the pumps are slowed to twenty per cent flow. To decrease cooling rate much more would require intermittent operation of the pump.

The curves also apply to the drop in inlet temperature entering the steam generator after a correction for transit time from the intermediate heat exchanger to steam generator. At full load operation, the transit time through the steam generator is thirty-four seconds. Thus, by the time the outlet sodium begins to drop from 777°F, the inlet temperature would be approximately 975°F. As the inlet sodium to the steam generator decreases in temperature, the stored heat in the metal will tend to slow the cooling rate below that of the intermediate heat exchanger. Only by operating the reactor at low power, could the cooling rate be extended to a number of hours, as is recommended for a normal shutdown.

Condition 4A

Stoppage of secondary sodium pump while the primary pump continues to operate.

This will separate thermally the intermediate heat exchanger from the steam generator, so that the thermal behavior of the two must be studied separately. For the intermediate heat exchanger, this is part of the general problem of the conditions under which rises in temperature may occur.

Rapid increases in temperature at the lower end of the intermediate heat exchanger may occur under the various contingencies listed below, which are of varying degrees of probability:

a. While in full operation, the reactor is scrammed and the primary and secondary pumps are simultaneously stopped.

   In this case, due to such gravity circulation as may continue to occur and due to the rapid heat conduction through the sodium itself, the temperature both in the reactor and the intermediate heat exchanger will tend to approach isothermal conditions at a mean value of 1/2 (1200°F ≠ 900), or 1050°F. The slow heat transfer through the lower tubesheet will tend to warm the secondary sodium in the lower barrel. Gravity circulation in the secondary circuit, unless shut off by valves, will slow this warming effect, and it will also tend to cool the primary sodium.

Due to various difficulties produced by this method of operation, it is recommended that both primary and secondary pumps be continued in operation at slow speed after scramming the reactor, until temperatures throughout the system have been lowered to approach 850^{O}F.

b. The reactor is scrammed, and the secondary pump stopped; but, due to malfunctioning of controls, the primary pump does not stop.

The cool sodium at the bottom of the reactor will be forced through the reactor, being warmed only by decay heat and by the sensible heat of the reactor. The temperature of the sodium leaving the reactor will, therefore, gradually drop. The temperature of the sodium entering the intermediate heat exchanger will remain at 1200^{O}F until the initial slug of hot sodium in the pipe line and at the top of the reactor has passed through, and will thereafter gradually drop. The sodium passing downward through the intermediate heat exchanger will no longer be cooled by the circulating secondary sodium, so that the temperature of the primary sodium at the lower end of the intermediate heat exchanger will gradually increase to a peak, and then drop as the gradually cooling sodium leaving the reactor reaches this point. As a result, the temperature of the primary sodium at the lower end of the intermediate heat exchanger will show a rapidly damped sine-wave fluctuation rising from the stated design value of 900^{O}F to somewhat above the mean temperature of $\frac{900 / 1200}{2}{}^{O}$F, or 1050^{O}F, and then dropping to this value. Any residual gravity circulation in the secondary sodium circuit will tend to lower these figures.

The time required for this to occur will depend upon the rate of operation of the primary pump. At full rated load, the sodium flow would be 317 pounds per second. The intermediate heat exchanger holds 7060 pounds of primary sodium in the active circuit, so that transit time through the unit would be twenty-two seconds. The volume of sodium in the reactor and in connecting pipes is, of course, unknown, but should be enough to increase the total circuit time at full load rate to between fifty-five and sixty seconds, and proportionally longer at part load pump speed.

c. The secondary sodium flow is stopped, but, due to malfunctioning of controls, neither the reactor nor the primary sodium pump is shut down.

This would result in a continuing flow of hot primary sodium to the intermediate heat exchanger, while outflow of heat to the secondary sodium has stopped. The temperature of the primary sodium leaving the intermediate heat exchanger would gradually rise above 900^{O}F, which would compel either a rise in reactor top temperature above 1200^{O}F, or shift in control rods. Assuming the latter happens, the entire mass of primary sodium could presently rise to 1200°F. The slug of secondary sodium within the lower intermediate heat exchanger barrel would only slowly rise above its stated normal cool temperature of 775°F. This would cause very high thermal stresses in the lower tubesheet and in the connecting shell and barrel.

This assumes not simply one control failure, but a succession of failures. Stoppage of either circulating pump should result in a shut down of the other pump, and also a scram of the reactor. A rise in sodium temperature entering the reactor should cause not only a shift in reactor control rods, but also, if it goes too far, in a reactor scram. Failure of any of these controls should result in warning signals in the control room. These signals would have to be ignored for thirty seconds or longer to cause appreciable damage.

Under case "a", the result would be gradual rise in temperature of the primary sodium at the lower end of the intermediate heat exchanger to approaching 1050°F, decreased by whatever loss through insulation and to the secondary sodium as might have occurred. Case "b" would represent a more rapid rise to the same or somewhat higher temperature, and has been taken as the maximum credible incident; case "c" being ruled out. During this incident, the barrel and the barrel contents will change but little in temperature; the shell wall will be heated most rapidly, and will increase in diameter; the tubesheet will be heated from top down, causing it to cup upward. This will result in mismatches between the different parts, which will be additive to the mismatches due to the steady-state temperature differentials. Knowing the magnitude of the mismatches, the resulting secondary stresses may be determined.

Condition 4B

Secondary Sodium Pump Stops, Temperature Changes in the Steam Generator

With the secondary sodium flow stopped, the steam generator is thermally isolated from the intermediate heat exchanger. Generation of steam will drop in rate, due to the lowered film coefficient of this stagnent sodium, and then will further decrease as the sodium temperature drops.

The steam generator contains 8340 pounds of sodium and 11970 pounds of thin metal. The stored heat per degree drop in temperature is

sodium 8340 x . 306 = 2550 BTU

metal 11970 x .16 - 1914 BTU

4464 BTU.

For water entering at $600^{O}F$, and leaving as steam at $1050^{O}F$ at 2200 psi, enthalpy added

= 1500 -617 = 883 BTU per pound

With the feedwater pump operating at 100 per cent of rating, or $\frac{116000}{3600}$ = 32.2 pounds per second, the enthalpy absorbed will be 28400 BTU per second, and the drop in mean sodium temperature initially will be $6.36^{O}F$ per second, or $190.8^{O}F$ in thirty seconds. Due to the lowered film coefficient, the drop in exit steam temperature will be greater than this. With the feedwater operating at less than 100 per cent of rating, the time will be proportionally increased.

For best results, at about this moment the feedwater flow should be automatically stopped. Continuation of the flow would result in unduly cooling the thick upper head of the steam generator, and presently in carrying wet steam into the generator head, which will score the valve seats, as well as cause shock cooling. Earlier stoppage of the flow will leave the mean sodium temperature high enough to cause undue temperature differentials across the lower tubesheet.

Condition 5

Stoppage of Feedwater pump.

As the quantity of water and steam in the tubes of the steam generator is small, the tubes will run dry very quickly after a feedwater pump stoppage. The steam generator sodium outlet temperature will rise to $1175^{O}F$ rapidly. The mass of shielding above the lower tubesheet protects the tubesheet from feeling this temperature change immediately. Should the sodium outlet temperature remain at $1175^{O}F$ for more than approximately two minutes, the top face of the tubesheet will begin to feel the change. From this time on, the stresses in the tubesheet will rise and increase to a high level.

To avoid this, should the feedwater flow stop, the reactor should be scrammed and both sodium pumps slowed. Lower the steam pressure to cause water in the lower head to boil out, thereby cooling the sodium.

Condition 6

For a minor leak or seep of water into sodium normal shutdown procedure should be employed. If the weep has grown into a small leak, the reactor should be scrammed and steam allowed to escape through the pressure control valve at 2200 psi. When the exiting steam temperature drops to $850^{O}F$, the sodium and feedwater flows should be stopped. Steam and water is then to be released through the dump valve located on the feedwater inlet line. When steam has been exhausted, close valve and drain sodium.

For a large leak, a rupture disc on the shell of the steam generator will burst. Upon indication of a large leak, the reactor should be scrammed and sodium and feedwater flows stopped. The dump valve on the feedwater inlet shall be opened to dump water and steam, causing pressure to drop rapidly.

Condition 7

A power failure, which causes the stoppage of all pumps, would isolate thermally the intermediate heat exchanger from the reactor and from the steam generator. The resulting temperature changes in the steam generator are similar to condition 5, a stoppage of the feedwater pump, except here the sodium will tend to approach an equilibrium temperature of $\frac{1175 + 775}{2} = 975^{o}F$. To continue cooling of the sodium below this temperature, the steam pressure is to be lowered so as to boil the water out of the lower head of the steam generator. The temperature throughout the intermediate heat exchanger will tend to equalize at a mean value, as discussed under condition 4A. Gravity flow of sodium will tend to cause some equalization between the steam generator and intermediate heat exchanger.

Condition 8

The thermal excursions with reactor scrammed and both sodium pumps continuing to operate will be similar to those in Condition 3 with the primary pump stopped, but less severe, because of the added heat storage within the reactor.

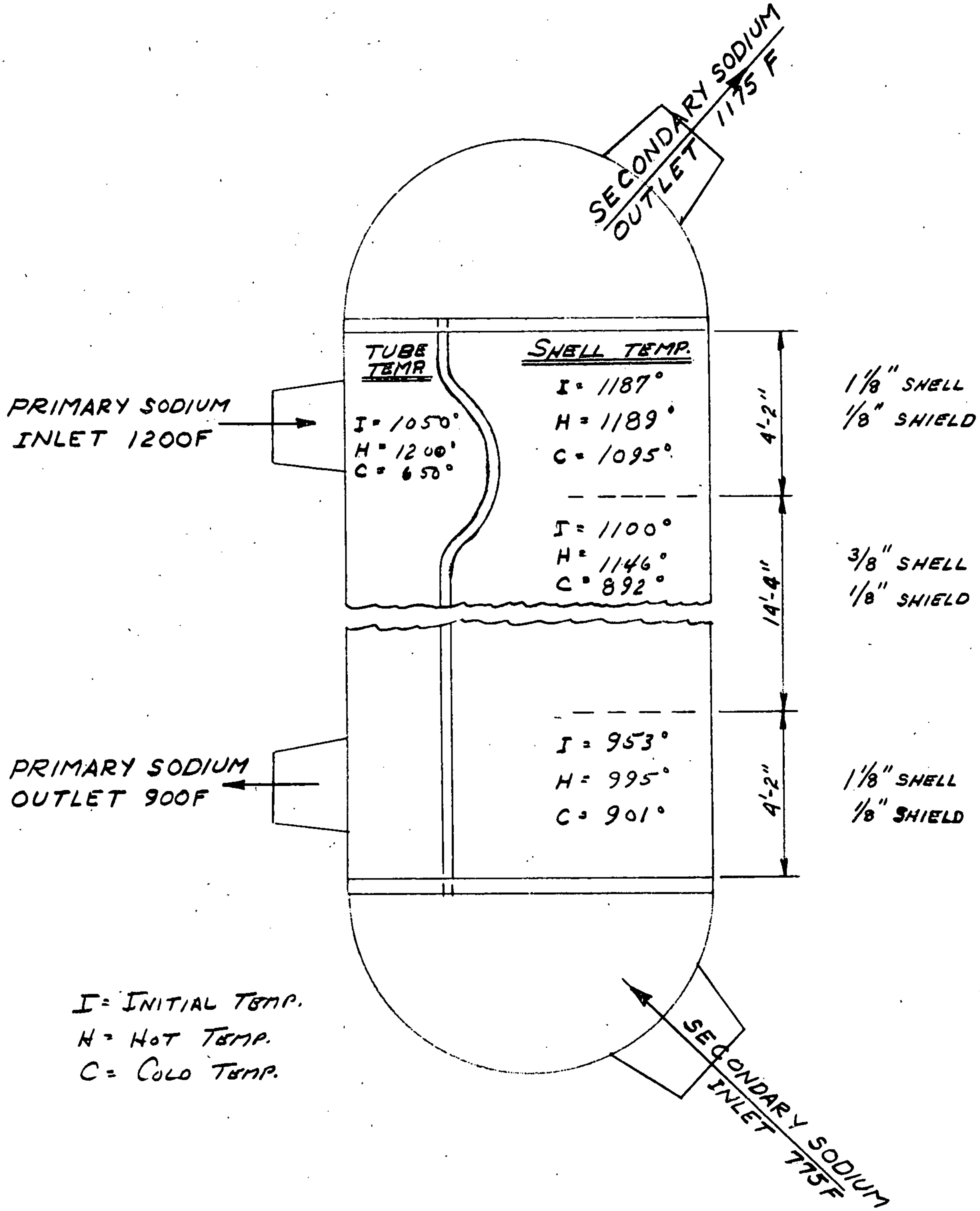
SUMMARY OF THERMAL TRANSIENTS

For the various casualty conditions listed in the specifications, as applied to the present intermediate heat exchanger and steam generator, the peak rates of change of sodium and steam temperatures to be used in design are as follows:

1. Primary Sodium Pump Stops, Secondary Sodium Pump Continues to Run (Condition 3) - At full speed operation of the secondary sodium pump, the secondary sodium exit temperature drops logarithmically from 1175 to 900^{o}F in thirty-six seconds, and at a decreasing rate, as shown in Figure 3.8 . The rate of drop in the steam generator will be less than that in the intermediate heat exchanger. For either case, a linear decrease from 1175 to 775^{o}F in forty seconds has been used in design.

2. Secondary Sodium Pump Stops, Primary Sodium Pump Continues to Run (Condition 4). This isolates thermally the steam generator from the I.H.X.

a. In the intermediate heat exchanger, continued heat input will raise the outlet sodium temperature so as to approach inlet temperature of 1200^{o}F, if no corrective action is initiated. As the outlet sodium temperature rises, the



INTERMEDIATE HEAT EXCHANGER
TUBE & SHELL TEMPERATURES DURING TRANSIENTS

FIGURE 3.8

temperature of the sodium entering the reactor also rises. This should scram the reactor and prevent any further rise. The transient is taken to be a 150°F rise in primary outlet temperature in fifteen seconds.

b. In the steam generator, the outlet steam temperature will drop as the sodium is cooled. If feedwater flow is allowed to continue at full flow, the entire unit will become flooded with 600°F water. This situation will cause high stresses in the upper head and must be avoided. When the secondary pump stops, the feedwater flow should be slowed. As the outlet steam temperature approaches 850°F, the feedwater flow should be stopped, and any steam generated allowed to exit through the pressure control valve set at a pressure slightly in excess of 2200 psi. This decreases the cooling rate of the upper head, lowering stresses there, and avoiding increased stresses elsewhere.

3. Stoppage of the feedwater pump while the sodium pumps continue to operate causes high stresses in the lower tubesheets of the intermediate heat exchanger and steam generator. In the intermediate heat exchanger, this condition is similar to 2-"a" above, except there will be a delay in rise of the exiting sodium temperature until the entering secondary sodium temperature rises above its normal operating temperature of 775°F.

In the steam generator, the amount of water available to cool this sodium after a stoppage of feedwater flow is small. Additional cooling of the sodium can be accomplished by reducing the steam pressure so as to boil the water out of the lower head of the steam generator. For this condition, a sudden 400°F rise from 775 to 1175°F is used to calculate temperature rises and the resulting stresses.

4. Following a reactor scram, there will be rapid decreases in the sodium temperature passing through the primary inlet nozzle in the intermediate heat exchanger, as the colder sodium in the bottom of the reactor reaches it. As listed in the specification

a. Primary sodium inlet temperature drops 60°F in first one-half second.

b. It drops a total of 130°F in six seconds.

c. The predicted sodium temperature at the end of the condition is the normal sodium outlet temperature.

This does not state the time required for the total drop. In the report for the 70 megawatt unit, the transient condition used throughout was the severe requirement of a drop of 490°F in fourteen seconds. In and adjacent to this inlet nozzle, this condition has continued to be used. Away from the inlet nozzle, the large heat storage in the intermediate heat exchanger will iron out this rapid transient, and the primary sodium temperature throughout reactor and intermediate heat exchanger will presently equalize at a mean value of 1050°F. This will leave the secondary sodium in the lower intermediate heat exchanger barrel at its original temperature of 775°F, and in the upper barrel at 1175°F, and place both tubesheets in bending. Time for the equalization will be at least one minute, but maximum stresses will not occur until two or three minutes later.

DIFFERENTIAL EXPANSION BETWEEN SHELL AND TUBES

Intermediate Heat Exchanger

To provide for freedom of differential expansion between tubes and shell and between different tubes, all tubes in the heat exchanger and steam generator are provided with a prebent sinewave; that is a curved portion forty-eight inches long with ten inch maximum offset, placed adjacent to the upper tubesheet. In order to furnish the necessary clearance for this sinewave, the tubes are placed in concentric circles, and the wave is given a double curvature to fit these circles. An area in the center of the tubesheet is left without tubes. This area serves a useful purpose in providing a turning area for the flow between the disk-and-doughnut baffles.

The behavior of these sinewave tubes under fatigue conditions at temperature has been investigated, and the results are covered in a separate research and development report.

The differential change in length to be provided for will depend upon the rate of change in temperature of the sodium, since the shell also changes in temperature as well as the tubes, although at a slower rate. The most rapid rate of cooling would occur with reactor scrammed, primary sodium pump stopped, and secondary sodium pump operating at maximum rate. Under these conditions the exit secondary sodium temperature of the intermediate heat exchanger would decrease at a logarithmically decreasing rate, which could not exceed 350°F in thirty-six seconds. With the reverse condition of secondary pump stopped and reactor and primary pump operating, the exit primary sodium temperature would rise, but would not reach more than partway to 1200°F, unless several successive safeguards failed to operate. The following computations are based on the more severe assumption of a rise to 1200°F and drop to 650°F, each in thirty seconds.

$\gamma = 11.2 \times 10^{-6}$

		AFTER THIRTY SECONDS			
		Temperature Rise		Temperature Drop	
Shell	Initial Temp. °F	Final Temp., °F	ΔL inch	Final Temp. °F	ΔL inch
Top 50 inches	1187	1189	+.0011	1095	-.0403
Middle 172 inches	1100	1146	+.0886	892	-.4007
Bottom 50 inches	953	995	+.0235	901	-.0289
			+.1132		-.4699
Tube					
272 inches	1050	1200	+.4326	650	-1.2429
	Difference		+.3194		-.7730

For the inside row of tubes, the offset is 9.29 inches on 15.125 inch circle.

$$\frac{2A}{L} = \frac{9.29}{40} = .1935 \qquad \frac{D}{L} = \frac{3}{48} = .0625$$

$$\frac{ED_0}{2L^2} = \frac{(23.4 \times 10^6)(.500)}{(2)\ (48)^2} = 2540$$

From Curve A, C' = 18

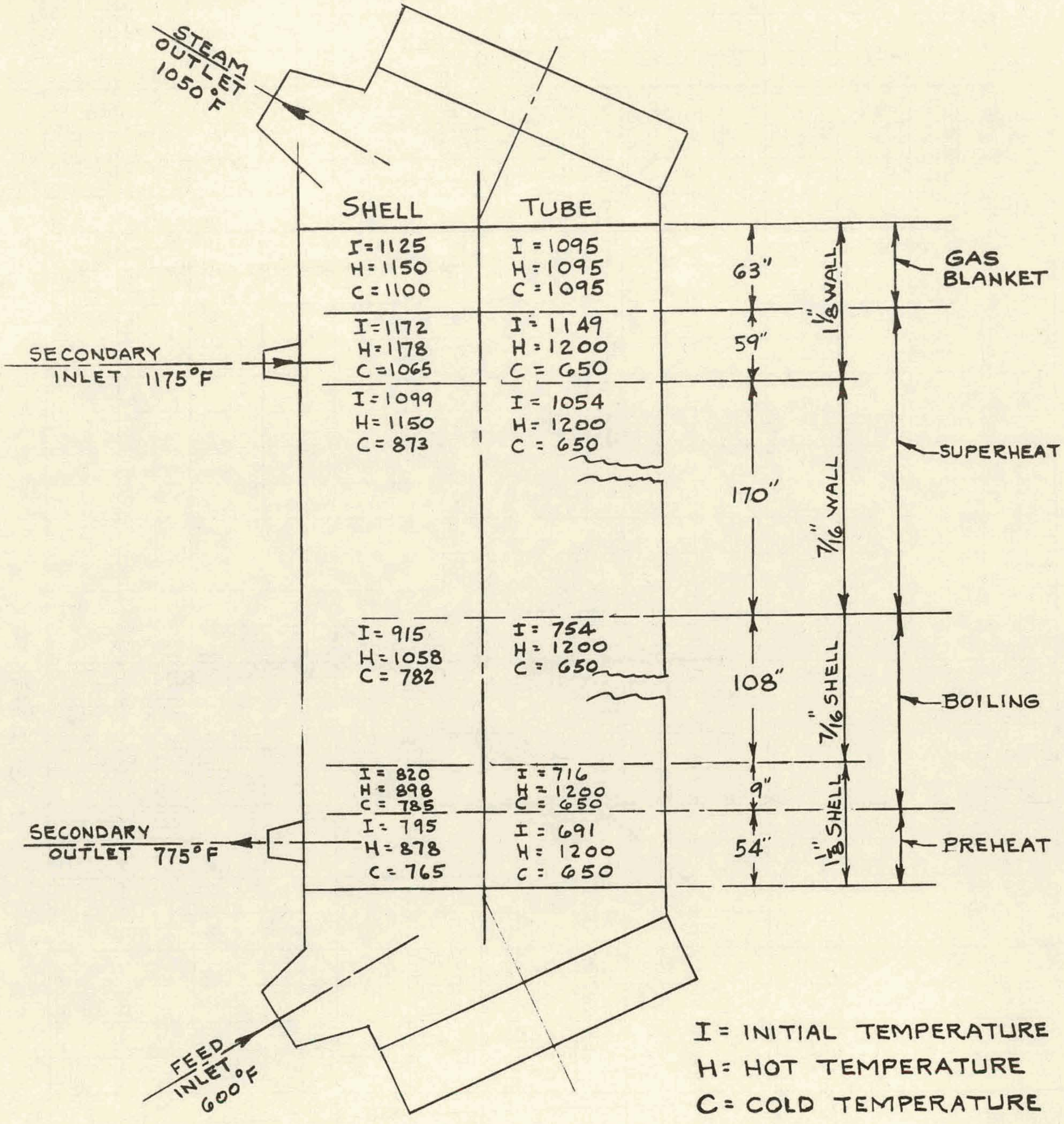
From Curve B, C'' = 0.922

The bending stresses become

For rising temperature: (18) (.922) (2540) (.3194) = 13464 psi

For falling temperature: (18) (.922) (2540) (.7730) = 32585 psi

Pressure stresses are negligible, and the combined stresses will be below allowable.



STEAM GENERATOR

TUBE AND SHELL TEMPERATURES DURING TRANSIENTS

FIG 3.9

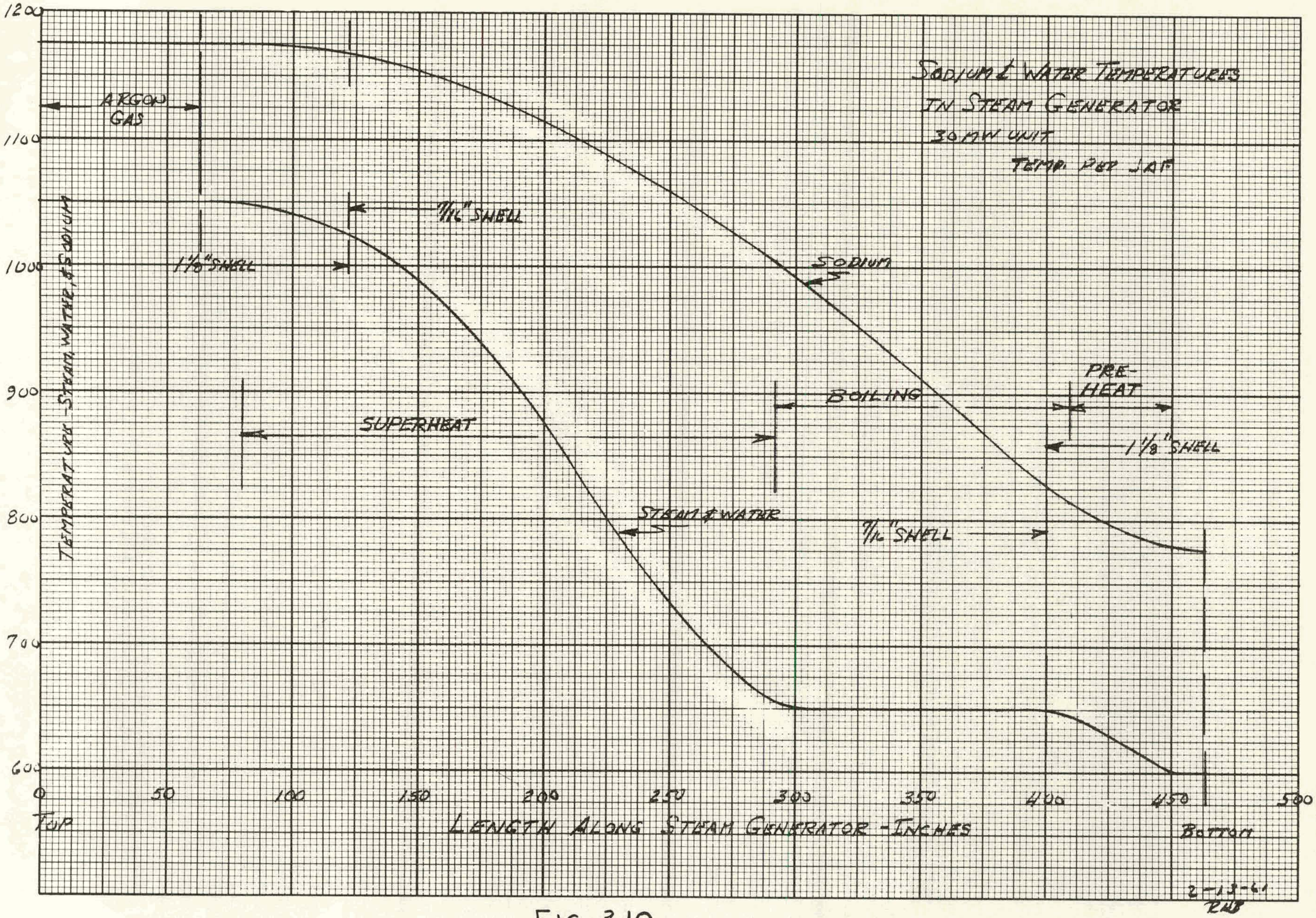

SODIUM & WATER TEMPERATURES
IN STEAM GENERATOR
30 MW UNIT
TEMP. PER JAF
TEMPERATURE - STEAM, WATER, & SODIUM
1200
1100
1000
900
800
700
600
0
50
100
150
200
250
300
350
400
450
500
TOP
LENGTH ALONG STEAM GENERATOR - INCHES
BOTTOM
ARGON GAS
1 1/8" SHELL
7/16" SHELL
SODIUM
SUPERHEAT
BOILING
PRE-HEAT
1 1/8" SHELL
STEAM & WATER
7/16" SHELL
2-13-61
RAB

FIG 3.10

Steam Generator

The necessary sine wave action in the steam generator has been computed on the assumption that the change in temperature of sodium from operating temperature to 650 or 1200°F has occurred in forty seconds. This would result in the following maximum differential changes in length between the shell and tubes:

	Heating	Cooling
Shell	0.34 inch	-0.69 inch
Tubes	1.18 inch	-1.24 inch
Differential	0.84 inch	0.55 inch

The stresses become 35,300 psi on heating and 23,100 psi on cooling. With the pressure stress added, the combined stresses are well within allowable.

A rupture in the steam line between the steam outlet and the turbine could cause a sudden decrease in steam pressure accompanied by a rapid outflow of steam and a drop in temperature below 650°F. This would cause a larger differential elongation, but the inherent flexibility of the sine wave tubes, both theoretically and as verified by experimental work, is such that it would not cause damage. The steam generator tubes have sine waves identical to those of the intermediate heat exchanger.

Transient temperature in shell for a sodium change of temperature in 40 sec.

For a 1 1/8" section with 1/8" shield

$$N_{Bi}^{-1} = \frac{(12)\,(12)}{(4000)\,(1.28125)} = .028$$

$$N_{Fo} = \frac{(.0066)\,(40)}{(1.28125)^2} = .161$$

$$\frac{1.125}{1.28125} = .876$$

From Porter's Tables: -

$$T_M = .205$$

For 7/16" section with 1/8" shield

$$N_{Bi}^{-1} = \frac{(12)\,(12)}{(4000)\,(.59375)} = .061$$

$$N_{Fo} = \frac{(.0066)\,(40)}{(.59375)^2} = .75$$

$$\frac{.4375}{.59375} = .737$$

$$T_M = .502$$

Mean temperature is for the shell only and does not include shield. Multiply above constants by change in sodium temperature to find shell temperature change to obtain shell H & C temperature given.

Sine Wave Movement—

Section	Length	ΔT Cooling $\gamma = 11(10^{-6})$	ΔL	ΔT Heating $\gamma = 11(10^{-6})$	ΔL
①	63	1095-1095	-	1095-1095	-
②	59	650-1149	-.324	1200-1149	+.0331
③	170	650-1054	-.755	1200-1054	+.2730
④	108	650-757	-.1271	1200-757	+.5260
⑤	9	650-718	-.0067	1200-718	+.0477
⑥	54	650-692	-.0249	1200-692	+.3018
			Σ -1.2377		Σ +1.1816

Shell Movement

Section	Length	ΔT Cooling $\gamma = 11(10^{-6})$	ΔL	ΔT Heating $\gamma = 11(10^{-6})$	ΔL
①	63	1100-1125	-.0173	1150-1125	+.0173
②	59	1172-1065	-.0695	1178-1172	+.0039
③	170	1099-873	-.4235	1150-1099	+.0955
④	108	915-782	-.1580	1058-915	+.1700
⑤	9	820-785	-.0035	898-820	+.0077
⑥	54	795-765	-.0178	878-795	+.0493
			Σ -.6896		Σ +.3437

Differential {
Expansion .8379" Tube Compressed
Contraction .5481" Tube Lengthened

Calculating max. stress in tubes

$$D = \frac{3 + 25}{2} = 14$$

$$\frac{2A}{L} = \frac{9.28}{48} = .1932 \qquad D/L = \frac{14}{48} = .0292 \text{ for max. tube OD}$$

$$\frac{ED_o}{2L^2} = \frac{(23.4 \times 10^6)\ (.5626)}{(2)\ (48)^2} = 2857$$

from curve A C' = 18

from curve B C'' = .818

Max bending stress = $S_B = (18)(.818)(2857)(.8379) = 35247$ psi max at inner row

PERMISSIBLE RATE OF STARTUP AND SHUTDOWN

The controlling factor in the allowable rate of startup and shutdown is the stresses developed in the inside surface of the thick walled upper head of the steam generator. These stresses will be compressive during heating and tensile during cooling. The accompanying tables may be summarized as follows:

	STRESSES	
Heating or Cooling Rate	3-1/4 Inch Thickness	7 Inch Thickness
400°F in 10 Minutes	58,000 psi	83,000 psi
400°F in 2 Hours	--	37,000 psi
1000°F in 5 Hours	10,800 psi	51,100 psi
1000°F in 10 Hours	--	24,600 psi

These figures do not take into full acount the effect of stress concentrations at surface irregularities. The allowable stress for 2500 cycles is 33,000 psi. It is recommended that the rate be kept to not more than 100°F per hour.

Startup & Shutdown Stresses
30 Mw Steam Generator

For any section - $N_{Bi}^{-1} \frac{12K}{hX}$ & $N_{Fo} = \frac{Dt}{X^2}$

where K = conductivity = 10.8×10^{-6}

D = Diffusivity = .0066

X = Thickness

t = Time

For a linear rise (or drop) in fluid temperature of 1000 F -

At a rate of 200F/Hr -

Thickness	Film Coeff. h	N_{Fo}	N_{Bi}^{-1}	$\frac{To-Tave}{T_f}$	To-Tave	Surface Stress psi
7"	50	2.42	.371	.135	135	51100
	4000	2.42	.0046	.135	135	51100
3-1/4"	50	11.23	.799	.0285	28.5	10800
	4000	11.23	.00999	.0285	28.5	10800
At a rate of 100F/Hr -						
7"	50	4.84	.371	.065	65	24600
	4000	4.84	.0046	.065	65	24600

For a linear rise (or drop) in fluid temperature of 400F -

At a rate of 200F/Hr

Thickness	Film Coeff. h	N_{Fo}	N_{Bi}^{-1}	$\frac{To-Tave}{F_f}$	To-Tave	Surface Stress psi
7"	50	.969	.371	.24	96	36400
	4000	.969	.0046	.31	124	47000
At a rate of 40F/min. (at end of change)						
7"	50	.0808	.425	.29	116	43100
	200	.0808	.106	.56	224	83200

For a 400 F change in 1 minute the maximum stress occurs at a time after the transient. Taking the transient as a sudden change & the stresses at the maximum -

7"	50	.108	.425	.36	144	53500
	200	.045	.106	.59	236	87700
3-1/4"	50	.190	.916	.225	90	33400
	200	.080	.229	.46	184	68300

NOZZLE REACTION STRESSES

The maximum stresses in the intermediate heat exchanger and steam genertor, computed by the Bijlaard Method, result from a circumferential moment of 40, 000 foot pounds. Adding in the circumferential pressure stress, the equivalent combined stress is 15, 920 psi in the intermediate heat exchanger, and 16, 270 psi in the steam generator. The allowable at 1200°F is 18, 000 psi.

Under the more likely assumption that the moment acts longitudinally, the computed stresses are considerably lower. Stresses due to four thousand pounds thrust are small.

NOZZLE LOCATION	COMPUTED MAXIMUM STRESS
Intermediate Heat Exchanger	
Hemispherical Nozzles	12, 870 psi
Shell Nozzles: -	
with longitudinal moment	9, 720 psi
with circumferential moment	15, 920 psi
Steam Generator	
with longitudinal moment	8, 980 psi
with circumferential moment	16, 270 psi

SHIELDING OF SHELL AND NOZZLE METAL, INTERMEDIATE HEAT EXCHANGER AND STEAM GENERATOR

The design of the nozzles in these 30 megawatt units is similar to that of the 70 megawatt unit described in APAE 78, Volume II, wherein the maximum transient was taken to be a 490°F change in fourteen seconds. For these units, the maximum change could be a 400°F change, and is taken to occur in the same fourteen seconds. This transient can occur only in the primary sodium inlet nozzle and must necessarily be less severe for any of the other nozzles, due to transit time through the units and heating or cooling which will occur during this transit time.

To carry the nozzle reactions, the metal adjacent to all shell nozzles is 1-1/8 inch thick, reducing to 3/8 inch in the intermediate heat exchanger, and 7/16 inch in the steam generator between nozzles.

Assuming an h value of 4000 for sodium-to-metal heat transfer and $E\alpha$ equal 255, the wetted surface stresses for shielded and unshielded plates 1 1/8 inch thick for various rates of temperature change are:

Temperature Change	Unshielded	Shielded
490°F in 14 seconds	123,200 psi	93,100 psi
400°F in 14 seconds	100,600 psi	76,000 psi
400°F in 40 seconds	87,500 psi	67,900 psi
300°F in 14 seconds	75,450 psi	57,000 psi

For a thinner section, the stresses are lower and the pressure stresses to be added to these are not large.

The tabular stress values for five hundred cycles at 1000°F is 51,000 psi. This represents half the total allowable range of stress at a given point. The 1/8 inch shielding is adequate to protect against a rapid drop in temperature from 1200°F to below 775°F in the primary inlet nozzle or the secondary exit nozzle of the intermediate heat exchanger, if, and provided, changes of the same magnitude but of opposite sign are not allowed to occur. The inherent margin of safety against failure from temperature excursions not too frequently repeated, in ductile materials, is such that a single reverse excursion would be very unlikely to cause difficulty, but this method of operation should be guarded against. To provide a margin of safety, 1/8 inch shields have been used for all metal thicker than 3/8 inch, although this is not theoretically needed in all cases.

STRESSES AT WELDS, TUBE-TO-TUBESHEETS

Extensive thermal cycling of 1/2 inch tubes has been conducted at ALCO PRODUCTS, INCORPORATED. The report covering this testing (APAE 81, Research and Development Reports for Sodium-to-Sodium Intermediate Heat Exchanger and Sodium-to-Water Steam Generator", Section 4) states there were no failures in stainless steel tubes. Also, computations have been made that show the rate of change in temperature of fluid through the tubes will be much lower than originally assumed. Risers are incorporated into the tubesheets of the IHX as much to facilitate welding as to reduce stresses.

LOAD ON SUPPORT BRACKETS

The intermediate heat exchanger and steam generator are assumed to rest on support brackets placed below the projecting portion of their lower tubesheets. No detailed design is given of the brackets, as this will depend upon the plant layout.

Computations are given for loads on the brackets based upon the worst possible combination of nozzle reactions. The actual forces will be much less, but at present are indeterminate.

As the most severe case, assume 4,000 pounds thrust and 40,000 foot pounds moment on each nozzle, all acting cumulatively.

For the intermediate heat exchanger:

The total moment is due to the 40,000 foot pounds moment on each nozzle, and the horizontal component of the 4,000 pounds thrust on each nozzle. Numerically, the moment is:

$$\begin{aligned} \text{Moment} &= 2000\,(278.75 + 30.125) + 2000\,(30.125) \\ &\quad + 4000\,(27.375) + 4000\,(27.375 + 224) \\ &\quad + 4\,(12)\,(40000) \\ &= 1793000 + 1920000 = 3713000 \text{ inch pounds.} \end{aligned}$$

The total load is made up of the weight of the vessel plus the vertical nozzle reactions. This value is -

$$27000 + 2000\,\sqrt{3}\,(2) =$$
$$= 27000 + 6928 = 33928\#$$

The 6928# load is not centrally located so the vertical reactions at A & B are not equal. The vertical reactions are -

$R_A = 13818\#$ $R_B = 20110\#$

The moment has reaction force of -

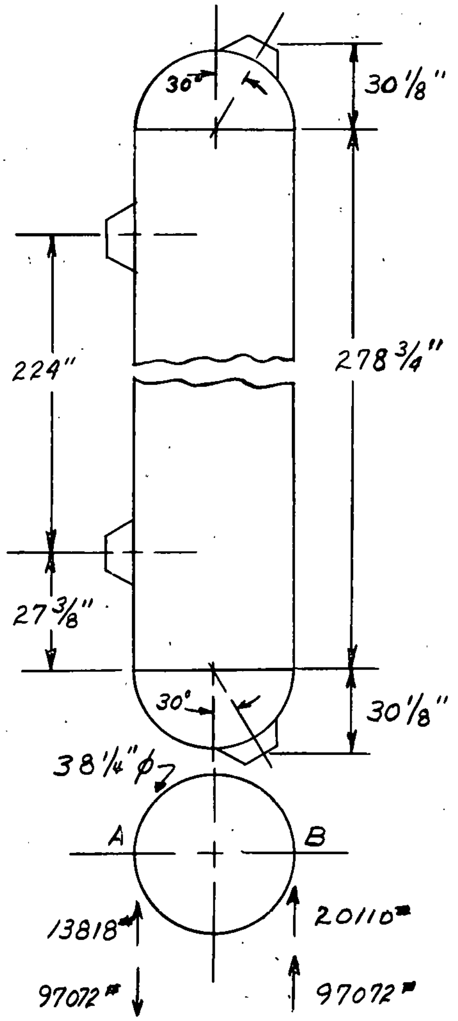
$$\frac{3713000}{38.25} = 97072\# \text{ @ A \& B}$$

one up & one down

For this worst case the total thrusts at A & B are -

Upward at B = 117182#
Downward at A = 83254#

This represents an impossible case as the moments & thrusts would tend to cancel each other. Also any slight movement would equalize out the thermal forces.



Stresses in the Shell:

For 3/8 inch shell $I = \frac{\pi R^3 t}{2} = \frac{\pi (18.375)^3 (.375)}{2} = 3655$

For 1-1/8 inch shell $I = \pi \frac{(19.125)^3}{2} \quad (1.125) = 12362$

Moment on 3/8 inch shell:

$$2000(278.75 + 30.125-50) + 4000 (224 + 27.375-50) +2 \times 40000 \times 12$$

$$M = 1233250 + 960000 = 2283250$$

Stress in 3/8 inch shell:

$$S = \frac{2283250 \times 18.375}{3655} = 11479 \text{ psi}$$

Moment on 1-1/8 inch shell:

$$2000 (278.75 + 30.125) + 4000 (224 + 27.375) + 3 \times 40000 \times 12$$

$$M = 1623250 + 1440000 = 3063250$$

Stress in 1-1/8 inch shell:

$$S = \frac{3063250 \times 19.125}{12362} = 4739 \text{ psi}$$

The stresses in the brackets must be calculated when designed.

For the Steam Generator

It is proposed to support the steam generator in the same manner as the IHX.

The total moment is due to the 40000 FT-LB moment on each nozzle and the horizontal component of the 4000 lb thrust on each nozzle.

Total Moment = 3276 (477.5 + 16)

+ 3276 (16) + 4000 (32.375)

+ 4000 (32.375 + 341) + (12)(40000) (4)

Moment = 5205900 In.-Lb.

The total vertical load is the weight of the vessel plus the vertical component of the thrust

Operating weight = 42000#
Vertical force = 4590#

The reactions to the vertical force are not equal. The reactions at A and B due to vessel weight and vertical forces combined are —

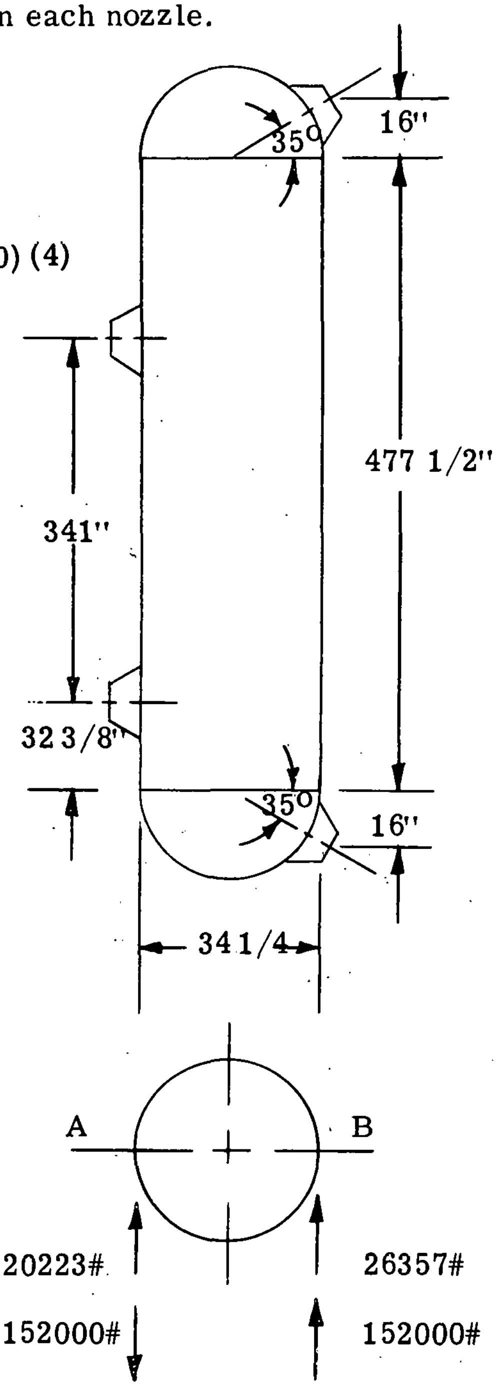
R_A = 20223# R_B = 26357#

The moment has reaction forces of

$$\frac{5205900}{34.25} \pm 152000\#$$

The total thrusts at A and B are

Upward at B = 178357#
Donward at A = 131777#



This represents an impossible case, as the moments and thrusts tend to balance each other. Also, any slight movement would equalize out the thermal forces.

Stresses in the Shell:

For the 7/16 inch shell $I = \frac{\pi R^3 T}{2} = \frac{\pi (16.4375)^3 (.4375)}{2} = 3052$

For 1 1/8 shell $I = \pi \frac{(17.125)^3 (1.125)}{2} = 8875$

Moment on 7/16 inch shell:

$$M = 3276(477.5 + 16 - 70.625) + (341 + 32.375 - 70.625)\ 4000$$

$$+ 2 \times 40000 \times 12$$

$$M = 3556000$$

Stress in 7/16 inch shell:

$$S = \frac{3556000}{3052} \times 16.4375 = 19150 \text{ psi}$$

Moment on 1-1/8" shell:

$$M = 3276\ (477.5 + 16) + (4000)(341 + 32.375) + 3 \times 40000 \times 12$$

$$M = 4550000$$

Stress in 1 1/8 inch shell:

$$S = \frac{4550000}{8875} \times 17.125 = 8780 \text{ psi}$$

These stresses are exaggerated because the vertical component of the nozzle thrust has been neglected, but actually operates to lessen the effect of the horizontal force in the above moment equations.

As in the intermediate heat exchanger, the bracket stresses can only be calculated when the brackets are designed.

INTERMEDIATE HEAT EXCHANGER TUBESHEET STRESSES

Stresses in the tubesheets and in the adjacent sections of shell and barrel in the intermediate heat exchanger have been studied for the following cases:

1. A pressure of 150 psi gauge in the secondary sodium circuit with zero pressure in the primary sodium circuit.

2. Thermal stresses due to the steady state $125^{O}F$ temperature differential between the primary and secondary circuits at the lower tubesheet.

3. Transient thermal stresses in the upper tubesheet resulting from a reactor scram with pumps operating at minimum speed as recommended. This has not been calculated directly, but can be taken as resulting in stresses approximately 75 per cent of those resulting from item 4 below. These stresses can be greatly reduced by slowing sodium pumps extending the transient upwards of five minutes or longer.

4. Transient thermal stresses resulting from a primary sodium pump stoppage with the secondary sodium flowing at full capacity. This has been taken as causing a $400^{O}F$ decrease in the secondary sodium outlet in forty seconds.

5. Transient thermal stresses caused by a rapid equalization in temperature throughout the primary sodium due to continued operation of the primary pump at full capacity after the secondary sodium pump has stopped and the reactor scrammed. This is treated as equivalent to a $150^{O}F$ rise in primary sodium at the lower tubesheet in fifteen seconds.

   Loss of control of the reactor, resulting in a rapid rise in primary sodium at the outlet $1200^{O}F$ would result in an increase in the stresses at the lower tubesheet by approximately fifty per cent.

Peak stresses resulting from these different conditions are summarized in Table 3.2. Comments are as follows:

Pressure Stresses (Item 1)

The normal working pressure in the heat exchanger will be well below the design values of 150 psig in the secondary and 100 psig in the primary. The high design pressures are used in order to allow relief gauges to be set at higher values. Direct membrane stresses under design pressure are below the allowable

TABLE 3.2
SUMMARY OF STRESSES
UPPER AND LOWER TUBESHEETS - HEAT EXCHANGER

	Type of Stress	150 Psi Barrel Side	Rapid[1] 400°F Drop Upper T's	Rapid[1] 150°F Rise Lower T's	Steady State 125$^{\circ}\Delta$T	Summation-Upper Tubesheet Maximum Stresses			Summation-Lower Tubesheet Maximum Stresses		
						Maximum Stress	Minimum Stress	Alternating Stress	Maximum Stress	Minimum Stress	Alternating Stress
Shell											
Inside Face	Long.	5500 C	45500 T	3200 T	2700 T	45500 T	5500 C	± 36800	5500 C	2700 T	± 9100
	Circ.	500 C	22200 C	14500 C	15000 C	22700 C	500 C	@ 950 F	15000 C	500 C	@ 1000 F
Outside Face	Long.	5500 T	45500 C	3200 C	2700 C	45500 C	5500 T	± 28800	5500 T	2700 C	± 15500
	Circ.	2800 T	52100 C	20000 C	18200 C	52100 C	2800 T	@ 1150 F	20000 C	2800 T	@ 950 F
Barrel											
Inside Face	Long.	10100 T	46900 T	16700 T	7300 T	57000 T	10100 T	± 34800	26800 T	7300 T	± 20000
	Circ.	1800 T	10800 C	2000 T	5900 C	10800 C	1800 T	@ 850 F	5900 C	1800 T	@ 800 F
Outside Face	Long.	7700 C	46900 C	16700 C	7300 C	54600 C	7700 C	± 31150	24400 C	7300 C	± 12200
	Circ.	3500 C	40300 C	8400 C	1500 C	43800 C	3500 C	@ 1100 F	11900 C	1500 C	@ 800 F
Tubesheet											
Outer Row											
Barrel Side	Rad.	1300 T	48900 T	7800 T	700 T	50200 T	1300 T	± 25100	9100 T	700 T	± 4550
	Circ.	2400 C	62400 T	7400 T	800 T	62400 T	2400 C	± 32400	7400 T	2400 C	± 4900
Shell Side	Rad.	1600 C	14900 T	10800 T	14500 T	14900 T	1600 C	± 8250	14500 T	1600 C	± 8050
	Circ.	2200 T	42000 T	17600 T	43100 T	44200 T	2200 T	± 23100	45300 T	2200 T	± 22650
Inner Row											
Barrel Side	Rad.	5400 C	40800 T	8500 T	700 T	40800 T	5400 C	± 23100	8500 T	5400 C	± 8950
	Circ.	4100 C	92800 T	7400 T	700 T	92800 T	4100 C	± 48450	7400 T	4100 C	± 5750
Shell Side	Rad.	5300 T	19400 C	4000 T	20000 T	19400 C	5300 T	± 12350	25300 T	4000 T	± 12650
	Circ.	4100 T	92800 T	32100 T	27300 T	96900 T	4100 T	± 48450	36200 T	4100 T	± 18100

NOTES: 1 - Transients include steady state differential. Stresses are additive to pressure stresses only.
2 - Radial and circumferential stresses in the tubesheet are not additive as they occur at different points.

of 6800 psi at 1200°F. Combined stresses, including discontinuity stresses, are the values given in the referenced table and are below allowable of 10200 psi at 1200°F. The combined stresses are not calculated for 100 psig shell pressure with zero barrel side pressure, because the minimum shell thickness is greater than the minimum barrel thickness and at a lower pressure will be less stressed than the thinner barrel at the higher pressure.

Thermal Stresses:

The maximum thermal stresses in the shell and barrel result from a 400°F drop in sodium temperature, which could occur on stoppage of primary sodium pump with the secondary sodium pump continuing to run at full speed, are in the tapered section connecting the upper tubesheet to the shell and barrel. Peak alternating stress values are computed as called for by the Navy Code. The allowable for 500 cycles at 1200°F is 39000 psi and at 1000°F is 51000 psi.

Shell	Alternating Stress
Inside Face	36, 800 psi
Outside Face	28, 800 psi
Barrel	
Inside Face	34, 800 psi
Outside Face	31, 150 psi

In computing these peak alternating stress values, the unlikely, but possible, assumption was made that the 400°F drop in temperature occured at a moment when the barrel pressure had dropped to zero, and was followed by a moment when full barrel pressure was accompanied by zero shell pressure with thermal stresses absent. This combination results in stresses below the allowable. At true metal temperature, the allowable is higher.

Note that in the shell and barrel longitudinal and circumferential stresses occur at the same point and so by Navy Code must be combined. In the tubesheet, the peak radial and circumferential stresses occur in different ligaments and need not be combined. In the upper tubesheet, peak thermal stresses in the ligaments occur when ligaments have dropped below 800°F and the allowable alternating stress equals 61, 000 psi. Tube sheet stresses are well below this figure.

Peak computed alternating stresses in the lower tubesheet are all relatively low. Warning should be given that if the secondary sodium pump is stopped and the reactor is allowed to go out of control, with the sodium temperatures throughout the entire lengths of the reactor and intermediate heat exchanger rising to 1200°F, the thermal stresses would rise to undesirable but apparently not dangerous values.

In computing these stresses, each tubesheet has been treated as a composite disk, consisting of a central core without tube holes, surrounded by an annular area with tube holes 1/2 inch diameter on 1 inch circular pitch, in turn attached to a solid ring. The shell and the barrel are welded to tapered sections 1 1/2 inches long, which form part of this ring. These tapered sections reduce the secondary stresses in the shell and barrel, but complicate stress calculations, since step by step numerical integration methods are needed to deal with the effect of the tapers upon stresses.

STEAM GENERATOR TUBESHEET STRESSES

Stresses in the lower tubesheet and adjacent sections of the shell and barrel of the steam generator have been studied for the following cases:

1. A pressure of 2500 psi on the steam-water side, with zero pressure on the secondary sodium side.

2. Thermal stresses due to a steady state temperature differential of 175°F between the incoming feedwater and the exiting sodium.

3. Transient thermal stresses due to a stoppage of feedwater flow with primary and secondary sodium flow continuing at full capacity. This has been treated as causing the exiting sodium temperature to rise to 1175°F in forty seconds.

4. One possible situation has been treated as outside the requirements of the specifications. A sudden relief of pressure on the steam side of the steam generator due to a rupture of the steam line could result in steam entering the upper head of the steam generator to drop to 600°F, and lower as the feedwater temperature drops below 600°F. A drop of more than 450°F would result in very high stresses in this upper head.

Pressure Stresses (Item 1)

The normal working pressure of the steam generator will be approximately 2200 psi. The higher design pressure is to allow relief valve settings in excess of operating without endangering the integrity of the unit. Direct membrane stresses are below allowable at the design temperatures of the unit, 1075°F in the upper head and 1200°F elsewhere. The values given in Table 3.3, include stresses due to discontinuites and are below allowable, except at the innermost ligament on the shell side of the upper tubesheet which exceeds the allowable by 3 1/2 per cent. This is not important as at this same point on the other side of the tubesheet the direction of the stress is revered, thus, the high stress decreases rapidly and is highly localized.

Thermal Stresses

The maximum thermal stress shown resulting from the 400°F temperature change, which occurs in the event of a feedwater flow stoppage and continuation of sodium flow, is at the junction of the tubesheet and shell and has a range of plus or minus 37600 against an allowable at 950°F of plus or minus 53500 for five hundred cycles. A full summary of the stresses is given in Table 3.3.

In computing thermal stresses, the shell and barrel walls were assumed straight. Because the stresses calculated were below allowable, there was no need to refine the calculations to account for the tapers. Stress concentrations at the junction of the tubesheet and shell or barrel will increase the stress beyond that shown, but inclusion of the taper will reduce the values, so that the final stresses are below allowable.

If the 400°F rise is allowed to continue, the tubesheet will continue to rise in temperature toward 1175°F. The barrel will continue to remain cool and maximum stress will occur in the barrel which may be very close to the allowable. For this reason, the exit sodium temperature should not be allowed to remain at 1175°F any longer than necessary.

STEAM GENERATOR TUBING

The steam generator tubes are stainless steel with an Inconel liner which is to be metallurgically bonded. With a good metallurgical bond, the differential expansion of the stainless and Inconel cannot take place, so that no gap will exist between the two metals.

STEAM OUTLET NOZZLE

The steam outlet nozzle on the upper head of the steam generator is similar in design to that of the 70 megawatt unit, as described in APAE No. 78, Volume II. For the worst thermal transient condition, the stresses in the present unit will not exceed those specified for the 70 megawatt unit which were well within allowable values.

TABLE 3.3
SUMMARY OF STRESSES
LOWER TUBE SHEET - STEAM GENERATOR

					Maximum Stresses		
Point	Type of Stress	2500 psi Barrel Side	Rapid [1] 400F Rise	Steady State 175FΔT	Maximum Stress	Minimum Stress	Alternating Stress
Shell							
Inside Face	Long.	8200C	27700T	12600T	27700T	8200C	±37600
	Circ.	700T	39600C	5100C	39600C	700T	@ 950
Outside Face	Long.	8200T	27700C	12600C	27700C	8200T	±36150
	Circ.	5600T	64100C	31600C	64100C	5600T	@ 950
Barrel							
Inside Face	Long.	17100T	37300T	11200T	54400T	11200T	±27200
	Circ.	3300T	21700T	20700T	25000T	3300T	@ 700
Outside Face	Long.	6000C	37300C	11200C	43300C	6000C	±21650
	Circ.	3300C	4200C	15400C	18700C	3300C	@ 700
Tube Sheet							
Outer Row							
Barrel Side	Rad.	11700T	5200T	1400T	16900T	1400T	±8450
	Circ.	1600C	4700T	1200T	6300T	1200T	±3150
Shell Side	Rad.	2700C	17400T	16400T	17400T	2700C	±10050
	Circ.	11000T	26000T	25000T	37000T	11000T	±18500
Inner Row							
Barrel Side	Rad.	8500C	7000T	1800T	15500T	1800T	±7750
	Circ.	12300C	4500T	1100T	12300C	4500T	±8400
Shell Side	Rad.	14000T	14400T	12600T	28400T	12600T	±14200
	Circ.	17600T	32600T	36600T	53800T	17600T	±26900

Notes: 1 - Transient includes steady state

MANHOLE COVER STRESSES

The maximum bending stress in manhole cover due to internal pressure occurs on the center line of the cover at the inner and outer faces and is 10575 psi. The maximum transient thermal stress would result from a rapid drop of steam temperature from 1050°F to 650°F, followed by a dwell. The maximum stress is calculated to be 46258 psi tension on the lower face, and 26714 psi tension on the upper face. With the pressure stress the maximum combined stress is 37289 psi against an allowable alternating stress of plus or minus 49500 psi.

During start up, thermal stresses will be in the opposite direction, and will approach 25000 psi, to which is added the pressure stress of 10575 psi. The corresponding allowable alternating stress at design temperature of 1075°F for one thousand start up cycles is plus or minus 40000 psi.

By the Navy Code, this combination of stresses is within the allowable. Detailed calculations are given in the Appendix.

STRESSES IN UPPER HEAD OF STEAM GENERATOR

High stresses occur in the upper head of the steam generator due to thermal transients. However, the tubesheet is thicker than any other part of the head and is thus the controlling factor. Stresses in the tubesheet for various conditions are discussed elsewhere.

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SECTION 4

STRESS ANALYSIS APPENDIX

STRUCTURAL DESIGN BASIS 4-A

Physical Properties of SS316 & Sodium

The following tabulation of data were extracted from various manufacturer's literature and technical publications. Values may be the results of one test or the average of several tests. Manufacturing variables, chemistry, grain size, heat treatment, and other conditions that would influence the test results are not known, and these data should, therefore, be used with caution.

A2

TYPE 316 SS - DENSITY APPROX. 0.29 #/in^3 AT RT

Temperature °F	70	600	800	900	1000	1100	1200		Ref.
High Temp. Tensile Strength 1,000 PSI	85.5	-	71.7	71	68.7	66.5 *	56.0	* 1110°F	1
	103.9	-	-	-	73.5	69.1 *	60.5		2
	75 min.	-	74.3	72.1	70.8	63.8 *	54.4		3
	82.5	-	71.5	70.0	67.5	63.0 *	56.5		5
	76	-	71.7	71	69.2	66.5 *	57.7		7
High Temp. Yield Strength 0.2% - 1,000 PSI	38.5	-	23.0	22.0	21.2	20.5	20.0		1
	36.8	-	-	-	20.3	19.6	20.5		2
	31	-	23	22	21	20.5	-		7
Thermal Expansion (Mean) in/in/°F X 10^{-6} Room Temp. to Indicated	-	9.75	10.6	-	10.3	-	10.5		1
	-	-	9.86	-	10.7	-	10.29		2
	-	-	-	-	-	-	10.80		3
	-	9.0	-	-	9.7	-	10.3		5
	-	-	10.2	-	10.5	-	10.8	* B&W	6
	-	9.37	9.81	-	-	-	10.28		8
Poisson's Ratio	.284	-	.312	.316	.320	.324	.328	*347 SS	3*
Modulus of Elasticity 1x10^6 PSI	28.9	-	24.1	23.4	22.8	22	21.4	*347 SS	2*
	28	-	24	-	22	-	21		6
	-	-	-	-	23.4	22.8	22.4		7
Thermal Conductivity BTU/Sq.Ft./in/Hr./°F	-	-	-	149 *	-	-	-	* 932°F	4
	-	-	-	145 *	147	-	-		5
	-	-	-	-	164	-	175	(18-8) ←	6
	-	-	-	-	141.6	-	151.2		8

TYPE 316 SS (Contd.)

Hours	100	1,000	10,000	100,000	Ref.
Stress Rupture - 1200°F - 1000 PSI	-	24.7	18.2	-	1
	31	25.0	18.0	12.5	2
	-	25.0	-	11.0	5
	-	25	18	16	6
	-	24	20	-	7
Stress For 1% Creep - 1200°F - 1000 PSI	-	-	12.7	6.6	1
	-	-	8.2	5.0	3
	-	-	11.0	6.0	5
	-	-	14.0	6.0	6
	-	-	12	-	7

List of References

1. "Steels for elevated Temperature Service", U.S. Steel Corp., 1952.
2. "Properties of carbon and Alloy Seamless Steel Tubing for High Temperature and Pressure Service", The B & W Tube Co., Technical Bulletin No. 6-E, 1948.
3. "Digest of Steels for High Temperature Service", 6th Ed., 1957, The Timken Roller Bearing Co.
4. "Stainless Steels", Allegheny-Ludlum Steel Corp.
5. "Metals Handbook", 1948 and 1954 supplement.
6. "Metal Data", S.L. Hoyt, 1952.
7. "The Reactor Handbook", Vol. 3, Sect. 1, General Properties of Materials, AEC, 1955.
8. ASTM Special Technical Publication No. 227.
9. ASTM Special Technical Publication No. 100.

MATERIAL DATA AT ELEVATED TEMPERATURES FOR LIQUID SODIUM & 316 SST ALLOY ARE GIVEN ON THE ACCOMPANYING CHARTS.

THERMAL DIFFUSIVITY

$$\alpha = K / \omega C_p$$

316 SST

AT $K = 12.1$ BTU/HR FT °F
$\omega = .29$ #/IN^3
$C_p = .16$ BTU/# °F

$$\alpha = \frac{12.1}{.29 \times 1728 \times .16} = .1509 \ FT^2/HR$$

$$\alpha = .1509 \times \frac{144}{3600} = .006 \ \frac{IN^2}{SEC}$$

THIS IS APPROXIMATELY THE VALUE AT 890 F

A5

Typical values of film coefficient h for heat flow between liquid sodium and 316 stainless steel

For temperature change from 1140°F to 650°F in 10" d. nozzle with mean velocity of sodium $= 18.8 \frac{ft}{sec} = 67,680 \frac{ft}{hr}$

Compute the Peclot Number $N_{Pe} = \frac{d u w C_p}{k}$

Calculate values of the Nusselt Number from

$$N_{Nu} = 7 + .025 N_{Pe}^{.8} \quad \text{(theoritical value within 10\%)}$$

or

$$N_{Nu} = .625 N_{Pe}^{.4} \quad \text{(average of test values)}$$

Then from the definition of the Nusselt Number

$$h = N_{Nu} \frac{K}{d}$$

Sodium Temp. °F	w $\frac{lb}{ft^3}$	C_p $\frac{Btu}{lb\,°F}$ From Curves	K $\frac{Btu}{hr\,ft\,°F}$	Péclot No. $N_{Pe} = \frac{duwC_p}{K}$ $\left(du = 56400 \frac{ft^2}{hr}\right)$	Nusselt No. From Formula	$h = N_{Nu}\frac{K}{d}$ $\frac{Btu}{hr\,ft^2\,°F}$
1140	50.0	.2991	36.3	23236	Theor 84.78	3693
					Ave 34.86	1519
895	52.1	.3016	39.2	22608	Theor 83.10	3909
					Ave 34.48	1622
650	54.2	.3083	42.6	22123	Theor 81.78	4181
					Ave 34.18	1747
					Average	2778

For same temperature change in tubes $d = .527$ in $= .043916$ ft with mean velocity of sodium $u = 3.323 \frac{ft}{sec} = 11,763 \frac{ft}{hr}$

Sodium Temp °F	w $\frac{lb}{ft^3}$	C_p $\frac{Btu}{lb\,°F}$ From Curves	K $\frac{Btu}{hr\,ft\,°F}$	Peclot No. $N_{Pe} = \frac{duwC_p}{K}$ $\left(du = 515.38 \frac{ft^2}{hr}\right)$	Nusselt No. From Formula	$h = N_{Nu}\frac{K}{d}$ $\frac{Btu}{hr\,ft^2\,°F}$
1140	50.0	.2991	36.3	216.5	Theor 8.84	7307
					Ave 5.37	4439
89.5	52.1	.3016	39.2	210.6	Theor 8.80	7855
					Ave 5.31	4740
650	54.2	.3083	42.6	206.1	Theor 8.78	8517
					Ave 5.27	5112
					Average	6330

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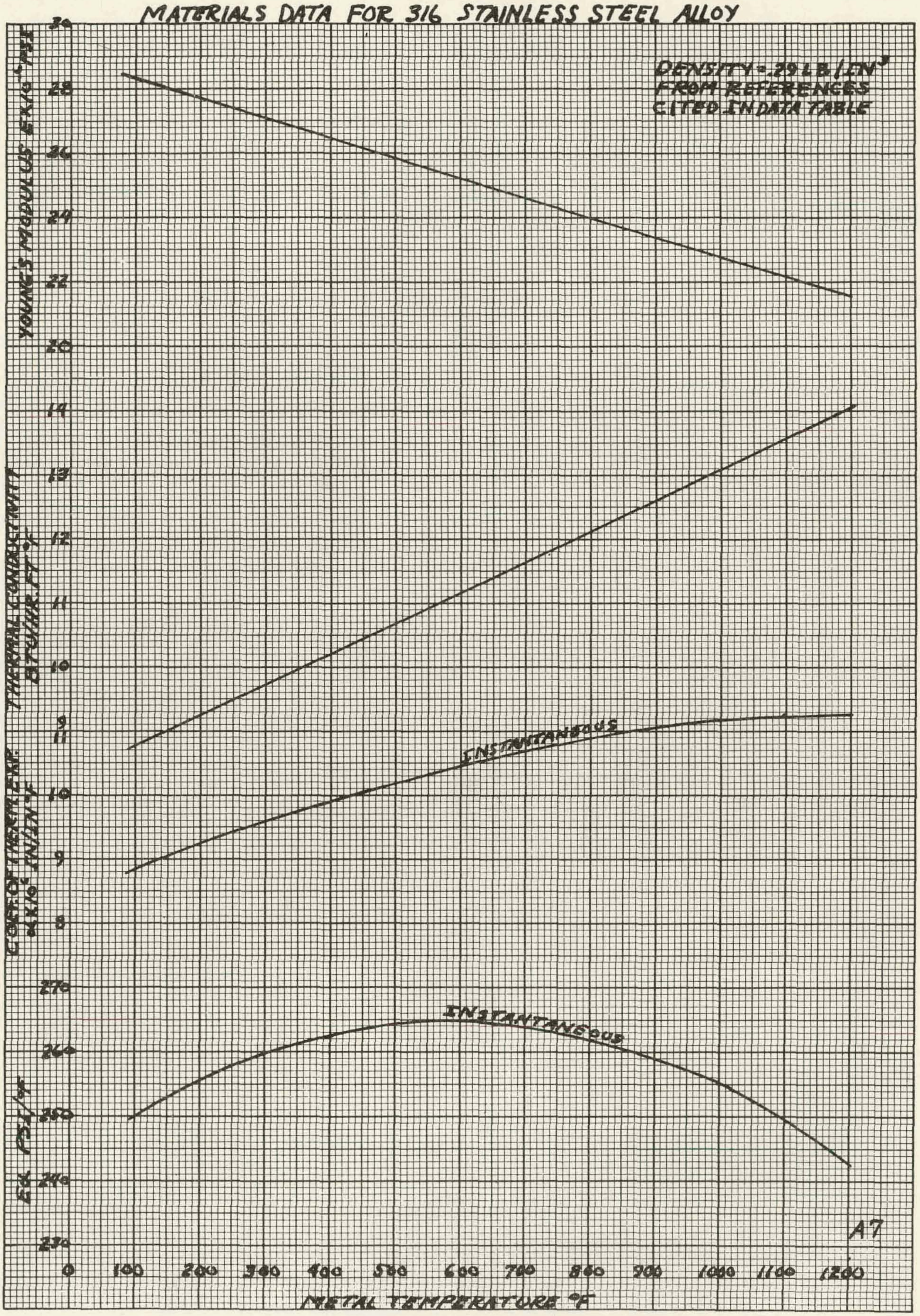
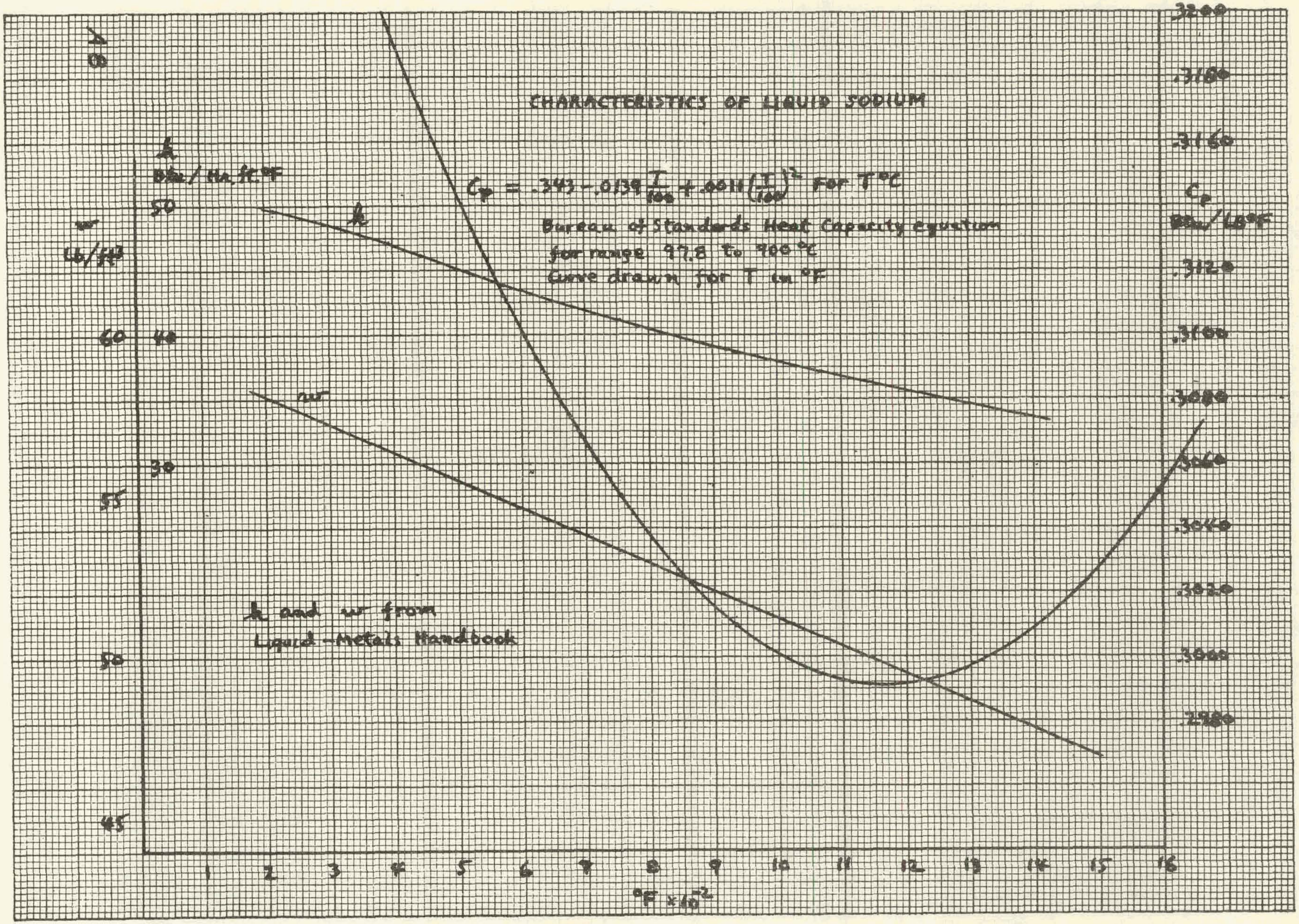
MATERIALS DATA FOR 316 STAINLESS STEEL ALLOY




CHARACTERISTICS OF LIQUID SODIUM
$C_p = .343 - .0139\frac{T}{100} + .0011\left(\frac{T}{100}\right)^2$ for T°C
Bureau of Standards Heat Capacity equation
for range 97.8 to 900 °C
Curve drawn for T in °F
k and w from
Liquid-Metals Handbook
k
Btu/Hr.ft.°F
w
Lb/ft³
C_p
Btu/LB°F
k
w
65
60
55
50
45
50
40
30
.3200
.3180
.3160
.3120
.3100
.3080
.3060
.3040
.3020
.3000
.2980
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
°F × 10⁻²

BASIC EQUATIONS

Tube sheet with central solid Core, reinforced by channel and shell walls – Horvay Method.

The Horvay Method takes into account stress concentrations in the ligaments.

A9

Circular Disk – Uniform Load: q (psi.)

After Timoshenko: $\phi = -\frac{qx^3}{16D} + \frac{C_1 x}{2} + \frac{C_2}{x}$ ---- page 95 - (92) ------ Ⓐ

(Strength of Materials – – Part II. – Third Edition)

$M_1 = D\left(\frac{d\phi}{dx} + \mu \frac{\phi}{x}\right)$ ------ page 93 – (88)

$M_2 = D\left(\frac{\phi}{x} + \mu \frac{d\phi}{dx}\right)$ ------ page 93 – (89)

$$\frac{d\phi}{dx} = -\frac{3qx^2}{16D} + \frac{C_1}{2} - \frac{C_2}{x^2}$$

therefore: $M_1 = D\left[-\frac{3qx^2}{16D} + \frac{C_1}{2} - \frac{C_2}{x^2} + \mu\left(-\frac{qx^2}{16D} + \frac{C_1}{2} + \frac{C_2}{x^2}\right)\right] =$

$$= -\frac{3qx^2}{16} + \frac{C_1 D}{2} - \frac{C_2 D}{x^2} - \frac{\mu q x^2}{16} + \frac{D\mu C_1}{2} + \frac{D\mu C_2}{x^2} =$$

$$M_1 = -\frac{(3+\mu)}{16} qx^2 + \frac{(1+\mu)}{2} DC_1 - (1-\mu)\frac{DC_2}{x^2}$$ -------- Ⓑ

$$M_2 = D\left[-\frac{qx^2}{16D} + \frac{C_1}{2} + \frac{C_2}{x^2} + \mu\left(-\frac{3qx^2}{16D} + \frac{C_1}{2} - \frac{C_2}{x^2}\right)\right] =$$

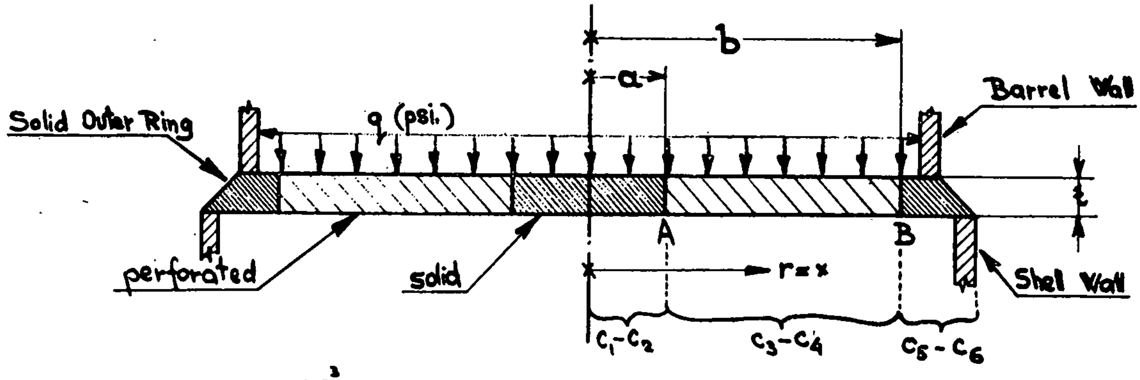
$$= -\frac{qx^2}{16} + \frac{C_1 D}{2} + \frac{C_2 D}{x^2} - \frac{3\mu q x^2}{16} + \frac{D\mu C_1}{2} - \frac{D\mu C_2}{x^2} =$$

$$M_2 = -\frac{(1+3\mu)}{16} qx^2 + \frac{(1+\mu)}{2} DC_1 + (1-\mu)\frac{DC_2}{x^2}$$ -------- Ⓒ

For a Disk with solid center, radius "a" and annular perforated area, radius "a" to "b"; equations Ⓐ Ⓑ and Ⓒ apply to area radius "0" to "a", constant "C_2" becomes zero.

For annular area μ becomes μ^* and D becomes D^* (Horvay's notation)

A 10



(1) $$\phi_A = -\frac{qa^3}{16D} + \frac{C_1 a}{2}$$

(2) $$\phi_A = -\frac{qa^3}{16D^*} + \frac{C_3 a}{2} + \frac{C_4}{a}$$

(3) $$\phi_B = -\frac{qb^3}{16D^*} + \frac{C_3 b}{2} + \frac{C_4}{b}$$

(4) $$M_{1A} = -\frac{3.3}{16}\, qa^2 + 0.65\ DC_1$$

(5) $$M_{1A} = \frac{(3+\mu^*)}{16} qa^2 + \frac{(1+\mu^*)}{2} D^* C_3 - (1-\mu^*)\frac{D^* C_4}{a^2}$$

(6) $$M_{1B} = -\frac{(3+\mu^*)}{16} qb^2 + \frac{(1+\mu^*)}{2} D^* C_3 - (1-\mu^*)\frac{D^* C_4}{b^2}$$

From properties of outside solid ring:

(7) $$M_{1B} = C_5\,\phi_B + C_6$$

Using Timoshenko equation – page 139 – (126):

$$\phi_B = \frac{M_t R^2}{E I_x}$$; where M_t = Ext. Twisting Moment Loading the Outer Ring
R = Radius of Centroid of Outer Ring
E = Modulus of Elasticity
I_x = Moment of Inertia of Outer Ring

$$D = \frac{Et^3}{12(1-\mu^2)}$$; where $\mu = 0.3$

Beam on an Elastic Foundation.

Basic Equations

$$y = e^{-\beta x}(C \cos \beta x + D \sin \beta x) \qquad (1)$$

$$\frac{dy}{dx} = -\beta e^{-\beta x}\left[(C-D)\cos \beta x + (C+D)\sin \beta x\right] \qquad (2)$$

$$\frac{d^2y}{dx^2} = \frac{M}{EI} = \beta^2 e^{-\beta x}\left[-2D \cos \beta x + 2C \sin \beta x\right] \qquad (3)$$

$$\frac{d^3y}{dx^3} = \frac{V}{EI} = -\beta^3 e^{-\beta x}\left[(2C-2D)\sin \beta x - (2C+2D)\cos \beta x\right] \qquad (4)$$

$$\frac{d^4y}{dx^4} = \frac{q}{EI} = -\frac{k}{EI}y = -4\beta^4 y \qquad (5)$$

For a tube – stiffness factor $k = \frac{Et}{R^2}$

$$\beta = \sqrt[4]{\frac{k}{4EI}} \qquad \text{where } I = \frac{t^3}{12(1-\mu)} = \frac{t^3}{10.92}$$

$$\beta = \frac{1.285}{\sqrt{Rt}} \qquad (6)$$

$$2EI\beta^2 = 2E\frac{t^3}{10.92} \cdot \frac{(1.285)^2}{Rt} = 0.3025\frac{Et^2}{R} \qquad (7)$$

R = mean radius. t = wall thickness.

At $x = 0$, these equations become:–

$$y_0 = C \qquad (8)$$

$$\theta_0 = (D-C)\beta \qquad (9)$$

A 12 $$M_0 = -2EI\beta^2 D \qquad (10)$$

$$V_0 = 2(C+D)EI\beta^3 \qquad (11)$$

Rearranging eq. (8) to (11):-

$$M_o = -2EI\beta^2\left(y_o + \frac{\theta_o}{\beta}\right) = -.3025\frac{Et^2}{R}\left(y_o + \frac{\theta_o}{\beta}\right) \quad (12)$$

$$V_o = 2EI\beta^2(2\beta y_o + \theta_o) = .3025\frac{Et^2}{R}(2y_o\beta + \theta_o) \quad (13)$$

$$y_o = \frac{M_o + V_o/\beta}{2EI\beta^2} \quad (14)$$

$$\theta_o = -\frac{2\beta M_o + V_o}{2EI\beta^2} \quad (15)$$

Bending Stress at origin $= \frac{M_o c}{I}$

$$= \frac{1.815E}{R}\left(y_o + \frac{\theta_o}{\beta}\right) \quad (16)$$

At a distance x from the origin, using Hetenyi's Tables - for A_x, B_x, C_x and D_x:-

$$M = A_x M_o + B_x\frac{V_o}{\beta} \quad (17)$$

$$V = -2B_x\beta M_o + C_x V_o \quad (18)$$

Also. $$M = -2EI\beta^2\left[C_x y_o + D_x\frac{\theta_o}{\beta}\right] \quad (19)$$

$$V = 2EI\beta^2\left[2\beta D_x y_o + A_x\theta_o\right] \quad (20)$$

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DIFFERENTIAL EXPANSION
BETWEEN SHELL & TUBES 4-B

B1

Differential Expansion between Shell and Tubes

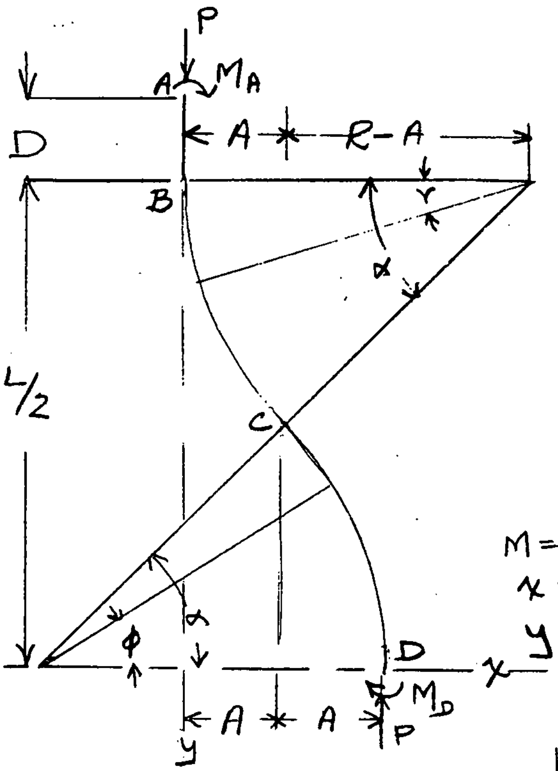
To reduce the stresses in the tubes and shell of a fixed tube sheet heat exchanger under differential expansions, the tubes will have part of their length prebent to a sine wave shape or an approximation to that shape, composed of a succession of circular arcs.

Between the upper end of the wave and the upper tube sheet and between the lower end of the tube and the nearest baffle, there will ordinarily be sections of straight tube, which influence the behavior of the wave. The accompanying charts enable these to be taken into account when computing maximum bending stresses and also maximum lateral movement at the center of the wave. Direct tensile or compressive forces in the tube add 2 to 3% to the bending stresses.

Results of extensive tests on sine wave tubes at room temperature and at 1150-1200°F are given in a separate report.

B2

Sine Wave Tube Derivation.

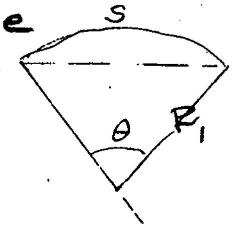


$$M = M_A \qquad x = 0 \qquad y = y$$

$$M = M_A - PR(1-\cos\gamma)$$
$$x = R(1-\cos\gamma)$$
$$y = \frac{L}{2} - R\sin\gamma$$

$$M = M_A - 2PA - PR(1-\cos\phi)$$
$$x = 2A - R(1-\cos\phi)$$
$$y = R\sin\phi$$

Cross-Curvature



$$L = 4R\sin\alpha$$
$$A = R_1\sin\theta/2$$
$$R = \frac{A}{2} + \frac{L^2}{32A}$$
$$\alpha = \sin^{-1}\frac{L}{4R} = \cos^{-1}\left(1-\frac{A}{R}\right)$$
$$S = R_1\theta$$

From symmetry - slope at D remains vertical.

Whence $\int_A^D M\,dL = \int_0^D M_A\,dL + \int_0^\alpha [M_A - PR(1-\cos\gamma)]R\,d\gamma$

$$+\int_0^\alpha [M_A - 2PA - PR(1-\cos\alpha)]\,R\,d\phi$$

$$= M_A D + 2M_A R\alpha - 2PAR\alpha = 0 \qquad B3$$

$$M_A = \frac{2PAR\alpha}{D+2R\alpha} = PA \times \frac{\text{Length } BCD}{\text{Length } ABCD} \qquad (1)$$

Using Moment Area Method:-

$$\Delta y = \int_A^D \frac{Mx\,dL}{EI} = \int_A^B \frac{Mx\,dL}{EI} + \int_B^C \frac{Mx\,dL}{EI} + \int_C^D \frac{Mx\,dL}{EI}$$

But from A to B, $x = 0$ $\quad \int_A^B \frac{Mx\,dL}{EI} = 0$ (a)

from B to C:-

$$\int_B^C \frac{Mx\,dL}{EI} = \frac{1}{EI}\int_0^\alpha \left[M_A - PR(1-\cos\gamma)\right]\left[R(1-\cos\gamma)\right] R\,d\gamma$$

$$= \frac{M_A}{EI}\left(R^2\alpha - R^2\sin\alpha\right) + \frac{PR^3}{EI}\left(-\frac{3\alpha}{2} + 2\sin\alpha - \frac{\sin 2\alpha}{4}\right) \quad \text{(b)}$$

from C to D

$$\int_C^D \frac{Mx\,dL}{EI} = \frac{1}{EI}\int_0^\alpha \left[M_A - 2PA + PR(1-\cos\phi)\right]\left[2A - R(1-\cos\phi)\right] R\,d\phi$$

$$= \frac{M_A}{EI}\left(2AR\alpha - R^2\alpha + R^2\sin\alpha\right) \quad \text{(c)}$$

$$+ \frac{PR}{EI}\left[4AR\alpha - 4AR\sin\alpha - 4A^2\alpha - \frac{3R^2\alpha}{2} + 2R^2\sin\alpha - \frac{R^2}{4}\sin 2\alpha\right]$$

Combining (a) (b) and (c)

$$\Delta y = \frac{M_A}{EI}(2AR\alpha) + \frac{P}{EI}\left[-4R^2(R-A)(\alpha - \sin\alpha) + \frac{R^3}{2}(2\alpha - \sin 2\alpha) - 4A^2R\alpha\right] \quad (2)$$

$$\Delta x = \int_A^D \frac{My\,dL}{EI} = \int_A^B \frac{My\,dL}{EI} + \int_B^C \frac{My\,dL}{EI} + \int_C^D \frac{My\,dL}{EI}$$

$$\int_A^B \frac{My\,dL}{EI} = \int_{L/2}^{D+L/2} \frac{M_A\,y\,dy}{EI} = \frac{M_A}{EI}\left[\frac{LD}{2} + \frac{D^2}{2}\right] \quad \text{(d)}$$

$$\int_B^C \frac{My\,dL}{EI} = \frac{1}{EI}\int_0^\alpha \left[M_A - PR(1-\cos\gamma)\right]\left[\frac{L}{2} - R\sin\gamma\right] R\,d\gamma$$

$$= \frac{M_A}{EI}\left[\frac{L\alpha R}{2} + R^2\cos\alpha - R^2\right] \qquad (e)$$

$$+ \frac{P}{EI}\left[-\frac{R^2L\alpha}{2} - R^3\cos\alpha + \frac{3R^3}{4} + \frac{R^2L}{2}\sin\alpha + \frac{R^3}{4}\cos 2\alpha\right]$$

$$\int_C^D \frac{My\,dL}{EI} = \frac{1}{EI}\int_0^\alpha \left[M_A - 2PA + PR - PR\cos\phi\right] R^2\sin\phi\, d\phi$$

$$= \frac{M}{EI}\left[R^2 - R^2\cos\alpha\right] + \frac{P}{EI}\left[R^2(R-2A)(1-\cos\alpha) - \frac{R^3}{4}(1-\cos 2\alpha)\right] \qquad (f)$$

Combining (d)(e) and (f):—

$$\Delta x = \frac{M}{2EI}\left[LD + D^2 + RL\alpha\right] + \qquad (3)$$

$$\frac{P}{EI}\left[-\frac{R^2L}{2}(\alpha - \sin\alpha) + 2R^2(R-A)(1-\cos\alpha) - \frac{R^3}{2}(1-\cos 2\alpha)\right]$$

Equations (1), (2) and (3) can be rearranged to dimensionless constants. Let $A = a$

$$L = C_1 a \qquad D = C_2 a \qquad R = C_3 a = \left(\frac{1}{2} + \frac{C_1^2}{32}\right)a$$

$$M_A = \frac{2PaR\alpha}{D+2R\alpha} = Pa\frac{2C_3\alpha}{C_2 + 2C_3\alpha} = C_4\,Pa$$

Whence $C_4 = \dfrac{\text{Length BCD}}{\text{Length ABCD}}$

Max moment, at D, $= (2 - C_4)Pa$ (4)

Substituting in (2) and rearranging:—

$$\Delta y = \frac{Pa^3}{EI}\left[2\alpha C_3C_4 + C_3\left[\frac{C_3^2}{2}(2\alpha - \sin 2\alpha) - 4C_3(C_3 - 1)(\alpha - \sin\alpha) - 4\alpha\right]\right] \qquad \text{B5}\ (5)$$

Total Movement Vertically $= 2\Delta y$.

Substituting in (3) and rearranging:-

$$\Delta x = P\alpha^3\left[\frac{C_4}{2}\left(C_1C_2+C_2^2+C_1C_3\alpha\right)+C_3\left[2C_3(C_3-1)(1-\cos\alpha)-\frac{C_3^2}{2}(1-\cos 2\alpha)\right.\right.$$
$$\left.\left. -\frac{C_1C_3}{2}(\alpha-\sin\alpha)\right]\right] \qquad (6)$$

Let $C_3\left[\frac{C_3^2}{2}(2\alpha-\sin 2\alpha)-4C_3(C_3-1)(\alpha-\sin\alpha)-4\alpha\right] = C_5$

$$C_3\left[2C_3(C_3-1)(1-\cos\alpha)-\frac{C_3^2}{2}(1-\cos 2\alpha)-\frac{C_1C_3}{2}(\alpha-\sin\alpha)\right] = C_6$$

Constants C_2 and C_4 depend of distance from ends of the sine wave to the nearest baffle. The other constants, including C_5 and C_6, depend only on the dimensions of the sinewave itself.

Rearranging:-

Max moment, per inch of elongation = $\frac{M_{max}}{2\Delta y}$

$$= \frac{(2-C_4)C_1^2}{2(2\alpha C_3C_4+C_5)}\;\frac{EI}{L^2}$$

Max Stress:= $\frac{(2-C_4)C_1^2}{2(2\alpha C_3C_4+C_5)}\;\frac{Ed_0}{2L^2}\Delta L$ (7)

Lateral Movement per inch of elongation = $\frac{\Delta x}{2\Delta y}$

$$= \frac{C_4\left(C_1C_2+C_2^2+C_1C_3\alpha\right)+2C_6}{4(2\alpha C_3C_4+C_5)} \qquad (8)$$

For $D=0$, $C_4=1$ and $C_2=0$.

B6 Coefficients in (7) and (8) can be expressed by a factor depending on sine wave size, multiplied by a factor dependent on D/L only.

Sine Wave Tube Graphs.

Let:-

E = Mod. of Elasticity
d_o = o.d. of tube = $2R_o$
L = Length of wave
$2A$ = Offset at mid-point of wave, measured at right angles to tube.
D = Distance from end of wave to nearest baffle or tube sheet. If different at the two ends, use mean value

$\Delta L = 2\Delta x$ = Up or down differential movement, tube vs shell.
Δx = resulting change in offset.

To determine resulting bending stress in Tube:-
Compute $2A/L$, D/L, and $\frac{Ed_o}{2L^2}$.

On chart A, read on Left, the value of C'.

On chart B, read on left, the value of C''

Then Bending stress $= C'C''\frac{Ed_o}{2L^2}\Delta L$.

To find Lateral movement at mid point of wave, multiply $\frac{\Delta x}{\Delta L}$ from chart A by correction factor on right of chart B, and by expected ΔL.

B7

Sine Wave Tube.

Ratio of Direct Stress to Bending Stress:-

S_D = Direct Stress = $\frac{\text{Thrust}}{\text{area}} = \frac{P}{\pi(r_o^2 - r_i^2)}$

Bending Moment = $PA(2-C_4)$

S_M = Bending Stress = $\frac{Mc}{I} = PA(2-C_4)\frac{4r_o}{\pi(r_o^4 - r_i^4)}$

$$\frac{S_D}{S_M} = \frac{P}{\pi(r_o^2 - r_i^2)} \times \frac{\pi(r_o^4 - r_i^4)}{4r_o PA(2-C_4)} = \frac{r_o^2 + r_i^2}{4r_o A(2-C_4)}$$

$C_4 = \frac{\text{Tube Length within Sine Wave}}{\text{Tube Length between Baffles.}}$

Assume thin walled tube - $r_i = r_o$ and $C_4 = 1$

Then $S_D = \frac{r_o}{2A} S_M$

For $r_o = 1/4''$ and $2A = 10''$ $S_D = .025 S_M$

Direct stress will be small as compared to bending stress.

88

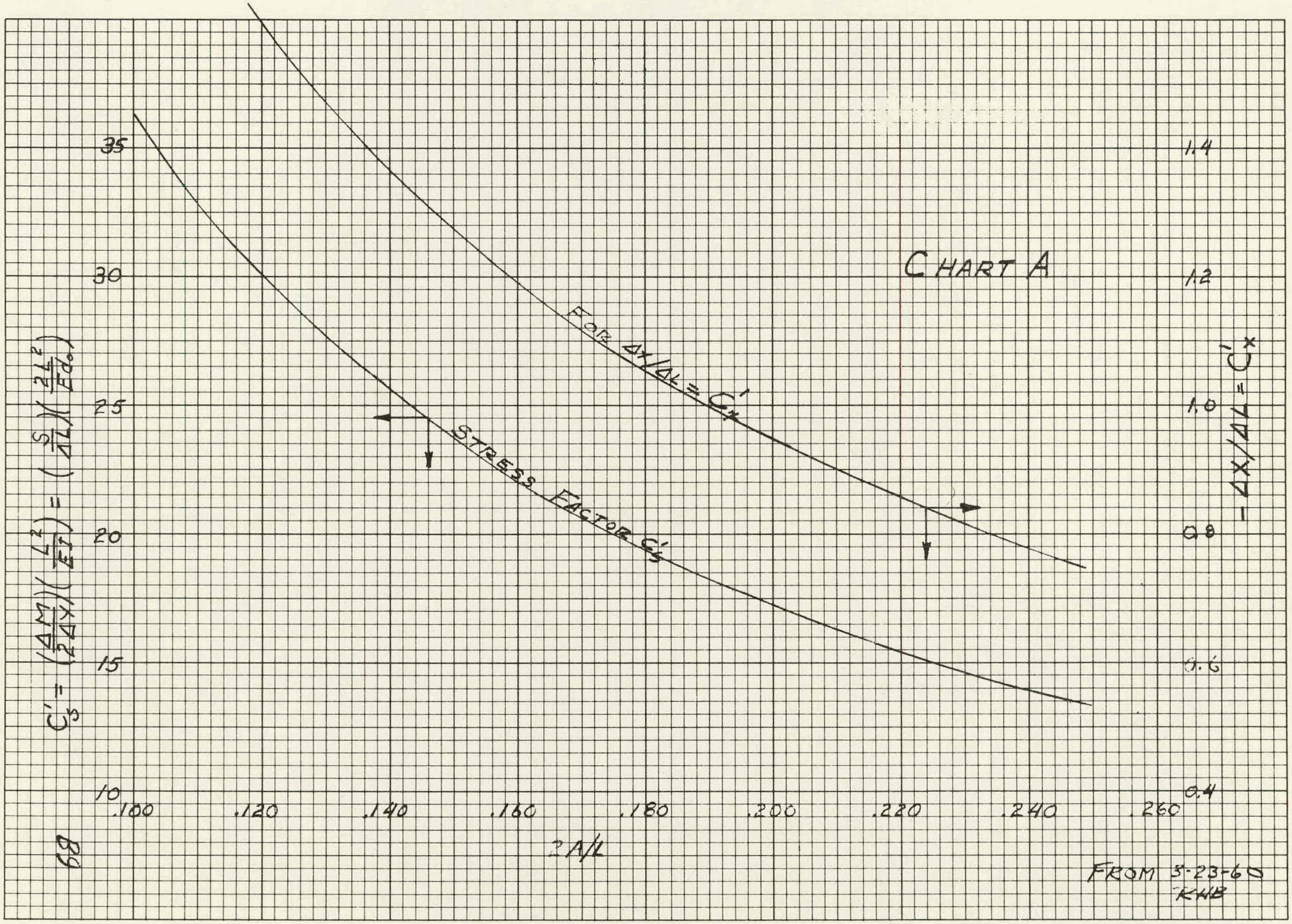


CHART A
For Δx/ΔL = C'x
STRESS FACTOR C's
C's = (ΔM/2Δx)(L²/EI) = (S/ΔL)(2L²/Ed₀)
−Δx/ΔL = C'x
35
30
25
20
15
10
1.4
1.2
1.0
0.8
0.6
0.4
.100
.120
.140
.160
.180
.200
.220
.240
.260
2A/L
FROM 5-23-60
KHB

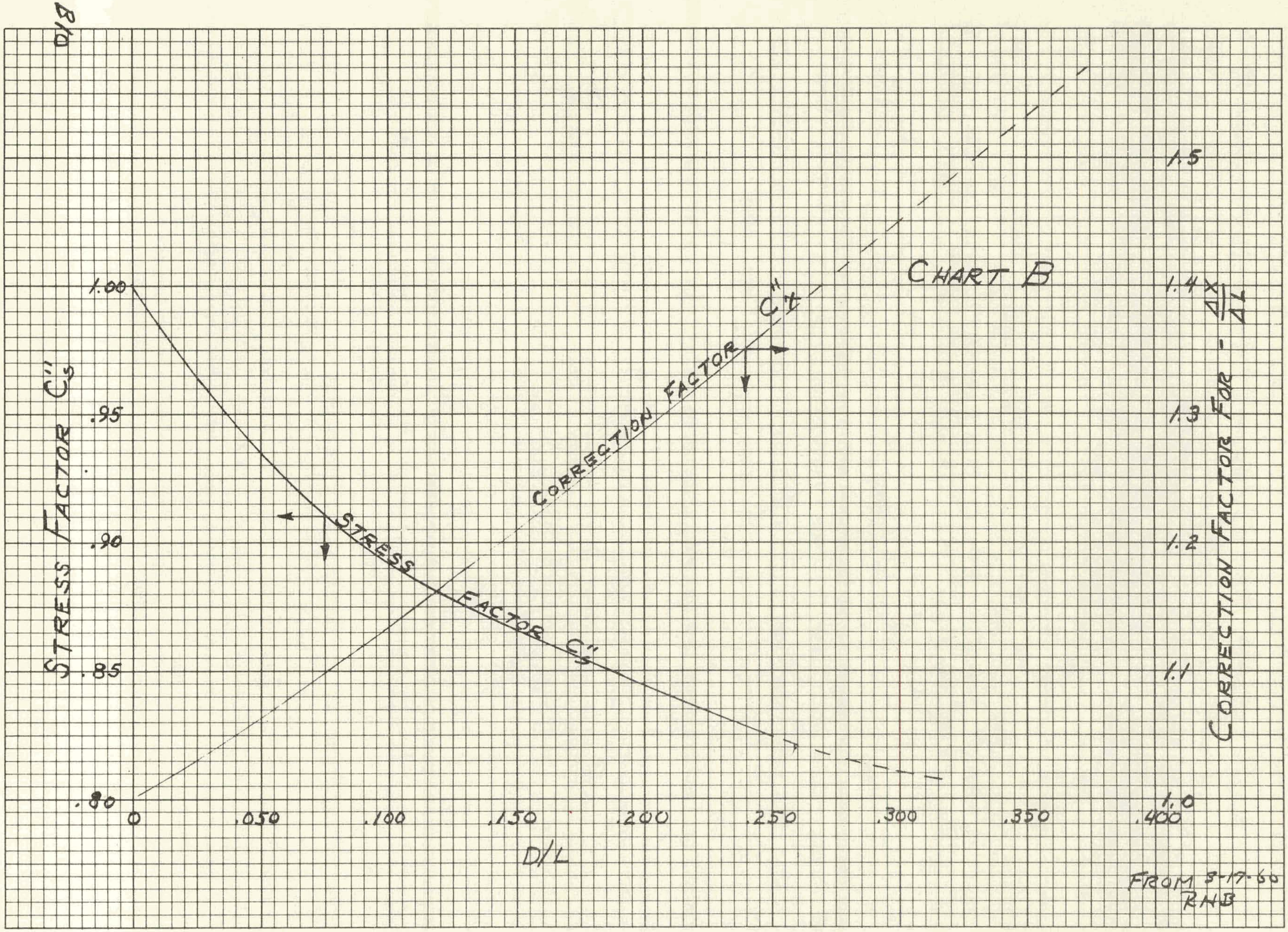


CHART B

FROM 3-17-60
RHB

NOZZLE REACTION STRESSES

FOR

IHX AND STEAM GENERATION 4-C

C1

NOZZLE REACTION STRESSES
30 MW IHX & STEAM GENERATOR
BIJLAARD THEORY (REF. NAVY CODE)

EXTERNAL NOZZLE LOADS MOMENT M = 480000 IN.#
THRUST P = 4000#

INTERNAL PRESSURE IHX – SHELL SIDE 100 PSI
– TUBE SIDE 150 PSI
STEAM GENERATOR – SHELL SIDE 150 PSI

IHX BARREL NOZZLE:-

MEAN RADIUS OF BARREL WALL $R = 18.625''$
THICKNESS OF BARREL WALL $t = 1.00''$
OUTER RADIUS OF NOZZLE $R_o = 8.25''$

FROM EQ. A5 2 $S = 1.82 \frac{R_o}{R}\sqrt{R/t} = 1.82 \frac{9.25}{18.625}\sqrt{\overset{4.32}{\frac{18.625}{1}}} = 3.48$

FROM FIG. A5-2 $\frac{\sigma t^2}{P} = .1$ $\frac{\sigma t^2}{\frac{M}{R}\sqrt{R/t}} = .1$

$$\sigma = \frac{(.1)(4000)}{(1)^2} = 400$$

$$\sigma = \frac{(.1)(480000)(4.32)}{(1)^2(18.625)} = 11110$$

PRESSURE STRESS $\sigma_p = \frac{qR}{2t} = \frac{(150)(18.125)}{(2)(1)} = 1360$

COMBINED STRESS $\sigma = 400 + 11110 + 1360 =$ 12870 PSI

IHX SHELL NOZZLE:-

MEAN RADIUS OF SHELL $A = 18.5625''$
THICKNESS OF SHELL $t = 1.125''$
OUTER RADIUS OF NOZZLE –
CIRCUMFERENTIAL MOMENT $R_o = 10.375''$
LONGITUDINAL MOMENT $R_o = 9.25''$

C2

$\beta = \frac{(.875)(R_0)}{A} = \frac{(.875)(9.25)}{18.5625} = .436 \quad \gamma = \frac{A}{t} = 18.625$

FROM FIGS. A5-4 & 5

$\frac{M_\phi}{P} = .030 \qquad \frac{N_\phi}{P/A} = 1.3$

$M_\phi = (.030)(4000) = 120 \qquad N_\phi = (1.3)\left(\frac{4000}{18.5625}\right) = 280$

STRESS DUE TO THRUST —

$\sigma_1 = \frac{280}{1.125} + \frac{(120)(6)}{(1.125)^2} = 249 + 569 = \underline{\underline{818 \text{ PSI}}}$

CIRCUMFERENTIAL PRESSURE STRESS $\sigma_C = \frac{(100)(18)}{1} = 1800$ PSI

LONGITUDINAL PRESSURE STRESS $\sigma_L = \frac{(100)(18)}{(2)(1)} = 900$ PSI

$\frac{M_N}{M/A\beta} = X$ OR $M_N = \frac{MX}{A\beta} \qquad \frac{N_N}{M/A^2\beta} = Y$ OR $N_N = \frac{MY}{A^2\beta}$

BENDING STRESS DUE TO MOMENT, $\sigma = \frac{6M_N}{t^2} = \frac{6MX}{A\beta t^2} - X F_B$

TENSILE STRESS DUE TO MOMENT, $\sigma = \frac{N_N}{t} = \frac{MY}{A^2\beta t} = Y F_T$

FOR LONGITUDINAL MOMENT —

$F_B = \frac{6M}{A\beta t^2} = \frac{(6)(480000)}{(18.5625)(.436)(1.125)^2} = 281000$

$F_T = \frac{M}{A^2\beta t} = \frac{(480000)}{(18.5625)^2(.436)(1.125)} = 2840$

FOR CIRCUMFERENTIAL MOMENT — $R_0 = 10.375''$

$\beta = \frac{(.875)(10.375)}{18.5625} = .49$

$F_B = \frac{(6)(480000)}{(18.5625)(.49)(1.125)^2} = 250000$

$F_T = \frac{480000}{(18.5625)^2(.49)(1.125)} = 2530$

$$\sigma_2 \begin{cases} \text{FIG A5-6} & \dfrac{M_x}{M/A\beta} = .017 \\ \text{FIG A5-8} & \dfrac{N_x}{M/A^2\beta} = .725 \end{cases} \qquad \sigma_3 \begin{cases} \text{FIG A5-7} & \dfrac{M_\phi}{M/A\beta} = .013 \\ \text{FIG A5-9} & \dfrac{N_\phi}{M/A^2\beta} = 1.5 \end{cases}$$

$$\sigma_4 \begin{cases} \text{FIG A5-10} & \dfrac{M_x}{M/A\beta} = .022 \\ \text{FIG A5-12} & \dfrac{N_x}{M/A^2\beta} = 2.2 \end{cases} \qquad \sigma_5 \begin{cases} \text{FIG A5-11} & \dfrac{M_\phi}{M/A\beta} = .05 \\ \text{FIG A5-13} & \dfrac{N_\phi}{M/A^2\beta} = .64 \end{cases}$$

LONGITUDINAL MOMENT

	X&Y FACTOR	REACTION STRESS	PRESSURE STRESS	COMBINED STRESS
σ_2 LONGITUDINAL	.017 × 281000 = .725 × 2840 =	4780 2060	+ 900 =	7740 PSI
σ_3 CIRCUMFERENTIAL	.013 × 281000 = 1.5 × 2840 =	3660 4260	+1800 =	9720 PSI

CIRCUMFERENTIAL MOMENT

σ_4 LONGITUDINAL	.022 × 250000 = 2.2 × 2530 =	5500 5560	+900 =	11960 PSI
σ_5 CIRCUMFERENTIAL	.05 × 250000 = .64 × 2530 =	12500 1620	+1800 =	15920 PSI

THE STRESSES DUE TO A CIRCUMFERENTIAL MOMENT ARE APPROXIMATE BECAUSE THE CURVES FROM WHICH THE X & Y'S ARE TAKEN DO NOT EXTEND TO $\beta > .50$. HOWEVER VERY CONSERVATIVE VALUES HAVE BEEN SELECTED & IN NO CASE WILL THE STRESS DUE TO A CIRCUMFERENTIAL MOMENT EXCEED THE GIVEN VALUES.

C 4

STEAM GENERATOR SHELL NOZZLE:-

MEAN RADIUS OF SHELL $A = 16.5625''$

THICKNESS OF SHELL $t = 1.125''$

OUTER RADIUS OF NOZZLE

CIRCUMFERENTIAL MOMENT $R_o = 10.625''$

LONGITUDINAL MOMENT $R_o = 9.25''$

CIRCUMFERENTIAL PRESSURE STRESS $\sigma_c = \frac{(150)(16)}{1} = 2400$ PSI

LONGITUDINAL PRESSURE STRESS $\sigma_L = \frac{(150)(16)}{(2)(1)} = 1200$ PSI

FOR LONGITUDINAL MOMENT $\beta = \frac{(.875)(9.25)}{16.5625} = .49$

FOR CIRCUMFERENTIAL MOMENT $\beta = \frac{(.875)(10.625)}{16.5625} = .562$

$\gamma = 16.5625$

FROM FIGS. A5-4 & 5 $\frac{M_\phi}{P} = .025$ $\frac{N_\phi}{P/A} = 1.2$

$M_\phi = (.025)(4000) = 100$ $N_\phi = (1.2)\frac{4000}{16.5625} = 290$

STRESS DUE TO THRUST -

$$\sigma_1 = \frac{290}{1.125} + \frac{(100)(6)}{(1.125)^2} = 258 + 474 = \underline{732 \text{ PSI}}$$

FOR LONGITUDINAL MOMENT -

$$F_B = \frac{6M}{A\beta t^2} = \frac{(6)(480000)}{(16.5625)(.49)(1.125)^2} = 280000$$

$$F_T = \frac{M}{A^2\beta t} = \frac{480000}{(16.5625)^2(.49)(1.125)} = 3180$$

FOR CIRCUMFERENTIAL MOMENT -

$$F_B = \frac{(6)(480000)}{(16.5625)(.562)(1.125)^2} = 244000$$

$$F_T = \frac{480000}{(16.5625)^2(.562)(1.125)} = 2780$$

C5

$$\sigma_2 \begin{cases} \text{FIG A5-6} \quad \dfrac{M_x}{M/A\beta} = .014 \\ \text{FIG A5-8} \quad \dfrac{N_x}{M/A^2\beta} = .65 \end{cases} \qquad \sigma_3 \begin{cases} \text{FIG A5-7} \quad \dfrac{M_\phi}{M/A\beta} = .011 \\ \text{FIG A5-9} \quad \dfrac{N_\phi}{M/A^2\beta} = 1.1 \end{cases}$$

$$\sigma_4 \begin{cases} \text{FIG A5-10} \quad \dfrac{M_x}{M/A\beta} = .025 \\ \text{FIG A5-12} \quad \dfrac{N_x}{M/A^2\beta} = 2.5 \end{cases} \qquad \sigma_5 \begin{cases} \text{FIG A5-11} \quad \dfrac{M_\phi}{M/A\beta} = .05 \\ \text{FIG A5-13} \quad \dfrac{N_\phi}{M/A^2\beta} = .6 \end{cases}$$

LONGITUDINAL MOMENT

	X & Y FACTOR	REACTION STRESS	PRESSURE STRESS	COMBINED STRESS
σ_2 LONGITUDINAL	.014 × 280000 =	3920	+ 1200 =	7180 PSI
	.65 × 3180 =	2060		
σ_3 CIRCUMFERENTIAL	.011 × 280000 =	3080	+ 2400 =	8980 PSI
	1.1 × 3180 =	3500		

CIRCUMFERENTIAL MOMENT

σ_4 LONGITUDINAL	.025 × 244000 =	6100	+ 1200 =	14250 PSI
	2.5 × 2780 =	6950		
σ_5 CIRCUMFERENTIAL	.05 × 244000 =	12200	+ 2400 =	16270 PSI
	.6 × 2780 =	1670		

C 6

SUMMARY OF NOZZLE STRESSES

IHX SHELL

		BENDING	MEMBRANE	PRESSURE	TOTAL
THRUST OF 4000#	σ_1	569	249	1800	2618
MOMENT 480000 IN.#					
ACTING LONGITUDINALLY					
LONGITUDINAL	σ_2	4780	2060	900	7740
CIRCUMFERENTIAL	σ_3	3660	4260	1800	9720
ACTING CIRCUMFERENTIALLY					
LONGITUDINAL	σ_4	5500	5560	900	11960
CIRCUMFERENTIAL	σ_5	12500	1620	900	15920

STEAM GENERATOR SHELL

THRUST OF 4000#	σ_1	474	258	2400	3132
MOMENT 480000 IN.#					
ACTING LONGITUDINALLY					
LONGITUDINAL	σ_2	3920	2060	1200	7180
CIRCUMFERENTIAL	σ_3	3080	3500	2400	8980
ACTING CIRCUMFERENTIALLY					
LONGITUDINAL	σ_4	6100	6950	1200	14250
CIRCUMFERENTIAL	σ_5	12200	1670	2400	16270

ALLOWABLE @ 1200°F = 18000 PSI

C 7

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SHIELDING OF SHELL AND BARREL METAL

IHX & STEAM GENERATOR 4-D

D1

SHIELDING OF SHELL & NOZZLES
IHX & STEAM GENERATOR

CALCULATION OF SURFACE STRESSES

THE MAXIMUM CHANGE, IF TAKEN AS FOR THE 70 MW UNITS, WOULD BE 490F IN 14 SECONDS. USING THIS AS THE WORST TRANSIENT —

FOR A 1 1/8" SECTION — UNSHIELDED —

$$N_{Bi}^{-1} = \frac{12K}{hX} = \frac{(12)(13.2)}{(4000)(1.125)} = .0352$$

$$N_{Fo} = \frac{(.0066)t}{X^2} = \frac{(.0066)(14)}{(1.125)^2} = .0729$$

FROM PORTERS TABLES

$$\frac{T_0 - T_m}{\Delta T_F} = .69$$

IF SHIELDED WITH 1/8" SST

$$N_{Bi}^{-1} = \frac{(12)(13.2)}{(4000)(1.25)} = .03165$$

& THE MAXIMUM STRESS OCCURS AT A TIME AFTER THE TRANSIENT. THE MAXIMUM ΔT — FROM PORTERS TABLES —

$$\frac{T_0 - T_m}{\Delta T_F} = .521$$

D2

IF THE TRANSIENT TAKES 40 SECONDS TO COMPLETE THE TEMPERATURE CHANGE – A LINEAR CHANGE

1 1/8" SECTION UNSHIELDED

$$N_{Bi}^{-1} = .0352 \quad \& \quad N_{Fo} = \frac{(.0066)(40)}{(1.125)^2} = .2085$$

$$\frac{T_o - T_m}{\Delta T_f} = .60$$

1 1/8" SECTION WITH 1/8" SHIELD

$N_{Bi}^{-1} = .03165$ & THE MAXIMUM ΔT OCCURS SOMETIME AFTER THE END OF THE TRANSIENT. FROM PORTER'S TABLES –

$$\frac{T_o - T_m}{\Delta T_f} = .466$$

$$\text{STRESS} = \frac{E\alpha\,\Delta T}{1-\mu} = \frac{255}{.7}\,\Delta T = 364.5\,\Delta T$$

STRESSES FOR RATES SPECIFIED FOR 300, 400 & 490 F ΔT –

	UNSHIELDED	SHIELDED
300 F IN 14 SECONDS	75450	57000
400 F IN 40 SECONDS	87500	67900
400 F IN 14 SECONDS	100600	76000
490 F IN 14 SECONDS	123200	93100

IN THINNER SECTIONS THE STRESSES WILL BE LOWER. D3

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IHX TUBESHEET STRESSES

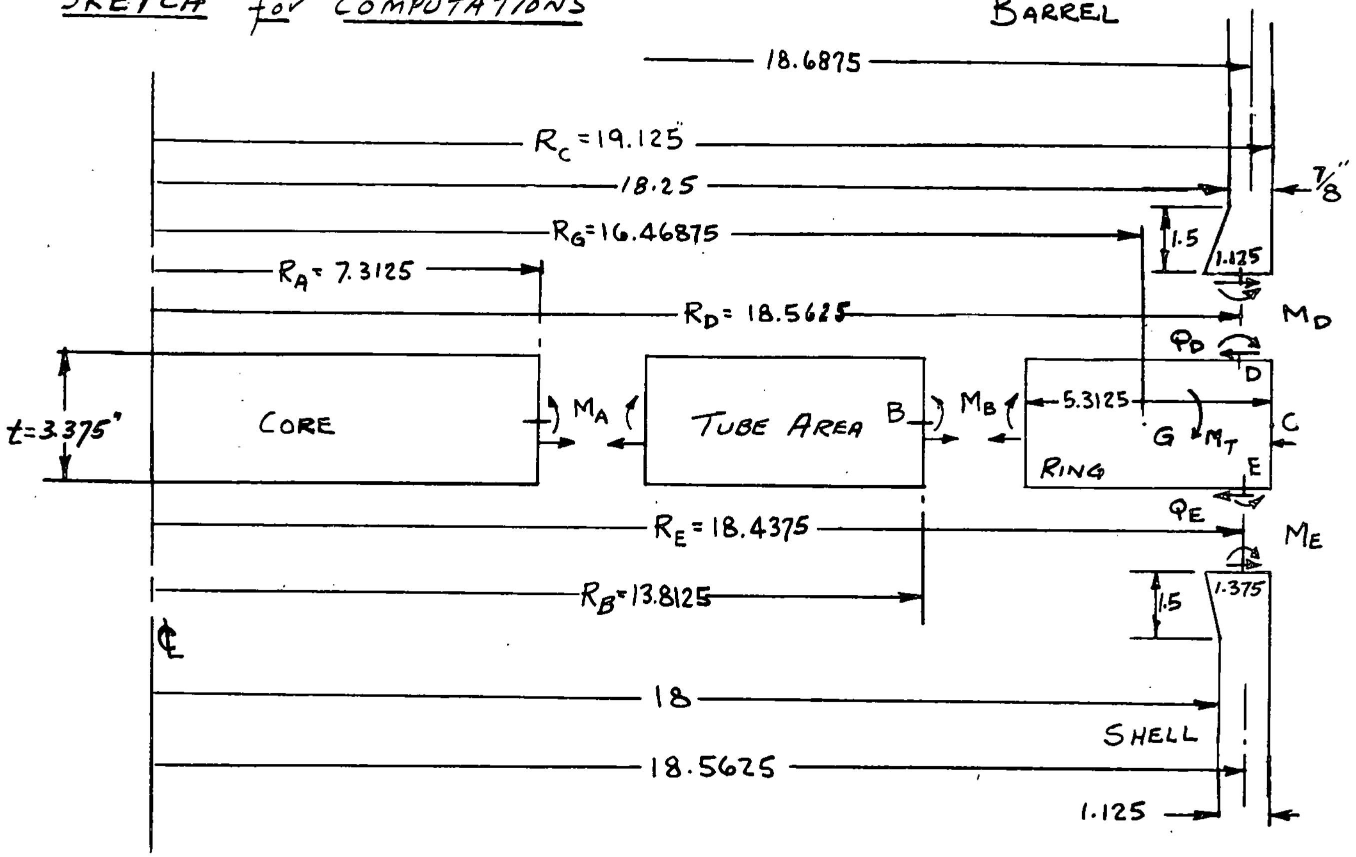
PRESSURE STRESSES 4-E

30 MW - IHX - UPPER TUBE SHEET

PRESSURE STRESS COMPUTATIONS - BARREL SIDE PRESSURE - 150 psi

T = 1200°F   E = 20.6 ×10⁶ psi   SHELL PRESSURE = 0

<u>SKETCH</u> for <u>COMPUTATIONS</u>



E2

<u>CORE and TUBE AREA</u>

USING paper of "Basic equations with $E = 20.6 \times 10^6$ psi and for the tube area using Horvay's curves ($\eta = 0.5$) $\nu^* = 0.40$

$E^* = 0.39 \times 20.6 \times 10^6 = 8.034 \times 10^6$ psi

$$\varphi_A = -\frac{R_A^3}{16D}p + \frac{R_A}{2}C_1 \quad (1) \qquad \varphi_A = -\frac{R_A^3}{16D^*}p + \frac{R_A}{2}C_3 + \frac{C_4}{R_A} \quad (2)$$

$$\varphi_B = -\frac{R_B^3}{16D^*}p + \frac{R_B}{2}C_3 + \frac{C_4}{R_B} \quad (3) \qquad M_{1A} = -\frac{3.3\,R_A^2}{16}p + 0.65DC_1 \quad (4)$$

$$M_{1A} = -\frac{(3+\nu^*)R_A^2}{16}p + \frac{(1+\nu^*)D^*}{2}C_3 - \frac{(1-\nu^*)D^*C_4}{R_A^2} \quad (5)$$

$$M_{1B} = -\frac{(3+\nu^*)R_B^2}{16}p + \frac{(1+\nu^*)D^*}{2}C_3 - \frac{(1-\nu^*)D^*}{R_B^2}C_4 \quad (6)$$

$$D = \frac{E\,t^3}{12(1-\nu^2)} = \frac{20.6 \times 10^6 \times 3.375^3}{12(.91)} = 72.5214 \times 10^6$$

$$D^* = \frac{E^*t^3}{12(1-\nu^{*2})} = \frac{8.034 \times 3.375^3}{12(.84)} = 30.6403 \times 10^6$$

$$\frac{R_A^3}{16D} = \frac{7.3125^3 \times 10^{-6}}{16 \times 72.5214} = 0.33699 \times 10^{-6} \qquad \frac{R_A^3}{16D^*} = \frac{7.3125^3 \times 10^{-6}}{16 \times 30.6403} = 0.79760 \times 10^{-6}$$

$$\frac{R_B^3}{16D^*} = \frac{13.8125^3 \times 10^{-6}}{16 \times 30.6403} = 5.37531 \times 10^{-6} \qquad \frac{3.3R_A^2}{16} = \frac{3.3 \times 7.3125^2}{16} = 11.02874$$

$$0.65D = 47.13891 \times 10^6 \qquad \frac{(3+\nu^*)R_A^2}{16} = \frac{3.4 \times 7.3125^2}{16} = 11.36294$$

$$\frac{(1+\nu^*)D^*}{2} = \frac{1.4 \times 30.6403 \times 10^6}{2} = 21.44821 \times 10^6 \qquad \frac{(1-\nu^*)D^*}{R_A^2} = \frac{0.6 \times 30.6403 \times 10^6}{7.3125^2} = 0.34381 \times 10^6$$

$$\frac{(3+\nu^*)R_B^2}{16} = \frac{3.4 \times 13.8125^2}{16} = 40.54185 \qquad \frac{(1-\nu^*)D^*}{R_B^2} = \frac{0.6 \times 30.6403 \times 10^6}{13.8125^2} = 0.09636 \times 10^6$$

ES

Substituting values into (1) = (2)

$$-0.33699\times10^{-6}p + 3.65625C_1 = -0.79760\times10^{-6}p + 3.65625C_3 + 0.13675C_4$$

$$C_1 = -0.12598\times10^{-6}p + C_3 + 0.037402C_4 \qquad (7)$$

From (4) = (5)

$$-11.02874p + 47.13891\times10^{6}C_1 = -11.36294p + 21.44821\times10^{6}C_3$$
$$- 0.34381\times10^{6}C_4$$

$$C_1 = -.00709\times10^{-6}p + 0.45500C_3 - .0072936C_4 \qquad (8)$$

From (7) = (8)

$$-0.12598\times10^{-6}p + C_3 + 0.037402C_4 = -.00709\times10^{-6}p + 0.45500C_3 - .0072936C_4$$

$$C_3 = 0.21815\times10^{-6}p - 0.08201C_4 \qquad (9)$$

Substituting (9) into (3) and into (6)

$$\phi_B = -5.37531\times10^{-6}p + 6.90625C_3 + 0.072398C_4$$
$$= -5.37531\times10^{-6}p + 6.90625(\overset{1.50660}{0.21815\times10^{-6}p} - \overset{-0.56638}{0.08201C_4}) + 0.072398C_4$$
$$= -3.86871\times10^{-6}p - 0.49398C_4$$

$$C_4 = -2.02437\phi_B - 7.83171\times10^{-6}p \qquad (10)$$

$$M_{1B} = -40.54185p + 21.44821\times10^{6}C_3 - 0.09636\times10^{6}C_4 =$$
$$= -40.54185p + 21.44821\times10^{6}(\overset{4.67893}{0.21815\times10^{-6}p} - \overset{-1.75897}{0.08201C_4}) - 0.09636\times10^{+6}C_4$$
$$= -35.86292p - 1.85533\times10^{6}C_4$$

$$C_4 = -0.538988\times10^{-6}M_{1B} - 19.32967\times10^{-6}p \qquad (11)$$

From (10) = (11)

$$-2.02437\varphi_B - 7.83171\times10^{-6}p_1 = -0.538988\times10^{-6}M_{1B} - 19.32967\times10^{-6}p$$

$$\varphi_B = +0.26625\times10^{-6}M_{1B} + 5.67977\times10^{-6}p \qquad (12)$$

$$M_B = 3.75587\times10^{6}\varphi - 3199.870$$

RING

External twisting moment per unit length at center G:

$$\frac{13.8125}{16.46875}M_B - \frac{13.8125}{16.46875}\times 2.65625\times\frac{\pi\times13.8125^2 p}{2\pi\,13.8125} - \frac{\pi p(17.875^2-13.8125^2)}{2\pi\,15.84375}\times$$

$$\frac{15.84375}{16.46875}\times0.625 - \frac{\pi p\times17.875^2}{2\pi\times18.6875\times7/8}\times\frac{18.6875}{16.46875}\times2.21875$$

$$+\frac{18.5625}{16.46875}M_D - \frac{18.4375}{16.46875}M_E + \frac{18.4375}{16.46875}\times1.6875\varphi_E - \frac{18.5}{16.46875}\times1.6875\varphi_D = M_t \qquad (13)$$

$$0.83871M_B - 15.38590p - 2.44270p - 24.59811p + 1.12334M_D$$

$$-1.11954M_E + 1.88923\varphi_E - 1.89564\varphi_D = M_t$$

$$0.83871M_B - 42.42671p + 1.12334M_D - 1.11954M_E + 1.88923\varphi_E$$

$$-1.89564\varphi_D = M_t$$

From Timoshenko Str. of Mat'l Vol II pg 140

$$\varphi_B = \varphi = \frac{12M_tR_G}{Et^3\ln\frac{R_C}{R_B}} = \frac{12\times16.46875\times10^{-6}M_t}{20.6\times3.375^3\ln\frac{19.125}{13.8125}} = 0.76685\times10^{-6}M_t$$

$$M_t = 1.30404\times10^{6}\varphi \qquad (14)$$

E5

Substituting (14) into (13)

$$0.83871 M_B + 1.12334 M_D - 1.11954 M_E + 1.88923 \varphi_E - 1.89564 \varphi_D$$
$$- 42.42671 p = -1.30404 \times 10^{6} \varphi \qquad (15)$$

From Roark pg 276 Cases 27 & 28

$$\Delta R_A = p \frac{b}{E}\left(\frac{a^2+b^2}{b^2-a^2} - J\right) = \frac{N_A}{3.375} \times \frac{7.3125}{20.6 \times 10^6}\left(\frac{7.3125^2}{7.3125^2} - 0.3\right)$$
$$= .073625 \times 10^{-6} N_A \qquad (16)$$

$$\Delta R_A' = -p \frac{a}{E}\left(\frac{b^2+a^2}{b^2-a^2} + J\right) + p \frac{a}{E}\left(\frac{2b^2}{b^2-a^2}\right)$$
$$= -\frac{N_A}{3.375} \frac{7.3125}{8.034 \times 10^{+6}}\left(\frac{13.8125^2+7.3125^2}{13.8125^2-7.3125^2} + 0.4\right) + \frac{N_B}{3.375} \frac{7.3125}{8.034 \times 10^{+6}}\left(\frac{13.8125^2 \times 2}{13.8125^2-7.3125^2}\right)$$
$$\Delta R_A' = 0.74942 \times 10^{-6} N_B - 0.58761 \times 10^{-6} N_A \qquad (17)$$

$$\Delta R_B = +p \frac{b}{E}\left(\frac{a^2+b^2}{b^2-a^2} - J^{*}\right) - p \frac{b}{E}\left(\frac{2a^2}{b^2-a^2}\right)$$
$$= + \frac{N_B}{3.375} \frac{13.8125}{8.034 \times 10^{+6}}\left(\frac{13.8125^2+7.3125^2}{13.8125^2-7.3125^2} - 0.4\right) - \frac{N_A}{3.375} \times \frac{13.8125}{8.034 \times 10^6} \times \frac{2 \times 7.3125^2}{13.8125^2-7.3125^2}$$
$$\Delta R_B = 0.70240 \times 10^{-6} N_B - 0.39675 \times 10^{-6} N_A \qquad (18)$$

$$\Delta R_B' = -\frac{N_B}{3.375} \frac{13.8125}{20.6 \times 10^6}\left(\frac{19.125^2+13.8125^2}{19.125^2-13.8125^2} + 0.3\right) - \frac{N_C}{3.375} \frac{13.8125}{20.6 \times 10^6} \frac{2 \times 19.125^2}{19.125^2-13.8125^2}$$
$$= -0.69150 \times 10^{-6} N_B - 0.83057 \times 10^{-6} N_C \qquad (19)$$

E 6

$$\Delta R_C = -\frac{N_C}{3.375}\,\frac{19.125}{20.6\times10^{6}}\left(\frac{13.8125^2+19.125^2}{19.125^2-13.8125^2}-0.3\right)-\frac{N_B}{3.375}\,\frac{19.125}{20.6\times10^{6}}\times\frac{2\times13.8125^2}{19.125^2-13.8125^2}$$

$$= -0.79241\times10^{-6}N_C - .59986\times10^{-6}N_B \qquad (20)$$

$$N_C \times 19.125 = \phi_D \times 18.5 + \phi_E \times 18.4375$$

$$N_C = .96732\ \phi_D + .96405\ \phi_E \qquad (21)$$

Now, (16) = (17)

$$.073625\ N_A = .74942\ N_B - .58761\ N_A$$

$$N_A = \frac{.74942\ N_B}{.661235} = 1.133364\ N_B \qquad (22)$$

Substituting into (18)

$$\Delta R_B = .70240\times10^{-6}N_B - .39675\times10^{-6}(1.133364 N_B) = .25274\times10^{-6}N_B \qquad (23)$$

Substituting (21) into (19) & (20)

$$\Delta R_B' = -.69150\times10^{-6}N_B - .83057\times10^{-6}(.96732\ \phi_D + .96405\ \phi_E)$$

$$= -.69150\times10^{-6}N_B - .80343\,\overset{\times10^{-6}}{\phi_D} - .80071\,\overset{\times10^{-6}}{\phi_E} \qquad (24)$$

$$\Delta R_C = -.79241\times10^{-6}(.96732\,\phi_D + .96405\,\phi_E) - .59986\times10^{-6}N_B$$

$$= -.76651\times10^{-6}\phi_D - .76392\times10^{-6}\phi_E - .59986\times10^{-6}N_B \qquad (25)$$

E7

$(23) = (24)$

$$.25274\, N_B = -.69150\, N_B - .80343\, \varphi_D - .80071\, \varphi_E$$

$$N_B = -.85087\, \varphi_D - .84799\, \varphi_E \qquad (26)$$

Substituting (26) into (23), (24), & (25)

$$\Delta R_B = .25274 \times 10^{-6}(-.85087\, \varphi_D - .84799\, \varphi_E)$$

$$\Delta R_B = -.21505 \times 10^{-6}\, \varphi_D - .21432 \times 10^{-6}\, \varphi_E \qquad (27)$$

$$\Delta R_B' = -.69150 \times 10^{-6}(\overset{.58838}{-.85087\, \varphi_D} \overset{+\ .58689}{-} .84799\, \varphi_E) - .80343 \times 10^{-6}\, \varphi_D - .80071 \times 10^{-6}\, \varphi_E$$

$$\Delta R_B' = -.21505 \times 10^{-6}\, \varphi_D - .21432 \times 10^{-6}\, \varphi_E$$

$$\Delta R_C = -.76651 \times 10^{-6}\, \varphi_D - .76392 \times 10^{-6}\, \varphi_E - .59986 \times 10^{-6}(-.85087\, \varphi_D - .84799\, \varphi_E)$$

$$\Delta R_C = -.25611 \times 10^{-6}\, \varphi_D - .25524 \times 10^{-6}\, \varphi_E. \qquad (28)$$

Let $\varphi_D = \varphi_E = \varphi$

The values for φ_D & φ_E are taken from the step by step integration tables. PP. E 19, 20, & 28

$$\Delta R_D = \Delta R_C - 1.6875\, \varphi$$

$$= -.25611\, (\overset{-.048471}{.189257\, \Delta R_D} \overset{+\ .081232}{- .317175\, \varphi} \overset{-\ 35.460}{- 138.455 \times 10^{-6}})$$

$$- .25524\, (\overset{-.070844}{.277560\, \Delta R_E} + \overset{-\ .132356}{.518556\, \varphi_E}) - 1.6875\, \varphi$$

$$\Delta R_D = -.048471\, \Delta R_D - .070844\, \Delta R_E - 1.738624\, \varphi + .00003546$$

$$\Delta R_D = -.067569\, \Delta R_E - 1.658247\, \varphi + .000033821. \qquad (29)$$

E 8

$$\Delta R_E = -.048471\,\Delta R_D - .070844\,\Delta R_E + 1.886376\,\varphi + .00003546$$

$$\Delta R_E = -.045264\,\Delta R_D + 1.761579\,\varphi + .00003311 \qquad (30)$$

Substituting (30) into (29),

$$\Delta R_D = -.067569\left[\overset{+.003058}{-.045264}\Delta R_D \overset{-.119028}{+1.761579}\,\varphi \overset{-.0\text{[illegible]}2237}{+.00003311}\right]$$

$$-1.658247\,\varphi + .000033821$$

$$\Delta R_D = -1.782727\,\varphi + .00030968$$

$$\Delta R_E = \Delta R_D + 3.375\,\varphi = -1.782727\,\varphi + .000030968 + 3.375\,\varphi$$

$$\Delta R_E = 1.592273\,\varphi + .000030968$$

Substituting into (15) M_B, M_E, φ_D, & φ_E

$$0.83871\left[\overset{3.150086}{3.75587} \times 10^6\varphi \overset{-2683.7630}{-3199.870}\right] + 1.12334\left[\overset{-356293}{-317173}\,\Delta R_D \overset{1,143,423}{+1017878}\,\varphi\right.$$

$$\left.+\overset{995.911}{886.562}\right] - 1.11954\left[\overset{+580617}{-518621}\,\Delta R_E \overset{+2091859}{-1868499}\,\varphi\right]$$

$$+ 1.88923\left[\overset{+524375}{277560}\,\Delta R_E + \overset{979672}{518556}\,\varphi\right] - 1.89564\left[\overset{-358763}{189257}\,\Delta R_D\right.$$

$$\left.\overset{+601250}{-317175}\,\varphi \overset{+262.461}{-138.455}\right] \overset{-6364.0065}{-42.42671 \times 150} = -1.30404 \times 10^6\,\varphi$$

$$9270330\,\varphi = 7789.3975 + 715056\,\Delta R_D - 1104992\,\Delta R_E$$

$$= 7789.3975 + 715056\left[\overset{-1,274,750}{-1.782727}\,\varphi \overset{+22.1439}{+.000030968}\right]$$

$$-1104992\left[\overset{-1,759,449}{1.592273}\,\varphi \overset{-34.2194}{+.000030968}\right]$$

$$12304529\,\varphi = 7777.322 \qquad \varphi = .00063207$$

E9

$$\Delta R_D = -1.782727\varphi + .000030968$$

$$\Delta R_D = -1.782727\overset{-.001126808}{(.00063207)} + .000030968 \qquad = -.0010958$$

$$\Delta R_E = 1.592273\varphi + .000030968$$

$$\Delta R_E = 1.592273\overset{.001006428}{(.00063207)} + .000030968 \qquad = .0010374$$

$$M_D = -\overset{+347.558}{317173(-.0010958)} + \overset{643.370}{1017878(.00063207)} + 886.562 = 1877$$

$$M_E = -\overset{-538.017}{518621(.0010374)} - \overset{-1181.022}{1868499(.00063207)} \qquad = -1719$$

$$Q_D = \overset{-207.388}{189257(-.0010958)} - \overset{-200.477}{317175(.00063207)} - 138.455 = -546$$

$$Q_E = \overset{287.941}{277560(.0010374)} + \overset{+327.764}{518556(.00063207)} = 616$$

$$M_B = \overset{2373.973}{3.75587(632.07)} - 3199.870 \qquad = -826$$

Substituting values into moment equation (15),

$$\overset{-692.774}{0.83871(-826)} + \overset{2108.509}{1.12334(1877)} - \overset{+1924.489}{1.11954(-1719)} + \overset{+1163.766}{1.88923(616)}$$

$$-\overset{+1035.019}{1.89564(-546)} - \overset{-6364.007}{42.42671(150)} = -1.30404 \times 632.07$$

$$-825 \qquad = -824$$

From (26),

$$N_B = -\overset{464.575}{.85087(-546)} - \overset{-522.362}{.84799(616)} \qquad = -58$$

$$N_A = 1.133364(-58) \qquad = -66$$

E10

$$C_4 = -2.02437\overset{-.00127954}{(.00063207)} - 7.83171\overset{-\ .00117476}{(.000150)} = -2454.3\times10^{-6}$$

$$C_4 = -.538988\overset{+.00044520}{(-.000826)} - 19.32967\overset{-\ .00289945}{(.000150)} = -2454.3\times10^{-6}$$

$$C_3 = .21815\overset{.0000327225}{(.000150)} - .08201\overset{+.0002012771}{(-.0024543)} = 234.0\times10^{-6}$$

$$M_R = -\frac{3.4}{16}(150)x^2 + (.7)(30.6403)(234.0) - (.6)(30.6403)(-2454.3)/x^2$$

$$M_R = -31.875x^2 + 5018.881 + 45120/x^2$$

$$M_T = -\frac{2.2}{16}(150)x^2 + 5018.881 - \frac{45120}{x^2}$$

$$M_T = -20.625x^2 + 5018.881 - 45120/x^2$$

AT THE INNER ROW, $x = 7.5625''$

$$M_R = -31.875(7.5625)^2 + 5018.881 + \frac{45120}{7.5625^2}$$

$$M_R = -1822.976 + 5018.881 + 788.930 = 3985$$

$$M_T = -20.625\overset{-1179.573}{(7.5625)^2} + 5018.881 - 788.930 = 3050$$

AT THE OUTER ROW, $X = 13.5625''$

$$M_R = -31.875\overset{-5863.132}{(13.5625^2)} + 5018.881 + \overset{+\ 245.296}{\frac{45120}{13.5625^2}} = -599$$

$$M_T = -20.625\overset{-3793.792}{(13.5625)^2} + 5018.881 - 245.296 = +980$$

STRESSES DUE TO N_A & N_B

INSIDE ROW –

$$\sigma_R = \frac{7.3125^2}{7.5625^2}\,\frac{N_A}{3.375}\left(\frac{13.8125^2 - 7.5625^2}{13.8125^2 - 7.3125^2}\right) + \frac{13.8125^2}{7.5625^2}\,\frac{N_B}{3.375}\left(\frac{7.5625^2 - 7.3125^2}{13.8125^2 - 7.3125^2}\right)$$

$$= .2770302(.9729176)(-66) + .9884166(.0270824)(-58)$$

$$= -17.789 - 1.553 = -19$$

E 11

$$\sigma_T = -\frac{\overset{a}{7.3125^2}}{\underset{r}{7.5625^2}}\frac{N_A}{3.375}\left(\frac{13.8125^2+7.5625^2}{13.8125^2-7.3125^2}\right) + \frac{13.8125^2}{7.5625^2}\frac{N_B}{3.375}\left(\frac{7.3125^2+7.5625^2}{13.8125^2-7.3125^2}\right)$$

$$\sigma_T = \overset{+33.020}{-(.2770302)(1.80593)(-66)} + \overset{-\quad 46.202}{(.9884166)(.80593)(-58)} = -13$$

OUTSIDE ROW R=13.5625

$$\sigma_R = \frac{\overset{a}{7.3125^2}}{\underset{r}{13.5625^2}}\frac{N_A}{3.375}\left(\frac{\overset{b}{13.8125^2}-\overset{r}{13.5625^2}}{\underset{b\,-}{13.8125^2}-\underset{a}{7.3125^2}}\right) + \frac{\overset{b}{13.8125^2}}{\underset{r}{13.5625^2}}\frac{N_B}{3376}\left(\frac{\overset{r\,-\quad a}{13.5625^2-7.3125^2}}{\underset{b-a}{13.8125^2-7.3125^2}}\right)$$

$$= \overset{-.283}{(.0861348)(.0498407)(-66)} + \overset{-16.936}{(.307320)(.950189)(-58)} = -17$$

$$\sigma_T = -\frac{7.3125^2}{13.5625^2}\frac{N_A}{3.375}\frac{13.8125^2+13.5625^2}{13.8125^2-7.3125^2} + \frac{13.8125^2}{13.5625^2}\frac{N_B}{3.375}\left(\frac{7.3125^2+13.5625^2}{13.8125^2-7.3125^2}\right)$$

$$= -\overset{-15.514}{(.0861348)(2.729005)(-66)} + \overset{-30.819}{(.307320)(1.729005)(-58)} = -46$$

COMBINED STRESSES $\quad 6/t^2 = 6/3.375^2 = .52675$

σ_1 = RADIAL STRESS ; σ_2 = TANGENTIAL STRESS

INSIDE ROW

σ_2/σ_1

BARREL SIDE (TOP)
$\sigma_1 : -19 - \overset{-2099}{.52675(3985)} = -2118$ $\quad$ 0.764 K=2.55 $\quad$ 5401 C
$\sigma_2 = -13 - \overset{-1607}{.52675(3050)} = -1620$ $\quad$ 4131 C

SHELL SIDE (BOTTOM)
$\sigma_1 = -19 + \overset{+2099}{.52675(3985)} : 2080$ $\quad$ 0.766 K=2.55 $\quad$ 5304 T
$\sigma_2 = -13 + \underset{+1607}{.52675(3050)}$ $\;$ 1594 $\quad$ 4065 T

OUTSIDE ROW

BARREL SIDE (TOP)
$\sigma_1 = -17 + \overset{316}{.52675(599)} = 299$ $\quad$ -.532 K= 4.3 $\quad$ 1286 T
$\sigma_2 : -46 - \overset{-316}{.52675(980)} = -562$ $\quad$ 2417 C

SHELL SIDE (BOTTOM)
$\sigma_1 = -17 - 316 = -333$ $\quad$ -.709 K= 4.7 $\quad$ 1565 C
$\sigma_2 = -46 + 516 = 470$ $\quad$ 2209 T

E 12

BARREL STRESSES AT JUNCTION WITH TUBE SHEET

$$\sigma_L = \frac{F}{t} \pm \frac{6M}{t^2} = \frac{PR_i^2}{2R_m t} \pm \frac{6M_D}{t^2}$$

$$= \frac{150 \times 18.000^2}{(2)(18.5625)1.125} \pm \frac{6 \times 1877}{1.125^2} = 1164 \pm 8898 = \begin{matrix} 10062 \text{ T INSIDE} \\ 7734 \text{ C OUTSIDE} \end{matrix}$$

$\Delta R_D = -.0010958$

$$\sigma_c = \overset{-1216}{\frac{(-1095.8)206}{18.5625}} + .3\overset{3019}{(10062)} = 1803 \text{ T INSIDE}$$

$$\sigma_c = \overset{-1216}{\frac{-1095.8 \times 20.6}{18.5625}} - .3\overset{2320}{(7734)} = 3536 \text{ C OUTSIDE}$$

SHELL STRESSES AT JUNCTION WITH TUBE SHEET

$$\sigma_L = \frac{6M_E}{t^2} = \frac{6(-1719)}{1.375^2} = 5455 \begin{matrix} \text{T outside} \\ \text{C inside} \end{matrix}$$

$\Delta R_E = .0010374$

$$\sigma_c = \overset{1159}{\frac{1037.4 \times 20.6}{18.4375}} + (.3)\overset{1637}{(5455)} = 2796 \text{ T OUTSIDE}$$

$$\sigma_c = \overset{1159}{\frac{1037.4 \times 20.6}{18.4375}} - (.3)\overset{-1637}{(5455)} = 478 \text{ C INSIDE}$$

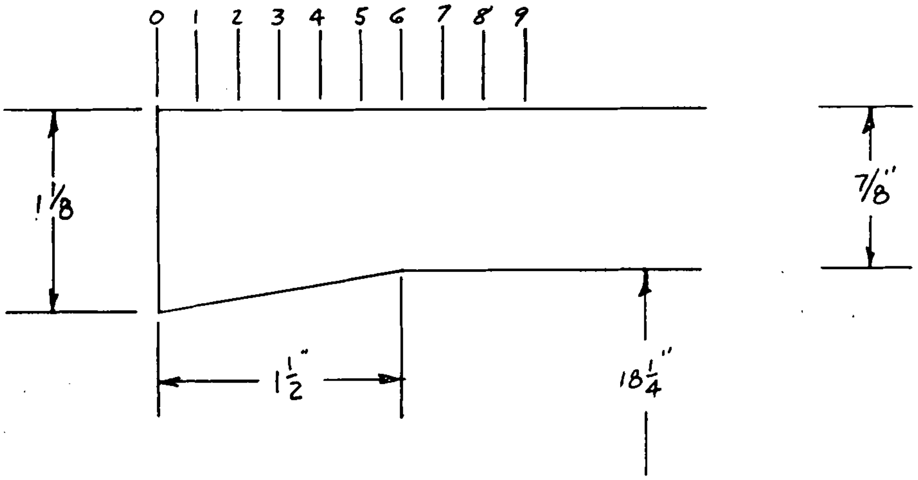
E 13

PHYSICAL PROPERTIES BARREL SIDE 30 MW IHX

$E = 20.6 \times 10^6$ $m = .25''$ POINT 6 & BEYOND ALIKE

$P = 150$ psi

POINT	0	1	2	3	4	5	6	7
DISTANCE	0	.25	.50	.75	1.00	1.25	1.50	1.75
t	1.125	1.08333	1.04167	1.000	.95833	.91667	.875	.875
t^3	1.423828	1.271400	1.130292	1.0000	.880127	.770263	.669922	.669922
R_M	18.5625	18.58334	18.60417	18.625	18.64584	18.66667	18.6875	18.6875
R_M^2	344.5664	345.3404	346.1151	346.8906	347.6673	348.4446	349.2227	349.2227
R_i	18.0000	18.04167	18.08333	18.12500	18.16667	18.20833	18.25000	18.25000
$10^6 C_1 = \frac{10.92\,m}{E t^3}$	.093076	.104235	.117248	.132524	.150574	.172051	.197820	.197820
$C_2 = \frac{m E t}{R_M^2}$	16815	16156	15499	14846	14196	13548	12904	12904
$C_3 = \frac{P R_i R_M}{E t}$	.0021626	.0022535	.0023517	.0024581	.0025737	.0026999	.0028381	.0028381
$I/c = t^2/6$								



E 14

30 MW IHX BARREL SIDE

TAPERED WALL CALCULATIONS –

IN THE STRAIGHT WALL PORTION M & V ARE GIVEN BY –

$$M_0 = -.3025 \frac{Et^2}{R}\left(Y_0 - \frac{\theta}{\beta}\right)$$

$$V_0 = .3025 \frac{Et^2}{R}\left(-2Y_0\beta + \theta\right)$$

$$\beta = \frac{1.285}{\sqrt{Rt}} = \frac{1.285}{\sqrt{18.6875 \times .875}} = .31778$$

$$Y_0 = \Delta R - \Delta R^\circ$$

$$\Delta R^0 = \frac{P R_i R_M}{Et} = \frac{150 \times 18.25 \times 18.6875}{20.6 \times 10^6 \times .875} = .0028381$$

$$.3025 \frac{Et^2}{R} = \frac{.3025 \times 20.6 \times .875^2}{18.6875} \times 10^6 = .25530 \times 10^6$$

$$M_0 = -.25530 \times 10^6 \Delta R + .80339 \times 10^6 \theta + 724.5669$$

$$V_0 = -.16226 \times 10^6 \Delta R + .25530 \times 10^6 \theta + 460.5101$$

E15

30 MW IHX UPPER TUBE SHEET - BARREL WALL

TRIAL COMPUTATION · $Y_8 = 0$ $\theta_8 = 1$ $m = .25$

POINT	Y	$C_2Y = -\Delta V$	V	$mV = \Delta M$	M	$C_1M = \Delta\theta$	θ	$m\theta = \Delta Y$
8	0	0	255300		803390	.079463	1	
			255300	63825			1.079463	.269866
7	.269866	3482			867215	.171552		
			251818	62955			1.251015	.312754
6	.582620	7518			930170	.184006		
			244300	61075			1.435021	.358755
5	.941375	12754			991245	.170545		
			231546	57887			1.605566	.401392
4	1.342767	19062			1049132	.157972		
			212484	53121			1.763538	.440885
3	1.783652	26480			1102253	.146075		
			186004	46501			1.909613	.477403
2	2.261055	35044			1148754	.134689		
			150960	37740			2.044302	.511076
1	2.772131	44787			1186494	.123674		
			106173	26543			2.167976	.541994
0	3.314125	27864	78309		1213037	.056452	2.224428	

$M_8 = -.25530 \times 10^6 \Delta R + .80339 \times 10^6 \theta$

$M_8 = 803390$

$V_8 = -.16226 \times 10^6 \Delta R + .25530 \times 10^6 \theta$

$= 255300$

E16

30 MW IHX - UPPER TUBE SHEET - BARREL WALL

TRIAL COMPUTATION $Y_8 = 1$ $\Theta_8 = 0$ $m = .25$

POINT	Y	$C_2 Y = \Delta V$	V	$mV = \Delta M$	M	$C M = \Delta \theta$	θ	$m\theta = \Delta Y$
8	1	6452	-162260		-255300	-.025252	0	
			-168712	-42178			-.025252	-.006313
7	.993687	12823			-297478	-.058847		
			-181535	-45384			-.084099	-.021025
6	.972662	12551			-342862	-.067825		
			-194086	-48522			-.151924	-.037981
5	.934681	12663			-391384	-.067338		
			-206749	-51687			-.219262	-.054816
4	.879865	12491			-443071	-.066715		
			-219240	-54810			-.285977	-.071494
3	.808371	12001			-497881	-.065981		
			-231241	-57810			-.351958	-.087990
2	.720381	11165			-555691	-.065154		
			-242406	-60602			-.417112	-.104278
1	.616103	9954			-616293	-.064239		
			-252360	-63090			-.481351	-.120338
0	.495765	4168	-256528		-679383	-.031617	-.512968	

$$M_8 = -.25530 \times 10^6 \Delta R + .80339 \times 10^6 \Theta + 724.5669 = -255300$$

$$V_8 = -.16226 \times 10^6 \Delta R + .25530 \times 10^6 \Theta + 460.5101 = -162260$$

E 17

30 MW IHX - UPPER TUBE SHEET - BARREL WALL

TRIAL COMPUTATION $Y_8 = 0 = \theta_8$

$m = .25$ $P = 150$ PSI

PT.	$Y \times 10^6$	$(Y-C_3)10^6$	$-\Delta V =$ $C_2(Y-C_3)$	V	$mV = \Delta M$	M	10^6 $C_1M = \Delta\theta$	$\theta \times 10^6$	10^6 $m\theta = \Delta Y$
			18 311						
8	0	-2838.1	-18.311	461		725	71.710	0	
				479.311	119.828			71.710	17.928
7	17.928	-2820.172	-36.391			844.828	167.124		
				515.702	128.926			238.834	59.709
6	77.637	-2760.463	-35.621			973.754	192.628		
				551.323	137.308			431.462	107.866
5	185.503	-2514.397	-34.065			1111.062	191.159		
				585.388	146.347			622.621	155.655
4	341.158	-2232.542	-31.693			1257.409	189.333		
				617.081	154.270			811.954	202.989
3	544.147	-1913.953	-28.415			1411.679	187.081		
				645.496	161.374			999.035	249.759
2	793.906	-1557.794	-24.144			1573.053	184.437		
				669.640	167.410			1183.472	295.868
1	1089.774	-1163.726	-18.801			1740.463	181.417		
				688.441	172.110			1364.889	341.222
0	1430.996	-731.604	-6.151	694.592		1912.573	89.007	1453.896	

$$M_8 = -.25530 \times 10^6 \Delta R + .80339 \times 10^6 \theta + 724.5669 = 725$$

$$V_8 = -.16226 \times 10^6 \Delta R + .25530 \times 10^6 \theta + 460.5101 = 461$$

E 18

FROM THE TABLES THE EQUATIONS ARE—

$$M_0 = -679383\ Y_8 + 1213037\ \theta_8 + 1912.573 \qquad (a)$$

$$V_0 = -256528\ Y_8 + 78309\ \theta_8 + 694.592 \qquad (b)$$

$$Y_0 = .495765\ Y_8 + 3.314125\ \theta_8 + 1430.996 \times 10^{-6} \qquad (c)$$

$$\theta_0 = -.512968\ Y_8 + 2.224428\ \theta_8 + 1453.896 \times 10^{-6} \qquad (d)$$

From (c),

$$Y_8 = 2.017085\ Y_0 - 6.684871\ \theta_8 - 2886.440 \times 10^{-6} \qquad (e)$$

Substituting (e) into (d)

$$\theta_0 = -.512968\left[\overset{-1.034700\ Y_0}{2.017085\ Y_0} \overset{+3.429125\ \theta_8}{-6.684871\ \theta_8} \overset{+1480.651}{-2886.440 \times 10^{-6}}\right]$$

$$+ 2.224428\ \theta_8 + 1453.896 \times 10^{-6}$$

$$\theta_8 = .176880\ \theta_0 + .183018\ Y_0 - 519.062 \times 10^{-6} \qquad (f)$$

Substituting (f) into (e)

$$Y_8 = 2.017085\ Y_0 - 6.684871\left[\overset{-1.182420\ \theta_0}{.176880\ \theta_0} \overset{-1.223452}{+.183018\ Y_0} \overset{+3469.863}{-519.062 \times 10^{-1}}\right]$$

$$- 2886.440 \times 10^{-6}$$

$$Y_8 = .793633\ Y_0 - 1.182420\ \theta_0 + 583.426 \times 10^{-6} \qquad (g)$$

Substituting (f) & (g) into (a)

$$M_0 = -679383\left[\overset{-539181}{.793633\ Y_0} \overset{+803316\ \theta_0}{-1.182420\ \theta_0} \overset{-396.370}{+583.426 \times 10^{-6}}\right] + 1213037$$

$$\left[\overset{214562\ \theta_0}{.176880\ \theta_0} \overset{+222008\ Y_0}{+.183018\ Y_0} \overset{-629.641}{-519.062 \times 10^{-6}}\right] + 1912.573$$

$$M_0 = -317173\ Y_0 + 1017878\ \theta_0 + 886.562 \qquad (h)$$

E 19

Substituting (f) & (g) into (b)

$$V_0 = -256528\left[\overset{-203589\,Y_0\,,}{.793633\,Y_0} - \overset{+\,303324\,\Theta_0}{1.182420\,\Theta_0} + \overset{-\,149.665}{583.426 \times 10^{-6}}\right]$$

$$+78309\left[\overset{13851\,\Theta_0}{.176880\,\Theta_0} + \overset{+\,14332\,Y_0}{.183018\,Y_0} - \overset{-\,406.472}{519.062 \times 10^{-6}}\right] + 694.592$$

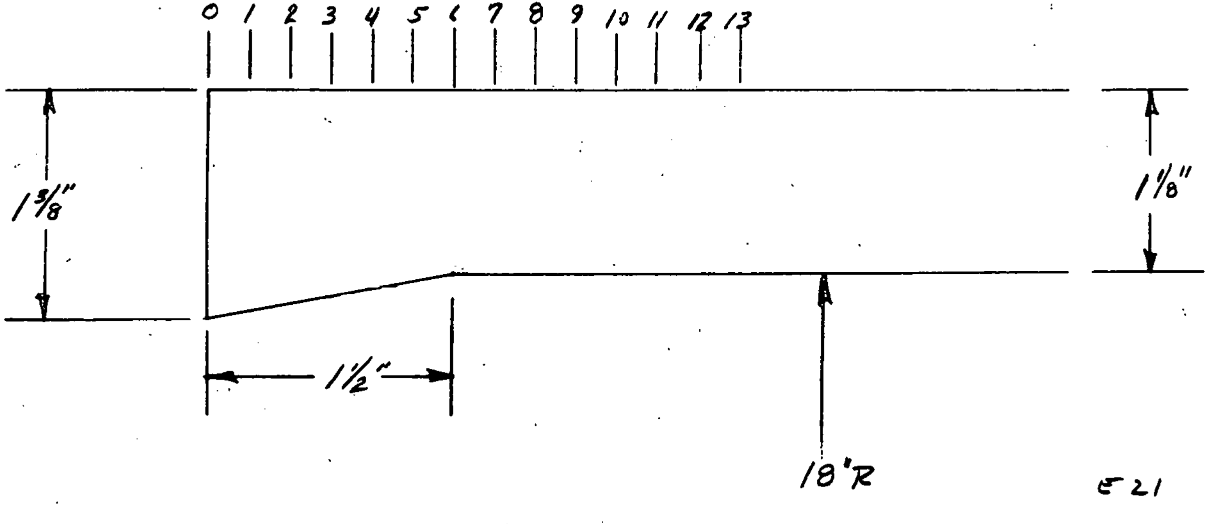
$$V_0 = -189257\,Y_0 + 317175\,\Theta_0 + 138.455 \qquad (j)$$

E20

PHYSICAL PROPERTIES SHELL SIDE 30MW IHX

$E = 21.6 \times 10^6$ $m = .25''$ POINT 6 & BEYOND ALIKE

POINT	0	1	2	3	4	5	6	7
DISTANCE	0	.25	.50	.75	1.00	1.25	1.50	1.75
t	1.375	1.333	1.29167	1.250	1.20833	1.16667	1.125	1.125
t^3	2.59961	2.37035	2.15503	1.95313	1.76425	1.58797	1.42383	1.42383
R_m	18.4375	18.45833	18.47917	18.500	18.52083	18.54167	18.5625	18.5625
R_m^2	339.9414	340.7099	341.4797	342.2500	343.0211	343.7935	344.5664	344.5664
R_i	17.750	17.79167	17.83333	17.875	17.91667	17.95833	18.000	18.000
$10^6 C_1 = \frac{10.92 m}{E t^3}$	.048618	.053321	.058648	.064711	.071639	.079591	.088767	.088767
$C_2 = \frac{m E t}{R_m^2}$	21842	21127	20426	19722	19022	18325	17631	17631
$C_3 = \frac{P R_i R_m}{E t}$	0	0	0	0	0	0	0	0
$I/c = t^2/6$	.315104	.296295	.278068	.260417	.243344	.226852	.210938	.210938



E21

30 MW IHX SHELL SIDE UPPER TUBESHEET

TRIAL COMPUTATION $M_{12}=1$ $V_{12}=\theta_{12}=Y_{12}=0$

POINT	$Y \times 10^6$	$C_2 Y = -\Delta V$	V	$mV=\Delta M$	M	10^6 $C_1 M=\Delta\theta$	$\theta \times 10^6$	$m\theta=\Delta Y$
12	0	0	0	0	1	.0443835	0	0
			0	0			.0443835	.0110959
11	.0110959	.0001956			1	.088767		
			-.0001956	-.0000489			.1331505	.0332876
10	.0443835	.0007825			.9999511	.0887627		
			-.0009781	-.0002445			.2219132	.0554783
9	.0998618	.0017607			.9997066	.0887410		
			-.0027388	-.0006847			.3106542	.0776636
8	.1775254	.0031300			.9990219	.0886802		
			-.0058688	-.0014672			.3993344	.0998336
7	.2773590	.0048901			.9975547	.0885499		
			-.0107589	-.0026897			.4878843	.1219711
6	.3993301	.0070406			.9948650	.0883112		
			-.0177995	-.0044499			.5761955	.1440489
5	.5433790	.0099574			.9904151	.0788281		
			-.0277569	-.0069392			.6550236	.1637559
4	.7071349	.0134511			.9834759	.0704552		
			-.0412080	-.0103020			.7254788	.1813697
3	.8885046	.0175231			.9731739	.0629751		
			-.0587311	-.0146828			.7884539	.1971135
2	1.0856181	.0221748			.9584911	.0562136		
			-.0809059	-.0202265			.8446675	.2111669
1	1.2967850	.0273972			.9382646	.0500292		
			-.1083031	-.0270758			.8946967	.2236742
0	1.5204592	.0166049	-.1249080	-.0312270	.9111888	.0221501	.9168468	

E22

30MW IHX SHELL SIDE UPPER TUBESHEET

TRIAL COMPUTATION $V_{12} = 1$ $M_{12} = \theta_{12} = Y_{12} = 0$

POINT	$Y \times 10^6$	$C_2Y = \Delta V$	V	$mV = \Delta M$	M	10^6 $C_1M = \Delta\theta$	$\theta \times 10^6$	$m\theta = \Delta Y$
12	0	0	1		0	0	0	
			1	.25			0	0
11	0	0			.25	.0221918		
			1	.25			.0221916	.0055480
10	.005548	.00009782			.500	.0443835		
			.99990218	.2499755			.0665753	.0166438
9	.0221918	.00039124			.7499755	.0665731		
			.99951092	.2498777			.1331484	.0332871
8	.0554789	.0009781			.9998532	.0887540		
			.9985328	.2496332			.2219024	.0554756
7	.1109545	.0019562			1.2494864	.1109182		
			.9965766	.2491442			.3328156	.0832039
6	.1941584	.0034232			1.4986306	.1330289		
			.9931534	.2482884			.4658445	.1164611
5	.3106195	.0056921			1.7469190	.1390390		
			.9874613	.2468653			.6048835	.1512209
4	.4618404	.0087851			1.9937843	.1428327		
			.9786762	.2446690			.7477162	.1869290
3	.6487694	.0127950			2.2384533	.1448526		
			.9658812	.2414703			.8925688	.2231422
2	.8719116	.0178097			2.4799236	.1454426		
			.9480715	.2370179			1.0380114	.2595028
1	1.1314144	.0239034			2.7169415	.1448700		
			.9241681	.2310420			1.1828814	.2957204
0	1.4271348	.0155857	.9397538		2.9479835	.0716625	1.2545431	
			.9085824					

E23

30 MW IHX - SHELL SIDE UPPER TUBESHEET

TRIAL COMPUTATION $Y_{12}=1$ $M_{12}=\theta_{12}=V_{12}=0$

POINT	Y	$C_2Y=-\Delta V$	V	$mV=\Delta M$	M	$C_1M=\Delta\theta$	θ	$m\theta=\Delta Y$
12	1	8815	0	0	0	0	0	0
			-8815	-2204			0	0
11	1	17631			-2204	-.0001956		
			-26446	-6612			-.0001956	-.0000489
10	.9999511	17630			-8816	-.0007826		
			-44076	-11019			-.0009782	-.0002446
9	.9997065	17626			-19835	-.0017607		
			-61702	-15426			-.0027389	-.0006847
8	.9990218	17614			-35261	-.0031300		
			-79316	-19829			-.0058689	-.0014672
7	.9975546	17588			-55090	-.0048902		
			-96904	-24226			-.0107591	-.0026898
6	.9948648	17540			-79316	-.0070406		
			-114444	-28611			-.0177997	-.0044499
5	.9904149	18149			-107927	-.0085900		
			-132593	-33148			-.0263897	-.0065974
4	.9838175	18714			-141075	-.0101065		
			-151307	-37827			-.0364962	-.0091241
3	.9746934	19223			-178902	-.0115769		
			-170530	-42632			-.0480731	-.0120183
2	.9626751	19664			-221534	-.0129925		
			-190194	-47548			-.0610656	-.0152664
1	.9474087	20016			-269082	-.0143477		
			-210210	-52552			-.0754133	-.0188533
0	.9285554	10141	-220351	-55088	-321634	-.0078186	-.0832319	

E24

30 MW IHX SHELL SIDE UPPER TUBESHEET

TRIAL COMPUTATION $\theta_{12}=1$ $M_{12}=V_{11}=Y_{12}=0$

POINT	Y	$GY=\Delta V$	V	$mV=\Delta M$	M	$GM=\Delta\theta$	θ	$m\theta=\Delta Y$
12	0	0	0		0		1	
			0	0			1	.2500
11	.2500	4407.8			0	0		
			-4407.8	-1102.0			1	.2500
10	.5000	8815.5			-1102.0	-.0000978		
			-13223.3	-3305.8			.9999022	.2499756
9	.7499756	13222.8			-4407.8	-.0003913		
			-26446.1	-6611.5			.9995109	.2498777
8	.9998533	17628.4			-11019.3	-.0009782		
			-44074.5	-11018.6			.9985327	.2496332
7	1.2494865	22029.7			-22037.9	-.0019562		
			-66104.2	-16526.0			.9965765	.2491441
6	1.4986306	26422.4			-38563.9	-.0034232		
			-92526.6	-23131.6			.9931533	.2482883
5	1.7469189	32012.3			-61695.5	-.0049104		
			-124538.9	-31134.7			.9882429	.2470607
4	1.9939796	37929.5			-92830.2	-.0066503		
			-162468.4	-40617.1			.9815926	.2453982
3	2.2393778	44165.0			-133447.3	-.0086355		
			-206633.4	-57658.4			.9729571	.2432393
2	2.4826171	50709.9			-185105.7	-.0108561		
			-257343.3	-64335.8			.9621010	.2405252
1	2.7231423	57531.8			-249441.5	-.0133005		
			-314875.1	-78718.8			.9488005	.2372001
0	2.9603424	32329.9	-347205.0		-328160.3	-.0079772	.9408233	

E 25

30 MW IHX SHELL CALCULATIONS

TAPERED WALL CALCULATIONS –

IN THE STRAIGHT WALL SECTION M & V ARE GIVEN BY –

$$M = .3025 \frac{Et^2}{R}\left(-Y + \frac{\theta}{\beta}\right)$$

$$V = .3025 \frac{Et^2}{R}\left(-2Y\beta + \theta\right)$$

$$\beta = \frac{1.285}{\sqrt{Rt}} = \frac{1.285}{\sqrt{(18.5625)(1.125)}} = .28194$$

$$M_{12} = -.424875 \times 10^6 Y_{12} + 1.51097 \times 10^6 \theta_{12}$$

$$V_{12} = -.278945 \times 10^6 Y_{12} + .424875 \times 10^6 \theta_{12}$$

WITH THESE EQUATIONS & FOUR MORE FROM THE TABLES M & V AT THE TUBESHEET ARE FOUND IN TERMS OF THE SLOPE & DISPLACEMENT AT THE TUBESHEET.

E26

COMBINING EQUATIONS - SHELL SIDE

$$M_0 = .9111888 M_{12} + 2.9479835 V_{12} - 321634 Y_{12} - 328160.3 \Theta_{12} \qquad (1)$$

$$V_0 = -.1249080 M_{12} + .9085824 V_{12} - 220351 Y_{12} - 347205 \Theta_{12} \qquad (2)$$

$$Y_0 = 1.5204592 \times 10^{-6} M_{12} + 1.4271348 V_{12} + .9285554 Y_{12} + 2.9603424 \Theta_{12} \qquad (3)$$

$$\Theta_0 = .9168468 \times 10^{-6} M_{12} + 1.2545439 V_{12} - .0832319 Y_{12} + .9408233 \Theta_{12} \qquad (4)$$

FOR THE STRAIGHT WALL -

$$M_{12} = -.424875 \times 10^6 Y_{12} + 1.51097 \times 10^6 \Theta_{12} \qquad (5)$$

$$V_{12} = -.238945 \times 10^6 Y_{12} + .424875 \times 10^6 \Theta_{12} \qquad (6)$$

SUBSTITUTING (5) & (6) INTO (1), (2) (3) & (4) -

$$M_0 = .9111888\left(\overset{-357141}{-424875 Y_{12}} \overset{[illegible]}{+1510970 \Theta_{12}}\right) + 2.9479835\left(\overset{[illegible]}{-238945 Y_{12}}\right.$$

$$\left.\overset{+1252524}{+424875 \Theta_{12}}\right) - 321634 Y_{12} - 328160 \Theta_{12}$$

$$M_0 = -141318\overset{\checkmark}{1} Y_{12} + 230114\overset{\checkmark}{3} \Theta_{12} \qquad (7)$$

$$V_0 = -.1249080\left(\overset{+53070}{-424875 Y_{12}} \overset{-188732}{+1510970 \Theta_{12}}\right) + .9085824\left(\overset{-217101}{-238945 Y_{12}}\right.$$

$$\left.\overset{+386034}{+424875 \Theta_{12}}\right) - 220351 Y_{12} - 347205 \Theta_{12}$$

$$V_0 = -384382 Y_{12} - 149903 \Theta_{12} \qquad (8)$$

$$Y_0 = 1.5204592\left(\overset{-.6460051}{-.424875 Y_{12}} \overset{2.2973682}{+1.51097 \Theta_{12}}\right) + 1.4271348\left(\overset{-.3410067}{-.238945 Y_{12}}\right.$$

$$\left.\overset{.6063539}{+.424875 \Theta_{12}}\right) + .9285554 Y_{12} + 2.9603424 \Theta_{12}$$

$$Y_0 = -.058\overset{\checkmark}{4}564 Y_{12} + 5.86406\overset{\checkmark}{4}5 \Theta_{12} \qquad (9)$$

E 27

$$\Theta_0 = .9168468\left(\overset{\overset{/}{-.3895453}}{-.424875}\,Y_{12} + \overset{\overset{/}{+1.3853280}}{1.51097}\,\Theta_{12}\right) + 1.2545439\left(\overset{-.2997670}{-.238945}\,Y_{12}\right.$$

$$\left.\overset{+.5330243}{+.424875}\,\Theta_{12}\right) - .0832319\,Y_{12} + .9408233\,\Theta_{12}$$

$$\Theta_0 = \overset{/}{-.7725442}\,Y_{12} + \overset{\checkmark}{2.8591756}\,\Theta_{12} \tag{10}$$

REARRANGING (10)

$$\Theta_{12} = \frac{1}{2.8591756}\left(\Theta_0 + .7725442\,Y_{12}\right) = .3497511\Theta_0 + .2701982\,Y_{12} \tag{11}$$

SUBSTITUTING THIS INTO (9)

$$Y_0 = -.0584584\,Y_{12} + 5.8640645\left(\overset{+2.0509630}{.3497511}\,\Theta_0 + \overset{+1.5844597}{.2701982}\,Y_{12}\right)$$

$$Y_{12} = \frac{1}{1.5260033}\left(Y_0 - 2.0509630\,\Theta_0\right) = .6553065\,Y_0 - 1.3440095\,\Theta_0 \tag{12}$$

SUBSTITUTING INTO (11) -

$$\Theta_{12} = .3497511\,\Theta_0 + .2701982\left(\overset{.1770626}{.6553065}\,Y_0 \overset{-.3631489}{-1.3440095}\,\Theta_0\right)$$

$$\Theta_{12} = -.0133978\,\Theta_0 + .1770626\,Y_0 \tag{13}$$

SUBSTITUTING (12) & (13) INTO (7) & (8)

$$M_0 = -1413181\left(\overset{-926067}{.6553065}\,Y_0 \overset{+1899329}{-1.3440095}\,\Theta_0\right)$$

$$+2301143\left(\overset{-30830}{-.0133978}\,\Theta_0 + \overset{+407446}{.1770626}\,Y_0\right)$$

$$M_0 = -518621\,Y_0 + 1868499\,\Theta_0 \tag{14}$$

$$V_0 = -384382\left(\overset{-251888}{.6553065}\,Y_0 \overset{+516613}{-1.3440095}\,\Theta_0\right)$$

$$-149903\left(\overset{+1943}{-.0133978}\,\Theta_0 + \overset{-25672}{.1770626}\,Y_0\right)$$

$$V_0 = -277560\,Y_0 + 518556\,\Theta_0 \tag{15}$$

E 28

30 MW IHX SHELL SIDE

CHECK CALCULATIONS $Y_{12} = \theta_{12} = 1$

POINT	Y	$C_2 Y = -\Delta V$	V	$mV = \Delta M$	M	$C_1 M = \Delta \theta$	θ	$m\theta = \Delta Y$
12	1	8816	185930		1086095	.048205	1	
			177114	44279			1.048205	.262051
11	1.262051	22251			1,130,374	.100340		
			154863	38716			1.148545	.287136
10	1.549187	27314			1.169090	.103777		
			127549	31887			1.252322	.313081
9	1.862268	32834			1200977	.106607		
			94715	23679			1.358929	.339732
8	2.202000	38823			1224656	.108709		
			55892	13973			1.467638	.366910
7	2.568910	45292			1238629	.109949		
			10600	2650			1.577587	.394397
6	2.963307	52246			1241790	.110230		
			-41646	-10412			1.687817	.421954
5	3.385261	59686			1231378	.098007		
			-101332	-25333			1.785824	.446456
4	3.831717	72887			1206045	.086400		
			-174219	-43555			1.872224	.468056
3	4.299773	84800			1162490	.075226		
			-259019	-64755			1.947450	.486863
2	4.786636	97772			1097735	.064380		
			-356791	-89198			2.011830	.502958
1	5.289594	111753			1008537	.053776		
			-468544	-117136			2.065606	.516402
0	5.805996	63470	-532014		891401	.021669	2.087275	

$M_{12} = -424875 + 1510970 = 1086095$

$V_{12} = -238945 + 424875 = 185930$

E 29

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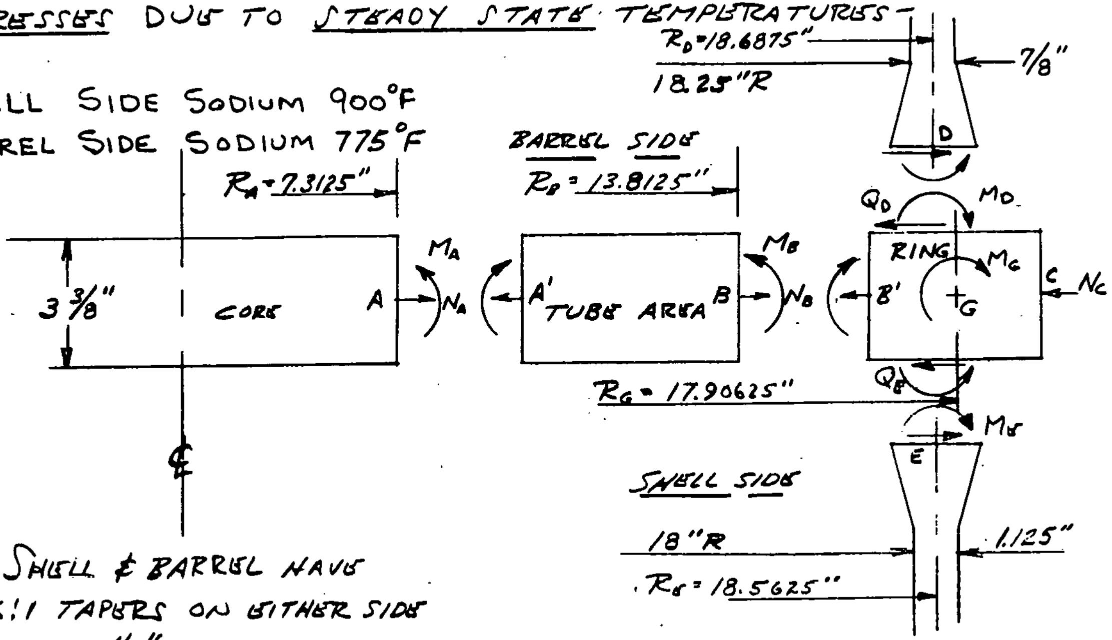
IHX TUBESHEET STRESSES

STEADY STATE & TRANSIENT
THERMAL STRESSES 4-F
LOWER TUBESHEET

30 MW IHX - LOWER TUBE SHEET

STRESSES DUE TO STEADY STATE TEMPERATURES -

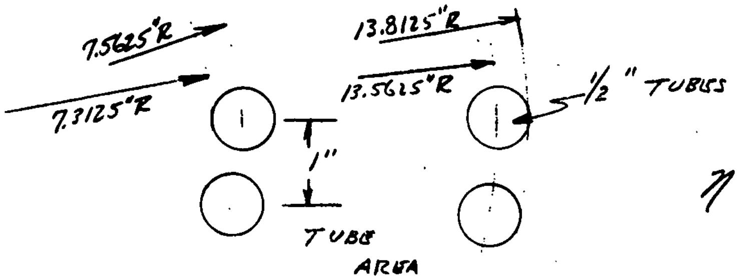
SHELL SIDE SODIUM 900°F
BARREL SIDE SODIUM 775°F



SHELL & BARREL HAVE
6:1 TAPERS ON EITHER SIDE
IN 1½" LENGTH.

MAX. THICKNESS - SHELL = 1 5/8"
BARREL = 1 3/8"

POSITIVE DIRECTION
AS SHOWN
ΔR = + OUTWARD
φ = + CCW



$\eta = \frac{.5}{1.0} = .500$

PHYSICAL CONSTANTS USED -

BARREL @ 775°F $E = 24.0 \times 10^6$ $\alpha = 10.8 \times 10^{-6}$
SHELL @ 900°F $E = 23.4 \times 10^6$ $\alpha = 11 \times 10^{-6}$
TUBE SHEET @ MEAN TEMP. $E = 23.7 \times 10^6$ $\alpha = 10.9 \times 10^{-6}$

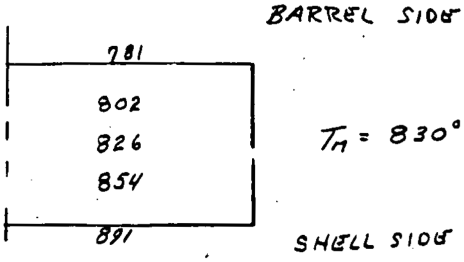
FROM HORVAY'S MIT PAPER $\frac{E^*}{E} = .40$ $E^* = 9.48 \times 10^6$
$\mu^* = .40$

TEMPERATURE BASE IS TAKEN AS 775°F

F2

CORE AREA -

STEADY STATE TEMPERATURES ARE AS GIVEN IN THE TEMPERATURE CALCULATIONS F43 & F44



FREE EXPANSION $\Delta R_A^o = R_A \alpha \Delta T$

$$= (7.3125)(10.9\times10^{-6})(830-775)$$

$$= 4384\times10^{-6}$$

$$\text{FREE ROTATION} = \frac{R_A \alpha \Delta T}{t} = \frac{(7.3125)(10.9\times10^{-6})(891-781)}{3.375} = 2598\times10^{-6}$$

FROM ROARK P. 276 # 28

$$\Delta R_A = \frac{N_A R_A}{E t}(1-\mu) + 4384\times10^{-6}$$

$$= \frac{7.3125\, N_A}{(23.7\times10^6)(3.375)}(1-.3) + 4384\times10^{-6}$$

$$\Delta R_A = .063994\times10^{-6} N_A + 4384\times10^{-6} \qquad (1)$$

FROM ROARK P. 197 #12

$$\theta_A = \frac{12(1-\mu)M_A R_A}{E t^3} + 2598\times10^{-6} = \frac{(12)(.7)(7.3125)M_A}{(23.7\times10^6)(3.375)^3} + 2598\times10^{-6}$$

$$\theta_A = .067418\times10^{-6} M_A + 2598\times10^{-6} \qquad (2)$$

TUBE AREA -

THE TUBE AREA IS TAKEN AS A SECTION AT A UNIFORM TEMPERATURE OF 775°F. NO FREE ROTATION.

FREE EXPANSIONS

$$\Delta R_A^o = (7.3125)(10.9\times10^{-6})(775-775) = 0$$

$$\Delta R_B^o = (13.8125)(10.9\times10^{-6})(775-775) = 0$$

FROM ROARK P. 276 # 27 & 28 –

$$\Delta R_{A'} = -\frac{N_A R_A}{E^* t}\left(\frac{R_B^2+R_A^2}{R_B^2-R_A^2}+\mu^*\right)+\frac{N_B R_A}{E^* t}\left(\frac{2R_B^2}{R_B^2-R_A^2}\right)$$

$$= -\frac{7.3125 N_A}{(9.48\times10^6)(3.375)}\left(\frac{13.8125^2+7.3125^2}{13.8125^2-7.3125^2}+.4\right)+\frac{7.3125 N_B}{(9.48\times10^6)(3.375)}\left(\frac{2\times13.8125^2}{13.8125^2-7.3125^2}\right)$$

$$\Delta R_{A'} = -.49798\times10^{-6} N_A + .63511\times10^{-6} N_B \qquad (3)$$

$$\Delta R_B = -\frac{N_A R_B}{E^* t}\left(\frac{2R_A^2}{R_B^2-R_A^2}\right)+\frac{N_B R_B}{E^* t}\left(\frac{R_B^2+R_A^2}{R_B^2-R_A^2}-\mu^*\right)$$

$$= -\frac{13.8125 N_A}{(9.48\times10^6)(3.375)}\left(\frac{2\times7.3125^2}{13.8125^2-7.3125^2}\right)+\frac{13.8125 N_B}{(9.48\times10^6)(3.375)}\left(\frac{13.8125^2+7.3125^2}{13.8125^2-7.3125^2}-.4\right)$$

$$\Delta R_B = -.33624\times10^{-6} N_A + .59526\times10^{-6} N_B \qquad (4)$$

FROM ROARK P. 201 # 25 & INTERPOLATING P. 215 TABLE –

$$\beta = \frac{7.3125}{13.8125} = .529$$

$$\theta_A = \frac{R_B}{E^* t^3}\left(-13.1\times1.048 M_A + 17.8 M_B\right)$$

$$\theta_A = -.52033\times10^{-6} M_A + .67463\times10^{-6} M_B \qquad (5)$$

$$\theta_B = \frac{R_B}{E^* t^3}\left(-9.3 M_A + 17.8\times.922 M_B\right)$$

$$\theta_B = -.35247\times10^{-6} M_A + .62200\times10^{-6} M_B \qquad (6)$$

COMBINE EQUATIONS OF CORE & TUBE AREA –

$$(1)=(3) \quad .063994 N_A + 4384 = -.49798 N_A + .63511 N_B$$

$$N_A = \frac{1}{.56197}\left(.63511 N_B - 4384\right) = 1.13015 N_B - 7801 \qquad (7)$$

$$(2)=(5) \quad .067418 M_A + 2598 = -.52033 M_A + .67463 M_B$$

$$M_A = \frac{1}{.58775}\left(.67463 M_B - 2598\right) = 1.14782 M_B - 4420 \qquad (8)$$

SUBSTITUTING (8) INTO (6) –

$$\theta_B = -.35247\times10^{-6}\left(1.14782 M_B - 4420\right) + .62200\times10^{-6} M_B$$

$$M_B = 4.5992\times10^6\,\theta_B - 7166 \qquad (9)$$

F4

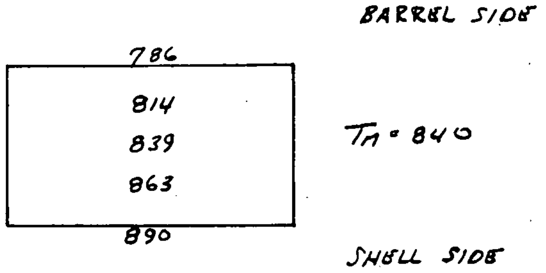
SUBSTITUTING (7) INTO (4) -

$$\Delta R_B = -.33624\times10^{-6}(\overset{-.38000}{1.13015 N_B} - \overset{+2623}{7801}) + .59526\times10^{-6} N_B$$

$$\Delta R_B = .21526\times10^{-6} N_B + 2623\times10^{-6} \qquad (10)$$

RING -

FREE EXPANSION



$$@\,G = (10.9\times10^{-6})(17.90625)(840-775)$$
$$= 12687\times10^{-6}$$

$$@\,B' = (10.9\times10^{-6})(13.8125)(840-775)$$
$$= 9786\times10^{-6}$$

$$\text{FREE ROTATION } @\,G = \frac{(10.9)(17.90625)(890-786)}{3.375} = 6014\times10^{-6}$$

FROM ROARK P. 276 # 27 & 28 -

$$\Delta R_{B'} = -\frac{N_B R_B}{E t}\left(\frac{R_C^2 + R_B^2}{R_C^2 - R_B^2} + \mu\right) - \frac{N_C R_B}{E t}\left(\frac{2 R_C^2}{R_C^2 - R_B^2}\right)$$

$$= -\frac{13.8125 N_B}{(23.7\times10^6)(3.375)}\left(\overset{2.30133+.3}{\frac{22^2 + 13.8125^2}{22^2 - 13.8125^2}} + .3\right) - \frac{13.8125 N_C}{(23.7\times10^6)(3.375)}\left(\overset{3.30[illegible]}{\frac{2\times 22^2}{22^2 - 13.8125^2}}\right)$$

$$\Delta R_{B'} = -.44921\times10^{-6} N_B - .57008\times10^{-6} N_C + 9786\times10^{-6} \qquad (11)$$

RESISTANCE TO ROTATION OF RING - FROM TIMOSHENKO - STR of MAT. PART II Pg 140

$$\theta_G = \frac{12 R_G M_G}{E t^3 \, Ln \, R_C/R_B} = \frac{(12)(17.90625) M_G}{(23.7\times10^6)(3.375)^3 \, Ln \, \underset{.46546}{\frac{22}{13.8125}}} = .50668\times10^{-6} M_G$$

$$M_G = 1.97363\times10^6(\theta_G - 6014\times10^{-6}) = 1.97363\times10^6\,\theta_G - 11869 \qquad (12)$$

F5

SHELL - FROM TAPER WALL CALCULATIONS - PP. F 33-40

$$M_E = -636143' \Delta R_E - 2310929\, \Theta_E + 16187 \qquad (13)$$

$$Q_E = 331369\, \Delta R_E + 636137\, \Theta_E - 8355 \qquad (14)$$

BARREL - FROM TAPER WALL CALCULATIONS - PP. F 25-32

$$M_D = -425809\, \Delta R_D + 1380085\, \Theta_D + 119 \qquad (15)$$

$$Q_D = 246147\, \Delta R_D - 425806\, \Theta_D - 220 \qquad (16)$$

LET N_C BE PROPORTIONAL TO Q_D & Q_E SUCH THAT -

$$N_C = \frac{18.6875}{22} Q_D + \frac{18.5625}{22} Q_E = .84943 Q_D + .84375 Q_E \qquad (17)$$

SUBSTITUTE (17) INTO (11) -

$$\Delta R_{B'} = -.44921 \times 10^{-6} N_B - .57008 \times 10^{-6} (\overset{-.4[illegible]}{.84943\, Q_D} + \overset{-.[illegible]}{.84375\, Q_E}) + 9786 \times 10^{-6}$$

$$\Delta R_{B'} = -.44921 \times 10^{-6} N_B - .48424 \times 10^{-6} Q_D - .48100 \times 10^{-6} Q_E + 9786 \times 10^{-6} \qquad (18)$$

$$(10) = (18) \quad .21526 N_B + 2623 = -.44921 N_B - .48424 Q_D - .48100 Q_E + 9786$$

$$N_B = \frac{1}{.66447} (-.48424\, Q_D - .48100\, Q_E + 7163)$$

$$N_B = -.72876\, Q_D - .72389\, Q_E + 10780 \qquad (19)$$

LET $\Theta_G = \Theta_B = \Theta_D = \Theta_E = \varphi$ = FINAL ROTATION OF RING

DISPLACEMENT OF POINT D NEGLECTING SMALL TERMS -

$$\Delta R_D = \Delta R_B - \frac{3.375}{2} \varphi$$

$$= -.44921 \times 10^{-6} N_B - .48424 \times 10^{-6} Q_D - .48100 \times 10^{-6} Q_E + 9786 \times 10^{-6} - 1.6875 \varphi$$

SUBSTITUTING FROM (19) -

$$= -.44921 \times 10^{-6} (\overset{+.32737}{-.72876\, Q_D} \overset{+.32519}{- .72389\, Q_E} \overset{-4842}{+ 10780}) - .48424 \times 10^{-6} Q_D$$

F6

$$-.48100 \times 10^{-6} \varphi_E + 9786 \times 10^{-6} - 1.6875 \varphi$$

$$\Delta R_D = -.15687 \times 10^{-6} \varphi_D - .15582 \times 10^{-6} \varphi_E + 4944 \times 10^{-6} - 1.6876 \varphi$$

SUBSTITUTING FOR φ_D & φ_E FROM (14) & (16)

$$= -.15687 (\overset{-.038613}{.246147} \Delta R_D \overset{+.066796}{-.425806} \varphi \overset{+.000035}{-.000220})$$

$$-.15582 (\overset{-.051634}{.331369} \Delta R_E \overset{-.099123}{+.636137} \varphi \overset{+.001302}{-.008355}) + .004944 - 1.6875 \varphi$$

$$\Delta R_D = -.038613 \Delta R_D - .051634 \Delta R_E - 1.719827 \varphi + .006281$$

$$\Delta R_D = -.049714 \Delta R_E - 1.655888 \varphi + .006047 \qquad (20)$$

$$\Delta R_E = \Delta R_D + \varphi t \qquad t = 3.375$$

$$\Delta R_E = -.038613 \Delta R_D - .051634 \Delta R_E + 1.655173 \varphi + .006281$$

$$\Delta R_E = -.036717 \Delta R_D + 1.573906 \varphi + .005973 \qquad (21)$$

SUBSTITUTING (21) INTO (20)

$$\Delta R_D = -.049714 (\overset{+.001825}{-.036717} \Delta R_D \overset{-.078245}{+1.573906} \varphi \overset{-.000297}{+.005973}) - 1.655888 \varphi$$

$$+ .006047$$

$$\Delta R_D = -1.737304 \varphi + .005761 \qquad (22)$$

$$\Delta R_E = \Delta R_D + 3.375 \varphi = -1.737304 \varphi + .005761 + 3.375 \varphi$$

$$\Delta R_E = 1.637696 \varphi + .005761 \qquad (23)$$

F7

$$\frac{13.8125}{17.90625} M_B + \frac{18.6875}{17.90625} M_D - \frac{18.5625}{17.90625} M_E + \frac{18.5625}{17.90625} \times 1.6875\, \varphi_E$$

$$- \frac{18.6875}{17.90625} \cdot 1.6875\, \varphi_D + M_G = 0$$

$$.77138\, M_B + 1.04363\, M_D - 1.036649\, M_E + 1.749346\, \varphi_E - 1.761126\, \varphi_D$$

$$+ M_G = 0$$

SUBSTITUTING VALUES FOR M_B, M_D, M_E, φ_E, φ_D, & M_G,

$$.77138\left(\overset{3.54773}{4.5992} \times 10^6 \varphi \overset{-5527.7091}{- 7166}\right) + 1.04363\left(\overset{-444367}{-425809}\, \Delta R_D \overset{+1440298}{+ 1380085}\, \varphi\right.$$

$$\left. \overset{+124}{+ 119}\right) - 1.036649\left(\overset{+659457}{-636143}\, \Delta R_E \overset{+2395622}{- 2310929}\, \varphi \overset{-16780}{+ 1.6187.}\right)$$

$$+ 1.749346\left(\overset{579679}{331369}\, \Delta R_E + \overset{1,112,821}{636137}\, \varphi - \overset{-14616}{8355}\right)$$

$$- 1.761126\left(\overset{-433496}{246147}\, \Delta R_D \overset{+749898}{- 425806}\, \varphi \overset{+387}{-} 220\right) + 1.97363 \times 10^6 \varphi$$

$$- 11869 = 0$$

$$11220002\, \varphi - 877883\, \Delta R_D + 1239136\, \Delta R_F - 48282 = 0$$

$$11220002\, \varphi - 877883\left(\overset{+1,525,150}{-1.737304}\, \varphi + \overset{-5057}{.005761}\right)$$

$$+ 1239136\left(\overset{2,029,328}{1.637696}\varphi \overset{+7139}{+} .005761\right) - 48282 = 0$$

$$14774480\, \varphi = 46200 \qquad \varphi = .003127$$

F8

$$\Delta R_D = -\overset{-5433}{1.737304}(3127\times10^{-6}) + 5761\times10^{-6} = 328\times10^{-6}$$

$$\Delta R_E = \overset{5121}{1.637696}(3127\times10^{-6}) + 5761\times10^{-6} = 10882\times10^{-6}$$

$$M_D = -\overset{-140}{.425809}(328) + \overset{4316}{1.380085}(3127) + 119 = 4295$$

$$M_E = -\overset{-6923}{.636143}(10882) - \overset{-7226}{2.310929}(3127) + 16187 = 2038$$

$$Q_D = \overset{81}{.246147}(328) - \overset{-1331}{.425806}(3127) - 220 = -1470$$

$$Q_E = \overset{3606}{.331369}(10882) + \overset{1989}{.636137}(3127) - 8355 = -2760$$

$$M_B = \overset{14382}{4.5992}(3127) - 7166 = 7216$$

$$M_G = \overset{6172}{1.97363}(3127) - 11869 = -5697$$

SUBSTITUTING INTO MOMENT EQUATION :—

$$.77138(7216) + 1.04363(4295) - 1.036649(2038) + 1.749346(-2760)$$

$$-1.761126(-1470) - 5697 = 0$$

FROM (8), $M_A = \overset{8283}{1.14782}(7216) - 4420 = 3863$

FROM (19) $N_B = -\overset{+1071}{.72876}(-1470) - \overset{+1998}{.72389}(-2760) + 10780 = 13849$

FROM (7) $N_A = \overset{15651}{1.13015}(\underset{N_B}{13849}) - 7801 = 7850$

STRESSES - STEADY STATE THERMAL WITHOUT PRESSURE

TUBE AREA: IN THE TUBE AREA, THE BENDING STRESSES ARE GIVEN BY: (ROARK)

RADIAL STRESS $= S_R = \dfrac{6}{t^2(R_B^2 - R_A^2)}\left[R_B^2 M_B - R_A^2 M_A - \dfrac{R_B^2 R_A^2}{R^2}(M_B - M_A)\right]$

TANGENTIAL STRESS $= S_T = \dfrac{6}{t^2(R_B^2 - R_A^2)}\left[R_B^2 M_B - R_A^2 M_A + \dfrac{R_B^2 R_A^2}{R^2}(M_B - M_A)\right]$

WHERE R IS RADIUS TO ANY POINT & OTHER TERMS ARE AS PREVIOUSLY DEFINED.

F9

$$\frac{6}{t^2(R_B^2-R_A^2)} = \frac{6}{(3.375)^2(13.8125^2-7.3125^2)} = .0038361$$

$R_B^2 = 13.8125^2 = 190.78515625$ $\quad R_A^2 = 7.3125^2 = 53.47265625$

$R_B^2 R_A^2 = 10201.789$

AT THE INNERMOST LIGAMENT $R = 7.5625''$

$$\frac{R_B^2 R_A^2}{R^2} = \frac{10201.789}{(7.5625)^2} = 178.380$$

$$S_R = .0038361\Big[\overset{1,376,706}{190.7852(7216)} - \overset{-206,565}{53.4727(3863)} - \overset{-598108}{178.380}\big(\underset{3353}{7216-3863}\big)\Big]$$

$= 2194$ C ON TOP

$$S_T = .0038361\Big[\overset{1765249}{1376706 - 206565 + 598108}\Big] = 6783 \text{ C ON TOP}$$

AT THE OUTERMOST LIGAMENT $R = 13.5625$

$$\frac{R_B^2 R_A^2}{R^2} = 55.4622$$

$$S_R = .0038361\Big[1376706 - 206565 - \overset{-185965}{55.4622(3353)}\Big] = 3775 \text{ C ON TOP}$$

$$S_T = .0038361\Big[1376706 - 206565 + 185965\Big] = 5202 \text{ C ON TOP}$$

THE NORMAL STRESS IS GIVEN BY (ROARK)

$$\text{RADIAL STRESS} = S_R = \frac{N_A}{t}\,\frac{R_A^2}{R^2}\left(\frac{R_B^2-R^2}{R_B^2-R_A^2}\right) + \frac{N_B}{t}\,\frac{R_B^2}{R^2}\left(\frac{R^2-R_A^2}{R_B^2-R_A^2}\right)$$

$$\text{TANGENTIAL STRESS} = S_T = -\frac{N_A}{t}\,\frac{R_A^2}{R^2}\left(\frac{R_B^2+R^2}{R_B^2-R_A^2}\right) + \frac{N_B}{t}\,\frac{R_B^2}{R^2}\left(\frac{R^2+R_A^2}{R_B^2-R_A^2}\right)$$

AT INNERMOST LIGAMENT $R = 7.5625''$

$\frac{R_A^2}{t\,R^2} = .27703$ $\quad \frac{R_B^2}{t\,R^2} = .98842$ $\quad \frac{R_B^2+R^2}{R_B^2-R_A^2} = 1.8059$

$\frac{R_B^2-R^2}{R_B^2-R_A^2} = .97292$ $\quad \frac{R^2-R_A^2}{R_B^2-R_A^2} = .027082$ $\quad \frac{R^2+R_A^2}{R_B^2-R_A^2} = .80593$

F10

$$S_R = 7850(\overset{2116}{.27703})(.97292) + 13849(\overset{371}{.98842})(.027082) = 2487 \ T$$

$$S_T = -7850(\overset{-3927}{.27703})(1.8059) + 13849(\overset{11032}{.98842})(.80593) = 7105 \ T$$

AT THE OUTERMOST LIGAMENT, $R = 13.5625$

$$\frac{R_A^2}{tR^2} = .086135 \qquad \frac{R_B^2}{tR^2} = .30732 \qquad \frac{R_B^2 + R^2}{R_B^2 - R_A^2} = 2.72901$$

$$\frac{R_B^2 - R^2}{R_B^2 - R_A^2} = .049841 \qquad \frac{R^2 - R_A^2}{R_B^2 - R_A^2} = .95016 \qquad \frac{R^2 + R_A^2}{R_B^2 - R_A^2} = 1.72901$$

$$S_R = 7850(\overset{33.7}{.086135})(.049841) + 13849(.30732)\overset{4043.95}{(.95016)} = 4078 \quad T$$

$$S_T = -7850(\overset{-1845.25}{.086135})(2.72901) + 13849(.30732)\overset{7358.80}{(1.72901)} = 5514 \quad T$$

__TUBE__ __AREA__ __STRESSES__ BECOME

__INNER__ __ROW__ $\eta = .500$ $\qquad\qquad \frac{\sigma}{\sigma_{max}}$

SHELL SIDE $\sigma_R = 2487 + 2194 = 4681$ $\quad .337 \quad K = 3.1 \quad \sigma_R = 14511$
(BOTTOM) $\sigma_T = 7105 + 6783 = 13888$ $\quad \sigma_T = 43053$

BARREL SIDE $\sigma_R = 2487 - 2194 = 293$ $\quad .910 \quad K = 2.5 \quad \sigma_R = 733$
(TOP) $\sigma_T = 7105 - 6783 = 322$ $\quad \sigma_T = 805$

__OUTER__ __ROW__

SHELL SIDE $\sigma_R = 4078 + 3775 = 7853$ $\quad 733 \quad K = 2.55 \quad \sigma_R = 20025$
(BOTTOM) $\sigma_T = 5514 + 5202 = 10716$ $\quad \sigma_T = 27326$

BARREL SIDE $\sigma_R = 4078 - 3775 = 303$ $\quad .971 \quad K = 2.4 \quad \sigma_R = 727$
(TOP) $\sigma_T = 5514 - 5202 = 312$ $\quad \sigma_T = 749$

F11

BARREL STRESSES - AT JUNCTION WITH TUBE SHEET

$$\frac{6}{t^2} = \frac{6}{1.875^2} = 1.70667$$

$$\Delta R_D = 328 \times 10^{-6}$$

$$\Delta R_D^\circ = (10.8 \times 10^{-6})(791 - 775) \begin{cases} \to (18.0) & = 3110 \times 10^{-6} \\ \to (19.375) & = 3348 \times 10^{-6} \end{cases}$$

LONGITUDINAL STRESS

$$S_L = \frac{6 M_D}{t^2} = 1.70667 \times 4295 = 7330 \quad \begin{matrix} C & \text{OUTSIDE} \\ T & \text{INSIDE} \end{matrix}$$

CIRCUMFERENTIAL STRESS $= S_c = \dfrac{\Delta R - \Delta R^\circ}{R} E \pm \mu S_L$

OUTER SURFACE $S_c = \overset{-3741}{\dfrac{328 - 3348}{19.375}(24.0)} - 0.3\overset{2199}{(7330)} = 5940 \text{ C}$

INNER SURFACE $S_c = \overset{-3709}{\dfrac{328 - 3110}{18}(24.0)} + 0.3\overset{2199}{(7330)} = 1510 \text{ C}$

SHELL STRESSES - AT JUNCTION WITH TUBE SHEET

$$\frac{6}{t^2} = \frac{6}{2.125^2} = 1.32872$$

$$\Delta R_E = 10882 \times 10^{-6}$$

$$\Delta R_E^\circ = (11 \times 10^{-6})(893 - 775) \begin{cases} \to 17.5 & = 22715 \times 10^{-6} \\ \to 19.625 & = 25473 \times 10^{-6} \end{cases}$$

LONGITUDINAL STRESS

$$S_L = \frac{6 M_E}{t^2} = 1.32872 \times 2038 = 2708 \quad \begin{matrix} C & \text{OUTSIDE} \\ T & \text{INSIDE} \end{matrix}$$

CIRCUMFERENTIAL STRESS $S_c = \dfrac{\Delta R - \Delta R^\circ}{R} E \pm \mu S_L$

OUTER SURFACE $S_c = \overset{-17398}{\dfrac{10882 - 25473}{19.625}(234)} - .3(\overset{-812}{2708}) = 18210 \text{ C}$

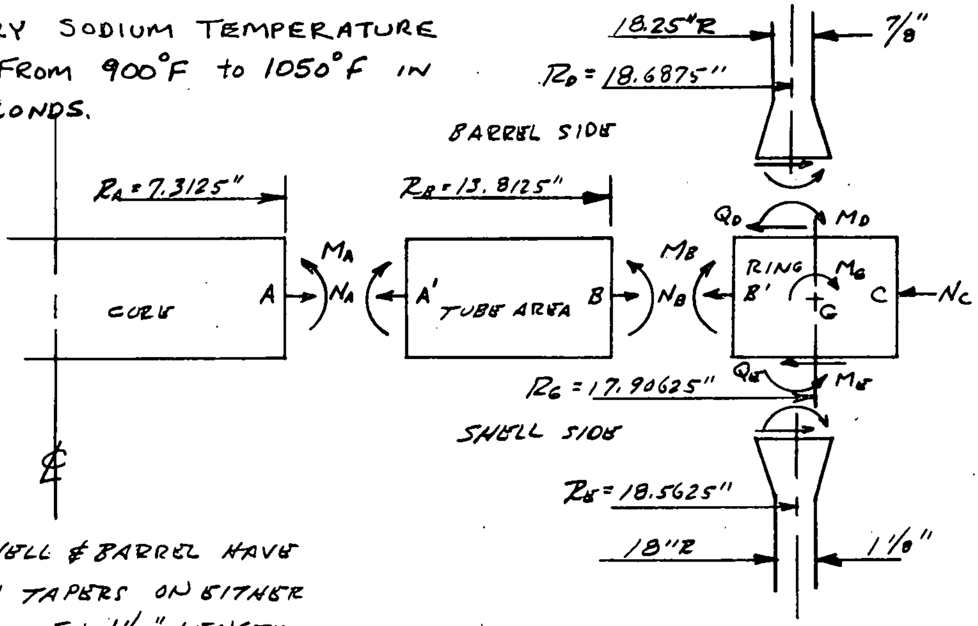
INNER SURFACE $S_c = \overset{-15822}{\dfrac{10882 - 22715}{17.5}(23.4)} + .3(\overset{+812}{2708}) = 15010 \text{ C}$

F12

30 MW IHX - LOWER TUBE SHEET

STRESSES DUE TO TRANSIENT TEMPERATURES

PRIMARY SODIUM TEMPERATURE RISES FROM 900°F to 1050°F IN 15 SECONDS.



SHELL & BARREL HAVE 6:1 TAPERS ON EITHER SIDE IN 1½" LENGTH

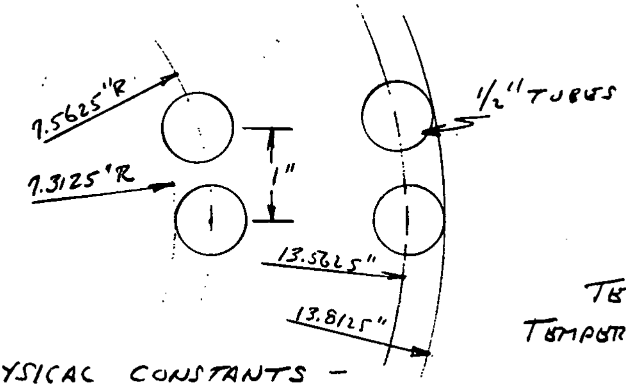
MAX THICKNESS SHELL 1 5/8"

BARREL 1 3/8"

POSITIVE DIRECTION AS SHOWN

ΔR = + OUTWARD

φ = + CCW



$$\eta = \frac{.5}{1.0} = .500$$

TEMPERATURE BASE = 775°F

TEMPERATURES @ 200 SEC AFTER SUDDEN 150°ΔT RISE IN PRIMARY SODIUM. SECONDARY NOT FLOWING.

PHYSICAL CONSTANTS -

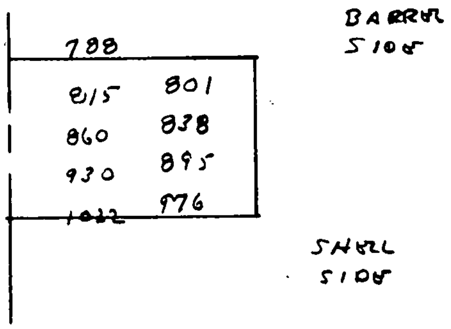
BARREL	$E = 24.0 \times 10^6$	$\alpha = 10.8 \times 10^{-6}$
SHELL	$E = 22.8 \times 10^6$	$\alpha = 11.2 \times 10^{-6}$
CORE	$E = 24 \times 10^6$	$\alpha = 10.8 \times 10^{-6}$
TUBE AREA	$E = 24.1 \times 10^6$	$\alpha = 10.7 \times 10^{-6}$
RING	$E = 24 \times 10^6$	$\alpha = 10.8 \times 10^{-6}$

FROM HORVAY'S MIT PAPER $\frac{E^*}{E} = .4$ $E^* = 24.1 \times 10^6 \times .4 = 9.64 \times 10^6$

$\nu^* = .40$

F13

CORE AREA - TEMPERATURES FROM TEMP. CALCULATIONS F41-49



$\overline{T}_{AVE}$

801
838
895
976
$4\overline{)3510}$
878

THERMAL MOMENT

801X.5	=	400.5
838X1.5	=	1257.0
895X2.5	=	2237.5
976X3.5	=	3416.0
		7311
878X4X2	=	7024
M_T	=	287

$$\text{EQUIVALENT } \Delta T = \frac{287 \times 6}{(4)^2} = 107.6\,^\circ F$$

MIDPOINT TO SURFACE

$$\text{FREE EXPANSION} = (7.3125)(10.8 \times 10^{-6})(878-775) = 8134.4 \times 10^{-6}$$

$$\text{FREE ROTATION} = \frac{(7.3125)(10.8 \times 10^{-6})(107.6)}{3.375/2} = 5035.68 \times 10^{-6}$$

FROM ROARK P.276 #28

$$\Delta R_A = \frac{N_A R_A}{Et}(1-\mu) + 8134.4 \times 10^{-6}$$

$$\Delta R_A = \frac{7.3125\, N_A}{(24 \times 10^6)(3.375)}(.7) + 8134 \times 10^{-6} = .063194 \times 10^{-6} N_A + 8134 \times 10^{-6} \qquad (1)$$

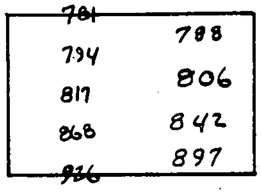
FROM ROARK P. 197 #12

$$\theta_A = \frac{12(1-\mu) M_A R_A}{Et^3} + 5036 \times 10^{-6}$$

$$\theta_A = \frac{(12)(.7)(7.3125) M_A}{(24 \times 10^6)(3.375)^3} + 5036 \times 10^{-6} = .066575 \times 10^{-6} M_A + 5036 \times 10^{-6} \qquad (2)$$

F14

TUBE AREA -



BARREL SIDE

SHELL SIDE

TAVG

$$\begin{array}{r} 788 \\ 806 \\ 842 \\ 897 \\ \hline 4\,)\,3333 \\ 833 \end{array}$$

THERMAL MOMENT

$788 \times 1/2 = 394$
$806 \times 1 1/2 = 1209$
$842 \times 2 1/2 = 2105$
$897 \times 3 1/2 = 3139.5$

$$\begin{array}{r} 6847.5 \\ 6664.0 \\ \hline M_T = 183.5 \end{array}$$

$833 \times 4 \times 2$

EQUIVALENT ΔT
FROM MID-POINT $= \frac{6(183.5)}{(4)^2} = 68.8°F$

FREE EXPANSION

$$\Delta R_A^{\circ} = (7.3125)(10.7\times10^{-6})(833-775) = 4538\times10^{-6}$$

$$\Delta R_B^{\circ} = (13.8125)(10.7\times10^{-6})(833-775) = 8572\ \times10^{-6}$$

FREE ROTATION

$$\Delta\theta_A^{\circ} = \frac{(7.3125)(10.7\times10^{-6})(68.8)}{3.375/2} = 3190\times10^{-6}$$

$$\Delta\theta_B^{\circ} = \frac{(13.8125)(10.7\times10^{-6})(68.8)}{3.375/2} = 6026\times10^{-6}$$

FROM ROARK P.276 #27 & 28

$$\Delta R_A' = -\frac{N_A R_A}{E^* t}\left(\frac{R_B^2+R_A^2}{R_B^2-R_A^2}+\mu^*\right)+\frac{N_B R_A}{E^* t}\left(\frac{2 R_B^2}{R_B^2-R_A^2}\right)$$

$$= -\frac{7.3125 N_A}{(9.64\times10^6)(3.375)}\left(\overset{1.77885+.4}{\frac{13.8125^2+7.3125^2}{13.8125^2-7.3125^2}}+.4\right)+\frac{7.3125 N_B}{(9.64\times10^6)(3.375)}\left(\overset{2.77885}{\frac{2\times13.8125^2}{13.8125^2-7.3125^2}}\right)$$

$$\Delta R_A' = -.48971\times10^{-6} N_A + .62457\times10^{-6} N_B + 4538\times10^{-6} \qquad (3)$$

F15

$$\Delta R_B = -\frac{N_A R_B}{E^* t}\left(\frac{2 R_A^2}{R_B^2 - R_A^2}\right) + \frac{N_B R_B}{E^* t}\left(\frac{R_B^2 + R_A^2}{R_B^2 - R_A^2} - \mu^*\right)$$

$$= -\frac{13.8125 N_A}{(9.64\times10^6)(3.375)}\left(\overset{.77885}{\frac{2\times7.3125^2}{13.8125^2-7.3125^2}}\right) + \frac{13.8125 N_B}{(9.64\times10^6)(3.375)}\left(\overset{1.77885}{\frac{13.8125^2+7.3125^2}{13.8125^2-7.3125^2}} - .4\right)$$

$$\Delta R_B = -.33066\times10^{-6} N_A + .58538\times10^{-6} N_B + 8572\times10^{-6} \qquad (4)$$

FROM ROARK P.201 #25 & INTERPOLATING P.215 TABLE

$$\beta = \frac{7.3125}{13.8125} = .529$$

$$\theta_{A'} = \frac{R_B}{E^* t^3}\left(-13.1\times1.048 M_A + 17.8 M_B\right) + 3190\times10^{-6}$$

$$\theta_{A'} = -.51169\times10^{-6} M_A + .66343\times10^{-6} M_B + 3190\times10^{-6} \qquad (5)$$

$$\theta_B = \frac{R_B}{E^* t^3}\left(-9.3 M_A + 17.8\times.922 M_B\right) + 6026\times10^{-6}$$

$$\theta_B = -.34662\times10^{-6} M_A + .61168\times10^{-6} M_B + 6026\times10^{-6} \qquad (6)$$

COMBINE EQUATIONS OF CORE & TUBE AREA –

$$(1)=(3) \quad .063194 N_A + 8134 = -.48971 N_A + .62457 N_B + 4538$$

$$N_A = \frac{1}{.552904}\left(.62457 N_B - 3596\right) = 1.12962 N_B - 6504 \qquad (7)$$

$$(2)=(5) \quad .666575 M_A + 5036 = -.51169 M_A + .66343 M_B + 3190$$

$$M_A = \frac{1}{.578265}\left(.66343 M_B - 1846\right) = 1.14728 M_B - 3192 \qquad (8)$$

SUBSTITUTING (8) INTO (6) –

$$\theta_B = -.34662\times10^{-6}\overset{-.39767 \quad +1106}{\left(1.14728 M_B - 3192\right)} + .61168\times10^{-6} M_B + 6026\times10^{-6}$$

$$M_B = 4.6727\times10^{6}\,\theta_B - 33326 \qquad (9)$$

SUBSTITUTING (7) INTO (4) –

$$\Delta R_B = -.33066\times10^{-6}\overset{-.37352 \quad +2151}{\left(1.12962 N_B - 6504\right)} + .58538\times10^{-6} N_B + 8572\times10^{-6}$$

$$\Delta R_B = .21186\times10^{-6} N_B + 10723\times10^{-6} \qquad (10)$$

FIG

RING

BARREL SIDE

~~989~~	
824	807
865	844
917	891
~~979~~	948

SHELL SIDE

TAVG

807
844
891
948
$4 \overline{)3490}$
872

THERMAL MOMENT

807 × ½ = 403.5
844 × 1½ = 1266.0
891 × 2½ = 2227.5
948 × 3½ = 3318.0
7215
872 × 4 × 2 = 6976
M_T = 239

$$\Delta T = \frac{6(239)}{(4)^2} = 89.6\ ^\circ F$$

FREE EXPANSION

$$@\ G \quad \Delta R_G^{\circ} = (17.90625)(10.8\times10^{-6})(872-775) = 18759\times10^{-6}$$

$$@\ B' \quad \Delta R_{B'}^{\circ} = (13.8125)(10.8\times10^{-6})(872\text{-}775) = 14470\times10^{-6}$$

$$\text{FREE ROTATION @ G -} \quad \frac{(10.8)(17.90625)(89.6)}{3.375/2} = 10268\times10^{-6}$$

FROM ROARK P.276 # 27 & 28 -

$$\Delta R_{B'} = -\frac{N_B R_B}{Et}\left(\frac{R_C^2+R_B^2}{R_C^2-R_B^2} + \mu\right) - \frac{N_C R_B}{Et}\left(\frac{2R_C^2}{R_C^2 - R_B^2}\right)$$

$$= -\frac{13.8125 N_B}{(24\times10^6)(3.375)}\left(\frac{\overset{-\,2.30133+3}{22^2+13.8125^2}}{22^2-13.8125^2} +.3\right) - \frac{13.8125 N_C}{(24\times10^6)(3.375)}\left(\frac{\overset{3.30133}{2\times22^2}}{22^2-13.8125^2}\right)$$

$$\Delta R_{B'} = -.39243\times10^{-6}N_B - .56296\times10^{-6}N_C + 14470\times10^{-6} \qquad (11)$$

RESISTANCE TO ROTATION OF RING - FROM ROARK P.231

$$\theta_G = -\frac{12 R_G M_G}{Et^3 Ln\ R_C/R_B} = -\frac{(12)(17.90625)M_G}{(24)(3.375)^3 Ln\ 22/13.8125} = .50035\times10^{-6}M_G$$

$$M_G = 1.99860\times10^6(\theta_G - 10268\times10^{-6}) = 1.99860\times10^6\theta_G - 20522 \quad (12)$$

F17

SHELL - FROM TAPER WALL CALCULATIONS F33-F40

$$M_E = -636143\ \Delta R_E - 2310929\ \varphi_E + 35525 \qquad (13)$$

$$Q_E = 331369\ \Delta R_E + 636137\ \varphi_E - 17515 \qquad (14)$$

BARREL - FROM TAPER WALL CALCULATIONS. F25-F32

$$M_D = -425809\ \Delta R_D + 1380085\varphi + 160.82 \qquad (15)$$

$$Q_D = 246147\ \Delta R_D - 425806\ \varphi_D - 266.88 \qquad (16)$$

LET N_C BE PROPORTIONAL TO Q_D & Q_E SUCH THAT-

$$N_C = \frac{18.6875}{22} Q_D + \frac{18.5625}{22} Q_E = .84943 Q_D + .84375 Q_E \qquad (17)$$

SUBSTITUTING (17) INTO (11) -

$$\Delta R_{B'} = -.39243 \times 10^{-6} N_B - .56296 \times 10^{-6} (.84943 Q_D + .84375 Q_E) + 14470 \times 10^{-6}$$

$$\Delta R_{D}' = -.39243 \times 10^{-6} N_B - .47820 \times 10^{-6} Q_D - .47500 \times 10^{-6} Q_E + 14470 \times 10^{-6} \qquad (18)$$

$$(10) = (18) \quad .21186 N_B + 10723 = -.39243 N_B - .47820 Q_D - .47500 Q_E + 14470$$

$$N_B = \frac{1}{.60429} (-.47820 Q_D - .47500 Q_E + 3747)$$

$$N_B = -.79134 Q_D - .78605 Q_E + 6201 \qquad (19)$$

LET. $\Theta_C = \Theta_B = \Theta_D = \Theta_E = \varphi$ = FINAL ROTATION OF RING-

DISPLACEMENT OF POINT D NEGLECTING SMALL TERMS -

$$\Delta R_D = \Delta R_B - \frac{3.375}{2} \varphi$$

$$= -.39243 \times 10^{-6} N_B - .47820 \times 10^{-6} Q_D - .47500 \times 10^{-6} Q_E$$

$$+ 14470 \times 10^{-6} - 1.6875 \varphi$$

F18

SUBSTITUTING FROM (19) -

$$\Delta R_D = -.39243\times10^{-6}(\overset{-.31055}{-.79134\,\Phi_D}\overset{-.30847}{-.78605\,\Phi_E}\overset{-2433}{+6201}) - .47820\times10^{-6}\Phi_D$$

$$-.47500\times10^{-6}\Phi_E + 14470\times10^{-6} - 1.6875\varphi$$

$$\Delta R_D = -.16765\times10^{-6}\Phi_D - .16653\times10^{-6}\Phi_E + 12037\times10^{-6} - 1.6875\varphi$$

SUBSTITUTING FOR Φ_D & Φ_E FROM (14) & (16) -

$$\Delta R_D = -.16765(\overset{-.041267}{.246147\,\Delta R_D}\overset{+.071386}{-.425806\,\varphi}\overset{+.000045}{-.00026688})$$

$$-.16653(\overset{-.055183}{.331369\,\Delta R_E}\overset{-.105936}{+.636137\,\varphi}\overset{+.002917}{-.017515}) + .012037$$

$$-1.6875\varphi$$

$$\Delta R_D = -.041267\,\Delta R_D - .055183\,\Delta R_E - 1.72205\varphi + .014999$$

$$\Delta R_D = -.052996\,\Delta R_E - 1.653804\varphi + .014405 \tag{20}$$

$$\Delta R_E = \Delta R_D + \varphi t \qquad t = 3.375$$

$$\Delta R_E = -.041267\,\Delta R_D - .055183\,\Delta R_E + 1.65295\varphi + .014999$$

$$\Delta R_E = -.039109\,\Delta R_D + 1.56651\varphi + .014215 \tag{21}$$

SUBSTITUTING (21) INTO (20)

$$\Delta R_D = -.052996(\overset{+.002073}{-.039109\,\Delta R_D}\overset{-.083019}{+1.56651\,\varphi}\overset{+.0007533}{+.014215})$$

$$-1.653804\varphi + .014405$$

$$\Delta R_D = -1.740434\varphi + .013680$$

$$\Delta R_E = \Delta R_D + 3.375\varphi = -1.740434\varphi + .015175 + 3.375\varphi$$

$$\Delta R_E = 1.63457\varphi + .013680$$

F19

$$\frac{13.8125}{17.90625} M_B + \frac{18.6875}{17.90625} M_D - \frac{18.5625}{17.90625} M_E + \frac{18.5625}{17.90625} \times 1.6875 \varphi_E$$

$$- \frac{18.6875}{17.90625} \times 1.6875 \varphi_D + M_G = 0$$

$$.77138 M_B + 1.04363 M_D - 1.036649 M_E + 1.749346 \varphi_E - 1.761126 \varphi_D$$

$$+ M_G = 0$$

SUBSTITUTING VALUES FOR M_B, M_D, M_E, φ_E, φ_D & M_G,

$$.77138 (\overset{3.604027}{4.67227 \varphi \times 10^6} \overset{-25707}{- 33326}) + 1.04363 (\overset{-444387}{-425809 \Delta R_D} \overset{+1,440,298}{+ 1380085 \varphi}$$

$$\overset{167.8366}{+ 160.82}) - 1.036649 (\overset{+659457}{-636143 \Delta R_E} \overset{+2,395,622}{- 2310929 \varphi} \overset{-36827}{+ 35525})$$

$$+ 1.749346 (\overset{579679}{331369 \Delta R_E} \overset{1,112,824}{+ 636137 \varphi} \overset{-30640}{- 17515})$$

$$- 1.761126 (\overset{-433496}{246147 \Delta R_D} \overset{+.749898}{- 425806 \varphi} \overset{+470.0093}{- 266.88}) + 1.99860 \times 10^6 \varphi$$

$$- 20522 = 0$$

$$11301669 \varphi - 877883 \Delta R_D + 1,239,136 \Delta R_E - 113058$$

$$11301669 \varphi - 877883 (\overset{+1,527894}{-1.74043 \varphi} \overset{-12009}{+ .013680}) + 1,239,136 (\overset{+2025455}{1.63457 \varphi}$$

$$\overset{+16951}{+ .013680}) - 113058 = 0$$

$$14855018 \varphi = 108116 \qquad \varphi = .007278$$

F20

$\Delta R_D = -1.74043(7278 \times 10^{-6}) + 13680 \times 10^{-6} = 1013 \times 10^{-6}$

$\Delta R_E = 1.63457(7278 \times 10^{-6}) + 13680 \times 10^{-6} = 25576 \times 10^{-6}$

$M_D = -.425809(1013) + 1.380085(7278) + 161 = 9774$

$Q_D = .246147(1013) - .425806(7278) - 267 = -3117$

$M_E = -.636143(25576) - 2.310929(7278) + 35525 = 2436$

$Q_E = .331369(25576) + .636137(7278) - 17515 = -4410$

$M_B = 4.6727(7278) - 33326 = 682$

$M_G = 1.99860(7278) - 20522 = -5976$

SUBSTITUTING INTO MOMENT EQUATION –

$77138(682) + 1.04363(9774) - 1.036649(2436) + 1.749346(-4410)$

$-1.761126(-3117) - 5976 = -1$ ✓

FROM (8) $M_A = 1.14728(682) - 3192 = -2410$

FROM (19) $N_B = -.79134(-3117) - .78605(-4410) + 6201 = 12134$

FROM (7) $N_A = 1.12962(12134) - 6504 = 7203$

STRESSES DUE TO TRANSIENT TEMPERATURES

TUBE AREA – IN THE TUBE AREA THE BENDING STRESSES ARE GIVEN BY – (ROARK)

RADIAL STRESS $= S_R = \dfrac{6}{t^2(R_B^2 - R_A^2)}\left[R_B^2 M_B - R_A^2 M_A - \dfrac{R_B^2 R_A^2}{R^2}(M_B - M_A)\right]$

TANGENTIAL STRESS $= S_T = \dfrac{6}{t^2(R_B^2 - R_A^2)}\left[R_B^2 M_B - R_A^2 M_A + \dfrac{R_B^2 R_A^2}{R^2}(M_B - M_A)\right]$

WHERE R IS RADIUS TO ANY POINT & OTHER TERMS ARE AS PREVIOUSLY DEFINED.

F21

$$\frac{6}{t^2(R_B^2-R_A^2)} = \frac{6}{(3.375)^2(13.8125^2-7.3125^2)} = .0038361$$

$R_B^2 = 13.8125^2 = 190.78515625$ $R_A^2 = 7.3125^2 = 53.47265625$

$R_B^2 R_A^2 = 10201.789$

AT THE INNERMOST LIGAMENT $R = 7.5625''$

$$\frac{R_B^2 R_A^2}{R^2} = \frac{10201.789}{7.5625^2} = 178.380$$

$$S_R = .0038361\left[\overset{130116}{190.7852(682)} \overset{+128869}{-53.4727(-2410)} \overset{[illegible]}{-178.380(682-\{-2410\})}\right]$$

$= 1122$ T ON TOP

$S_T = .0038361\left[130116+128869+551551\right] = 3109$ C ON TOP

AT THE OUTERMOST LIGAMENT, $R = 13.5625''$

$$\frac{R_B^2 R_A^2}{R} = 55.4622$$

$$S_R = .0038361\left[130116+128869 \overset{-171489}{-55.4622(3092)}\right] = 336 \text{ C ON TOP}$$

$S_T = .0038361\left[130116+128869+171489\right] = 1651$ C on TOP

THE NORMAL STRESS IS GIVEN BY: (ROARK)

$$\text{RADIAL STRESS} = S_R = \frac{N_A}{t}\frac{R_A^2}{R^2}\left(\frac{R_B^2-R^2}{R_B^2-R_A^2}\right) + \frac{N_B}{t}\frac{R_B^2}{R^2}\left(\frac{R^2-R_A^2}{R_B^2-R_A^2}\right)$$

$$\text{TANGENTIAL STRESS} = S_t = -\frac{N_A}{t}\frac{R_A^2}{R^2}\left(\frac{R_B^2+R^2}{R_B^2-R_A^2}\right) + \frac{N_B}{t}\frac{R_B^2}{R^2}\left(\frac{R^2+R_A^2}{R_B^2-R_A^2}\right)$$

AT THE INNERMOST LIGAMENT, $R = 7.5625''$

$\frac{R_A^2}{tR^2} = .27703$ $\frac{R_B^2}{tR^2} = .98842$ $\frac{R_B^2+R^2}{R_B^2-R_A^2} = 1.8059$

$\frac{R_B^2-R^2}{R_B^2-R_A^2} = .97292$ $\frac{R^2-R_A^2}{R_B^2-R_A^2} = .027082$ $\frac{R^2+R_A^2}{R_B^2-R_A^2} = .80593$

F22

$$S_R = 7203\,(.27703)(.97292) + 12134\,(.98842)(.027082) = 2266 \text{ T}$$

-3604

$$S_T = -7203\,(.27703)(1.8059) + 12134\,(.98842)(.80593) = 6062 \text{ T}$$

AT THE OUTERMOST LIGAMENT $R = 13.5625$

$$\frac{R_A^2}{t R^2} = .086135 \qquad \frac{R_B^2}{t R^2} = .30732 \qquad \frac{R_B^2 + R^2}{R_B^2 - R_A^2} = 2.72901$$

$$\frac{R_B^2 - R^2}{R_B^2 - R_A^2} = .049841 \qquad \frac{R^2 - R_A^2}{R_B^2 - R_A^2} = .95016 \qquad \frac{R^2 + R_A^2}{R_B^2 - R_A^2} = 1.72901$$

$$S_R = 7203.\,(.086135)(.049841) + 12134\,(.30732)(.95016) = 3574 \text{ T}$$

-1653

$$S_T = -7203\,(.086135)(2.72901) + 12134\,(.30732)(1.72901) = 4755 \text{ T}$$

<u>TUBE</u> <u>AREA</u> <u>STRESSES</u> BECOME

<u>INNER</u> <u>ROW</u> $\eta = .500$ $\frac{\sigma}{\sigma_{max}}$

BARREL SIDE (TOP)

$\sigma_R = 2266 + 1122 = 3388$ $.871$ $K = 2.5$ $\sigma_R = 8470$ T

$\sigma_T = 6062 - 3109 = 2953$ $\sigma_T = 7382$ T

SHELL SIDE BOTTOM

$\sigma_R = 2266 - 1122 = 1144$ $.125$ $K = 3.5$ $\sigma_R = 4004$ T

$\sigma_T = 6062 + 3109 = 9171$ $\sigma_T = 32098$ T

OUTER ROW

Barrol SIDE (TOP)

$\sigma_R = 3574 - 336 = 3238$ $.961$ $K = 2.4$ $\sigma_R = 7771$ T

$\sigma_T = 4755 - 1651 = 3104$ $\sigma_T = 7450$ T

SHELL SIDE (BOTTOM)

$\sigma_R = 3574 + 336 = 3910$ $.610$ $K = 2.75$ $\sigma_R = 10752$ T

$\sigma_T = 4755 + 1651 = 6406$ $\sigma_T = 17616$ T

BARREL STRESSES AT JUNCTION WITH TUBE SHEET

$$\frac{6}{t^2} = \frac{6}{1.875^2} = 1.70667$$

$$\Delta R_D = 1013 \times 10^{-6}$$

$$\Delta R_D^{\circ} = (10.8 \times 10^{-6})(793-775), \begin{matrix} (18) \\ (19.375) \end{matrix} \begin{matrix} = 3259 \times 10^{-6} \\ = 3767 \times 10^{-6} \end{matrix}$$

LONGITUDINAL STRESSES

$$S_L = \frac{6\,M_D}{t^2} = 1.70667 \times 9774 = 16681 \ \begin{matrix} C & \text{OUTSIDE} \\ T & \text{INSIDE} \end{matrix}$$

CIRCUMFERENTIAL STRESS $S_C = \frac{\Delta R - \Delta R^{\circ}}{R} E \pm \mu S_L$

OUTER SURFACE $S_C = \frac{1013 - 3767}{19.375}(24.0) - 0.3(16681) = 8415\ C$

INNER SURFACE $S_C = \frac{1013 - 3259}{18}(24) + 0.3(16681) = 2009\ T$

SHELL STRESSES AT JUNCTION WITH TUBE SHEET

$$\frac{6}{t^2} = \frac{6}{2.125^2} = 1.32872$$

$$\Delta R_E = 25576 \times 10^{-6}$$

$$\Delta R_E^{\circ} = (11.2 \times 10^{-6})(\overset{191}{966 - 775}) \times \begin{matrix} 17.5 \\ 19.625 \end{matrix} \begin{matrix} = 37436 \times 10^{-6} \\ = 41982 \times 10^{-6} \end{matrix}$$

LONGITUDINAL STRESS

$$S_L = \frac{6\,M_E}{t^2} = 1.32872 \times 2436 = 3237 \ \begin{matrix} C & \text{OUTSIDE} \\ T & \text{INSIDE} \end{matrix}$$

CIRCUMFERENTIAL STRESS $S_C = \frac{\Delta R - \Delta R^{\circ}}{R} E \pm \mu S_L$

OUTER SURFACE $S_C = \frac{25576 - 41982}{19.625}(22.8) - .3(3237) = 20031\ C$

INNER SURFACE $S_C = \frac{25576 - 37436}{17.5}(22.8) + .3(3237) = 14481\ C$

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PHYSICAL PROPERTIES - LOWER TUBE SHEET
30 MW IHX BARREL SIDE

$\alpha = 10.8 \times 10^{-6}$
$E = 24.0 \times 10^{6}$
$m = .25$

1 - STEADY STATE 2 - TRANSIENT

POINT 7 & BEYOND ALIKE

	POINT	0	1	2	3	4	5	6	7
	DISTANCE	0	.25	.50	.75	1.00	1.25	1.50	1.75
	t	1.375	1.29167	1.20833	1.125	1.04167	.95833	.875	.875
	t^3	2.599609	2.155037	1.764236	1.423828	1.130292	.880127	.66992	.66992
	R_m	18.6875	18.6875	18.6875	18.6875	18.6875	186875	18.6875	18.6875
	R_m^2	349.2227	349.2227	349.2227	349.2227	349.2227	349.2227	349.2227	349.2227
	R_i	18.0000	18.0417	18.0833	18.1250	18.1667	18.2083	18.2500	18.2500
	$10^6 C_1 = \frac{10.92\, m}{E t^3}$	.043757	.052783	.064476	.079890	.100638	.129243	.169796	.169796
	$10^{-6} C_2 = \frac{m E t}{R_M^2}$	.023624	.022192	.020760	.019329	.017897	.016465	.015033	.015033
1	T	792	789	786	784	781	778	775	775
	ΔT	0	1	2	3	4	2	0	0
	$C_3 = \alpha R_m (T-775)$	.003431	.002826	.002220	.001816	.001211	.000605	0	0
	$10^6 C_4 = \frac{m \alpha \Delta T}{t}$	0	2.0903	4.4690	7.2000	10.3680	5.6348	0	0
2	T	794	792	789	786	782	778	775	775
	ΔT	0	3	7	6	5	2	0	0
	$C_3 = \alpha R_m (T-775)$	.003835	.003431	.002826	.002220	.001413	.000605	0	0
	$10^6 C_4 = \frac{m \alpha \Delta T}{t}$	0	6.2710	15.6414	14.4000	12.9600	5.6348	0	0

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TAPERED WALL CALCULATIONS – BARREL SIDE

IN THE STRAIGHT WALL PORTION, M & V ARE GIVEN BY:

$$M = -3025\,\frac{Et^2}{R}\left[\Delta R - \frac{\theta}{\beta}\right] \qquad \Delta R = Y - \Delta R^\circ$$

$$V = -.3025\,\frac{Et^2}{R}\left[2\beta\,\Delta R - \theta\right]$$

$$\beta = \frac{1.285}{\sqrt{R_m t}} = \frac{1.285}{\sqrt{18.6875 \times .875}} \qquad .31778$$

$$.3025\,\frac{Et^2}{R} = \frac{.3025 \times 24.0 \times 10^6 \times .875^2}{18.6875} = .297441 \times 10^6$$

$$M = -.297441 \times 10^6 \left[Y - \quad 0 \quad - \frac{\theta}{.31778}\right]$$

$$M = -297441\,Y + 935997\,\theta$$

$$V = -297441\left[2(.31778)(Y - \quad 0 \quad) + \theta\right]$$

$$= -189042\,Y + 297441\,\theta$$

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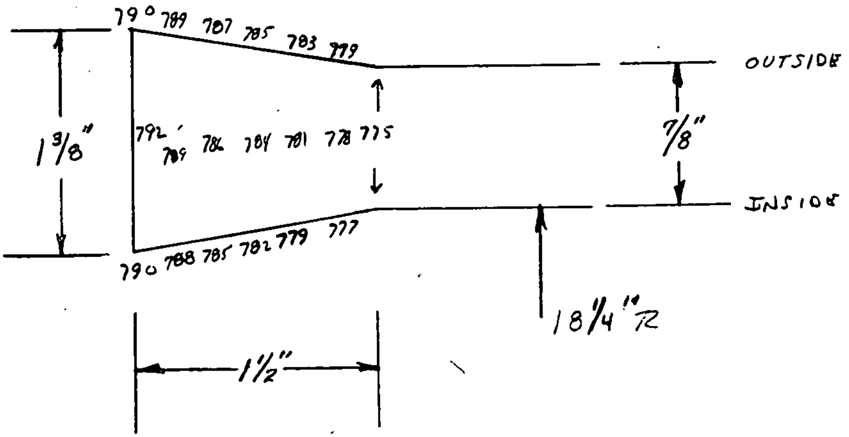
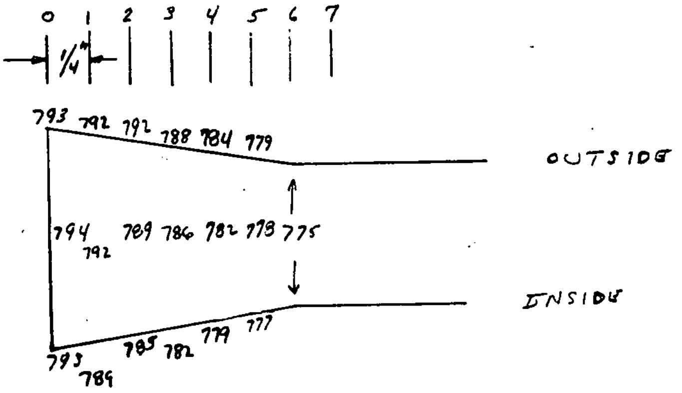
DIMENSIONS & TEMPERATURES   BARREL WALL



STEADY-STATE TEMPERATURES



TRANSIENT TEMPERATURES

TRIAL COMPUTATIONS - LOWER TUBE SHEET - BARREL WALL

$Y_7 = 1$ $\theta_7 = 0$ $M_7 = -297441$ $Y_7 = -189042$

POINT	Y	CY=-ΔV	V	mV=ΔM	M	CM=Δθ	θ	mθ=ΔY
7	1	7516	-189042		-297441	-.025252	0	
			-196558	-49140			-.025252	-.006313
6	.993687	14938			-346581	-.058848		
			-211496	-52874			-.084100	-.021025
5	.972662	16015			-399455	-.051627		
			-227511	-56878			-.135727	-.033932
4	.938730	16800			-456333	-.045924		
			-244311	-61078			-.181651	-.045413
3	.893317	17267			-517411	-.041336		
			-261578	-65394			-.222987	-.055747
2	.837570	17388			-582805	-.037577		
			-278966	-69742			-.260564	-.065141
1	.772429	17142			-652547	-.034443		
			-296108	-74027			-.295007	-.073752
0	.698677	8253	-304361		-726574	-.015896	-.310903	

$Y_7 = 0$ $\theta_7 = 1$ $M_7 = 935997$ $V_7 = 297441$

POINT	Y	CY=-ΔV	V	mV=ΔM	M	CM=Δθ	θ	mθ=ΔY
7	0	0	297441		935997	.079464	1	
			297441	74360			1.079464	.269866
6	.269866	4057			1010357	.171555		
			293384	73346			1.251019	.312755
5	.582621	9593			1083703	.140061		
			283791	70948			1.391080	.347770
4	.930391	16651			1154651	.116202		
			267140	66785			1.507282	.376820
3	1.307211	25267			1221436	.097581		
			241873	60468			1.604863	.401216
2	1.708427	35467			1281904	.082652		
			206406	51602			1.687515	.421879
1	2.130306	47276			1333506	.070386		
			159130	39782			1.757901	.439475
0	2.569781	30354	128776		1373288	.030045	1.787946	

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TRIAL COMPUTATION - LOWER TUBE SHEET - BARREL WALL - STEADY STATE

$\theta_7 = Y_7 = 0$ $M_7 = 0$ $V_7 = 0$

POINT	Y	C_3	$Y-C_3$	$\Delta V = -C_2(Y-C_3)$	V	$mV = \Delta M$	M	$10^6 C_1 M$	$10^6 C_4$	$\Delta\theta = C_1M - C_4$	θ	$m\theta = \Delta Y$
7	0	0	0	0	0		0	0	0	0	0	
					0	0					0	0
6	0	0	0	0			0	0	0	0		
					0	0					0	0
5	0	.000605	-.000605	9.96			0	0	5.6348	-.0000056348		
					9.96	2.49					-.00000563	-.000001
4	-.000001	.001211	-.001212	21.69			2.49	.2506	10.3680	-.00001011		
					31.65	7.91					-.000016	-.000004
3	-.000005	.001816	-.001821	35.20			10.40	.8309	7.2000	-.000006		
					66.85	16.71					-.000022	-.000006
2	-.000011	.002220	-.002231	46.32			27.11	1.7479	4.4690	-.000003		
					113.17	28.29					-.000025	-.000006
1	-.000017	.002826	-.002843	63.09			55.40	2.9242	2.0903	.000001		
					176.26	44.07					-.000024	-.000006
0	-.000023	.003431	-.003454	40.80	217.06		99.47	2.1763	0	.000002	-.000022	

TRIAL COMPUTATION - LOWER TUBE SHEET - BARREL WALL - TRANSIENT

$\Theta_7 = Y_7 = 0$ $M_7 = 0$ $V_7 = 0$

POINT	Y	C_3	$Y-C_3$	$\Delta V = -C_2(Y-C_3)$	V	$mV = \Delta M$	M	C_1M	C_4	$\Delta\Theta = C_1M - C_4$	Θ	$m\theta = \Delta Y$
7	0	0	0	0	0		0	0	0	0	0	
					0	0					0	0
6	0	0	0	0			0	0	0	0		
					0	0					0	0
5	0	.000605	-.000605	+9.96			0	0	.000006	-.000006		
					+9.96	+2.49					-.000006	-.000002
4	-.000002	.001413	-.001415	+ 23.30			+2.49	0	.000013	-.000013		
					+33.26	+8.32					-.000019	-.000005
3	-.000007	.002220	-.002227	43.05			+10.81	.000001	.000014	-.000013		
					76.31	19.08					-.000032	-.000008
2	-.000015	.002826	-.002841	58.98			29.89	.000002	.000016	-.000014		
					135.29	33.82					-.000046	-.000012
1	-.000027	.003431	-.003458	76.74			63.71	.000003	.000006	-.000003		
					212.03	53.01					-.000049	-.000012
0	-.000039	.003835	-.003874	45.76	257.79		116.72	.000003	0	.000003	-.000046	

SOLUTION OF EQUATIONS - BARREL SIDE - STEADY STATE

$$M_0 = -726574\,Y_7 + 1373288\,\theta_7 + 99 \qquad (A)$$

$$V_0 = -304361\,Y_7 + 128776\,\theta_7 + 217 \qquad (B)$$

$$Y_0 = .698677\,Y_7 + 2.569781\,\theta_7 - .000023 \qquad (C)$$

$$\theta_0 = -.310903\,Y_7 + 1.787946\,\theta_7 - .000022 \qquad (D)$$

REARRANGING (C) -

$$Y_7 = \frac{1}{.698677}\left(Y_0 - 2.569781\,\theta_7 + .000023\right) = 1.43128\,Y_0 - 3.67807\,\theta_7 + .000033$$

SUBSTITUTING INTO (D)

$$\theta_0 = -.310903\left(\overset{-.444989}{1.43128\,Y_0} \overset{+1.143525}{- 3.67807\,\theta_7} \overset{-.000010}{+ .000033}\right) + 1.787946\,\theta_7 - .000022$$

$$\theta_7 = \frac{1}{2.931469}\left(\theta_0 + .444989\,Y_0 + .000032\right) = .341126\,\theta_0 + .151797\,Y_0 + .000011$$

SUBSTITUTE INTO EQUATION FOR Y_7 -

$$Y_7 = 1.43128\,Y_0 - 3.67807\left(\overset{-1.254685}{.341126\,\theta_0} \overset{-.558320}{+ .151797\,Y_0} \overset{-.000040}{+ .000011}\right) + .000033$$

$$Y_7 = .87296\,Y_0 - 1.254685\,\theta_0 - .000007$$

SUBSTITUTE FOR Y_7 & θ_7 IN (A) & (B)

$$M_0 = -726574\left(\overset{-634270}{.87296\,Y_0} \overset{+911621}{- 1.254685\,\theta_0} \overset{+5}{- .000007}\right) + 99$$
$$+1373288\left(\overset{+46[illegible]}{.341126\,\theta_0} \overset{+208461}{+ .151797\,Y_0} \overset{+15}{+ .000011}\right)$$

$$M_0 = -425809\,Y_0 + 1380085\,\theta_0 + 119$$

$$V_0 = -304361\left(\overset{-265695}{.87296\,Y_0} \overset{+381877}{- 1.254685\,\theta_0} \overset{+2}{- .000007}\right) + 217$$
$$+128776\left(\overset{+43929}{.341126\,\theta_0} \overset{+19548}{+ .151797\,Y_0} \overset{+1}{+ .000011}\right)$$

$$V_0 = -246147\,Y_0 + 425806\,\theta_0 + 220$$

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FOR THE TRANSIENT CASE – BARREL SIDE

$$M_0 = -726574\,Y_7 + 1373288\,\Theta_7 + 116.72 \qquad (A)$$

$$V_0 = -304361\,Y_7 + 128776\,\Theta_7 + 257.79 \qquad (B)$$

$$Y_0 = .698677\,Y_7 + 2.569781\,\Theta_7 - .000039 \qquad (C)$$

$$\Theta_0 = -.310903\,Y_7 + 1.787946\,\Theta_7 - .000046 \qquad (D)$$

REARRANGING (C) –

$$Y_7 = \frac{1}{.698677}\left(Y_0 - 2.569781\,\Theta_7 + .000039\right) = 1.43128\,Y_0 - 3.67807\,\Theta_7 + .000056$$

SUBSTITUTING INTO (D)

$$\Theta_0 = -.310903\left(\overset{-.444989}{1.43128\,Y_0} \overset{+1.143523}{-3.67807\,\Theta_7} \overset{-.000017}{+.000056}\right) + 1.787946\,\Theta_7 - .000046$$

$$\Theta_7 = \frac{1}{2.931469}\left(\Theta_0 + .444989\,Y_0 + .000063\right) = .341126\,\Theta_0 + .151797\,Y_0 + .000021$$

SUBSTITUTE INTO EQUATION FOR Y_7

$$Y_7 = 1.43128\,Y_0 - 3.67807\left(\overset{-1.254685}{.341126\,\Theta_0} \overset{-.558320}{+.151797\,Y_0} \overset{-.000077}{+.000021}\right) + .000056$$

$$Y_7 = .872960\,Y_0 - 1.254685\,\Theta_0 - .000021$$

SUBSTITUTE FOR Y_7 & Θ_7 IN (A) & (B)

$$M_0 = -726574\left(\overset{-634270}{.872960\,Y_0} \overset{+911621}{-1.254685\,\Theta_0} \overset{+15.26}{-.000021}\right) + 116.72$$

$$+1373288\left(\overset{468464}{.341126\,\Theta_0} \overset{+208461}{+.151797\,Y_0} \overset{+28.84}{+.000021}\right)$$

$$M_0 = -425809\,Y_0 + 1380085\,\Theta_0 + 160.82$$

$$V_0 = -304361\left(\overset{-265695}{.872960\,Y_0} \overset{+381877}{-1.254685\,\Theta_0} \overset{6.39}{-.000021}\right) + 257.79$$

$$+128776\left(\overset{43929\,\Theta_0}{.341126\,\Theta_0} \overset{19548}{+.151797\,Y_0} \overset{2.70}{+.000021}\right)$$

$$V_0 = -246147\,Y_0 + 425806\,\Theta_0 + 266.88$$

F32

PHYSICAL PROPERTIES – LOWER TUBE SHEET
30 MW IHX – SHELL SIDE

$E = 23.4 \times 10^6$ psi
$m = .25$
$\alpha = 11 \times 10^{-6}$

1 – STEADY STATE
2 – TRANSIENT
POINT 7 & BEYOND ALIKE

	POINT	0	1	2	3	4	5	6	7
	DISTANCE	0	.25	.50	.75	1.0	1.25	1.5	1.75
	t	1.625	1.54167	1.45833	1.375	1.29167	1.20833	1.125	1.125
	t^3	4.291016	3.664159	3.101469	2.599609	2.155037	1.764236	1.423828	1.423828
	R_m	18.5625	18.5625	18.5625	18.5625	18.5625	18.5625	18.5625	18.5625
	R_m^2	344.5664	344.5664	344.5664	344.5664	344.5664	344.5664	344.5664	344.5664
	R_i							18.00000	18.00000
	$10^6 C_1 = \frac{10.92h}{Et^3}$	.027189	.031840	.037617	.044879	.054137	.066129	.081939	.081939
	$10^{-6} C_L = \frac{mEt}{R_m^2}$	.027589	.026174	.024759	.023345	.021930	.020515	.019100	.019100
1	T	894	895	896	897	897	898	899	900
	ΔT	0	0	0	0	0	0	0	0
	$C_3 = \alpha R_m(T-775)$	.024298	.024503	.024707	.024911	.024911	.025115	.025319	.025523
	$10^6 C_4 = \frac{m\alpha\Delta T}{t}$	0	0	0	0	0	0	0	0
2	T	1000	1003	1007	1012	1018	1025	1033	1042
	ΔT	-74	-68	-60	-53	-46	-40	-32	-23
	$C_3 = \alpha R_m(T-775)$	.045942	.046555	.047372	.048392	.049618	.051047	.052680	.054518
	$10^6 C_4 = \frac{m\alpha\Delta T}{t}$	-125.2308	-121.2970	-113.1431	-106.0000	-97.9352	-91.0347	-78.2222	-56.2222

F33

TAPERED WALL CALCULATIONS: SHELL SIDE.

IN THE STRAIGHT WALL PORTION M & V ARE GIVEN BY

$$M = -.3025\,\frac{Et^2}{R}\left[\Delta R - \frac{\theta}{\beta}\right] \qquad \Delta R = Y - \Delta R^{\circ}$$

$$= Y - .16335$$

$$V = -.3025\,\frac{Et^2}{R}\left[2\beta\Delta R - \theta\right]$$

$$\beta = \frac{1.285}{\sqrt{R_m t}} = \frac{1.285}{\sqrt{18.5625 \times 1.125}} = .28121$$

$$.3025\,\frac{Et^2}{R} = \frac{.3025 \times 23.4 \times 10^6 \times 1.125^2}{18.5625} = .482625 \times 10^6$$

$$M = -.482625 \times 10^6\left[Y - .025523 - \frac{\theta}{.28121}\right]$$

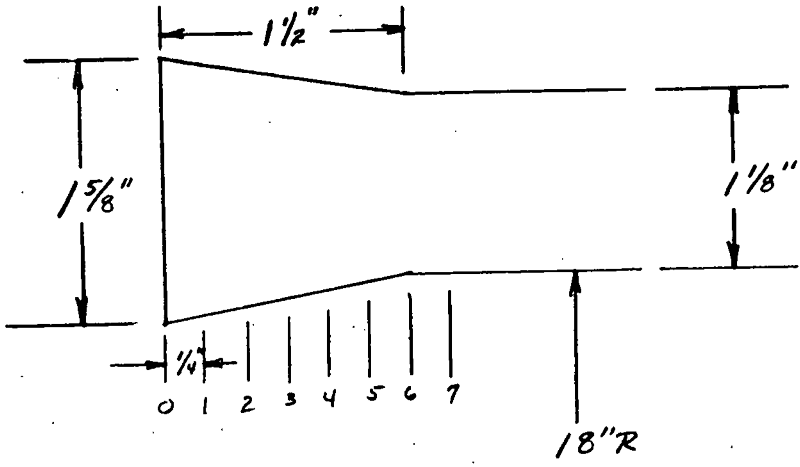
$$M = -482625\,Y + 1716244\,\theta + 12318$$

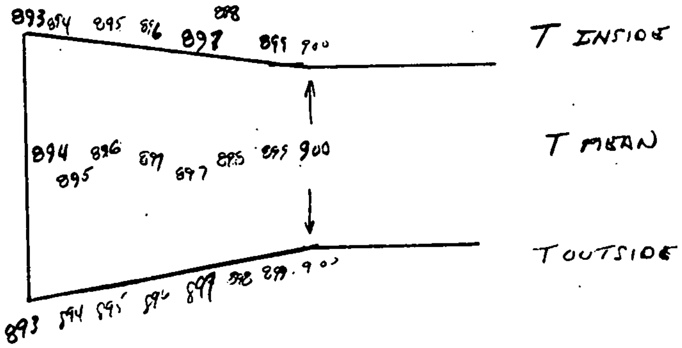
$$V = -.482625 \times 10^6\left[2(.28121)(Y - .025523) + \theta\right]$$

$$= -271438\,Y + 482625\,\theta + 6928$$

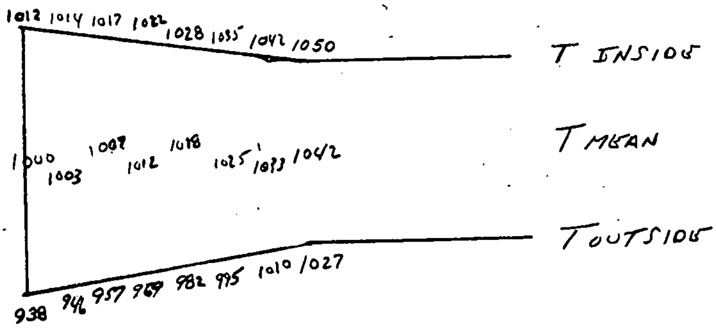
F34

DIMENSIONS & TEMPERATURES
SHELL SIDE





STEADY STATE



TRANSIENT

F35

TRIAL COMPUTATIONS - LOWER TUBE SHEET - SHELL WALL

$Y_7=1$ $\theta_7=0$ $M_7=-482625$ $V_7=-271438$

POINT	Y	$C_2Y=-\Delta V$	V	$mV=\Delta M$	M	$C_1M-\Delta\theta$	θ	$m\theta=\Delta Y$
7	1	9550	-271438		-482625	-.019773	0	
			-280988	-70247			-.019773	-.004943
6	.995057	19006			-552872	-.045302		
			-299994	-74999			-.065075	-.016269
5	.978788	20080			-627871	-.041520		
			-320074	-80019			-.106595	-.026649
4	.952139	20880			-707890	-.038323		
			-340954	-85239			-.144918	-.036230
3	.915909	21382			-793129	-.035595		
			-362336	-90584			-.180513	-.045128
2	.870781	21560			-883713	-.033243		
			-383896	-95974			-.213756	-.053439
1	.817342	21393			-979687	-.031193		
			-405289	-101322			-.244949	-.061237
0	.756105	10430	-415719		-1081009	-.014696	-.259645	

$Y_7=0$ $\theta_7=1$ $M_7=1716244$ $V_7=482625$

POINT	Y	$C_2Y=-\Delta V$	V	$mV=\Delta M$	M	$C_1M=\Delta\theta$	θ	$m\theta=\Delta Y$
7	0	0	482625		1716244	.070314	1	
			482625	120656			1.070314	.267579
6	.267579	5110			1836900	.150514		
			477515	119379			1.220828	.305207
5	.572786	11751			1956279	.129367		
			465764	116441			1.350195	.337549
4	.910335	19964			2072720	.112211		
			445800	111450			1.462406	.365602
3	1.275937	29787			2184170	.098023		
			416013	104003			1.560429	.390107
2	1.666044	41250			2288173	.086074		
			374763	93691			1.646503	.411626
1	2.077670	54381			2381864	.075839		
			320382	80096			1.722342	.430586
0	2.508256	34600	285782		2461960	.033469	1.755811	

F36

TRIAL COMPUTATION LOWER TUBE SHEET - SHELL WALL = STEADY STATE

$\theta_7 = Y_7 = 0$ $M_7 = 12318$ $V_7 = 6928$

POINT	Y	C_3	$Y - C_3$	$\Delta V = -C_2(Y-C_3)$	V	$mV = \Delta M$	M	$C_1 M$	C_4	$\Delta\theta = C_1 M - C_4$	θ	$m\theta = \Delta Y$
7	0	.025523	-.025523	244	6928		12318	.000505	0		0	
					7172	1793					.000505	.000126
6	.000126	.025319	-.025193	481			14111	.001156	0			
					7653	1913					.001661	.000415
5	.000541	.025115	-.024574	504			16024	.001059	0			
					8157	2039					.002720	.000680
4	.001221	.024911	-.023690	520			18063	.000978	0			
					8677	2169					.003698	.000925
3	.002146	.024911	-.022765	531			20232	.000908	0			
					9208	2302					.004606	.001152
2	.003298	.024707	-.021409	530			22534	.000847	0			
					9738	2435					.005453	.001363
1	.004661	.024503	-.019842	519			24969	.000795	0			
					10257	2564					.006248	.001562
0	.006223	.024298	-.018075	249	10506		27533	.000374	0		.006622	

F37

TRIAL COMPUTATION - LOWER TUBE SHEET - SHELL WALL - TRANSIENT

$\theta_7 = Y_7 = 0$ $M_7 = 26312$ $V_7 = 14798$

POINT	Y	C_3	$Y - C_3$	$\Delta V = -C_1(Y-C_3)$	V	$mV = \Delta M$	M	$C_1 M$	C_V	$\Delta\theta = C_1 M - C_V$	θ	$m\theta = \Delta Y$
7	0	.054518	-.054518	521	14798		26312	.001078	-.000028	.001050	0	
					15319	3830					.001050	.000263
6	.000263	.052680	-.052417	1001			30142	.002470	-.000078	.002392		
					16320	4080					.003442	.000861
5	.001124	.051047	-.049923	1024			34222	.002263	-.000091	.002172		
					17344	4336					.005614	.001404
4	.002528	.049618	-.047090	1033			38558	.002087	-.000098	.001989		
					18377	4594					.007603	.001901
3	.004429	.048392	-.043963	1026			43162	.001937	-.000106	.001831		
					19403	4851					.009434	.002359
2	.006788	.047372	-.040584	1005			48003	.001806	-.000113	.001693		
					20408	5102					.011127	.002782
1	.009570	.046555	-.036985	968			53105	.001691	-.000121	.001570		
					21376	5344					.012697	.003174
0	.012744	.045942	-.033198	458	21834		58449	.000795	-.000063	.000732	.013429	

SOLUTION OF EQUATIONS - SHELL SIDE - STEADY STATE

$$M_0 = -1081009\, Y_7 + 2461960\, \Theta_7 + 27533 \qquad (A)$$

$$V_0 = -415719\, Y_7 + 285782\, \Theta_7 + 10506 \qquad (B)$$

$$Y_0 = .756105\, Y_7 + 2.508256\, \Theta_7 + .006223 \qquad (C)$$

$$\Theta_0 = -.259645\, Y_7 + 1.755811\, \Theta_7 + .006622 \qquad (D)$$

REWRITING (C) -

$$Y_7 = \frac{1}{.756105}\left(Y_0 - 2.508256\, \Theta_7 - .006223\right) = 1.32257\, Y_0 - 3.31734\, \Theta_7 - .008230$$

SUBSTITUTING IN (D) -

−.343399 [illegible] +.002137

$$\theta_0 = -.259645\left(1.32257\, Y_0 - 3.31734\, \theta_7 - .008230\right) + 1.755811\, \Theta_7 + .006622$$

$$\Theta_7 = \frac{1}{2.617142}\left(\theta_0 + .343399\, Y_0 - .008759\right) = .382096\, \theta_0 + .131211\, Y_0 - .003347$$

SUBSTITUTING IN EQUATION FOR Y_7 -

−1.267543 [illegible] +.011103

$$Y_7 = 1.32257\, Y_0 - 3.31734\left(.382096\, \theta_0 + .131211\, Y_0 - .003347\right) - .008230$$

$$Y_7 = .88730\, Y_0 - 1.267542\, \theta_0 + .002873$$

SUBSTITUTING FOR Y_7 & Θ_7 IN (A) & (B) -

[illegible] [illegible] −3106

$$M_0 = -1081009\left(.88730\, Y_0 - 1.267542\, \theta_0 + .002873\right) + 27533$$

[illegible] [illegible] −8240

$$+ 2461960\left(.382096\, \theta_0 + .131211\, Y_0 - .003347\right)$$

$$M_0 = -636143\, Y_0 + 2310929\, \theta_0 + 16187$$

−368867 +526941 −1194

$$V_0 = -415719\left(.88730\, Y_0 - 1.267542\, \theta_0 + .002873\right) + 10506$$

109196 +37498 −957

$$+ 285782\left(.382096\, \theta_0 + .131211\, Y_0 - .003347\right)$$

$$V_0 = -331369\, Y_0 + 636137\, \theta_0 + 8355$$

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SOLUTION OF EQUATIONS - SHELL SIDE TRANSIENT

$$M_0 = -1081009\, Y_7 + 2461960\, \theta_7 + 58449 \qquad (A)$$

$$V_0 = -415719\, Y_7 + 285782\, \theta_7 + 21834 \qquad (B)$$

$$Y_0 = .756105\, Y_7 + 2.508256\, \theta_7 + .012744 \qquad (C)$$

$$\theta_0 = -.259645\, Y_7 + 1.755811\, \theta_7 + .013429 \qquad (D)$$

REWRITING (C) -

$$Y_7 = \frac{1}{.756105}(Y_0 - 2.508256\,\theta_7 - .012744) = 1.32257\, Y_0 - 3.31734\,\theta_7 - .016855$$

SUBSTITUTING IN (D)

$$\theta_0 = -.259645\left(1.32257\, Y_0 - 3.31734\,\theta_7 \overset{+.004376}{-.016855}\right) + 1.755811\,\theta_7 + .013429$$

$$\theta_7 = \frac{1}{2.617142}(\theta_0 + .343399\, Y_0 - .017805) = .382096\,\theta_0 + .131211\, Y_0 - .006803$$

SUBSTITUTING IN EQUATION FOR Y_7

$$Y_7 = 1.32257\, Y_0 - 3.31734\left(.382096\,\theta_0 + .131211\, Y_0 \overset{+.022568}{-.006803}\right) - .016855$$

$$Y_7 = .88730\, Y_0 - 1.267542\,\theta_0 + .005713$$

SUBSTITUTING FOR Y_7 & θ_7 IN (A) & (B)

$$M_0 = -1081009\left(.88730\, Y_0 - 1.267542\,\theta_0 \overset{-6176}{+.005713}\right) + 58449$$

$$+ 2461960\left(.382096\,\theta_0 + .131211\, Y_0 - \overset{16748}{.006803}\right)$$

$$M_0 = -636143\, Y_0 + 2310929\,\theta_0 + 35525$$

$$V_0 = -415719\left(.88730\, Y_0 - 1.267542\,\theta_0 \overset{-\ 2375}{+.005713}\right) + 21834 +$$

$$285782\left(.382096\,\theta_0 + .131211\, Y_0 - \overset{1944}{.006803}\right)$$

$$V_0 = -331369\, Y_0 + 636137\,\theta_0 + 17515$$

F40

30 MW IHX - LOWER TUBE SHEET

STEADY-STATE & TRANSIENT TEMPERATURES

THE MAXIMUM TRANSIENT CONSIDERED IS A CHANGE IN PRIMARY OUTLET SODIUM TEMPERATURE FROM 900° TO 1050°F. THIS CHANGE CAN OCCUR IN 15 SECONDS. A RISE TO 1050° IS ASSUMED TO BE THE LIMITING TEMPERATURE BEFORE SOME TYPE OF CORRECTIVE ACTION TAKES PLACE.

THE MAXIMUM STRESSES WILL OCCUR AT SOME TIME AFTER THE END OF THE TRANSIENT. THIS TIME OF MAXIMUM STRESS IS CALCULATED ON THE FOLLOWING PAGE.

THE PHYSICAL PROPERTIES USED FOR THE MATERIAL ARE -

SODIUM

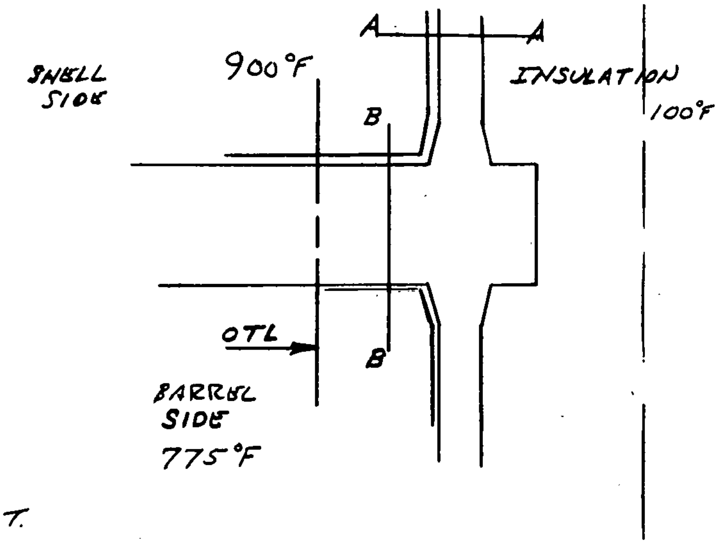
FILM COEFFICIENT = $h = 4000$

DIFFUSIVITY = $\alpha = \frac{K}{\rho C_p} = .0066$

STAINLESS STEEL (316) CONDUCTIVITY = $K = 12.6$

TUBE SHEET THICKNESS = $X = (3.375 + .250 + .015625) = 3.640625''$

STEADY-STATE BOUNDARY TEMPERATURES



SECTION A-A 800° ΔT

		900
SODIUM h=4000	.00025	900
1/8" SST SHIELD K=12.6	.0008	900
1/8" SODIUM K=39	.0003	900
1 1/8" SHELL K=12.6	.0074	899
6" INSULATION K=.05	10.0000	100
	10.0087	

TAKE SHELL AS AT UNIFORM TEMP. OF 900°F

SECTION B-B 125° ΔT

			900
SODIUM h=4000	.00025	1.75	
1/4" SST SHIELD K=12.6	.0004	2.0	
1/4" SODIUM K=39	.0001	.5	895
3 3/8" TUBE SHEET K=12.6	.0223	113.3	782
1/8" SODIUM K=39	.0003	1.5	
1/8" SHIELD K=12.6	.0008	4.1	
SODIUM h=4000	.00025	1.75	775
	.0244		

ΔT THRU TUBE SHEET 895-782°F

THIS GRADIENT APPLIES THRU CORE AREA ALSO

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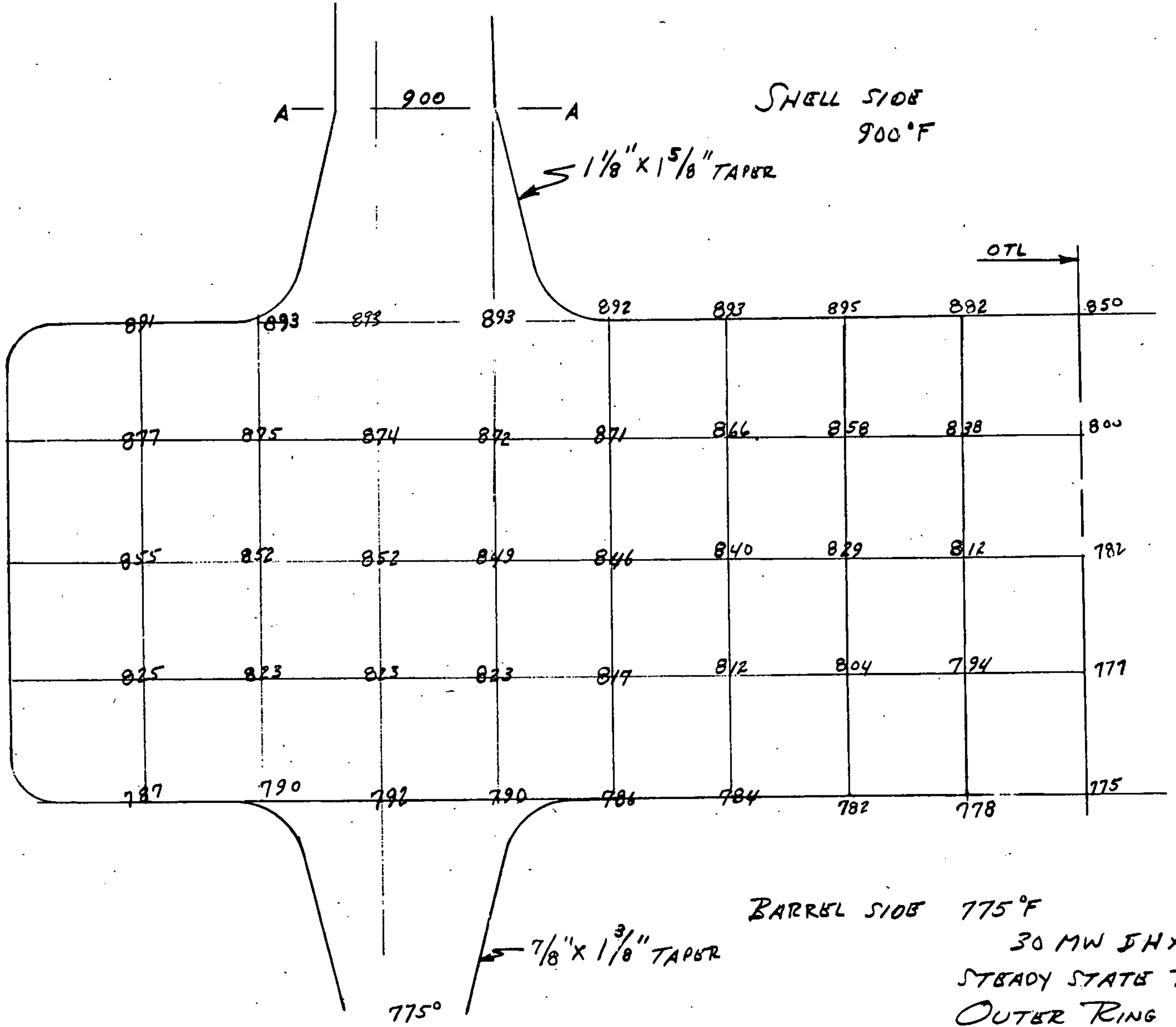
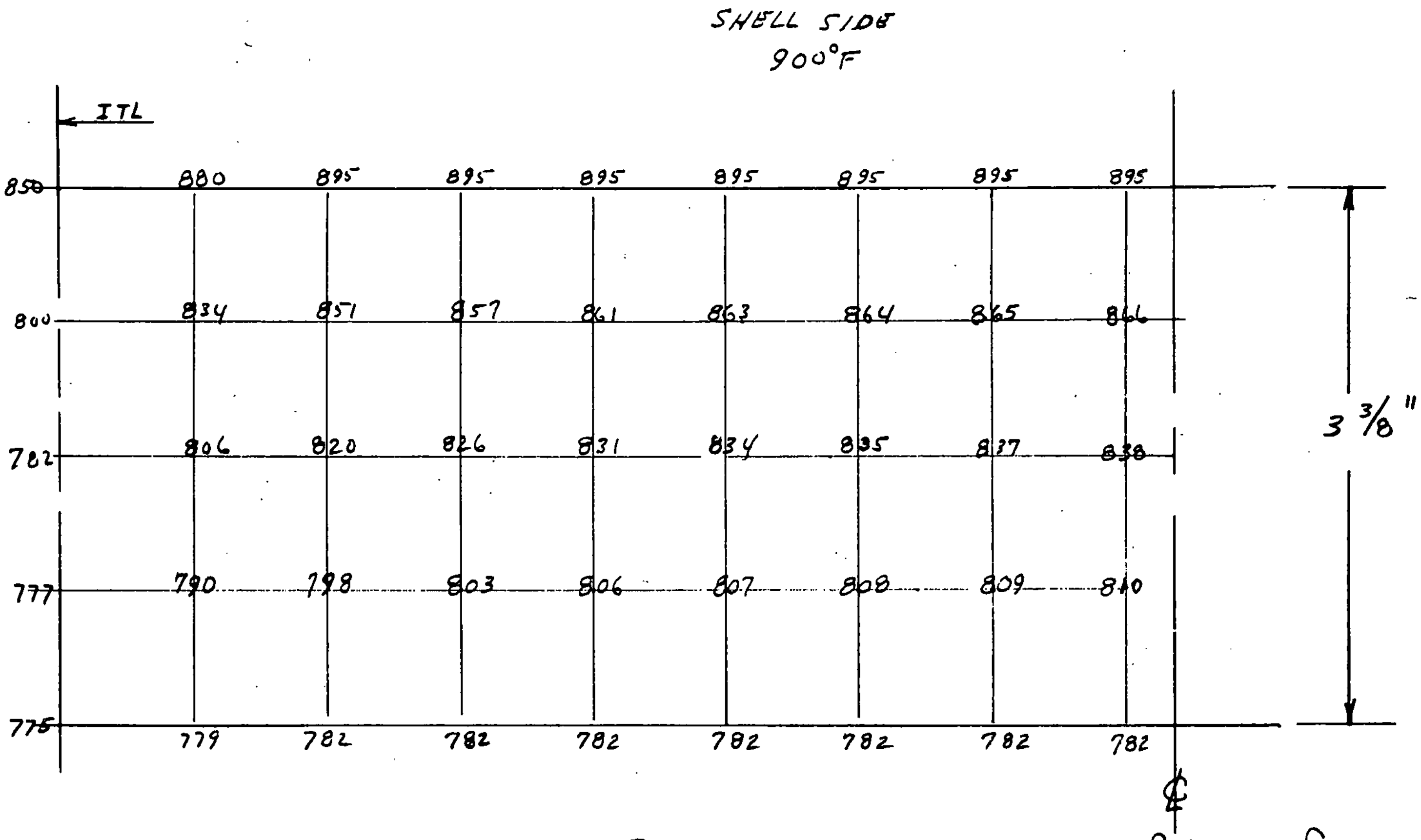


SHELL SIDE
900°F

BARREL SIDE 775°F
30 MW IHX
STEADY STATE TEMPERATURES
OUTER RING

F43



850	880	895	895	895	895	895	895	895
800	834	851	857	861	863	864	865	866
782	806	820	826	831	834	835	837	838
777	790	798	803	806	807	808	809	810
775	779	782	782	782	782	782	782	782

STEADY STATE
TEMPERATURES
CORE AREA
30MW IHX

TRANSIENT TEMPERATURES FOR A SUDDEN UNIT RISE IN PRIMARY SODIUM TEMPERATURE THRU TUBE SHEET WITH 1/4" SHIELD & 1/4" SODIUM

POINT	$N_{Fo}=.030$ $t=60$		$N_{Fo}=.045$ $t=90$		$N_{Fo}=.070$ $t=141$		$N_{Fo}=.100$ $t=201$		$N_{Fo}=.150$ $t=301$	
0	0	0	.002	.0000902	.014	.0006314	.048	.0021648	.130	.0058630
.1	0	0	.003	.0002481	.018	.0014886	.055	.0045485	.139	.0114953
.2	.001	.0000727	.007	.0005089	.032	.0023264	.077	.0055979	.166	.0120682
.3	.004	.0002508	.018	.0011286	.058	.0036366	.116	.0072732	.212	.0132924
.4	.013	.0006851	.042	.0022134	.103	.0054281	.174	.0091698	.276	.0145452
.5	.037	.0015799	.089	.0038003	.173	.0073871	.255	.0108885	.358	.0152866
.6	.094	.0030738	.172	.0056244	.273	.0089271	.360	.0117720	.457	.0149439
.7	.206	.0046762	.302	.0068554	.408	.0092616	.488	.0110776	.573	.0130071
.8	.392	.0049784	.484	.0061468	.575	.0073025	.639	.0081153	.702	.0089154
.9	.654	.0011213	.714	.0012242	.769	.0013185	.806	.0013819	.841	.0014419
.927	.739	.0000673	.781	.0000712	.821	.0000748	.853	.0000777	.880	.0000802
1.0	.967		.973		.979		.982		.985	
Σ		.0165055		.0278403		.0477827		.0720672		.1109392
M_N	.135	.0580047	.179	.0769099	.241	.1035491	.302	.1297587	.387	.1662802
Δ		.0414992		.0490696		.0557664		.0576915		.0553410
ΔT										

$$\frac{3.375}{3.640625} = .927$$

$$N_{Bi}^{-1} = \frac{12(12.6)}{(4000)(3.640625)}$$

$$N_{Bi}^{-1} = .010$$

$$N_{Fo} = \frac{.0066\,t}{(3.640625)^2}$$

$$N_{Fo} = .00049796\,t$$

MAXIMUM ΔT OCCURS AT APPROXIMATELY 200 SEC. AFTER SUDDEN CHANGE. USE $t=200$ SEC FOR TRANSIENT TEMP. CALCULATIONS.

TAKING THE WORST CONDITION AS OCCURRING 200 SEC AFTER A SUDDEN CHANGE, CALCULATE GRADIENTS THRU SHELL & TUBE SHEET FOR THIS TIME — FOR A 150°F CHANGE

FOR 3 3/8" TUBE SHEET WITH 1/4" SHIELD

$$N_{Bi}^{-1} = \frac{(12)(12.6)}{(4000)(3.640625)} = .010$$

$$N_{Fo} = \frac{(.0066)(200)}{(3.640625)^2} = .100$$

SECTION

POINT	ΔT	T (TRANSIENT CHANGE)
0	.048	7
.1	.055	8
.2	.077	12
.3	.116	17
.4	.174	26
.5	.255	38
.6	.360	54
.7	.488	73
.8	.639	96
.9	.806	121
927	.853	128
M_N	.302	45

FOR A 5 1/8" SECTION, .25625" OF WHICH IS SHIELDING

$$N_{Bi}^{-1} = \frac{(12)(12.6)}{(4000)(5.125)} = .007$$

$$N_{Fo} = \frac{(.0066)(200)}{(5.125)^2} = .050$$

SECTION

POINT	ΔT	T (TRANSIENT CHANGE)
0	.004	1
.1	.006	1
.2	.012	2
.3	.027	4
.4	.055	8
.5	.108	16
.6	.195	29
.7	.326	49
.8	.508	76
.9	.732	110
.95	.860	129
1.0	.980	147
$M_{N_{0-.95}}$		

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IN THE TUBE AREA THE THE METAL IS HEATED THRU THE SODIUM. USING A CONDUCTIVITY OF SODIUM & STAINLESS, THE EQUIVALENT IS —

$$\frac{\text{SODIUM AREA} \times K_{NA} + \text{METAL AREA} \times K_{SST}}{\text{TOTAL AREA}}$$

$$= \frac{\overset{5.655}{.145 \times 39} + \overset{10.6875}{12.5 \times .855}}{1} - 16.34 \approx 16$$

THE TUBE AREA IS UNSHIELDED. AT THE TIME BEING CONSIDERED HEAT HAS GONE THRU THE TUBE SHEET & HEATED THE SODIUM. A THICKNESS OF SODIUM MUST BE ADDED TO THE TUBE SHEET TO OBTAIN A ZERO TEMPERATURE CHANGE AT THE BOTTOM SIDE OF THE ADDED SODIUM.

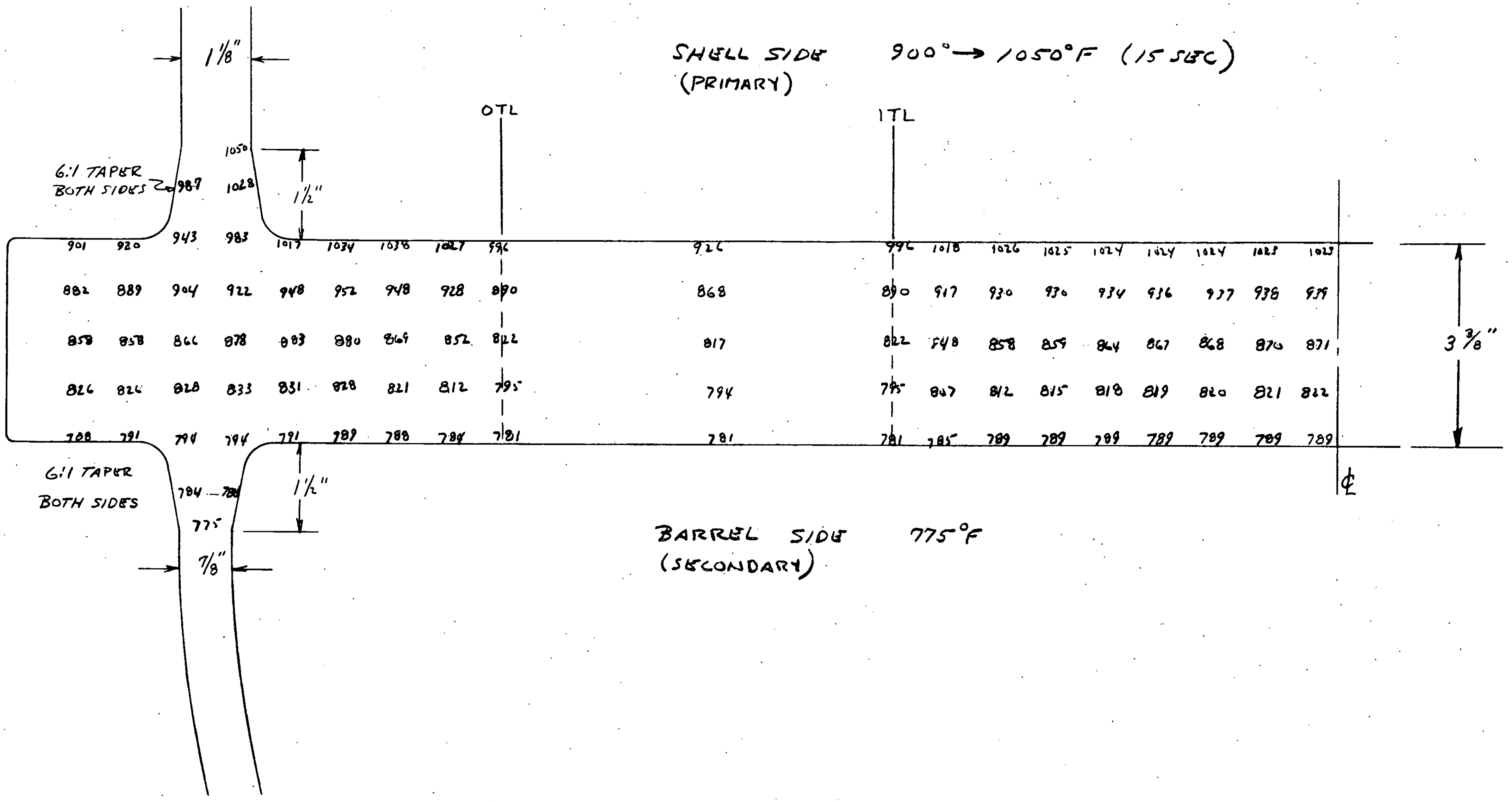
TUBE SHEET = 3.375" SODIUM = 4.338" OR 1.446" EQUIV. SST

$$\text{TUBE SHEET} = \frac{3.375}{3.375 + 1.446} = 70\%$$

$$N_{Bi}' = \frac{(12)(16)}{(4000)(4.821)} = .010 \qquad N_{Fo} = \frac{(.0066)(200)}{(4.821)^2} = .057$$

POINT	ΔT	T (TRANSIENT CHANGE)	0-.3 BELOW TUBE SHEET
0	.008	1	IN SODIUM
.1	.010	2	
.2	.019	3	
.3	.037	6	TUBE SHEET SURFACE (BARREL SIDE)
.4	.071	11	
.5	.129	19	
.6	.220	33	
.7	.353	53	
.8	.528	79	
.9	.740	111	
1.0	.976	146	

F47



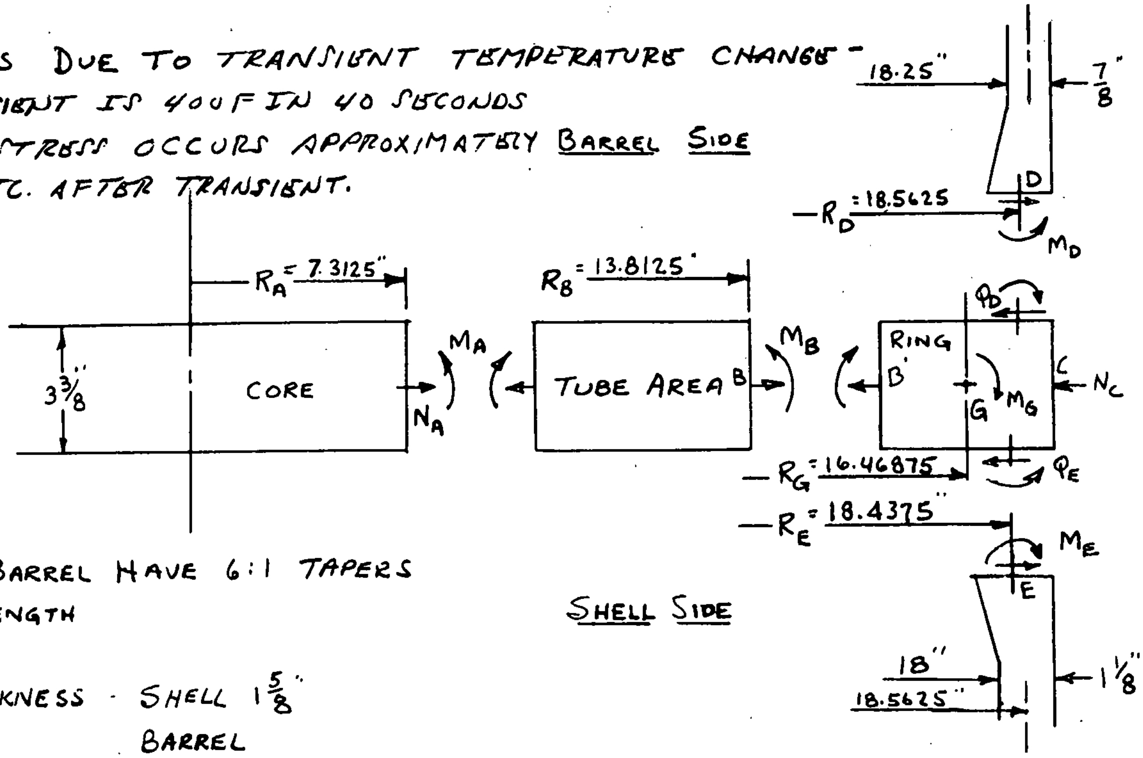
TRANSIENT TEMPERATURES
30 MW IHX LOWER TUBE SHEET
200 SEC AFTER 150°ΔT IN PRIMARY SODIUM
TUBE SHEET SHIELDED BOTH SIDES

F49

IHX TUBESHEET STRESSES
TRANSIENT THERMAL STRESSES
UPPER TUBESHEET 4-G

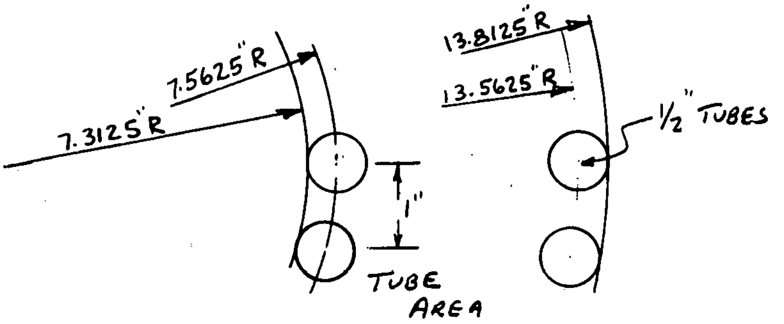
30 MW IHX - UPPER TUBE SHEET

STRESSES DUE TO TRANSIENT TEMPERATURE CHANGE -
TRANSIENT IS 400F IN 40 SECONDS
MAX STRESS OCCURS APPROXIMATELY BARREL SIDE
20 SEC. AFTER TRANSIENT.



SHELL & BARREL HAVE 6:1 TAPERS
IN $1\frac{1}{2}$" LENGTH

MAX THICKNESS - SHELL $1\frac{5}{8}$"
BARREL



POSITIVE DIRECTION
AS SHOWN
ΔR = + OUTWARD
φ = + CCW

$\eta = \frac{0.5}{1.0} = .500$

PHYSICAL CONSTANTS USED

BARREL @ ≈ 1000°F $E = 22.8 \times 10^6$ $\alpha = 11.2 \times 10^{-6}$
SHELL @ ≈ 1000°F $E = 22.8 \times 10^6$ $\alpha = 11.2 \times 10^{-6}$
TUBE SHEET CORE & RING @ ≈ 1100°F $E = 22.2 \times 10^6$ $\alpha = 11.2 \times 10^{-6}$
TUBE AREA @ ≈ 975°F $E = 22.4 \times 10^6$ $\alpha = 11.15 \times 10^{-6}$
FROM HORVAY'S MIT PAPER $\frac{E^*}{E} = 0.40$ $E^* = 8.96 \times 10^6$

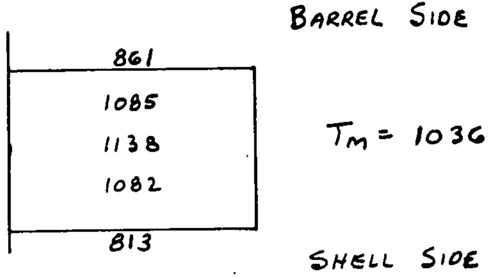
$\mu^* = .40$

G2

TEMPERATURE BASE IS TAKEN AS 775° F

CORE AREA

TEMPERATURES ARE AS GIVEN IN THE TEMPERATURE CALCULATIONS, G 21 ET SEQ.



FREE EXPANSION $\Delta R^\circ = R_A \alpha \Delta T$

$= 7.3125 (11.2 \times 10^{-6})(1036 - 775)$

$= 21376 \times 10^{-6}$

FREE ROTATION $= \frac{R_A \alpha \Delta T}{t} = \frac{7.3125(11.2 \times 10^{-6})(813-861)}{3.375} = -1165 \times 10^{-6}$

FROM ROARK. P276 #28

$$\Delta R_A = \frac{N_A R_A}{E t}(1-\mu) + 21376 \times 10^{-6}$$

$$= \frac{7.3125 \, N_A}{(22.2 \times 10^6)(3.375)}(1-0.3) + 21376 \times 10^{-6}$$

$$= .068318 \times 10^{-6} N_A + 21376 \times 10^{-6} \qquad (1)$$

FROM ROARK P 197 #12

$$\theta_A = \frac{12(1-\mu) M_A R_A}{E t^3} - 1165 \times 10^{-6} = \frac{12(.7) 7.3125 \, M_A}{(22.2 \times 10^6) \, 3.375^3} - 1165 \times 10^{-6}$$

$$\theta_A = .071973 \times 10^{-6} M_A - 1165 \times 10^{-6} \qquad (2)$$

TUBE AREA

THE TUBE AREA IS TAKEN AS A SECTION AT A UNIFORM TEMPERATURE OF 783°F NO FREE ROTATION.

FREE EXPANSIONS

$\Delta R_A^\circ = 7.3125 (11.15 \times 10^{-6})(783 - 775) = 652 \times 10^{-6}$

$\Delta R_B^\circ = 13.8125 (11.15 \times 10^{-6})(783 - 775) = 1232 \times 10^{-6}$

G3

FROM ROARK P276 #27 & 28

$$\Delta R_{A}' = -\frac{N_A R_A}{E^* t}\left(\frac{R_B^2 + R_A^2}{R_B^2 - R_A^2} + \mu^*\right) + \frac{N_B R_A}{E^* t}\ \frac{2 R_B^2}{R_B^2 - R_A^2}$$

$$= -\frac{7.3125\, N_A}{8.96\times10^6\times3.375}\left(\frac{13.8125^2+7.3125^2}{13.8125^2-7.3125^2}+.4\right) + \frac{7.3125\, N_B}{8.96\times10^6\,(3.375)}\ \frac{2\times13.8125^2}{(13.8125^2-7.3125^2)}$$

$$\Delta R_A' = -.52688\times10^{-6} N_A + .67197\times10^{-6} N_B + 652\times10^{-6} \qquad (3)$$

$$\Delta R_B = \frac{-N_A R_B}{E^* t}\left(\frac{2 R_A^2}{R_B^2 - R_A^2}\right) + \frac{N_B R_B}{E^* t}\left(\frac{R_B^2 + R_A^2}{R_B^2 - R_A^2} - \mu^*\right)$$

$$\Delta R_B = -\frac{13.8125\, N_A}{8.96\times10^6(3.375)}\left(\frac{2\times7.3125^2}{13.8125^2-7.3125^2}\right) + \frac{13.8125\, N_B}{8.96\times10^6(3.375)}\left(\frac{13.8125^2+7.3125^2}{13.8125^2-7.3125^2} - 0.4\right)$$

$$\Delta R_B = -.35575\times10^{-6} N_A + .62981\times10^{-6} N_B + 1232\times10^{-6} \qquad (4)$$

FROM ROARK P 201 #25

$$\theta_A = \frac{R_B}{E^* t^3}\left(-13.1\times1.048\, M_A + 17.8\, M_B\right) = \frac{13.8125\left(-13.1\times1.048\, M_A + 17.8\, M_B\right)}{8.96\times3.375^3\times10^6}$$

$$\theta_A = -.55052\times10^{-6} M_A + .71378\times10^{-6} M_B \qquad (5)$$

$$\theta_B = \frac{R_B}{E^* t^3}\left(-9.3 M_A + 17.8\times.932\, M_B\right) = \frac{13.8125\left(-9.3 M_A + 17.8\times.932\, M_B\right)}{8.96\times10^6\times3.375^3}$$

$$\theta_B = -.37293\times10^{-6} M_A + .66524\times10^{-6} M_B \qquad (6)$$

COMBINE EQUATIONS OF CORE & TUBE AREA

$$(1) = (3) \quad .068318\, N_A + 21376 = -.52688\, N_A + .67197\, N_B + 652$$

$$N_A = \frac{1}{.59520}\left[.67197\, N_B - 20734\right] = 1.12898\, N_B - 34835 \qquad (7)$$

$$(2) = (5) \quad .071973\, M_A - 1165 = -.55052\, M_A + .71378\, M_B$$

$$M_A = \frac{1}{.62249}\left[.71378\, M_B + 1165\right] = 1.14665\, M_B + 1872 \qquad (8)$$

SUBSTITUTING (8) INTO (6),

$$\theta_B = -.37293\times10^{-6}\left(\overset{-.42762}{1.14665\, M_B} + \overset{-698.12496}{1872}\right) + .66524\times10^{-6} M_B$$

$$M_B = 4.20840\times10^6\,\theta_B + 2938 \qquad (9)$$

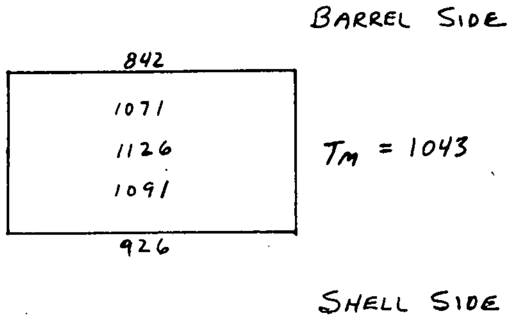
G4

SUBSTITUTING (7) INTO (4),

$$\Delta R_B = -.35575 \times 10^{-6} (\overset{-.40163}{1.12898 N_B} - \overset{+12393}{34835}) + .62981 \times 10^{-6} N_B + 1232 \times 10^{-6}$$

$$\Delta R_B = .22818 \times 10^{-6} N_B + 13625 \times 10^{-6} \qquad (10)$$

RING



FREE EXPANSION

$$@ G = (11.2 \times 10^{-6})(16.46875)(1043-775)$$
$$= 49433 \times 10^{-6}$$

$$@ B' = (11.2 \times 10^{-6})(13.8125)(1043-775)$$
$$= 41460 \times 10^{-6}$$

$$\text{FREE ROTATION } @ G = \frac{(11.2 \times 10^{-6})(16.46875)(926-842)}{3.375} = 4591 \times 10^{-6}$$

FROM ROARK:- P.276 #27 & 28 -

$$\Delta R_{B'} = -\frac{N_B R_B}{Et}\left(\frac{R_c^2 + R_B^2}{R_c^2 - R_B^2} + \mu\right) - \frac{N_c R_B}{Et}\left(\frac{2 R_c^2}{R_c^2 - R_B^2}\right)$$

.18÷351 3.1[illegible]+.3

$$= \frac{13.8125 N_B}{(22.2 \times 10^6)(3.375)}\left(\frac{19.125^2 + 13.8125^2}{19.125^2 - 13.8125^2} + .3\right) - \frac{13.8125 N_c}{(22.2 \times 10^6)(3.375)}\left(\frac{2 \times 19.125^2}{19.125^2 - 13.8125^2}\right)$$

$$\Delta R_{B'} = -.64166 \times 10^{-6} N_B - .77071 \times 10^{-6} N_c + 41460 \times 10^{-6} \qquad (11)$$

RESISTANCE TO ROTATION OF RING - TIMOSHENKO S. OF M. VOL II P.140

$$\Theta_G = -\frac{12 R_G M_G}{Et^3 L_N R_c/R_B}, \quad \frac{-(12)(16.46875) M_G}{(22.2 \times 10^6)(3.375)^3 L_N \frac{19.125}{13.8125}} = .71162 \times 10^{-6} M_G$$

$$M_G = 1.4052 \times 10^6 (\Theta_G - 4591 \times 10^{-6}) = 1.4052 \times 10^6 \Theta_G - 6451 \qquad (12)$$

G5

<u>SHELL</u> - FROM TAPERED WALL CALCULATIONS - G 16 & 17

$$M_G = -518621\,\Delta R_G - 1868499\,\theta_G + 33507 \qquad (13)$$

$$Q_G = 277560\,\Delta R_G + 518556\,\theta_G - 15666 \qquad (14)$$

BARREL - FROM TAPERED WALL CALCULATIONS - G 20

$$M_D = -317173\,\Delta R_D + 1017878\,\theta_D + 13160 \qquad (15)$$

$$Q_D = 189257\,\Delta R_D - 317175\,\theta_D - 7221 \qquad (16)$$

LET N_C BE PROPORTIONAL TO Q_D & Q_G SUCH THAT -

$$N_C = \frac{18.5625}{19.125} Q_D + \frac{18.4375}{19.125} Q_G = .97059\,Q_D + .96405\,Q_G \qquad (17)$$

SUBSTITUTE (17) INTO (11) -

$$\Delta R_{B'} = -.64166 \times 10^{-6} N_B - .77071 \times 10^{-6} (.97059\,Q_D + .96405\,Q_G) + 41460 \times 10^{-6}$$

$$\Delta R_{B'} = -.64166 \times 10^{-6} N_B - .74804 \times 10^{-6} Q_D - .74300 \times 10^{-6} Q_G + 41460 \times 10^{-6} \qquad (18)$$

(18) = (10)

$$-.64166\,N_B - .74804\,Q_D - .74300\,Q_G + 41460 = .22818\,N_B + 13625$$

$$N_B = \frac{1}{.86984}(-.74804\,Q_D - .74300\,Q_G + 27835)$$

$$N_B = -.85997\,Q_D - .85418\,Q_G + 32000 \qquad (19)$$

LET $\theta_6 = \theta_B = \theta_D = \theta_G = \varphi$ FINAL ROTATION OF RING

DISPLACEMENT OF POINT D, NEGLECTING SMALL TERMS -

$$\Delta R_D = \Delta R_B - \frac{3.375}{2}\varphi$$

$$= -.64166 \times 10^{-6} N_B - .74804 \times 10^{-6} Q_D - .74300 \times 10^{-6} Q_G$$

$$+ 41460 \times 10^{-6} - 1.6875\,\varphi$$

SUBSTITUTING FROM (19) —

$$= -.64166\times10^{-6}(-.85997\,Q_D - .85418\,Q_G + .52000) - .74804\times10^{-6}\,Q_D$$

$$-.74300\times10^{-6}\,Q_G + 41460\times10^{-6} - 1.6875\varphi$$

$$\Delta R_D = -.19623\times10^{-6}Q_D - .19491\,Q_G - 1.6875\varphi + 20927\times10^{-6}$$

SUBSTITUTING FROM (14) & (16) —

$$\Delta R_D = -.19623(.189257\,\Delta R_D - .317175\varphi - .007221) - 1.6875\varphi + .020927$$

$$-.19491(.277560\,\Delta R_G + .518556\,\varphi - .015666)$$

$$= -.03714\,\Delta R_D - .05410\,\Delta R_G - 1.72633\varphi + .025397$$

$$\Delta R_D = -.05216\,\Delta R_G - 1.6645\varphi + .024488 \qquad (20)$$

$$\Delta R_G = \Delta R_D + \varphi t = -.05216\,\Delta R_G - 1.6645\varphi + .024488 + 3.375\varphi$$

$$\Delta R_G = 1.6257\,\varphi + .023274 \qquad (21)$$

SUBSTITUTE (21) INTO (20) —

$$\Delta R_D = -.05216\,(1.6257\varphi + .023274) - 1.6645\varphi + .024488$$

$$\Delta R_D = -1.7493\,\varphi + .023274 \qquad (22)$$

EQUILIBRIUM OF OUTER RING — PER RADIAN

$$13.8125\,M_B + 18.5625\,M_D - 18.5625(1.6875)\,Q_D - 18.4375\,M_G$$

$$+18.4375(1.6875)\,Q_G + 16.46875\,M_E = 0$$

SUBSTITUTING INTO MOMENT EQUATION —

+ 58124.515   + 40531   [illegible]

$$13.8125(4.20840\times10^{6}\varphi+2938)+18.5625(-317173\Delta R_D+1017878\varphi$$

[illegible]

$$+13160)-31.3242(189257\Delta R_D-317175\varphi-7221)$$

[illegible]

$$-18.4375(-518621\Delta R_G-1868499\varphi+33507)+31.1133(277560\Delta R_G$$

[illegible]

$$+518556\varphi-15666)+16.46875(1.4052\times10^{6}\varphi-6451)=0$$

$$160.684464\times10^{6}\varphi-11.815848\times10^{6}\Delta R_D+18.197883\times10^{6}\Delta R_G=700391$$

[illegible]

$$160.684464\varphi-11.815848(-1.7493\varphi+.023274)$$

[illegible]

$$+18.197883(1.6257\varphi+.023274)=.700391$$

$$210.938125\varphi=.551855\qquad\varphi=2616\times10^{-6}$$

- .004576

$$\Delta R_D=-1.7493(2616\times10^{-6})+.023274=.018698$$

- .004253

$$\Delta R_G=1.6257(2616\times10^{-6})+.023274=.027527$$

- 5931   2663

$$M_D=-317173(.018698)+1.017878(2616)+13160=9892$$

- 14276   - 4888

$$M_G=-518621(.027527)-1.868499(2616)+33507=14343$$

3539   - 830

$$Q_D=189257(.018698)-.317175(2616)-7221=-4512$$

7640   - 1357

$$Q_G=277560(.027527)+.518556(2616)-15666=-6669$$

11009

$$M_B=4.20840(2616)+2938=13947$$

3676

$$M_C=1.4052(2616)-6451=-2775$$

SUBSTITUTING INTO MOMENT EQUATION —

192693   183630   + 141335   - 264449

C8 $$13.8125(13947)+18.5625(9892)-31.3242(-4512)-18.4375(14343)$$

- 207495   - 45701

$$+31.1133(-6669)+16.46875(-2775)\overset{?}{=}0=-47\ \checkmark$$

FROM (8), $M_A = \overset{15992}{1.14665(13947)} + 1872 = 17864$

FROM (19) $N_B = -\overset{3880}{.85997(-4512)} - \overset{5697}{.85418(-6669)} + 32000 = 41577$

FROM (7) $N_A = \overset{46940}{1.12898(41577)} - 34835 = 12105$

<u>STRESSES</u> - DUE TO THERMAL TRANSIENT

<u>TUBE AREA</u>: IN THE TUBE AREA, THE BENDING STRESSES ARE GIVEN BY:

$$\text{RADIAL STRESS} = S_R = \frac{6}{t^2(R_B^2 - R_A^2)}\left[R_B^2 M_B - R_A^2 M_A - \frac{R_B^2 R_A^2}{R^2}(M_B - M_A)\right]$$

$$\text{TANGENTIAL STRESS} = S_T = \frac{6}{t^2(R_B^2 - R_A^2)}\left[R_B^2 M_B - R_A^2 M_A + \frac{R_B^2 R_A^2}{R^2}(M_B - M_A)\right]$$

WHERE R IS RADIUS TO ANY POINT & OTHER TERMS ARE AS PREVIOUSLY DEFINED

$$\frac{6}{t^2(R_B^2 - R_A^2)} = \frac{6}{(3.375^2)(13.8125^2 - 7.3125^2)} = .0038361$$

$R_B^2 = 13.8125^2 = 190.78515625$ $\quad$ $R_A^2 = 7.3125^2 = 53.47265625$

$R_B^2 R_A^2 = 10201.789$

AT THE INNERMOST LIGAMENT, $R = 7.5625$

$$\frac{R_B^2 R_A^2}{R^2} = 178.380$$

$$S_R = .0038361\left[\overset{2\,660,881}{190.7852(13947)} - \overset{-955236}{53.4727(17864)} - \overset{+\ 698714}{178.380(13947-17864)}\right]$$

= 9223 C ON TOP

$$S_T = .0038361\left[2660881 - 955236 - 698714\right]$$

= 3863 C ON TOP

G9

AT THE OUTERMOST LIGAMENT, $R = 13.5625$

$$\frac{R_B^2 \quad R_A^2}{R^2} = 55.4622$$

$$S_R = .0038361\left[2660881 - 955236 - \overset{+217245}{55.4622(-3917)}\right]$$

$$= 7376 \text{ C} \quad \text{ON TOP}$$

$$S_T = .0038361\left[2660881 - 955236 - 217245\right]$$

$$= 5710 \text{ C} \quad \text{ON TOP}$$

THE NORMAL STRESSES ARE GIVEN BY:

$$\text{RADIAL STRESS} = S_R = \frac{N_A}{t}\frac{R_A^2}{R^2}\left(\frac{R_B^2 - R^2}{R_B^2 - R_A^2}\right) + \frac{N_B}{t}\frac{R_B^2}{R^2}\left(\frac{R^2 - R_A^2}{R_B^2 - R_A^2}\right)$$

$$\text{TANGENTIAL STRESS} = S_T = -\frac{N_A}{t}\frac{R_A^2}{R^2}\left(\frac{R_B^2 + R^2}{R_B^2 - R_A^2}\right) + \frac{N_B}{t}\frac{R_B^2}{R^2}\left(\frac{R^2 + R_A^2}{R_B^2 - R_A^2}\right)$$

AT THE INNERMOST LIGAMENT, $R = 7.5625$

$$\frac{R_A^2}{tR^2} = .27703 \qquad \frac{R_B^2}{tR^2} = .98842 \qquad \frac{R_B^2 + R^2}{R_B^2 - R_A^2} = 1.8059$$

$$\frac{R_B^2 - R^2}{R_B^2 - R_A^2} = .97292 \qquad \frac{R^2 - R_A^2}{R_B^2 - R_A^2} = .027082 \qquad \frac{R^2 + R_A^2}{R_B^2 - R_A^2} = .80593$$

$$S_R = 12105\overset{3263}{(.27703)}(.97292) + 41577\overset{1113}{(.98842)}(.027082) = 4376 \quad \text{T}$$

$$S_T = -12105\overset{-6056}{(.27703)}(1.8059) + 41577\overset{33120}{(.98842)}(.80593) = 27064 \quad \text{T}$$

G10

AT THE OUTERMOST LIGAMENT, $R = 13.5625$

$$\frac{R_A^2}{tR^2} = .086135 \qquad \frac{R_B^2}{tR^2} = .30732 \qquad \frac{R_B^2 + R^2}{R_B^2 - R_A^2} = 2.72901$$

$$\frac{R_B^2 - R^2}{R_B^2 - R_A^2} = .049841 \qquad \frac{R^2 - R_A^2}{R_B^2 - R_A^2} = .95016 \qquad \frac{R^2 + R_A^2}{R_B^2 - R_A^2} = 1.72901$$

$$S_R = 12105\overset{52}{(.086135)}(.049841) + 41577\overset{12141}{(.30732)}(.95016) = 12193 \quad T$$

$$S_T = -12105\overset{-2845}{(.086135)}(2.72901) + 41577\overset{22092}{(.30732)}(1.72901) = 19247 \quad T$$

TUBE AREA STRESSES BECOME

INNER ROW $\eta = .500$

$\frac{\sigma}{\sigma_{max}}$

SHELL SIDE (BOTTOM)

$\sigma_R = 4376 + 9223 = 13599$ $\quad .440 \quad K = 3.0 \quad$ $\sigma_R = 40797$

$\sigma_T = 27064 + 3863 = 30927$ $\quad$ $\sigma_T = 92781$

BARREL SIDE (TOP)

$\sigma_R = 4376 - 9223 = -4847$ $\quad -.209 \quad K = 4.0 \quad$ $\sigma_R = -19388$

$\sigma_T = 27064 - 3863 = 23201$ $\quad$ $\sigma_T = 92804$

OUTER ROW

SHELL SIDE (BOTTOM)

$\sigma_R = 12193 + 7376 = 19569$ $\quad .784 \quad K = 2.5 \quad$ $\sigma_R = 48923$

$\sigma_T = 19247 + 5710 = 24957$ $\quad$ $\sigma_T = 62393$

BARREL SIDE (TOP)

$\sigma_R = 12193 - 7376 = 4817$ $\quad .356 \quad K = 3.1 \quad$ $\sigma_R = 14933$

$\sigma_T = 19247 - 5710 = 13537$ $\quad$ $\sigma_T = 41965$

G11

BARREL STRESSES – AT JUNCTION WITH TUBE SHEET

$$\frac{6}{t^2} = \frac{6}{1.125^2} = 4.74074$$

$$\Delta R_D = 18698 \times 10^{-6}$$

$$\Delta R_D^0 = (11.2 \times 10^{-6})(\overset{190}{965 - 775}) \begin{matrix} \nearrow 18.000 = 38304 \times 10^{-6} \\ \searrow 19.125 = 40698 \times 10^{-6} \end{matrix}$$

LONGITUDINAL STRESS

$$S_L = \frac{6M_D}{t^2} = 4.74074 \times 9892 = 46895 \quad \begin{matrix} C & \text{OUTSIDE} \\ T & \text{INSIDE} \end{matrix}$$

$$\text{CIRCUMFERENTIAL STRESS} = S_C = \frac{\Delta R - \Delta R^0}{R} E \pm \mu S_L$$

$$\text{OUTER SURFACE} \quad S_C = \frac{\overset{-22000}{18698 - 40698}}{19.125} \times 22.8 - 0.3\overset{-14069}{(46895)} = 40296 \text{ C}$$

$$\text{INNER SURFACE} \quad S_C = \frac{\overset{-19606}{18698 - 38304}}{18} \times 22.8 + 0.3\overset{+14069}{(46895)} = 10765 \text{ C}$$

SHELL STRESSES AT JUNCTION WITH TUBE SHEET

$$\frac{6}{t^2} = \frac{6}{1.375^2} = 3.17355$$

$$\Delta R_E = 27527 \times 10^{-6}$$

$$\Delta R_E^0 = (11.2 \times 10^{-6})(\overset{279}{1054 - 775}) \begin{matrix} 17.750 = 55465 \times 10^{-6} \\ \searrow 19.125 = 59762 \times 10^{-6} \end{matrix}$$

LONGITUDINAL STRESS

$$S_L = \frac{6M_E}{t^2} = 3.17355 \times 14343 = 45518 \quad \begin{matrix} C & \text{OUTSIDE} \\ T & \text{INSIDE} \end{matrix}$$

$$\text{OUTER SURFACE} \quad S_C = \frac{\overset{-38429}{27527 - 59762}}{19.125} \times 22.8 - 0.3\overset{-13655}{(45518)} = 52084 \text{ C}$$

$$\text{INNER SURFACE} \quad S_C = \frac{\overset{-35887}{27527 - 55465}}{17.75} \times 22.8 + 0.3\overset{+13655}{(45518)} = 22232 \text{ C}$$

G12

PHYSICAL PROPERTIES - UPPER TUBE SHEET
30 MW IHX - SHELL & BARREL WALLS

$m = .25$
$E = 22.8 \times 10^6$
$\alpha = 11.2 \times 10^{-6}$

PHYSICAL PROPERTIES & CALCULATIONS IN COMMON WITH PRESSURE CASE ARE GIVEN IN PRESSURE STRESS CALCULATIONS SECTION E PP. E21 ET SEQ.

BARREL

POINT	0	1	2	3	4	5	6	7
t	1.125	1.08333	1.04167	1.000	.95833	.91667	.875	.875
R_M	18.5625	18.58334	18.60417	18.625	18.64584	18.66667	18.6875	18.6875
T	966	954	946	940	935	932	930	930
ΔT	227	217	211	209	208	208	207	206
$C_3 = \alpha R_M (T-775)$	.039709	.037256	.035631	.034419	.033413	.032823	.032442	.03442
$10^6 C_4 = \frac{m \alpha \Delta T}{t}$	564.98	560.86	567.17	585.20	607.72	635.34	662.40	659.20
SHELL								
t	1.375	1.33333	1.29167	1.250	1.20833	1.16667	1.125	1.125
R_M	18.4375	18.45833	18.47917	18.500	18.52083	18.54167	18.5625	18.5625
T	1054	1044	1032	1026	1022	1019	1018	1016
ΔT	192	210	233	243	249	252	253	253
$C_3 = \alpha R_M (T-775)$	.057614	.055611	.053190	.052007	.051236	.050671	.050520	.050104
$10^6 C_4 = \frac{m \alpha \Delta T}{t}$	390.98	441.00	505.08	544.32	576.99	604.80	629.69	629.69

G14

POINT	10^6 Y	10^6 C_3	10^6 $Y-C_3$	$\Delta V = -C_2(Y-C_3)$	V	$mV=\Delta M$	M	C_1M	10^6 C_4	10^6 $\Delta\theta = C_1M - C_4$	10^6 θ	10^6 $m\theta = \Delta Y$
12	0	50104	-50104	-442	0		0	0	314.84	-314.84	0	
					442	110					-314.84	-79
11	-79	50104	-50183	-885			110	10	629.69	-619.68		
					1327	332					-934.53	-234
10	-313	50104	-50417	-889			442	39	629.69	-591		
					2216	554					-1526	-382
9	-695	50104	-50799	-896			996	88	629.69	-542		
					3112	778					-2068	-517
8	-1212	50104	-51316	-905			1774	157	629.69	-473		
					4017	1004					-2541	-635
7	-1847	50104	-51951	-916			2778	247	629.69	-383		
					4933	1233					-2924	-731
6	-2578	50520	-53098	-936			4011	356	629.69	-274		
					5869	1467					-3198	-800
5	-3378	50671	-54049	-990			5478	436	604.80	-169		
					6859	1715					-3367	-842
4	-4220	51236	-55456	-1055			7193	515	576.98	-62		
					7914	1978					-3429	-857
3	-5077	52007	-57084	-1126			9171	593	544.32	49		
					9040	2260					-3380	-845
2	-5922	53190	-59112	-1207			11431	670	505.08	165		
					10247	2562					-3215	-804
1	-6726	55611	-62337	-1317			13993	746	441.00	305		
					11564	2891					-2910	-728
0	-7454	57614	-65068	-711	12275		16884	410	195.49	215	-2695	

SOLUTION OF EQUATIONS - SHELL SIDE

FROM THE PRESSURE CALCULATIONS, THE EQUATIONS FOR THE STRAIGHT WALL ARE

$$M_{12} = -424875\,Y_{12} + 1510970\,\theta_{1} + 424875(.050104)$$

$$-1510970(.00062969)$$

$$M_{12} = -424875\,Y_{12} + 1510970\,\theta_{12} + 20338 \qquad (A)$$

$$V_{12} = -238945\,Y_{12} + 424875\,\theta_{12} + 238945(.050104)$$

$$-424875(.00062969)$$

$$V_{12} = -238945\,Y_{12} + 424875\,\theta_{12} + 11704 \qquad (B)$$

FROM THE TAPERED WALL CALCULATIONS FOR THE PRESSURE CASE & THE PREVIOUS PAGE, THE EQUATIONS ARE —

$$M_0 = .9111868\,M_{12} + 2.9479835\,V_{12} - 321634\,Y_{12} - 328160\,\theta_{12} + 16884 \qquad (C)$$

$$V_0 = -.1249080\,M_{12} + .9085824\,V_{12} - 220351\,Y_{12} - 347205\,\theta_{12} + 12275 \qquad (D)$$

$$Y_0 = 1.5204592\times10^{-6}\,M_{12} + 1.4271348\times10^{-6}\,V_{12} + .9285554\,Y_{12} + 2.9609424\,\theta_{12} - .007454 \qquad (E)$$

$$\theta_0 = .9168468\times10^{-6}\,M_{12} + 1.2545439\times10^{-6}\,V_{12} - .0082319\,Y_{12} + .9408233\,\theta_{12} - .007695 \qquad (F)$$

SUBSTITUTE (A) & (B) ENTO (C) (D) (E) & (F) —

$$M_0 = .9111888(-424875\,Y_{12} + 1510970\,\theta_{12} + 20338) - 321634\,Y_{12} - 328160\,\theta_{12}$$

$$+ 2.9479835(-238945\,Y_{12} + 424875\,\theta_{12} + 11704) + 16884$$

$$M_0 = -1413181\,Y_{12} + 2301143\,\theta_{12} + 69919 \qquad (G)$$

$$V_0 = -.1249080(-424875\,Y_{12} + 1510970\,\theta_{12} + 20338) - 220351\,Y_{12}$$

$$+ .9085824(-238945\,Y_{12} + 424875\,\theta_{12} + 11704) - 347205\,\theta_{12} + 12275$$

$$V_0 = -384382\, Y_{12} - 149903\, \theta_{12} + 20869 \qquad (H)$$

$$\overset{+.03[illegible]3}{}$$

$$Y_0 = 1.5204592(-.424875\, Y_{12} + 1.510978\, \theta_{12} + .020838) + .9285554\, Y_{12}$$

$$\overset{+.0[illegible]703}{}$$

$$+1.4271348(-.238945\, Y_{12} + .424875\, \theta_{12} + .011704) + 2.9603424\, \theta_{12} - .007454$$

$$Y_0 = -.0584564\, Y_{12} + 5.8640645\, \theta_{12} + .040172 \qquad (J)$$

$$\theta_0 = .9168466(-.424875\, Y_{12} + 1.510978\, \theta_{12} + .020838) - .0872319\, Y_{12} - .002695$$

$$\overset{+.014[illegible]3}{}$$

$$+1.2545439(-.238945\, Y_{12} + .424875\, \theta_{12} + .011704) + .9408233\, \theta_{12}$$

$$\theta_0 = -.7725412\, Y_{12} + 2.8591752\, \theta_{12} + .030635 \qquad (K)$$

REARRANGING (K) –

$$\theta_{12} = .3497511\, \theta_0 + .2701982\, Y_{12} - .010715 \qquad (L)$$

SUBSTITUTING INTO (J) –

$$Y_0 = -.0584564\, Y_{12} + .040172 + 5.8640645(.3497511\, \theta_0 + .2701952\, Y_{12} - .010715)$$

$$Y_{12} = .6553065\, Y_0 - 1.3440095\, \theta_0 + .014850 \qquad (M)$$

SUBSTITUTE (M) INTO (L) –

$$\theta_{12} = .3497511\, \theta_0 - .010715 + .2701982(.6553065\, Y_0 - 1.3440095\, \theta_0 + .014850)$$

$$\theta_{12} = -.0133978\, \theta_0 + .1770626\, Y_0 - .006703 \qquad (N)$$

SUBSTITUTE (M) & (N) INTO (G) & (H)

$$\overset{-20856}{}$$

$$M_0 = -1413181(.6553065\, Y_0 - 1.3440095\, \theta_0 + .014850) + 69919$$

$$\overset{-15426}{}$$

$$+2301143(-.0133978\, \theta_0 + .1770626\, Y_0 - .006703)$$

$$M_0 = -518621\, Y_0 + 1868499\, \theta_0 + 33507 \qquad (O)$$

G16

$$-5703$$

$$V_0 = -384382\,(.6553065\,Y_0 - 1.3440095\,\Theta_0 + .014850) + 20369$$

$$-\,149903\,(-.0133970\,\Theta_0 + .1770626\,Y_0 - .006703)$$

$$V_0 = -277560\,Y_0 + 518556\,\Theta_0 + 15666 \qquad (P)$$

EQUATIONS (O) & (P) ARE THE EQUATIONS FOR M_E & Q_E USED IN THE CALCULATIONS.

30 MW IHX UPPER TUBE SHEET

BARREL WALL

IN THE STRAIGHT UNIFORM SECTION OF THE BARREL M & V ARE GIVEN BY—

$$M = -.3025 \frac{Et^2}{R} \left(Y_0 - \theta_0/\beta \right)$$

$$V = .3025 \frac{Et^2}{R} \left(-2\beta Y_0 + \theta_0 \right)$$

$$Y_0 = \Delta R - \Delta R^{\circ}$$

$$\theta_0 = \theta - \theta^{\circ}$$

$$\theta_0 = \frac{\alpha \Delta T}{t} = \frac{(11.2 \times 10^{-6})(206)}{.875} = 2636.8 \times 10^{-6}$$

$$\Delta R^{\circ} = \alpha R_M \Delta T = (11.2 \times 10^{-6})(18.6875)(930-775) = .03442$$

$$\beta = \frac{1.285}{\sqrt{Rt}} = \frac{1.285}{\sqrt{(18.6875 \times .875)}} = .31778$$

$$.3025 \frac{Et^2}{R} = \frac{(.3025)(22.8 \times 10^6)(.875)^2}{18.6875} = .25530 \times 10^6$$

$$M = -.25530 \times 10^6 \Delta R + .80339 \times 10^6 \theta + 6663$$

$$V = -.16226 \times 10^6 \Delta R + .25530 \times 10^6 \theta + 4912$$

G18

TRIAL COMPUTATION - UPPER TUBE SHEET BARREL WALL
STEADY STATE + TRANSIENT

$\theta_8 = Y_8 = 0 \quad M_0 = 6669 \quad V_8 = 4912$

POINT	10^6 Y	10^6 C_3	10^6 $Y-C_3$	$\Delta V = -C_2(Y-C_3)$	V	$mV = \Delta M$	M	10^6 $C_1 M$	10^6 C_4	10^6 $C_1 M - C_4$	10^6 G	10^6 $mG = \Delta Y$
8	0	34420	-34420	-222	4912		6669	660	330	330	0	
					5134	1284					330	82
7	82	34420	-34338	-443			7953	1573	659	914		
					5577	1394					1244	311
6	393	32442	-32049	-414			9347	1849	662	1187		
					5991	1498					2431	608
5	1001	32823	-31822	-431			10845	1866	635	1231		
					6422	1606					3662	916
4	1917	33413	-31496	-447			12451	1875	608	1267		
					6869	1717					4929	1232
3	3149	34419	-31270	-464			14168	1878	585	1293		
					7333	1833					6222	1556
2	4705	35631	-30926	-479			16001	1876	567	1309		
					7812	1953					7531	1883
1	6588	37256	-30668	-495			17954	1871	561	1310		
					8307	2077					8841	2210
0	8798	39709	-30911	-260	8567		20031	932	282	650	9491	

SOLUTION OF THE EQUATIONS - BARREL SIDE
COEFFICIENTS FOR Y_8 & Θ_8 FROM PRESSURE CALCULATIONS -

$M_0 = -679383\,Y_8 + 1213037\,\Theta_8 + 20031$ (A)

$V_0 = -256528\,Y_8 + 78309\,\Theta_8 + 8567$ (B)

$Y_0 = .495765\,Y_8 + 3.314125\,\Theta_8 + .008798$ (C)

$\Theta_0 = -.512968\,Y_8 + 2.224428\,\Theta_8 + .009491$ (D)

REARRANGING (C) -

$Y_8 = 2.017085\,Y_0 - 6.664871\,\Theta_8 - .017746$ (E)

SUBSTITUTING (E) INTO (D)

$\Theta_0 = -.512968(2.017055\,Y_0 - 6.684871\,\Theta_8 - .017746) + 2.224428\,\Theta_8 + .009491$

$\Theta_8 = .176880\,\Theta_0 + .183018\,Y_0 - .0032889$ (F)

SUBSTITUTING (F) INTO (E) -

$Y_8 = 2.017065\,Y_0 - 6.664871(.176880\,\Theta_0 + .183018\,Y_0 - .0032889) - .017746$

$Y_8 = .793637\,Y_0 - 1.182420\,\Theta_0 + .004240$ (G)

SUBSTITUTING (F) & (G) INTO (A) & (B) -

$M_0 = -679383(.793637\,Y_0 - 1.182420\,\Theta_0 + .004240) + 20031$
$+ 1213037(.176880\,\Theta_0 + .183018\,Y_0 - .0032889)$

$M_0 = -317173\,Y_0 + 1017878\,\Theta_0 + 13160$

$V_0 = -256528(.793633\,Y_0 - 1.182420\,\Theta_0 + .004240) + 8567$
$+ 78309(.176880\,\Theta_0 + .183018\,Y_0 - .0032889)$

G20 $V_0 = -189257\,Y_0 + 317175\,\Theta_0 + 7221$

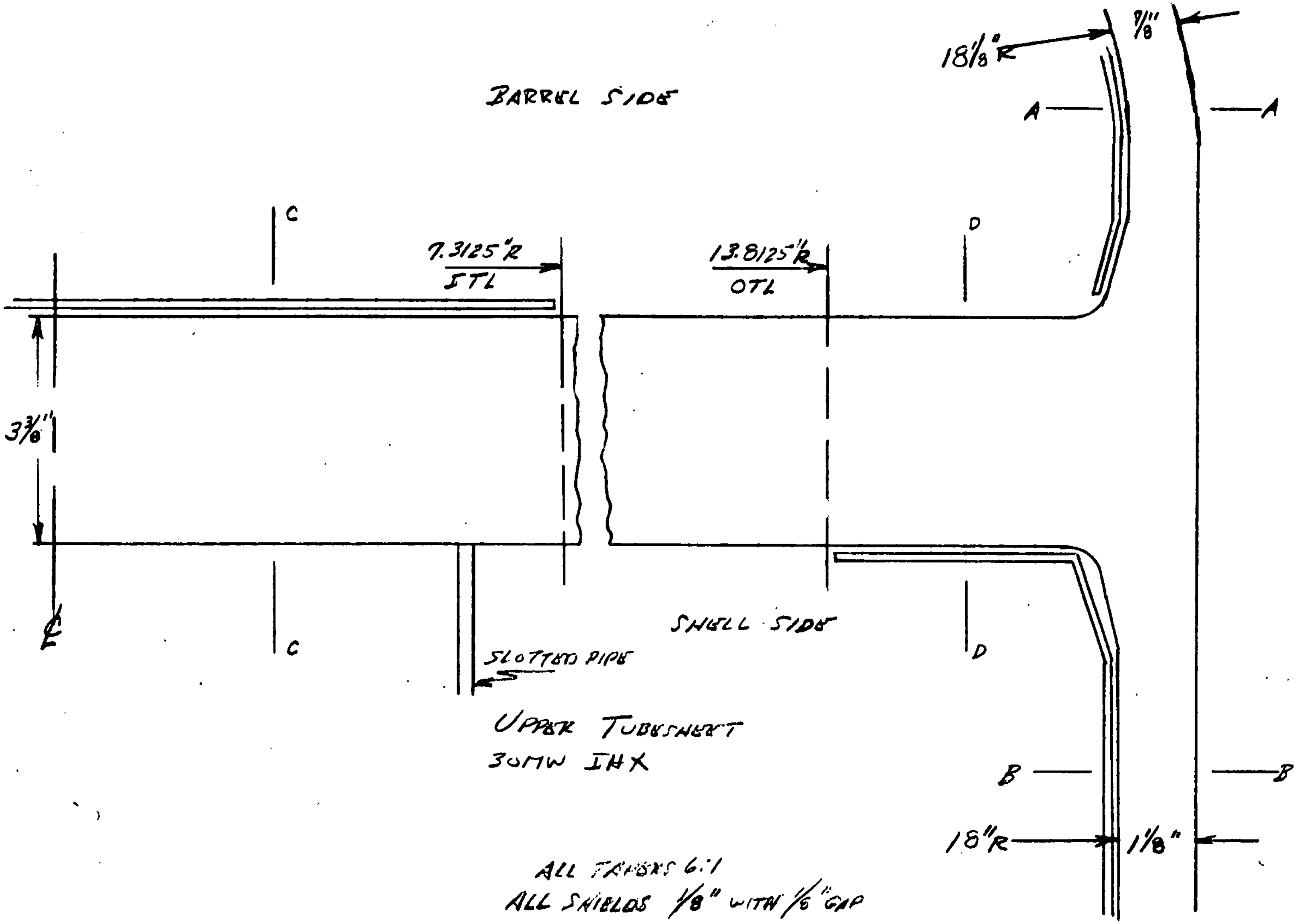
TRANSIENT TEMPERATURES
UPPER TUBESHEET 30 MW IHX

THE TRANSIENT TEMPERATURES IN THE UPPER TUBESHEET ARE BASED ON A COOLING RATE FOR SODIUM OF 10°/SEC FOR 40 SEC. OR A DROP IN TEMPERATURE OF 400°F. THE SHELL IS 1 1/8" THICK WITH 1/8" SHIELDING. THE BARREL IS 7/8" THICK WITH 1/8" SHIELDING. THE TUBESHEET IS 3 3/8" THICK & IS PARTIALLY SHIELDED.

FROM THE CALCULATIONS ON THE FOLLOWING PAGE THE WORST TEMPERATURE CONDITION OCCURS 60 SEC AFTER START OF THE TRANSIENT (OR 20 SEC AFTER END OF TRANSIENT) & ALL TEMPERATURES WILL BE CALCULATED FOR THIS TIME.

BECAUSE THE WORST TIME IS ONLY A SHORT TIME AFTER THE TRANSIENT THE TEMPERATURES ARE CALCULATED AS FOR A 60 SECOND GRADUAL CHANGE (10°/SEC) WITH A 20 SECOND GRADUAL CHANGE OF OPPOSITE SIGN IMPOSED UPON IT.

G21



UPPER TUBESHEET
30MW IHX

ALL TAPERS 6:1
ALL SHIELDS 1/8" WITH 1/6" GAP

STEADY STATE DISTRIBUTION

SECTION A-A 1175°-100°F

SODIUM h=4000	.00025	
1/8" SST SHIELD K=12.5	.000834	
1/8" SODIUM K=39	.000267	1175
7/8" SHELL K=12.5	.00584	1174
6" INSULATION K=.06	8.34	
	8.347191	

SECTION B-B 1200°-100°F

SODIUM h=4000	.00025	
1/8" SST SHIELD K=12.5	.000834	
1/8" SODIUM K=39	.000267	1200
1 1/8" SHELL K=12.5	.00750	1199
6" INSULATION K=.06	8.34	
	8.348851	

SECTION C-C 1200°-1175°F

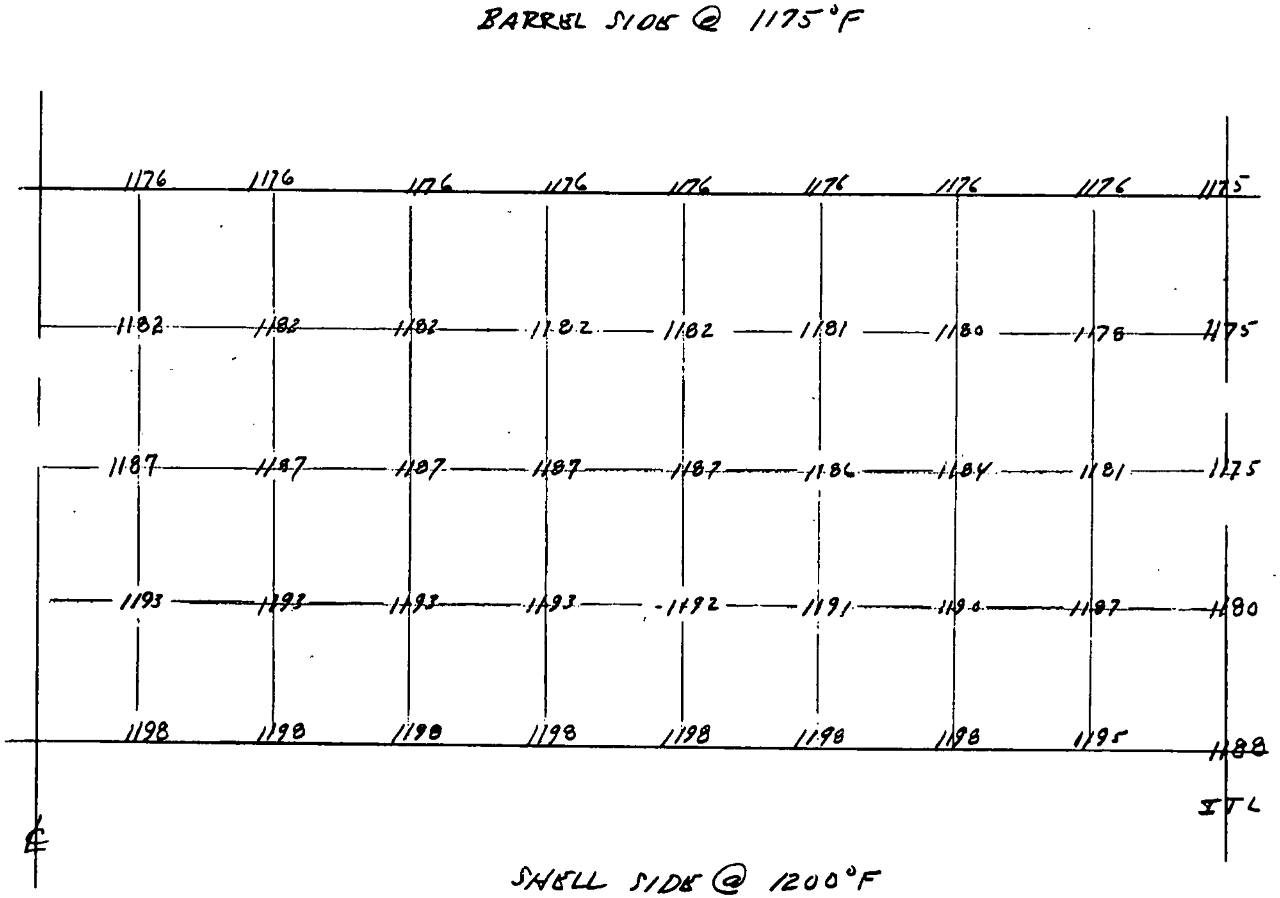
		1200
SODIUM h=4000	.000250	
1/8" SST SHIELD K=11.5	.000834	1199
1/8" SODIUM K=39	.000267	1198
3 3/8" TUBESHEET K=11	.02245	1176
SODIUM h=4000	.000250	1175
	.024051	

SECTION D-D 1200°-1175°F

SAME AS C-C FOR STEADY STATE PURPOSES

G23

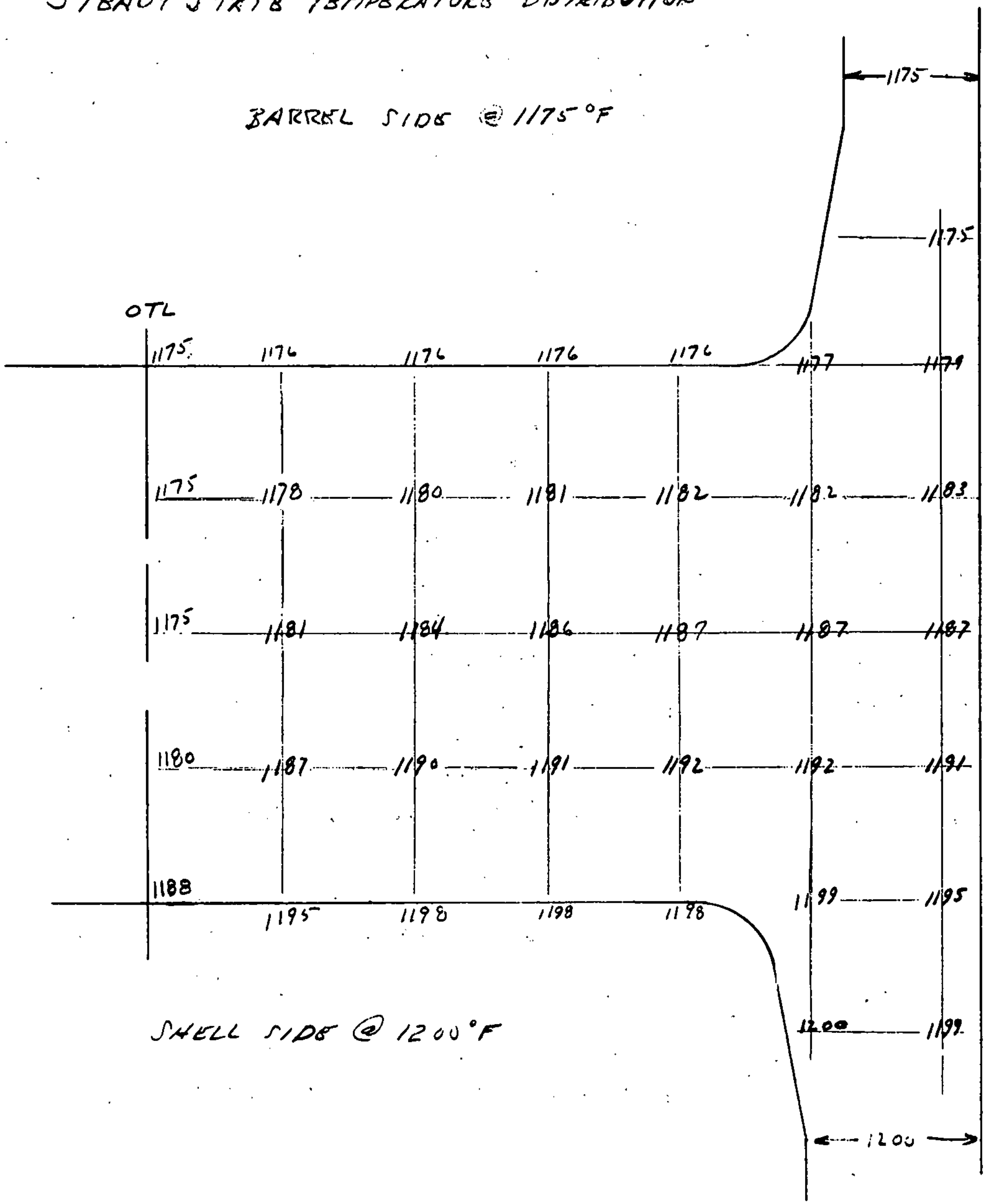
G24



1176	1176	1176	1176	1176	1176	1176	1176	1175
1182	1182	1182	1182	1182	1181	1180	1178	1175
1187	1187	1187	1187	1187	1186	1184	1181	1175
1193	1193	1193	1193	1192	1191	1190	1187	1180
1198	1198	1198	1198	1198	1198	1198	1195	1188

UPPER TUBE SHEET 30MW IHX
STEADY STATE TEMPERATURES

UPPER TUBE SHEET 30 MW IHX
STEADY STATE TEMPERATURE DISTRIBUTION



30 MW IHX TRANSIENT TEMPERATURES
CHANGE FOR UNIT CHANGE IN FLUID TEMPERATURE

GRADUAL CHANGE

POINT	$N_{Fo} = .161$ $t = 40$		$N_{Fo} = .080$ $t = 20$		$N_{Fo} = .241$ $t = 60$		$N_{Fo} = .322$ $t = 80$	
0	.040	.0017069	.004	.0001706	.096	.0043944	.156	.0066534
.1	.044	.0034232	.006	.0004668	.102	.0079356	.163	.0126814
.2	.058	.0039324	.010	.0006780	.119	.0080602	.181	.0122718
.3	.082	.0047396	.020	.0011560	.149	.0086122	.213	.0123114
.4	.121	.0057838	.039	.0018642	.193	.0092254	.260	.0121280
.5	.176	.0066528	.071	.0026838	.254	.0096012	.321	.0121330
.6	.253	.0070334	.128	.0035584	.335	.0093130	.401	.0111478
.7	.359	.0063902	.220	.0039160	.439	.0078142	.500	.0089000
.8	.500	.0034710	.364	.0025269	.570	.0039569	.622	.0043179
.878	.640	.0004867	.524	.0003985	.693	.0005270	.736	.0005597
.9	.684		.579		.734		.768	
1.0	.920		.890		.934		.943	
Σ		.0436191		.0174192		.0691481		.0934052
MN	.206	.0794011	.117	.0450967	.275	.1059966	.337	.1298940
Δ		.0357820		.0276775		.0368485		.0364888
ΔT		.2785		.2154		.2868		.2840

TO CALCULATE ΔT AT ANY TIME –

TAKE LINEAR CHANGE ΔT FOR TIME t & MULTIPLY BY t TIMES RATE (10°/SEC) & ADD TO THIS A ΔT AT (t−40) WITH A RATE OF CHANGE OF −10°/SEC. THIS GIVES ΔT FOR t.

$$N_{Fo} = \frac{(.0066)t}{(1.28125)^2} = .00402t$$

$$N_{Bi}^{-1} = \frac{(12)(13)}{(4000)(1.28125)} = .030$$

$$\frac{1.125}{1.28125} = .878$$

ΔT AT VARIOUS TIMES -

@ $t = 40$ SEC

$\Delta T = (.2785)(400) = 111$

@ $t = 60$ SEC

$\Delta T = (.2868)(600) - (.2154)(200) = 172 - 43 = 129$

@ $t = 80$ SEC

$\Delta T = (.284)(800) - (.2785)(400) = 227 - 111 = 116$

FROM A CURVE PLOTTED ON ABOVE DATA THE MAXIMUM ΔT OCCURS AT $t = 60$ SEC APPROXIMATELY.

TEMPERATURES ARE CALCULATED FOR THIS TIME BY TAKING A LINEAR CHANGE (10°/SEC) FOR 60 SEC & ADDING TO THIS A LINEAR CHANGE (-10°/SEC) FOR 20 SEC. THIS IS BECAUSE THE MAXIMUM ΔT OCCURS SHORTLY AFTER THE END OF THE TRANSIENT & NEITHER A LINEAR CHANGE NOR A SUDDEN CHANGE CAN BE USED FOR THIS IN-BETWEEN CASE.

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SECTION A 7/8" WALL WITH 1/8" SHIELD

$$N_{Bi}^{-1} = \frac{(12)(13)}{(4000)(.93125)} = .042$$

$$N_{FO} = \frac{.0066t}{(.93125)^2} = .00761t$$

GRADUAL CHANGE

	$N_{FO} = .457$ $t = 60$	$N_{FO} = .152$ $t = 20$
0	.247	.032
.1	.253	.038
.2	.271	.050
.3	.302	.072
.4	.345	.107
.5	.402	.159
.6	.475	.232
.7	.548	.335
.8	.652	.473
.9	.792	.656
.94	.830	.750
1.0	.935	.890

SECTION B 1 1/8" WALL WITH 1/8" SHIELD

$$N_{Bi}^{-1} = \frac{(12)(13)}{(4000)(1.28125)} = .030$$

$$N_{FO} = \frac{.0066t}{(1.28125)^2} = .00402t$$

GRADUAL CHANGE

	$N_{FO} = .241$ $t = 60$	$N_{FO} = .080$ $t = 20$
0	.096	.004
.1	.102	.006
.2	.119	.010
.3	.149	.020
.4	.193	.039
.5	.254	.071
.6	.335	.128
.7	.439	.220
.8	.570	.364
.878	.693	.524
.9	.734	.579
1.0	.934	.890

TEMPERATURE CHANGES AT POINTS BECOME—

PT		ΔT
0	(.247)(600) -(.032)(200) =	142
.1	(.253)(600) - (.038)(200) =	145
.2	(.271)(600) - (.050)(200) =	153
.3	(.302)(600) - (.072)(200) =	167
.4	(.345)(600) - (.107)(200) =	185
.5	(.402)(600) - (.159)(200) =	209
.6	(.475)(600) - (.232)(200) =	239
.7	(.548)(600) - (.335)(200) =	261
628 .8	(.652)(600) - (.473)(200) =	296
.9	(.792)(600) - (.652)(200) =	344
.94	(.830)(600) - (.750)(200) =	348

PT		ΔT
0	(.096)(600) -(.004)(200) =	57
.1	(.102)(600) - (.006)(200) =	60
.2	(.119)(600) - (.010)(200) =	69
.3	(.149)(600) - (.020)(200) =	85
.4	(.193)(600) - (.039)(200) =	107
.5	(.254)(600) - (.071)(200) =	138
.6	(.335)(600) - (.128)(200) =	175
.7	(.439)(600) - (.220)(200) =	220
.8	(.570)(600) - (.364)(200) =	269
.878	(.693)(600) - (.524)(200) =	310

SECTION C - FOR THE CORE AREA OF THE TUBE SHEET THERE IS COOLING FROM BOTH SIDES. THE BARREL SIDE IS SHIELDED & THE SHELL SIDE UNSHIELDED. COOLING FROM BOTH SIDES ALLOWS THE MIDDLE OF THE TOTAL THICKNESS TO BE TREATED AS INSULATED SO THAT PORTERS' TABLES MAY BE USED TO CALCULATE A GRADIENT FROM EITHER SIDE. THE TOTAL THICKNESS IS $3.375 + .125 + .03125 = 3.53125''$. THE THICKNESS FOR CALCULATION OF TEMPERATURES IS HALF THIS OR 1.765625". FOR THE BARREL SIDE WITH A SHIELD COOLING EXTENDS INTO THE TUBE SHEET FOR ONLY $1.765625 - .15625 = 1.609375'$ OR FOR $\frac{1.609375}{1.765625} = 90\%$ OF TOTAL THICKNESS.

FOR COOLING FROM EITHER SIDE -

$$N_{Bi}' = \frac{(12)(13)}{(4000)(1.765625)} = .022 \qquad N_{Fo} = \frac{.0066\,t}{(1.765625)^2} = .002117t$$

$N_{Fo} = .127$
$t = 60$

$N_{Fo} = .042$
$t = 20$

PT	TEMP		PT	TEMP		ΔT (= DIFF.)
0	.023	14	0	0	0	14
.1	.027	16	.1	0	0	16
.2	.037	22	.2	.001	0	22
.3	.057	34	.3	.002	0	34
.4	.089	53	.4	.008	2	51
.5	.139	83	.5	.020	4	79
.6	.212	127	.6	.049	10	117
.7	.318	190	.7	.114	23	167
.8	.466	280	.8	.243	49	231
.9	.666	400	.9	.482	96	304
1.0	.933	560	1.0	.887	177	383

ABOVE VALUES GOOD FOR SECTION D ALSO EXCEPT SHIELDING IS ON SHELL SIDE.

G29

IN THE TUBE AREA THE TUBESHEET IS COOLED BY THE SECONDARY SODIUM IN THE TUBES. FOR A 1" PITCH & 1/2" x 20GA (.091" WALL) THE DISTANCE FROM INSIDE WALL OF ONE TUBE TO THE CORRESPONDING POINT ON THE ADJACENT TUBE IS .682" & EACH TUBE CAN BE CONSIDERED TO COOL HALF OF THIS DISTANCE.

$N_{Bi}^{-1} = \frac{(12)(13)}{(4000)(.341)} = .1142 \qquad N_{Fo} = \frac{.0066\,\tau}{(.341)^2} = .0501\,\tau$

$(N_{Fo})_{600} = 3.01 \qquad \left(\frac{\Delta T_M}{\Delta T_F}\right)_{600} = .86$

$(N_{Fo})_{200} = 1.0 \qquad \left(\frac{\Delta T_M}{\Delta T_F}\right)_{200} = .62$

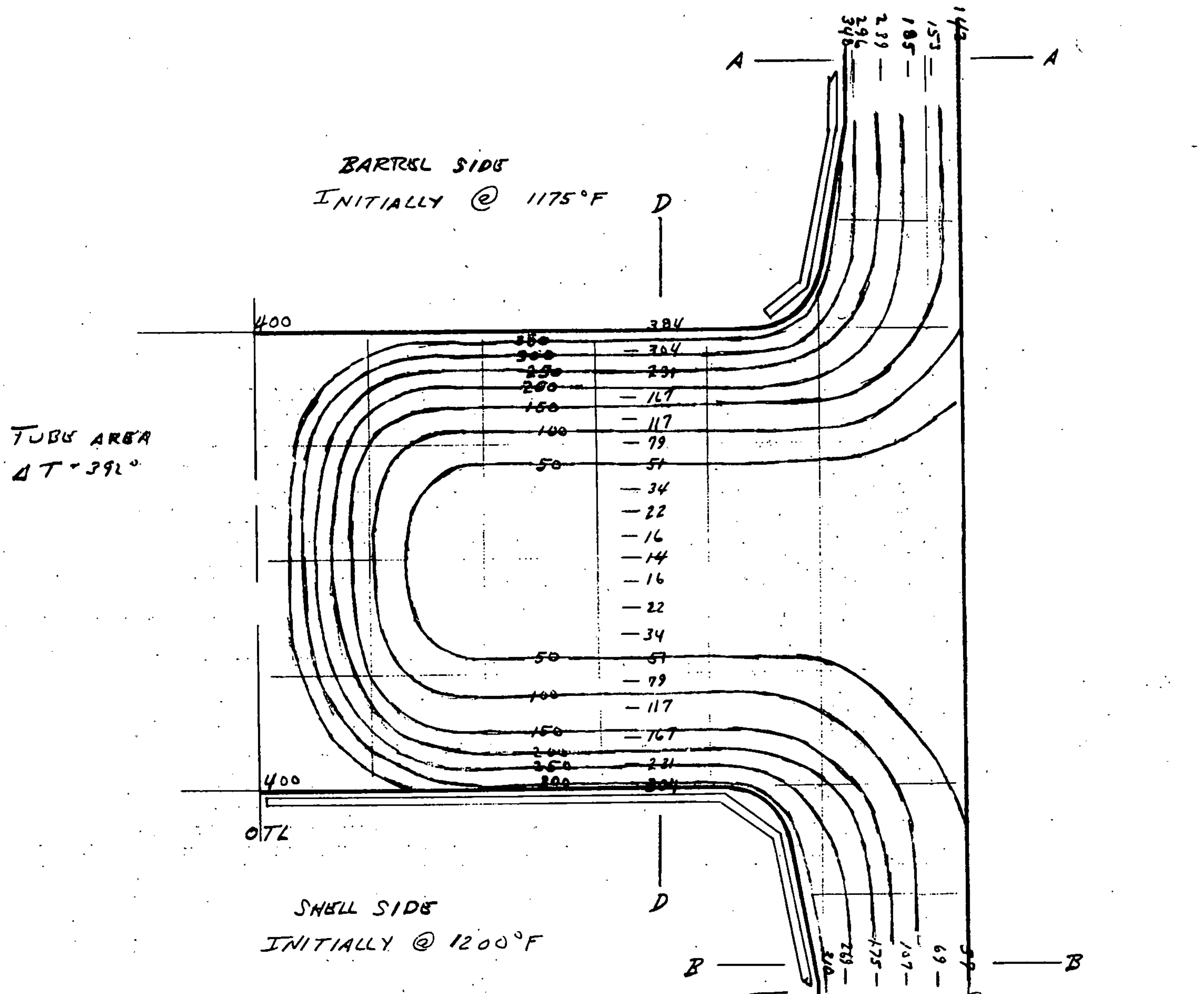
$\Delta T_M = (.86)(600) - (.62)(200) = 392°$

THE MEAN TEMPERATURE IN THE TUBE AREA IS THEN TAKEN TO BE A 392° CHANGE.

AT THE EDGE OF THE TUBES AT THE ITL & OTL THE FULL 400° CHANGE WILL HAVE OCCURRED.

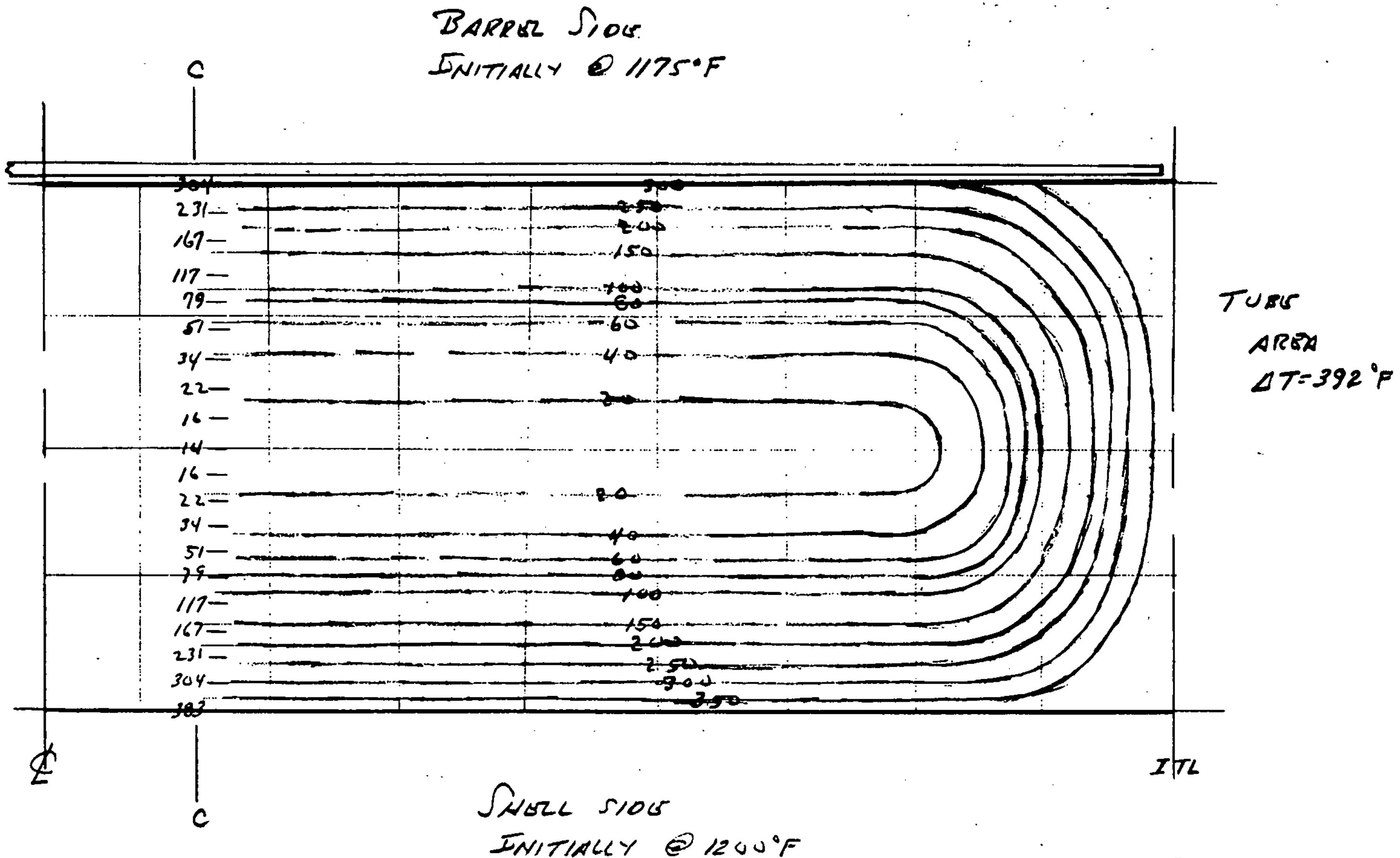
ON THE FIGURE THE TEMPERATURES ARE THE FINAL TRANSIENT TEMPERATURES INCLUDING STEADY STATE DIFFERENCES. TEMPERATURES ARE OBTAINED BY SUBTRACTING THE CALCULATED

G30 CHANGE FROM THE STEADY STATE TEMPERATURE.



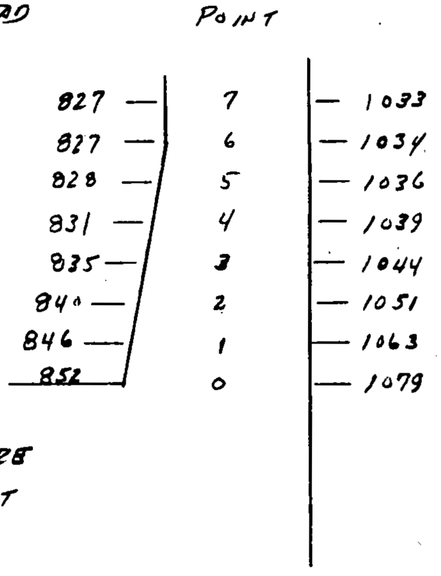
TEMPERATURE CHANGES
20 SEC AFTER 400°ΔT IN 40 SEC.

G31



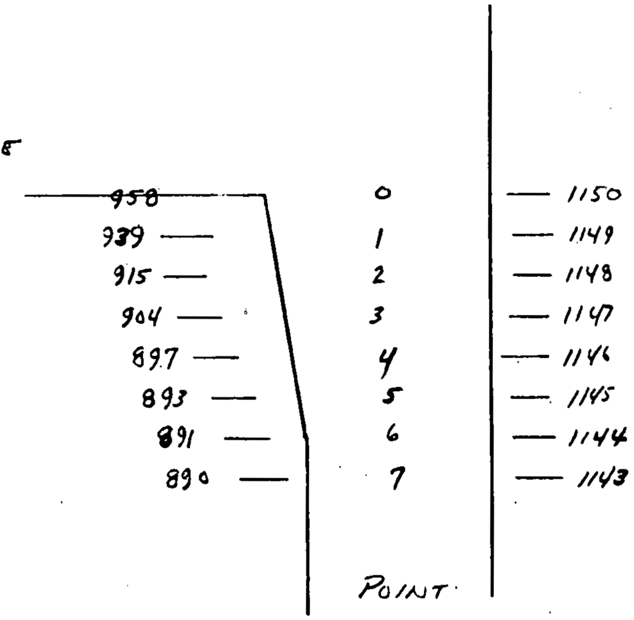
TEMPERATURE CHANGES
20 SEC AFTER 400°ΔT
IN 40 SEC

TRANSIENT TEMPERATURE DISTRIBUTION
SHELL & BARREL - UPPER HEAD
30 MW IHX



827	7	1033
827	6	1034
828	5	1036
831	4	1039
835	3	1044
840	2	1051
846	1	1063
852	0	1079

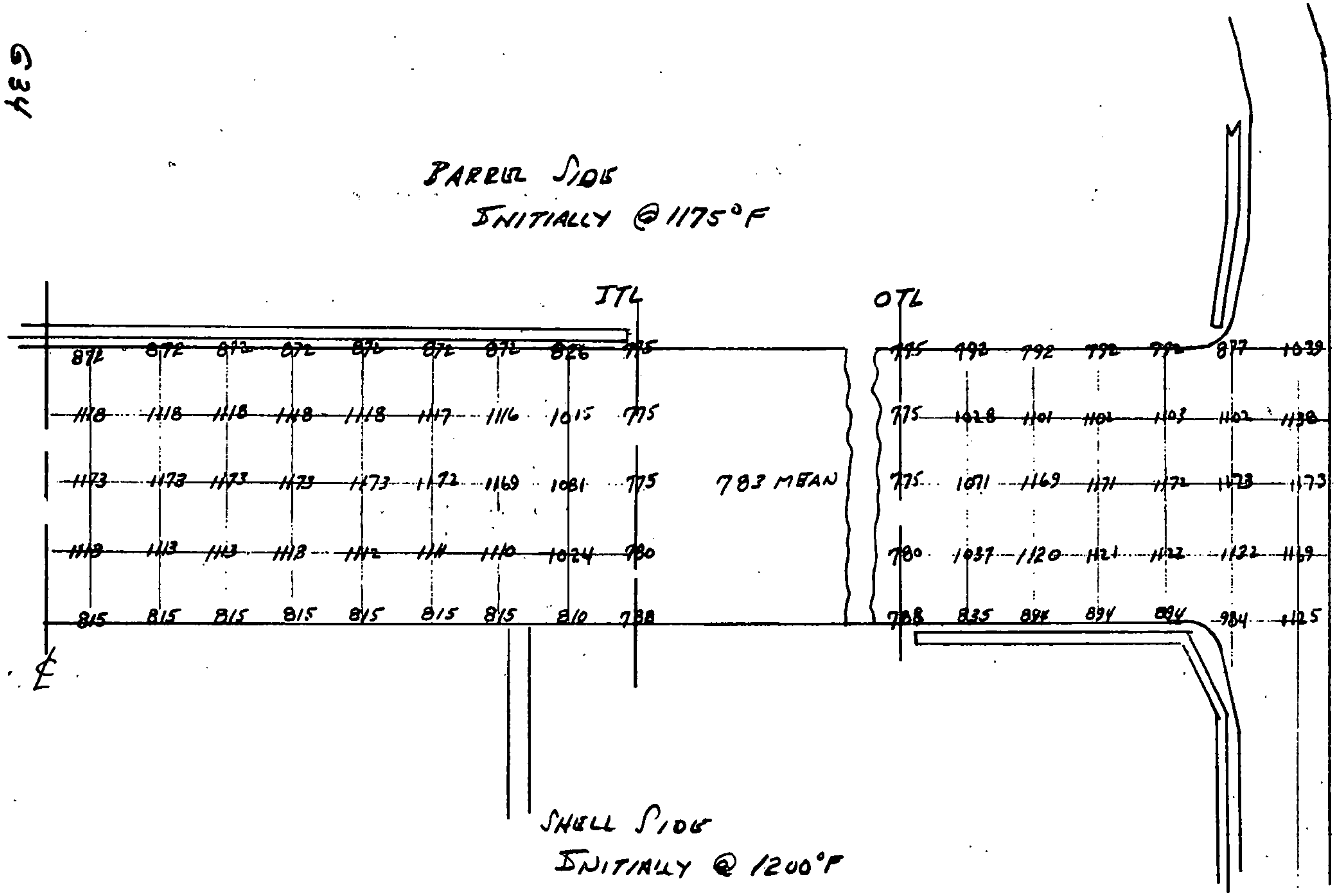
USE AVERAGE TEMPERATURE
OF INSIDE & OUTSIDE AT A POINT
FOR MEAN TEMPERATURE



958	0	1150
939	1	1149
915	2	1148
904	3	1147
897	4	1146
893	5	1145
891	6	1144
890	7	1143

G33

G 34



30 MW IHX
TEMPERATURE DISTRIBUTION
20 SEC. AFTER 400° ΔT IN 40 SEC.
UPPER TUBE SHEET

STEAM GENERATOR TUBESHEET CALCULATIONS

PRESSURE STRESSES 4-H

3-20-61
RHB

30 MW STEAM GENERATOR

PRESSURE STRESS CALCULATIONS (T=1075°F)
2500 PSI BARREL SIDE PRESSURE
SHELL PRESSURE = 0

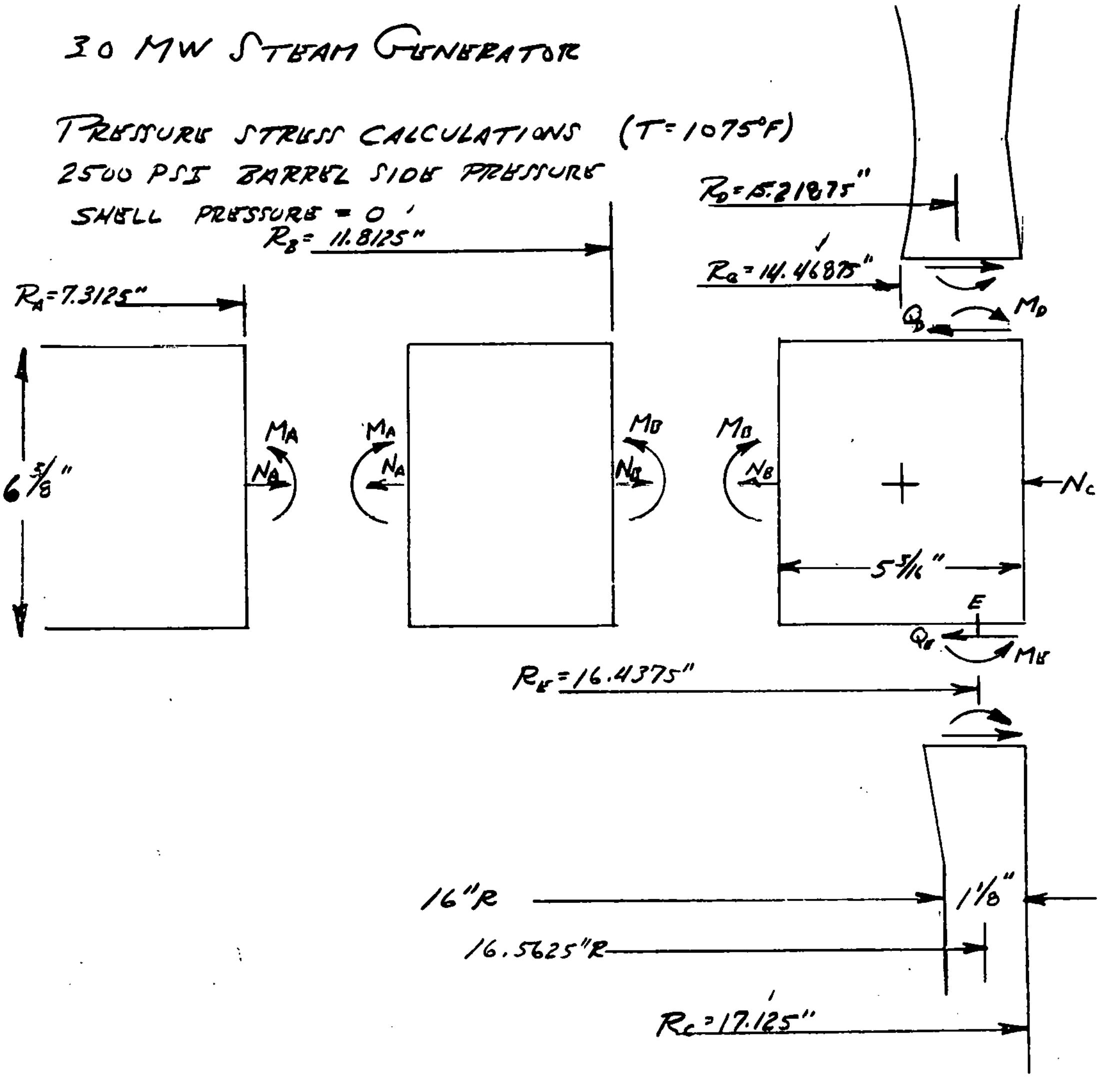


FIGURE IS OF UPPER TUBE SHEET. HOWEVER VALUES FOR LOWER TUBE SHEET ARE SUCH THAT STRESSES APPLY EQUALLY FOR EITHER TUBE SHEET WITHOUT ANY SIGNIFICANT ERROR.

H2

CORE & TUBE AREA –

USING PAPER OF "BASIC EQUATIONS" – $E = 22.5 \times 10^6$

FOR TUBE AREA USING HORVAY'S CURVES FOR $\eta = .50$

$E^* = (22.5 \times 10^6)(.39) = 8.775 \times 10^6 \quad \mu^* = .40$

$$\varphi_A = -\frac{R_A^3}{16D}p + \frac{R_A}{2}C_1 \qquad (1)$$

$$\varphi_A = -\frac{R_A^3}{16D^*}p + \frac{R_A}{2}C_3 + \frac{C_4}{R_A} \qquad (2)$$

$$\varphi_B = -\frac{R_B^3}{16D^*}p + \frac{R_B}{2}C_3 + \frac{C_4}{R_B} \qquad (3)$$

$$M_{1A} = -\frac{3.3R_A^2}{16}p + .65DC_1 \qquad (4)$$

$$M_{1A} = -\frac{(3+\mu^*)R_A^2}{16}p + \frac{(1+\mu^*)}{2}D^*C_3 - \frac{(1-\mu^*)D^*}{R_A^2}C_4 \qquad (5)$$

$$M_{1B} = -\frac{(3+\mu^*)R_B^2}{16}p + \frac{(1+\mu^*)D^*}{2}C_3 - \frac{(1-\mu^*)}{R_B^2}D^*C_4 \qquad (6)$$

$$D = \frac{Et^3}{12(1-\mu^2)} = \frac{(22.5\times10^6)(6.625)^3}{(12)(1-.3^2)} = 599.125\times10^6$$

$$D^* = \frac{E^*t^3}{12(1-\mu^{*2})} = \frac{(8.775\times10^6)(6.625^3)}{(12)(1-.4^2)} = 253.130\times10^6$$

$$\frac{R_A^3}{16D} = \frac{7.3125^3}{(16)(599.125\times10^6)} = .0407906\times10^{-6} \qquad \frac{R_A^3}{16D^*} = \frac{7.3125^3}{(16)(253.13\times10^6)} = .0965459\times10$$

$$\frac{R_B^3}{16D^*} = \frac{11.8125^3}{(16)(253.13\times10^6)} = .4069696\times10^{-6} \qquad \frac{3.3R_A^2}{16} = \frac{(3.3)(7.3125)^2}{16} = 11.02874$$

$$\frac{(3+\mu^*)R_A^2}{16} = \frac{(3.4)(7.3125)^2}{16} = 11.36294 \qquad \frac{(1+\mu^*)D^*}{2} = (.7)(253.13\times10^6) = 177.191\times10^6$$

$$\frac{(1-\mu^*)D^*}{R_A^2} = \frac{(.6)(253.13\times10^6)}{(7.3125)^2} = 2.840293\times10^6 \qquad \frac{(3+\mu^*)R_B^2}{16} = \frac{(3.4)(11.8125)^2}{16} = 29.65122$$

$$\frac{(1-\mu^*)}{R_B^2}D^* = \frac{(.6)(253.13\times10^6)}{(11.8125)^2} = 1.088457\times10^6 \qquad .65D = 389.43125\times10^6$$

H3

SUBSTITUTING IN VALUES —

(1) = (2)

$-.0407906\times10^{-6}P+3.65625C_1=-.0965459\times10^{-6}P+3.65625C_3+.136752C_4$

$C_1=-.01524931\times10^{-6}P+C_3+.03740226C_4$ (7)

(4) = (5)

$-11.02874P+389.43125\times10^{6}C_1=-11.36294P+177.191\times10^{6}C_3-2.840293\times10^{6}C_4$

$C_1=-.0008581746\times10^{-6}P+.4549994C_3-.007293439C_4$ (8)

(7) = (8)

$-.01524971\times10^{-6}P+C_3+.03740226C_4=-.0008581746\times10^{-6}P+.4549994C_3-.007293439C_4$

$C_3=.02640573\times10^{-6}P-.08201038C_4$ (9)

SUBSTITUTING (9) INTO (3) & (6) —

$+.1559588 \qquad -.4843731$

$\varphi_B=-.4069696\times10^{-6}P+5.90625(.02640573\times10^{-6}P-.08201038C_4)$

$+.08465608C_4$

$C_4=-2.5017656\varphi_B-.6279702\times10^{-6}P$ (10)

$M_B=-29.65122P+177.191(.02640573P-.08201038\times10^{6}C_4)-1088457C_4$

$C_4=-1.598747\times10^{-6}P-.06402066\times10^{-6}M_B$ (11)

(10) = (11)

$-2.5017657\varphi_B-.6279702\times10^{-6}P=-1.598747\times10^{-6}P-.06402066\times10^{-6}M_B$

$M_B=39.07747\times10^{6}\varphi_B-15.16349P$ (12)

H4

SUBSTITUTING INTO (5)

$$M_A = -11.36294P + 177.191\times10^6(.02640573\times10^{-6}P - .08201038C_4)$$

$$-2.840293\times10^6 C_4$$

$$= -6.68408P - 17.371794(-1.598747P - .06402066 M_B)$$

$$M_A = 21.08902P + 1.11215 M_B \qquad (13)$$

OUTER RING—

FROM TIMOSHENKO - STRENGTH OF MAT'L. VOL. II P. 140

$$\varphi = \frac{12 M_T R_C}{E t^3 Ln \, R_C/R_B} = \frac{(12)(14.46875)\,M_T}{(22.5\times10^6)(6.625)^3 Ln \frac{17.125}{11.8125}} = .07146\times10^{-6} M_T$$

$.37137$

$$M_T = 13.9938\times10^6 \varphi \qquad (14)$$

FROM ROARK P. 276 # 27 & 28 - CHANGE IN RADIUS OF CORE & TUBE AREA

$$\Delta R_A = \frac{N_A R_A}{E t}(1-\mu) = \frac{7.3125 N_A}{22.5\times10^6(6.625)}(1-.3) = .0343396\times10^{-6} N_A \qquad (15)$$

$$\Delta R_A = -\frac{N_A R_A}{E t}\left(\frac{R_B^2+R_A^2}{R_B^2-R_A^2}+\mu\right) + \frac{N_B R_A}{E t}\left(\frac{2R_B^2}{R_B^2-R_A^2}\right)$$

$$\Delta R_A = -\frac{7.3125 N_A}{(22.5\times10^6)(6.625)}\left(\frac{11.8125^2+7.3125^2}{11.8125^2-7.3125^2}+.3\right) + \frac{7.3125 N_B}{(22.5\times10^6)(6.625)}\left(\frac{2\times11.8125^2}{11.8125^2-7.3125^2}\right)$$

$$\Delta R_A = -.124734\times10^{-6} N_A + .159073\times10^{-6} N_B \qquad (16)$$

$$\Delta R_B = -\frac{N_A R_B}{E t}\left(\frac{2R_A^2}{R_B^2-R_A^2}\right) + \frac{N_B R_B}{E t}\left(\frac{R_B^2+R_A^2}{R_B^2-R_A^2}-\mu\right)$$

$$= -\frac{11.8125 N_A}{(22.5\times10^6)(6.625)}\left(\frac{2\times7.3125^2}{11.8125^2-7.3125^2}\right) + \frac{11.8125 N_B}{(22.5\times10^6)(6.625)}\left(\frac{11.8125^2+7.3125^2}{11.8125^2-7.3125^2}-.3\right)$$

$$\Delta R_B = -.0984739\times10^{-6} N_A + .153946\times10^{-6} N_B \qquad (17)$$

$$\Delta R_B = \frac{-N_B R_B}{E t}\left(\frac{R_C^2+R_B^2}{R_C^2-R_B^2}+\mu\right) - \frac{N_C R_B}{E t}\left(\frac{2 R_C^2}{R_C^2-R_B^2}\right)$$

$$= -\frac{11.8125 N_B}{(22.5\times10^6)(6.625)}\left(\frac{17.125^2+11.8125^2}{17.125^2-11.8125^2}+.3\right) - \frac{11.8125 N_C}{(22.5\times10^6)(6.625)}\left(\frac{2\times17.125^2}{17.125^2-11.8125^2}\right)$$

$$\Delta R_B = -.246875\times10^{-6} N_B - .302346\times10^{-6} N_C \qquad (18)$$

$$\Delta R_C = \frac{-N_B R_C}{E t}\left(\frac{2 R_B^2}{R_C^2-R_B^2}\right) - \frac{N_C R_C}{E t}\left(\frac{R_C^2+R_B^2}{R_C^2-R_B^2}-\mu\right)$$

$$= -\frac{17.125 N_B}{(22.5\times10^6)(6.625)}\left(\frac{2\times 11.8125^2}{17.125^2-11.8125^2}\right) - \frac{17.125 N_C}{(22.5\times10^6)(6.625)}\left(\frac{17.125^2+11.8125^2}{17.125^2-11.8125^2}-.3\right)$$

$$\Delta R_C = -.208553\times10^{-6} N_B - .288972\times10^{-6} N_C \qquad (19)$$

LET Q_D & Q_G BE RELATED TO N_C BY—

$$N_C = \frac{15.21875}{17.125} Q_D + \frac{16.4375}{17.125} Q_G = .88869 Q_D + .95985 Q_G \qquad (20)$$

$(15) = (16)$

$$.0343396 N_A = -.124734 N_A + .159073 N_B$$

$$N_A = \frac{.159073}{.1590736} N_B = N_B \qquad (21)$$

SUBSTITUTING (21) INTO (17)

$$\Delta R_B = -.0984735\times10^{-6} N_B + .153946\times10^{-6} N_B = .0554721\times10^{-6} N_B \qquad (22)$$

SUBSTITUTING (20) INTO (18) & (19)

$$\Delta R_B = -.246875\times10^{-6} N_B - .302346\times10^{-6}(\overset{-.268692}{.88869\, Q_D} + \overset{-.290207}{.95985\, Q_G})$$

$$\Delta R_B = -.246875\times10^{-6} N_B - .268692\times10^{-6} Q_D - .290207\times10^{-6} Q_G \qquad (23)$$

$$\Delta R_C = -.208553\times10^{-6} N_B - .288972\times10^{-6}(\overset{-.256807}{.88869\, Q_D} + \overset{-.277370}{.95985\, Q_G})$$

$$\Delta R_C = -.208553\times10^{-6} N_B - .256807\times10^{-6} Q_D - .277370\times10^{-6} Q_G \qquad (24)$$

H6

(22) = (23)

$.0554721\,N_B = -.246875\,N_B - .268692\,Q_D - .290207\,Q_E$

$N_B = -.888687\,Q_D - .959841\,Q_E$ (25)

SUBSTITUTING (25) INTO (22), (23), & (24) —

$\overset{-.0492973}{}\quad\overset{-.0532444}{}$

$\Delta R_B = .0554721 \times 10^{-6}(-.888687\,Q_D - .959841\,Q_E)$

$\Delta R_B = -.0492973 \times 10^{-6} Q_D - .0532444 \times 10^{-6} Q_E$ (26)

$\overset{+.2193946}{}\quad\overset{+.236961}{}$

$\Delta R_B = -.246875 \times 10^{-6}(-.888687\,Q_D - .959841\,Q_E) - .268692 \times 10^{-6} Q_D - .290207 \times 10^{-6} Q_E$

$\Delta R_B = -.049297 \times 10^{-6} Q_D - .053246 \times 10^{-6} Q_E$

$\overset{+.1853383}{}\quad\overset{+.200178}{}$

$\Delta R_C = -.208553 \times 10^{-6}(-.888687\,Q_D - .959841\,Q_E) - .256807 \times 10^{-6} Q_D - .277370 \times 10^{-6} Q_E$

$\Delta R_C = -.071469 \times 10^{-6} Q_D - .077192 \times 10^{-6} Q_E$ (27)

$\theta_D = \theta_E = \varphi_B = \varphi$ = ROTATION OF OUTER RING —

THE EQUATIONS FOR THE TAPERED WALLS ARE —

FOR THE BARREL — (SEE G19 ET SEQ. FOR CALCULATIONS)

$M_0 = -3.208679 \times 10^6 Y_0 + 15.269456 \times 10^6 \theta_0 + 6315$

$V_0 = -1.305405 \times 10^6 Y_0 + 3.208691 \times 10^6 \theta_0 + 6792$

TO MAINTAIN THE SAME CONVENTION THROUGHOUT
M_0 & V_0 BECOME —

$M_D = -3.208679 \times 10^6 \Delta R_D + 15.269456 \times 10^6 \theta_D + 6315$ (28)

$Q_D = 1.305405 \times 10^6 \Delta R_D - 3.208691 \times 10^6 \theta_D - 6792$ (29)

H 7

FOR THE SHELL THE TAPERED WALL EQUATIONS ARE —
SEE H13 ET SEQ

$$M_0 = -.615606 \times 10^6 Y_0 + 2.098929 \times 10^6 \Theta_0$$

$$V_0 = -.349028 \times 10^6 Y_0 + .615896 \times 10^6 \Theta_0$$

ADJUSTING FOR SYMBOLISM ~~&~~ CONVENTION —

$$M_E = -.615606 \times 10^6 \Delta R_E - 2.098929 \times 10^6 \Theta_E \qquad (30)$$

$$Q_E = .349028 \times 10^6 \Delta R_E + .615896 \times 10^6 \Theta_E \qquad (31)$$

LET $\Theta_D = \Theta_0 = \Theta_E = \varphi$

$$\Delta R_D = \Delta R_C - 3.3125\varphi$$

$$= -.071469(\overset{-.093296}{1.305405 \Delta R_D} \overset{+.229322}{-3.20869\,\Theta_D} \overset{+.000485}{-.006792})$$

$$-.077192(\overset{-.026942}{.349028 \Delta R_E} \overset{-.047542}{+.615896\,\Theta_E}) - 3.3125\varphi$$

$$= -.093296 \Delta R_D - .026942 \Delta R_E + .000485 - 3.13072\varphi$$

$$\Delta R_D = -.024643 \Delta R_E + .0004436 - 2.86356\varphi \qquad (32)$$

$$\Delta R_E = \Delta R_C + 3.3125\varphi$$

$$= -.093296 \Delta R_D - .026942 \Delta R_E + .000485 + 3.49426\varphi$$

$$\Delta R_E = -.090848 \Delta R_D + .0004723 + 3.40261\varphi \qquad (33)$$

SUBSTITUTING (33) INTO (32)

$$\Delta R_D = -.024643(\overset{+.0022388}{-.090848 \Delta R_D} \overset{-.000011639}{+.0004723} \overset{-.08\text{[illegible]}}{+3.40261\varphi})$$

$$+.0004436 - 2.86356\varphi$$

$$= .0022388 \Delta R_D + .000432 - 2.94741\varphi$$

$$\Delta R_D = -2.95402\varphi + .0004330 \qquad (34)$$

NOW SUBSTITUTE (34) INTO (33) -

$$\Delta R_E = -.090648(\overset{+.268367}{-2.95402\varphi} \overset{-.000039337}{+.0004330}) + .0004723 + 3.40261\varphi$$

$$\Delta R_E = 3.67098\varphi + .0004330 \qquad (35)$$

TAKING MOMENTS ABOUT THE OUTER RING @ G -

$$\frac{11.8125}{14.46875} M_B + \frac{15.21875}{14.46875} M_D - \frac{15.21875}{14.46875}(3.3125) Q_D$$

$$+ \frac{16.4375}{14.46875}(3.3125) Q_E - \frac{16.4375}{14.46875} M_E - \frac{11.8125}{14.46875} \overset{-12.8063}{\frac{(\pi)(11.8125)^2}{(2\pi)(11.8125)}}(2.65625)P$$

$$- \frac{13.140625}{14.46875} \overset{-1.3376}{\frac{\pi\left[(14)^2(.96852)^2 - 11.8125^2\right]}{2\pi\, 13.140625}}(.87339)P$$

$$- \frac{15.5625}{14.46875} \overset{-7.5755}{\frac{\pi\, 14^2}{2\pi\, 15.21875}}(1.09375)P = M_T$$

$$.816415 M_B + 1.051836 M_D - 3.48421 Q_D + 3.76323 Q_E - 1.13607 M_E$$

$$-21.7214 P = -13.9938 \times 10^6 \varphi \qquad (36)$$

SUBSTITUTING IN FROM PREVIOUS EQUATIONS -

$$.816415(\overset{+31.903432}{39.07747 \times 10^6 \varphi} \overset{-12.3797}{-15.16349P}) + 1.051836(\overset{-3.3750041}{-3.208679 \times 10^6 \Delta R_D}$$

$$\overset{+16.06096}{+15.269456 \times 10^6 \varphi} \overset{+6642}{+6315}) - 3.48421(\overset{-4.54831}{1.305406 \times 10^6 \Delta R_D}$$

$$\overset{+11.179751}{-3.208691 \times 10^6 \varphi} \overset{+23665}{-6792}) + 3.76323(\overset{+1.31347}{.348028 \times 10^6 \Delta R_E} \overset{+2.317758}{+.615896 \times 10^6 \varphi})$$

$$-1.13607(\overset{+.6993715}{-.615606 \times 10^6 \Delta R_E} \overset{+2.38453}{-2.098929 \times 10^6 \varphi}) - 21.7214P$$

$$= -13.9938 \times 10^6 \varphi$$

$$77.84023 \times 10^6 \varphi - 34.1611(2500) - 7.92331 \times 10^6 \Delta R_D + 2.01284 \times 10^6 \Delta R_E$$

$$+30307 = 0$$

$$77.84023\times10^6\varphi-54946-7.92331\times10^6(\overset{+23.40562}{-2.95402\varphi}\overset{-.0034308}{+.0004330})$$

$$+2.01284\times10^6(\overset{+7.389095}{3.67098\varphi}\overset{.087156}{+.0004330})=0$$

$$108.63495\times10^6\varphi=57505\qquad\varphi=.00052934$$

$$\Delta R_D=\overset{-.00156368}{-2.95402(.00052934)}+.0004330=-.0011307$$

$$\Delta R_E=\overset{+.0019432}{3.67098(.00052934)}+.0004330=.0023762$$

$$M_D=\overset{+3678}{-3.208679(-1130.7)}\overset{+8083}{+15.269456(529.34)}+6315=18026$$

$$Q_D=\overset{-1476}{1.305405(-1130.7)}\overset{-1698}{-3.208691(529.34)}-6792=-9966$$

$$M_E=\overset{-1463}{-.615606(2376.2)}\overset{-1111}{-2.098929(529.34)}=-2574$$

$$Q_E=\overset{+829}{.349028(2376.2)}\overset{+326}{+.615896(529.34)}=1155$$

$$M_B=\overset{+20685}{39.07747(529.34)}\overset{-37909}{-15.16349(2500)}=-17224$$

SUBSTITUTING BACK INTO THE MOMENT EQUATION (36) –

$$\overset{-14062}{.816415(-17224)}\overset{+19960}{+1.051836(18026)}\overset{+34724}{-3.48421(-9966)}\overset{+4347}{+3.76323(1155)}$$

$$\overset{+2924}{-1.13667(-2574)}\overset{-54304}{-21.7214(2500)}=\overset{-7407}{-13.9938(529.34)}$$

$$-7411=-7407$$

$$M_A=\overset{+52723}{21.08902(2500)}\overset{-19156}{+1.11215(-17224)}=33567$$

$$N_B=\overset{+8857}{-.888687(-9966)}\overset{-1109}{-.959841(1155)}=7748$$

$$N_A=N_B=7748$$

H10

$$C_4 = -2.5017656\overset{-.0013242546}{(.00052934)} - .6279702\overset{-.00\text{[illegible]}}{(.002500)} = -2894.21 \times 10^{-6}$$

$$C_3 = .02640573\overset{+.000066014}{(.002500)} - .08201038\overset{+.00023735}{(-.00289421)} = 303.369 \times 10^{-6}$$

$$M_R = -\frac{3.4}{16}(2500)x^2 + \frac{1.4}{2}(253.130)(303.369) + (.7)(253.130)(-2894.21)/x^2$$

$$M_R = -531.25x^2 + 53754 + 512828/x^2$$

$$M_T = -\overset{343.75}{\frac{(2.2)}{16}(2500)}x^2 + 53754 + 512828/x^2$$

MOMENTS BECOME-

AT INSIDE ROW- $R = 7.5625''$

$$M_R = \overset{-30383}{(-531.25)(7.5625)^2} + 53754 + \overset{+8967}{(512828)/(7.5625)^2} = 32338$$

$$M_T = \overset{-19660}{(-343.75)(7.5625)^2} + 53754 + \overset{8967}{512828/(7.5625)^2} = 43061$$

AT THE OUTSIDE ROW- $R = 11.5625'$

$$M_R = \overset{-71024}{(-531.25)(11.5625)^2} + 53754 + \overset{\text{[illegible]}}{512828/(11.5625)^2} = -13434$$

$$M_T = \overset{-45952}{(-343.75)(11.5625)^2} + 53754 + 3836 = 11634$$

STRESSES DUE TO N_A & N_B (ROARK P 276 #27 & #28)

AT INSIDE ROW-

$$\sigma_R = \frac{7.3125^2}{7.5625^2}\frac{N_A}{6.625}\overset{.956790}{\left(\frac{11.8125^2 - 7.5625^2}{11.8125^2 - 7.3125^2}\right)} + \frac{11.8125^2}{7.5625^2}\frac{N_B}{6.625}\overset{.0432098765}{\left(\frac{7.5625^2 - 7.3125^2}{11.8125^2 - 7.3125^2}\right)}$$

$$\sigma_R = .13503 N_A + .015913 N_B$$

$$\sigma_R = .13503\overset{1046}{(7748)} + .015913\overset{+123}{(7748)} = 1169$$

$$\sigma_T = -\frac{7.3125^2}{7.5625^2}\frac{N_A}{6.625}\overset{2.285857}{\left(\frac{11.8125^2 + 7.5625^2}{11.8125^2 - 7.3125^2}\right)} + \frac{11.8125^2}{7.5625^2}\frac{N_B}{6.625}\overset{1.285857}{\left(\frac{7.3125^2 + 7.5625^2}{11.8125^2 - 7.3125^2}\right)}$$

$$\sigma_T = -.322600 N_A + .47354 N_B$$

$$\sigma_T = \overset{-2500}{(-.3226)(7748)} + \overset{+3669}{(.47354)(7748)} = 1169$$

H11

AT THE OUTSIDE ROW -

$$\sigma_R = \frac{7.3125^2}{11.5625^2}\overset{.06037295}{\frac{N_A}{6.625}}\overset{.0675012145}{\left(\frac{11.8125^2-11.5625^2}{11.8125^2-7.3125^2}\right)} + \overset{.15751}{\frac{11.8125^2}{11.5625^2}}\frac{N_B}{6.625}\overset{.771198765}{\left(\frac{11.5625^2-7.3125^2}{11.8125^2-7.3125^2}\right)}$$

$$\sigma_R = (.0040994)N_A + .14684 N_B$$

$$\sigma_R = (.0040994)\overset{32}{(7748)} + \overset{1138}{(.14684)(7748)} = 1170$$

$$\sigma_T = -\frac{7.3125^2}{11.5625^2}\overset{.06037295}{\frac{N_A}{6.625}}\overset{3.1747458}{\left(\frac{11.8125^2+11.5625^2}{11.8125^2-7.3125^2}\right)} + \frac{11.8125^2}{11.5625^2}\frac{N_B}{6.625}\left(\frac{7.3125^2+11.5625^2}{11.8125^2-7.3125^2}\right)$$

$$\sigma_T = \overset{-1485}{-(.191669)(7748)} + \overset{+2655}{(.34261)(7748)} = 1170$$

FOR THE TUBESHEET $6/t^2 = \dfrac{6}{(6.625)^2} = .13670$

INNER ROW -

			σ_P/σ		
BARREL SIDE (TOP)	$\sigma_R = 1169 - \overset{4421}{(32338)(.13670)}$	$= -3252$	.689	K=2.6	8455 C
	$\sigma_T = 1169 - (43061)\overset{5886}{(.13670)}$	$= -4717$			12264 C
SHELL SIDE (BOTTOM)	$\sigma_R = 1169 + 4421$	$= 5590$	.792	K=2.5	13975 T
	$\sigma_T = 1169 + 5886$	$= 7055$			17638 T

OUTER ROW -

BARREL SIDE (TOP)	$\sigma_R = 1170 + 13434\overset{1836}{(.13670)}$	$= 3006$	-.140	K=3.9	11723 T
	$\sigma_T = 1170 - 11634\overset{1590}{(.13670)}$	$= -420$			1638 C
SHELL SIDE (BOTTOM)	$\sigma_R = 1170 - 1836$	$= -666$	-.241	K=4.0	2664 C
	$\sigma_T = 1170 + 1590$	$= 2760$			11040 T

BARREL - AT TUBE SHEET JUNCTION $\sigma_P = \dfrac{PR_i^2}{2R_m t} = \dfrac{(2500)(14)^2}{(15.21875)(3.0625)} = 5562$

$$\sigma_L = \frac{(6)(18026)}{(3.0625)^2} = 11532 \begin{array}{l} -5562 = 5970\text{C OUTSIDE} \\ +5562 = 17094\text{ T INSIDE} \end{array}$$

$\Delta R_0 = -.0011307$

INNER FACE $\sigma_C = \overset{-1859}{\dfrac{(-1130.7)}{13.6875}(22.5)} + \overset{5128}{(.3)(17094)} = 3269$ T

OUTER FACE $\sigma_C = \overset{-1519}{\dfrac{-1130.7}{16.75}(22.5)} - \overset{1791}{(.3)(5970)} = 3310$ C

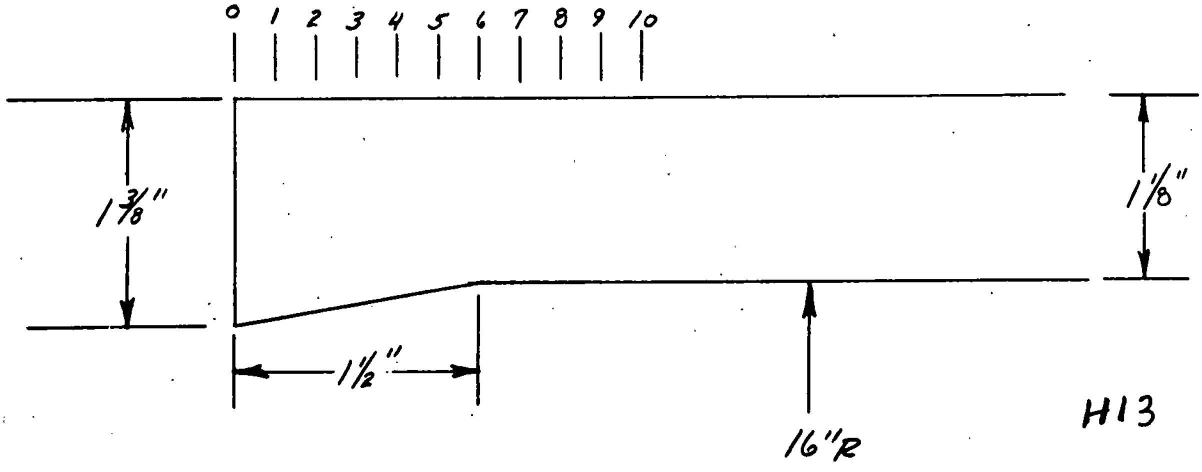
H12 THE SHELL STRESSES ARE MUCH SMALLER THAN IN BARREL.

PHYSICAL PROPERTIES SHELL SIDE 30MW S.G.

$E = 22.5 \times 10^6$ $m = .25''$ POINT 6 & BEYOND ALIKE

$P = 0$

POINT	0	1	2	3	4	5	6	7
DISTANCE	0	.250	.500	.750	1.000	1.250	1.500	1.750
t	1,375	1.333	1.29167	1.250	1.20833	1.16667	1.125	1.125
t^3	2,59961	2.37035	2.15503	1,95313	1.76425	1.58797	1.42383	1.42383
R_M	164375	16.45833	16.47917	16.500	16.52083	16.54167	165625	16.5625
R_M^2	270.1914	270.8767	271.5629	272.25	272.9378	273.6267	274.3164	274.3164
R_i	15.750	15.79167	15.83333	15.875	15.91667	15.95833	16.000	16.000
$10^6 C_1 = \frac{10.92\,m}{Et^3}$	.0466737	.0511879	.0563024	.0621225	.0687733	.0764078	.0852162	.0852162
$10^{-6} C_2 = \frac{mEt}{R_M^2}$	.0286255	.0276879	.0268584	.0258264	.0249027	.0239834	.0230687	.0230687
$C_3 = \frac{PR_iR_M}{Et}$	0	0	0	0	0	0	0	0
$I/c = t^2/6$	.315104	.296295	.278068	.260417	.243344	.226852	.210938	.210938



H13

30 MW STEAM GENERATOR - SHELL SIDE

TAPERED WALL PRELIMINARY CALCULATIONS -

FOR THE STRAIGHT WALL SECTION -

$$M_0 = -.3025 \frac{Et^2}{R}\left(Y_0 - \frac{\theta_0}{\beta}\right)$$

$$V_0 = .3025 \frac{Et^2}{R}\left(-2Y_0\beta + \theta_0\right)$$

$$\beta = \frac{1.285}{\sqrt{RE}} = \frac{1.285}{\left[(16.5625)(1.125)\right]^{1/2}} = .29769$$

$$.3025 \frac{Et^2}{R} = (.3025)\frac{(27.5\times10^6)(1.125)}{(16.5625)} = .520100\times10^6$$

AT POINT 9 — IN THE STRAIGHT WALL PORTION

$$M_9 = -.520100\times10^6\, Y_9 + 1.74712\times10^6\, \theta_9$$

$$V_9 = -.309657\times10^6\, Y_9 + .520100\times10^6\, \theta_9$$

H14

30 MW STEAM GENERATOR - SHELL SIDE

TRIAL COMPUTATION

$\theta_9 = 0 \quad Y_9 = 1$

POINT	Y	$G_2Y=-\Delta V$	V.	$mV=\Delta M$	M	$GM=\Delta\theta$	θ	$m\theta=\Delta Y$
9	1	11534	-309657		-520100	-.0221604	0	
			-321191	-80298			-.0221604	-.0055401
8	.9944599	22941			-600398	-.0511636		
			-344132	-86033			-.0733240	-.0183310
7	.9761289	22979			-686431	-.0584950		
			-367111	-91778			-.1318190	-.0329548
6	.9431741	21758			-778209	-.0663160		
			-388869	-97217			-.1981350	-.0479588
5	.8952153	21470			-875426	-.0668894		
			-410339	-102585			-.2650244	-.0662561
4	.8289592	20643			-978011	-.0672610		
			-430982	-107746			-.3322854	-.0830714
3	.7458878	19264			-1085757	-.0674499		
			-450246	-112562			-.3997353	-.0999338
2	.6459540	17349			-1198319	-.0674682		
			-467595	-116899			-.4672035	-.1168009
1	.5291531	14651			-1315218	-.0673232		
			-482246	-120562			-.5345267	.1336317
0	.3955214	5661	-487907		-1435780	-.0335066	-.5680333	

$M_9 = -520100$

$V_9 = -309657$

H15

30 MW STEAM GENERATOR – SHELL SIDE

TRIAL COMPUTATION

$\theta_9 = 1 \quad Y_9 = 0$

POINT	Y	$C_2Y=\Delta V$	V	$mV=\Delta M$	M	$C_1M=\Delta\theta$	θ	$m\theta=\Delta Y$
9	0	0	520100		1747120	.0744415	1.	
			520100	130025			1.0744415	.2686104
8	.2686104	6196			1877145	.1599632		
			513904	128476			1.2344047	.3086012
7	.5772116	13316			2005621	.1709114		
			500588	125147			1.4053161	.3513290
6	.9285406	21420			2130768	.1815760		
			479168	119792			1.5868921	.3967230
5	1.3252636	31784			2250560	.1719603		
			447384	111846			1.7588524	.4397131
4	1.7649767	43953			2362406	.1624705		
			403431	100858			1.9213229	.4803307
3	2.2453074	57988			2463264	.1530241		
			345443	86361			2.0743470	.5185868
2	2.7638942	74234			2549625	.1435500		
			271209	67802			2.2178970	.5544742
1	3.3183684	91879			2617427	.1339806		
			179330	44832			2.3518776	.5879694
0	3.9063378	55914	123416		2662259	.0621287	2.4140063	

$M_9 = 1747120$

$V_9 = 520100$

H16

30 MW STEAM GENERATOR – SHELL SIDE

CHECK CALCULATION $Y_9 = \theta_9 = 1$

POINT	Y	$C_2Y=-\Delta V$	V	$mV=\Delta M$	M	$C_1M=\Delta\theta$	θ	$m\theta=\Delta Y$
9	1	11537	210443		1227020	.0522810	1	
			198906	49726			1.0522810	.2630702
8	1.2630702	29137			1276746	.1087994		
			169769	42442			1.1610804	.2902701
7	1.5533403	35834			1319188	.1124162		
			133935	33484			1.2734966	.3183742
6	1.8717145	43178			1352672	.1152696		
			90757	22689			1.3887662	.3471916
5	2.2189061	53217			1375361	.1050883		
			37540	9385			1.4938545	.3734636
4	2.5923697	64557			1384746	.0952336		
			-27017	-6754			1.5890881	.3972720
3	2.9896417	77212			1377992	.0856043		
			-104229	-26057			1.6746924	.4186731
2	3.4083148	91542			1351935	.0761172		
			-195771	-48943			1.7508096	.4377024
1	3.8460172	106488			1302992	.0666974		
			-302259	-75565			1.8175070	.4543768
0	4.3003940	61550	-363809		1227427	.0286443	1.8461513	

$M_9 = -520100 + 1747120 = 1227020$

$V_9 = -309657 + 520100 = 210443$

H17

CALCULATION OF M_o & V_o

$$M_o = -1435780\,Y_g + 2662259\,\theta_g \qquad (1)$$

$$V_o = -487907\,Y_g + 123416\,\theta_g \qquad (2)$$

$$Y_o = .3955214\,Y_g + 3.9063378\,\theta_g \qquad (3)$$

$$\theta_o = -.5680333\,Y_g + 2.4140063\,\theta_g \qquad (4)$$

REWRITING (3)

$$Y_g = \frac{1}{.3955214}\left(Y_o - 3.9063378\,\theta_g\right)$$

$$Y_g = 2.52831\,Y_o - 9.87643\,\theta_g \qquad (5)$$

SUBSTITUTING (5) INTO (4)

$$\theta_o = -.5680333(\overset{-1.436160}{2.52831\,Y_o} \overset{+5.61014}{- 9.87643\,\theta_g}) + 2.4140063\,\theta_g$$

$$\theta_g = .12462\,\theta_o + .17898\,Y_o \qquad (6)$$

SUBSTITUTING (6) INTO (5)

$$Y_g = 2.52831\,Y_o - 9.87643(\overset{-1.23080}{.12462\,\theta_o} \overset{-1.76768}{+ .17898\,Y_o})$$

$$Y_g = .76063\,Y_o - 1.23080\,\theta_o \qquad (7)$$

SUBSTITUTING (6) & (7) INTO (1) & (2)

$$M_o = -1435780(\overset{-1092097}{.76063\,Y_o} \overset{+1767158}{- 1.23080\,\theta_o}) + 2662259(\overset{+331771}{.12462\,\theta_o} \overset{+476491}{+ .17898\,Y_o})$$

$$M_o = -615606\,Y_o + 2098929\,\theta_o$$

$$V_o = -487907(\overset{-371117}{.76063\,Y_o} \overset{+600516}{- 1.23080\,\theta_o}) + 123416(\overset{+15380}{.12462\,\theta_o} \overset{-22089}{+ .17898\,Y_o})$$

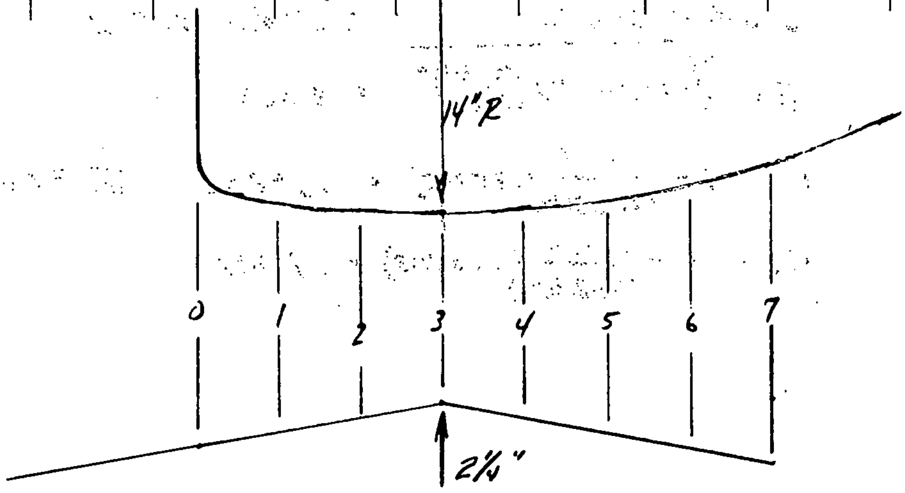
$$V_o = -349028\,Y_o + 615896\,\theta_o$$

H18

PHYSICAL PROPERTIES BARREL SIDE 30MW S.G.

$E = 22.5 \times 10^6$ $m = 1.0''$ POINT 7 & BEYOND ALIKE
$P = 2500$

POINT	0	1	2	3	4	5	6	7
DISTANCE	0	1	2	3	4	5	6	7
t	3.0625	2.71875	2.4375	2.250	2.375	2.5625	2.84375	3.125
t^3	28.723	20.096	14.482	11.391	13.396	16.826	22.997	30.518
R_M	15.53125	15.359375	15.21875	15.125	15.1875	15.28125	15.421875	15.5625
R_M^2	241.22	235.91	231.61	228.77	230.66	233.52	237.83	242.19
R_i	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
$10^6 C_1 = \frac{10.92m}{E t^3}$	.016897	.024151	.033513	.042607	.036230	.028844	.021104	.015903
$10^{-6} C_2 = \frac{mEt}{R_M^2}$	.285657	.259302	.236794	.221292	.231672	.246901	.269034	.290320
$C_3 = \frac{PR_i R_M}{Et}$	.007889	.008788	.009712	.010457	.009947	.009276	.008436	.007747
$I/c = \frac{t^2}{6}$								



H19

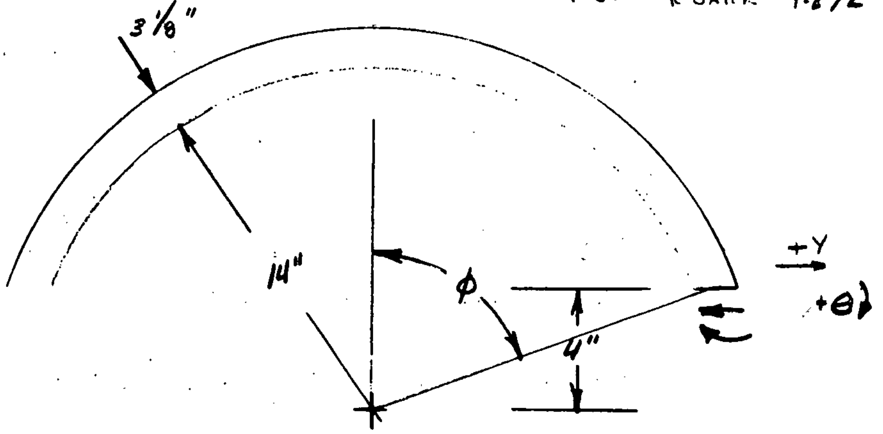
30 MW STEAM GENERATOR - BARREL SIDE

TAPERED WALL PRELIMINARY CALCULATIONS

IT IS ASSUMED ON THE BARREL SIDE THAT AT SOME DISTANCE AWAY FROM THE TUBESHEET THE THICKNESS IS CONSTANT @ 3 1/8"

TO CALCULATE M_0 & V_0 FOR THE ARC -

REF - ROARK P.272 # 14&15



$$\phi = TAN^{-1} \frac{15\,9/16}{4} = TAN^{-1}\, 3.890625 = 75^\circ\text{-}35.13'$$

$$\sin\phi = .96852 \qquad \cot\phi = .25703$$

$$\beta = \sqrt[4]{(3)(1-.3^2)\left(\frac{15.5625}{3.125}\right)^2} = 2.8685$$

$$K_1 = 1 - \frac{1-.6}{(2)(2.8685)}(.25703) = .98208 \qquad \frac{1}{K_1} = 1.01824$$

$$K_2 = 1 - \frac{1+.6}{(2)(2.8685)}(.25703) = .92832$$

H20

$$Y = \frac{-15.5625\,V}{(22.5\times10^6)(3.125)}(2.8685)(.96852)^2(.92832+1.01824)$$

$$-\frac{M}{(22.5\times10^6)(3.125)}\left(\frac{2\times2.8685^2\times.96852}{.98208}\right)$$

$$Y = -1.1592755\times10^{-6}V - .2308176\times10^{-6}M \qquad (1)$$

$$\theta = .2308176\times10^{-6}V + \frac{M}{(22.5\times10^6)(3.125)}\left(\frac{4\times2.8685^3}{15.5825\times.98208}\right)$$

$$\theta = .2308176\times10^{-6}V + .087855\times10^{-6}M \qquad (2)$$

THE CONSTANT TERM TO BE ADDED DUE TO PRESSURE IS —

CIRCUMFERENTIAL FORCE IN SPHERE = F_c

$$F_c = \frac{P\pi R_i^2}{2\pi R_m} = \frac{(2500)(14)^2}{(2)(15.5825)} = 15743$$

INCREASE IN RADIUS OF SPHERE = ΔR_m

$$\Delta R_m = \frac{R_m}{t}\frac{(1-\mu)}{E}F_c = \frac{15.5625}{3.125}\frac{(1-.3)}{22.5\times10^6}(15743) = .002439$$

THE HORIZONTAL MOVEMENT IS —

$$\Delta R_m \sin\phi = (.002439)(.96852) = .002362$$

& THE HORIZONTAL COMPONENT OF Fc —

$$F_c \sin\phi = (15743)(.96852) = 15247$$

HORIZONTAL DISPLACEMENT = (1.1592755)(.015247) = .017683

ANGULAR VARIATION AT EDGE = (.2308176)(.0015247) = .003519

EQUATIONS (1) & (2) BECOME

$$Y = -1.1592755 \times 10^{-6} V + .2308176 \times 10^{-6} M + (2362 - 17683) 10^{-6} \quad (3)$$

$$\Theta = -.2308176 \times 10^{-6} V + .087855 \times 10^{-6} M - .003519 \quad (4)$$

FOR CALCULATION PURPOSES ALTER EQUATIONS TO OBTAIN M & V IN TERMS OF Y & Θ — REWRITING (3)

$$V = \frac{10^6}{1.1592755} \left(-Y + .2308176 \times 10^{-6} M - .015321 \right)$$

$$V = -.86261 \times 10^6 Y + .199105 M - 13216 \quad (5)$$

SUBSTITUTING INTO (4)

$$\Theta = -.2308176 \times 10^{-6} \left(\overset{+.199105}{-.86261 \times 10^6 Y} + \overset{-.045957}{.199105 M} \overset{+3055}{- 13216} \right) + .087855 \times 10^{-6} M$$

$$- .003519$$

$$= +.199105 Y + .041898 \times 10^{-6} M - .000469$$

$$M = -4.75214 \times 10^6 Y + 23.8675 \times 10^6 \Theta + 11194 \quad (6)$$

SUBSTITUTING INTO (5)

$$V = -.86261 \times 10^6 Y + .199105 \left(\overset{-.94617}{-4.75214 \times 10^6 Y} + \overset{+4.7521}{23.8675 \times 10^6 \Theta} \right.$$

$$\left. \overset{+2228}{+11194} \right) - 13216$$

$$V = -1.80878 \times 10^6 Y + 4.75214 \times 10^6 \Theta - 10987 \quad (7)$$

THESE [(6) & (7)] ARE EQUATIONS FOR POINT 7 IN SUBSEQUENT CALCULATIONS.

H22

30 MW STEAM GENERATOR BARREL SIDE

TRIAL CALCULATION $Y_7 = 1$ $\theta_7 = 0$

$m = 1.5''$

POINT	Y	$C_2 Y = -\Delta V$	V	$mV = \Delta M$	M	$C_1 M = \Delta\theta$	θ	$m\theta = \Delta Y$
7	1	145160	-1819767		-4740946	-.0376976	0	
			-1964927	-1964927			-.0376976	
6	.9623024	258892			-6705873	-.1415207		
			-2223819	-2223819			-.1792183	
5	.7830841	193344			-8929692	-.2575680		
			-2417163	-2417163			-.4367863	
4	.3462978	80228			-11346855	-.4110966		
			-2497391	-2497391			-.8478829	
3	-.5015851	-110997			-13844246	-.5898618		
			-2386394	-2386391			-1.4377447	
2	-1.9393298	-459222			-16230637	-.5439373		
			-1927172	-1927172			-1.9816820	
1	-3.9210118	-1016726			-18157809	-.4385292		
			-910446	-910446			-2.4202112	
0	-6.3412230	-905707	-4739		-19068255	-.1610982	-2.5813094	

$M_7 = -4752140 + 11194 = -4740946$

$V_7 = -1808780 - 10987 = -1819767$

H 23

30 MW STEAM GENERATOR BARREL S105

TRIAL CALCULATION $\theta_7 = 1$ $Y_7 = 0$

$m = 1.0''$

POINT	Y	GY = ΔV	V	mV = ΔM	M	GM = Δθ	θ	mθ = ΔY
7	0		4741153		23876694	.1898714	1	
			4741153	4741153			1.1898714	1.1898714
6	1.1898714	320116			28619847	.6039933		
			4421037	4421037			1.7938647	
5	2.9837361	736687			33040884	.9530313		
			3684350	3684350			2.7468960	
4	5.7306321	1327627			36725234	1.3305552		
			2356723	2356723			4.0774512	
3	9.8080833	2170450			39081957	1.6651649		
			186273	186273			5.7426161	
2	15.5506994	3682312			39268230	1.3159962		
			-3496039	-3496039			7.0586123	
1	22.6093117	5862640			35772191	.8639342		
			-9358679	-9358679			7.9225465	
0	30.5318582	4360820	-13719499		26413512	.2231516	8.1456981	

$M_7 = 23867500 + 11194 = 23876694$

$V_7 = 4752140 - 10987 = 4741153$

H24

30 MW STEAM GENERATOR BARREL SIDE

TRIAL CALCULATION $\theta_7 = Y_7 = 0$

$P = 2500$ PSI

PT.	Y	Y-C_3	$-\Delta V = C_2(Y-C_3)$	V	$mV = \Delta M$	M	$C_1M = \Delta\theta$	θ	$m\theta = \Delta Y$
7	0	-.007889	-1145	-10987		11194	.0000890	0	
				-9842	-9842			.0000890	
6	.0000890	-.0083470	-2246			1352	.0000285		
				-7596	-7596			.0001175	
5	.0002065	-.0090695	-2239			-6244	-.0001801		
				-5357	-5357			-.0000626	
4	.0001439	-.0098031	-2271			-11601	-.0004208		
				-3086	-3086			-.0004829	
3	-.0003390	-.0107960	-2389			-14687	-.0006258		
				-697	-697			-.0011087	
2	-.0014477	-.0111597	-2643			-15384	-.0005156		
				+1946	1946			-.0016243	
1	-.0030720	-.0118600	-3075			-13438	-.0003245		
				5021	5021			-.0019488	
0	-.0050208	-.0129098	-1844	6865		-8417	-.0000711	-.0020199	

$M = 11194$

$V = -10987$

H25

30 MW STEAM GENERATOR BARREL SIDE

CHECK CALCULATION $Y = \theta = 1$

$P = 2500$ psi

PT	Y	$Y-C_3$	$-\Delta V = C_2(Y-C_3)$	V	$mV = \Delta M$	M	$C_1M = \Delta\theta$	θ	$m\theta = \Delta Y$
7	1	.992253	144035	2932373		19126554	.1520848	1	
				2788338	2788338			1.1520848	
6	2.1520848	2.1436488	576714			21914892	.4624919		
				2211624	2211624			1.6145767	
5	37666615	3.7573855	927702			24126516	.6959052		
				1283922	1283922			2.3104862	
4	6.077144	6.067197	1405600			25410438	.920620		
				-121678	-121678			3.231102	
3	9.308246	9.297789	2057526			25288760	1.077478		
				-2179204	-2179204			4.308580	
2	13.616826	13.607114	3222083			23109556	.774471		
				-5401287	-5401287			5.083051	
1	18.699877	18.691089	4846637			17708269	.427672		
				-10247924	-10247924			5.510723	
0	24.210600	24.202711	3456837	-13704761		7460345	.063029	5.573752	

$M = -4752140 + 23867500 + 11194 = 19126554$

$V = -1808780 + 4752140 - 10987 = 2932373$

H26

COMBINING TABLES TO DETERMINE COEFFICIENTS –

$$M_0 = -19068255\,Y_7 + 26.413512\,\theta_7 - 8417 \qquad (1)$$

$$V_0 = -4739\,Y_7 - 13719499\,\theta_7 + 6865 \qquad (2)$$

$$Y_0 = -6.341223\,Y_7 + 30.5318582\,\theta_7 - .0050208 \qquad (3)$$

$$\theta_0 = -2.5813094\,Y_7 + 8.1456981\,\theta_7 - .0020199 \qquad (4)$$

REARRANGING (3) –

$$Y_7 = \frac{1}{6.341223}\left(-Y_0 + 30.5318582\,\theta_7 - .0050208\right)$$

$$Y_7 = -.157698\,Y_0 + 4.81482\,\theta_7 - .00079177 \qquad (5)$$

SUBSTITUTING (5) INTO (4)

$$\theta_0 = -2.5813094\Big(\overset{+.4070673}{-.157698\,Y_0} + \overset{-12.4285[illegible]}{4.81482\,\theta_7} - \overset{+.0020438}{.00079177}\Big)$$

$$+ 8.1456981\,\theta_7 - .0020199$$

$$= .4070673\,Y_0 - 4.282842\,\theta_7 + .0000239$$

$$\theta_7 = \frac{1}{4.282842}\left(-\theta_0 + .4070673\,Y_0 + .0000239\right)$$

$$\theta_7 = -.2334898\,\theta_0 + .09504607\,Y_0 + .00000558 \qquad (6)$$

SUBSTITUTING (6) INTO (5) –

$$Y_7 = -.157698\,Y_0 + 4.81482\Big(\overset{-1.124211[illegible]}{-.2334898\,\theta_0} + \overset{+.4576257}{.09504607\,Y_0} + \overset{+.0000[illegible]}{.00000558}\Big)$$

$$- .00079177$$

$$Y_7 = .299932\,Y_0 - 1.124211\,\theta_0 - .0007649 \qquad (7)$$

H27

SUBTITUTE (6) ∉ (7) INTO (1) ∉ (2)

$-5719150 \quad +2143\!6.742 \quad +14585$

$$M_0 = -19068255(.299932\,Y_0 - 1.124211\,\theta_0 - .0007649)$$

$-6167286 \quad +2510501 \quad +147$

$$+26413512(-.2334898\,\theta_0 + .09504607\,Y_0 + .00000558) - 8417$$

$$M_0 = -3208679\,Y_0 + 15269456\,\theta_0 + 6315 \qquad (8)$$

$-1421 \quad +5328 \quad +4$

$$V_0 = -4739(.299932\,Y_0 - 1.124211\,\theta_0 - .0007649) + 6865$$

$+3203363 \quad -1303984 \quad -77$

$$-13719499(-.2334898\,\theta_0 + .09504607\,Y_0 + .00000558)$$

$$V_0 = -1305405\,Y_0 + 3208691\,\theta_0 + 6792 \qquad (9)$$

H28

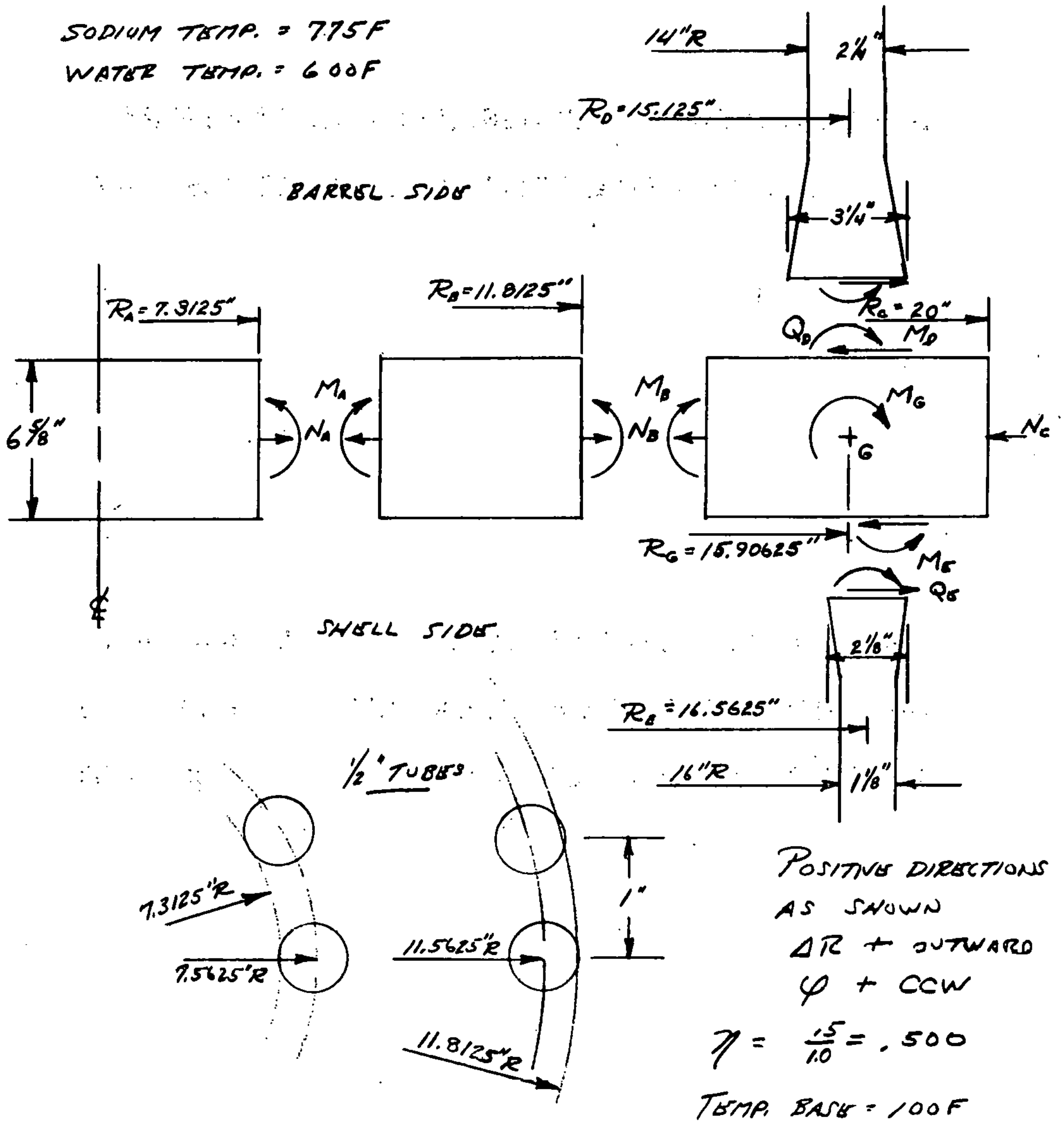
STEAM GENERATOR TUBESHEET CALCULATIONS

STEADY STATE & TRANSIENT THERMAL STRESS 4-I

30 MW STEAM GENERATOR - LOWER TUBE SHEET

STEADY STATE THERMAL STRESSES

SODIUM TEMP. = 775F
WATER TEMP. = 600F



POSITIVE DIRECTIONS
AS SHOWN
ΔR + OUTWARD
φ + CCW

$\eta = \frac{.5}{1.0} = .500$

TEMP. BASE = 100F

PHYSICAL CONSTANTS USED -

$E = 24.6 \times 10^6$ PSI $\quad \alpha = 10.7 \times 10^{-6} \quad \mu = .3$

$E^* = 9.84 \times 10^6$ PSI $\quad \mu^* = .4$

I 2

CORE - TEMPERATURES AS GIVEN IN TEMPERATURE CALCULATIONS
I26-I28

604 BARREL SIDE
622
641
664
692 SHELL SIDE

$$T_{MEAN} = 1/4\left(\frac{604}{2} + 622 + 641 + 664 + \frac{692}{2}\right)$$

$$T_{MEAN} = 644\ °F$$

THERMAL MOMENT

$$604 \times .25 \times .5 = 75.5$$
$$622 \times 1 \times 1 = 622$$
$$641 \times 2 \times 1 = 1282$$
$$664 \times 3 \times 1 = 1992$$
$$692 \times 3.75 \times .5 = 1297.5$$
$$5269$$
$$644 \times 4 \times 2 = 5152$$
$$M = 117$$

$$\Delta T = \frac{6M}{t^2} = \frac{(6)(117)}{(4)^2}$$

$$\Delta T = 44°$$

$$\text{FREE EXPANSION} = (7.3125)(10.7\times10^{-6})(644-100) = 42565\times10^{-6}$$

$$\text{FREE ROTATION} = \frac{(7.3125)(10.7\times10^{-6})(44)}{6.625/2} = 1039\times10^{-6}$$

FROM ROARK P. 276 #28 -

$$\Delta R_A = \frac{N_A R_A}{Et}(1-\mu) + 42565\times10^{-6}$$

$$= \frac{7.3125\ N_A}{(24.6\times10^6)(6.625)}(1-.3) + 42565\times10^{-6}$$

$$\Delta R_A = .031408\times10^{-6}\ N_A + 42565\times10^{-6} \qquad (1)$$

FROM ROARK P. 197 #12

$$\theta_A = \frac{12(1-\mu)M_A R_A}{Et^3} + 1039\times10^{-6}$$

$$= \frac{12(1-.3)(7.3125)M_A}{(24.6\times10^6)(6.625)^3} + 1039\times10^{-6}$$

$$\theta_A = .008587\times10^{-6}\ M_A + 1039\times10^{-6} \qquad (2)$$

TUBE AREA - TAKEN AS A SECTION AT UNIFORM TEMPERATURE
OF ≈ 600°F - NO ROTATION

$$\Delta R_A^{\circ} = (7.3125)(10.7\times10^{-6})(500) = 39122\times10^{-6} \quad \Delta R_B^{\circ} = (11.8125)(10.7\times10^{-6})(500) = 63197\times10^{-6}$$

FROM ROARK P.276 # 27 & 28

$$\Delta R_A = -\frac{N_A R_A}{E^* t}\left(\frac{R_B^2 + R_A^2}{R_B^2 - R_A^2} + \mu^*\right) + \frac{N_B R_A}{E^* t}\,\frac{2R_B^2}{R_B^2 - R_A^2}$$

$$= -\overset{.11217}{\frac{7.3125\,N_A}{(9.84\times10^6)(6.625)}}\left(\overset{2.24265\ +.4}{\frac{11.8125^2 + 7.3125^2}{11.8125^2 - 7.3125^2}} + .4\right) + \frac{7.3125\,N_B}{(9.84\times10^6)(6.625)}\left(\overset{3.24265}{\frac{2\times11.8125^2}{11.8125^2 - 7.3125^2}}\right)$$

$$\Delta R_A = -.29643\times10^{-6} N_A + .36373\times10^{-6} N_B + 39122\times10^{-6} \qquad (3)$$

$$\Delta R_B = \frac{-N_A R_B}{E^* t}\left(\frac{2R_A^2}{R_B^2 + R_A^2}\right) + \frac{N_B R_B}{E^* t}\left(\frac{R_B^2 + R_A^2}{R_B^2 - R_A^2} - \mu^*\right)$$

$$= -\frac{11.8125\,N_A}{(9.84\times10^6)(6.625)}\left(\frac{2\times7.3125^2}{11.8125^2 - 7.3125^2}\right) + \overset{.9120}{\frac{11.8125\,N_B}{(9.84\times10^6)(6.625)}}\left(\frac{11.8125^2 + 7.3125^2}{11.8125^2 - 7.3125^2} - .4\right)$$

$$\Delta R_B = -.22517\times10^{-6} N_A + .33589\times10^{-6} N_B + 63197\times10^{-6} \qquad (4)$$

FROM ROARK P.201 #25 & PLOT OF P.215 #25

$$\theta_A = \frac{R_B}{E^* t^3}\left(-19.1\times1.039\,M_A + 24\,M_B\right) = \frac{\overset{.0041284695}{11.8125}(-19.8449\,M_A + 24\,M_B)}{(9.84\times10^6)(6.625)^3}$$

$$\theta_A = -.081929\times10^{-6} M_A + .099083\times10^{-6} M_B \qquad (5)$$

$$\theta_B = \frac{R_B}{E^* t^3}\left(-15\,M_A + \overset{22.0056}{23.2\times.9485}\,M_B\right)$$

$$\theta_B = -.061927\times10^{-6} M_A + .090848\times10^{-6} M_B \qquad (6)$$

COMBINE EQUATIONS OF CORE & TUBE AREA -

$$(1) = (3)\quad .031408\,N_A + 42565 = -.29643\,N_A + .36373\,N_B + 39122$$

$$N_A = \frac{1}{.327838}\left(.36373\,N_B - 3443\right) = 1.10948\,N_B - 10502 \qquad (7)$$

$$(2) = (5)\quad .008587\,M_A + 1039 = -.081929\,M_A + .099083\,M_B$$

$$M_A = \frac{1}{.090516}\left(.099083\,M_B - 1039\right) = 1.09465\,M_B - 11479 \qquad (8)$$

I4

SUBSTITUTING (8) INTO (6) –

$$\overset{-.067788}{}\qquad\overset{+711}{}$$

$$\theta_B = \mp .061927\times10^{-6}(1.09465 M_B - 11479) + .090848\times10^{-6} M_B$$

$$M_B = \frac{10^6}{.02306}\left(\theta_B - 711\times10^{-6}\right) = 43.365\times10^6\,\theta_B - 30833 \qquad (9)$$

SUBSTITUTING (7) INTO (4) –

$$\overset{-.2[illegible]}{}\qquad\overset{+2365}{}$$

$$\Delta R_B = \mp .22517\times10^{-6}(1.10948 N_B - 10502) + .33389\times10^{-6} N_B + 63197\times10^{-6}$$

$$\Delta R_B = .08407\times10^{-6} N_B + 65562\times10^{-6} \qquad (10)$$

RING

$$T_{MEAN} = \tfrac{1}{4}\left(\frac{618}{2} + 634 + 649 + 668 + \frac{690}{2}\right)$$

$$= 651\,^\circ F$$

618 BARREL SIDE
634
649
668
690 SHELL SIDE

THERMAL MOMENT

618 × .25 × .5 = 77.25
634 × 1 × 1 = 634 –
649 × 2 × 1 = 1298 –
668 × 3 × 1 = 2004 –
690 × 3.75 × .5 = 1293.75
5307
651 × 4 × 2 = 5208
$M_T = 99$

$$\Delta T = \frac{6 M_T}{t^2} = \frac{(6)(99)}{(4)^2} = 37^\circ$$

$$\text{FREE EXPANSION @ }B' = (11.8125)(10.7\times10^{-6})(651-100) = 69643\times10^{-6}$$

$$\text{FREE ROTATION} = \frac{(45.90625)(10.7\times10^{-6})(37)}{6.625/2} = 1901\times10^{-6}$$

FROM ROARK P. 276 # 27&28 –

$$\Delta R_B' = -\frac{N_B R_B}{Et}\left(\frac{R_C^2 + R_B^2}{R_C^2 - R_B^2} + \mu\right) - \frac{N_C R_B}{Et}\left(\frac{2 R_C^2}{R_C^2 - R_B^2}\right)$$

$$= \frac{-11.8125 N_B}{(24.6\times10^6)(6.625)}\left(\frac{20^2 + 11.8125^2}{20^2 - 11.8125^2} + .3\right) - \frac{11.8125 N_C}{(24.6\times10^6)(6.625)}\left(\frac{2\times20^2}{20^2 - 11.8125^2}\right)$$

I.5

$$\Delta R_{B'} = -.17188\times10^{-6} N_B - .22262\times10^{-6} N_C + 69643\times10^{-6} \qquad (11)$$

RESISTANCE OF RING TO ROTATION ROARK P. 231

$$\theta_G = \varphi = -\frac{12 M_G R_C}{E t^3 L_N \, R_C/R_B} = \frac{(-12)(15.90625) M_G}{(24.6\times10^6)(6.625)^3 L_N \frac{20}{11.8125}} = .050731\times10^{-6} M_G$$

$$M_G = \frac{10^6}{.050731}\left(\varphi - 1901\times10^{-6}\right) = 19.7118\times10^6 \varphi - 37472 \qquad (12)$$

SHELL – TREAT THE SHELL AS OF UNIFORM THICKNESS OF 1 5/8".
STIFFNESS IS SMALL RELATIVE TO TUBE SHEET & BARREL.
MEAN SHELL TEMPERATURE IS TAKEN AS 733°F – NO ROTATION

$$\beta = \frac{1.285}{\sqrt{R_m t}} = \frac{1.285}{\left[(16.5625)(1.625)\right]^{1/2}} = \frac{1.285}{5.187876} = .24769$$

$$.3025\frac{Et^2}{R_m} = (.3025)\frac{(24.6\times10^6)(1.625)^2}{16.5625} = 1.18643\times10^6$$

EQUATIONS OF SEMI-INFINITE BEAM ON ELASTIC FOUNDATION –

$$M_E = -.3025\frac{Et^2}{R_m}\left(\Delta R_E - \Delta R_E^\circ + \theta_E/\beta\right)$$

$$M_E = -1.18643\times10^6 \Delta R_E - \frac{1.18643\times10^6}{.24769}\theta_E + (16.5625)(10.7\times10^{-6})(733-100)(1.18643\times10^6)$$

$$M_E = -1.18643\times10^6 \Delta R_E - 4.78998\times10^6 \theta + 133093 \qquad (13)$$

$$Q_E = .3025\frac{Et^2}{R_m}\left[2\beta\left(\Delta R_E - \Delta R_E^\circ\right) + \theta_E\right]$$

$$= 1.18643\times10^6\left[2\times.24769\left(\Delta R_E - 16.5625\times10.7\times10^{-6}\times633\right) + \theta_E\right]$$

$$Q_E = .58773\times10^6 \Delta R_E + 1.18643\times10^6 \theta_E - 65932 \qquad (14)$$

I 6

BARREL – TREAT BARREL WALL AS OF UNIFORM THICKNESS OF $2\frac{3}{4}''$. TEMPERATURE TAKEN AS MEAN OF 609 °F – NO ROTATION.

$$\Delta R_D^{\circ} = (15.125)(10.7\times10^{-6})(609-100) = 82375\times10^{-6}$$

$$\beta = \frac{1.285}{\sqrt{Rt}} = \frac{1.285}{[(15.125)(2.75)]^{1/2}} = \frac{1.285}{6.44932} = .19925$$

$$.3025\,\frac{Et^2}{R_m} = (.3025)\frac{(24.6\times10^6)(2.75)^2}{15.125} = 3.72009\times10^6$$

$$M_D = -3.72009\times10^6\,\Delta R_D + \frac{3.72009\times10^6}{.19925}\,\Theta_D + (3.72009)(82375)$$

$$M_D = -3.72009\times10^6\,\Delta R_D + 18.6705\times10^6\,\Theta_D + 306442 \qquad (15)$$

$$\overset{}{Q_D} = (3.72009\times10^6)(2)(.19925)\,\Delta R_D - 3.72009\times10^6\,\Theta_D - \overset{122117}{(3.72009)(2)(.19925)(82375)}$$

$$Q_D = 1.48246\times10^6\,\Delta R_D - 3.72009\times10^6\,\Theta_D - 122117 \qquad (16)$$

$$N_C = \frac{15.125}{20}Q_D + \frac{16.5625}{20}Q_B = .75625\,Q_D + .828125\,Q_B \qquad (17)$$

SUBSTITUTING (17) INTO (11) –

$$\Delta R_B = -.17188\times10^{-6}N_B - .22262\times10^{-6}(.75625\,Q_D + .828125\,Q_B) + 69643\times10^{-6}$$

$$\Delta R_B = -.17188\times10^{-6}N_B - .16836\times10^{-6}Q_D - .184357\times10^{-6}Q_B + 69643\times10^{-6} \qquad (18)$$

(10) = (18) –

$$.08407\,N_B + 65562 = -.17188\,N_B - .16836\,Q_D - .184357\,Q_B + 69643$$

$$N_B = \frac{1}{.25595}(-.16836\,Q_D - .184357\,Q_B + 4081)$$

$$N_B = -.65778\,Q_D - .72029\,Q_B + 15945 \qquad (19)$$

SUBSTITUTING (19) & (17) INTO (11) –

$$\Delta R_B = -.17188\times10^{-6}(\overset{+.11306}{-.65778\,Q_D}\ \overset{+.12350}{-.72029\,Q_B}\ \overset{-2741}{+15945}) + 69643\times10^{-6}$$

$$-.22262\times10^{-6}(\overset{-.16836}{.75625\,Q_D}\ \overset{-.18436}{+.828125\,Q_B})$$

I 7

$$\Delta R_B = -.05530 \times 10^{-6} \varphi_D - .06056 \times 10^{-6} \varphi_G + 66902 \times 10^{-6} \qquad (20)$$

SUBSTITUTE (19) INTO (10) -

$$\overset{-.05530}{} \quad \overset{-.06055}{} \quad \overset{+1340}{}$$

$$\Delta R_B = .08407 \times 10^{-6} (-.65778\, \varphi_D - .72029\, \varphi_G + 15945) + 65562 \times 10^{-6}$$

$$\Delta R_B = -.05530 \times 10^{-6} \varphi_D - .06055 \times 10^{-6} \varphi_G + 66902 \times 10^{-6} \quad (\text{CHECK})$$

$$\Delta R_D = \Delta R_B + (15.125 - 11.8125)(10.7 \times 10^{-6})(651 - 100) - \frac{6.625}{2} \varphi$$

$$= -.05530 \times 10^{-6} \varphi_D - .06056 \times 10^{-6} \varphi_G + 66902 + 19530 - 3.3125 \varphi$$

$$\overset{-.08193}{} \quad \overset{+.20572}{} \quad \overset{+6753}{}$$

$$= -.05530(1.48246\, \Delta R_D - 3.72009\, \varphi - 122117) + 66902 + 19530$$

$$\overset{-.03559}{} \quad \overset{-.07195}{} \quad \overset{+3993}{}$$

$$-.06056(.58773\, \Delta R_G + 1.18643\, \varphi - 65932) - 3.3125 \varphi$$

$$= -.08198\, \Delta R_D - .03559\, \Delta R_G - 3.17863 \varphi + 97178 \times 10^{-6}$$

$$\Delta R_D = -.03289\, \Delta R_G - 2.93779 \varphi + 89815 \times 10^{-6}$$

$$\Delta R_G = \Delta R_B + (16.5625 - 11.8125)(10.7 \times 10^{-6})(651 - 100) + \frac{6.625}{2} \varphi$$

$$= \Delta R_D + 28005 \times 10^{-6} - 18424 \times 10^{-6} + 6.625 \varphi$$

$$= -.03289\, \Delta R_G - 2.93779 \varphi + 89815 \times 10^{-6} + 28005 \times 10^{-6}$$

$$-19530 \times 10^{-6} + 6.625 \varphi$$

$$\Delta R_G = 3.5698\, \varphi + 95160 \times 10^{-6} \qquad (21)$$

$$\overset{-.11741}{} \quad \overset{-3130}{}$$

$$\Delta R_D = -.03289(3.5698\, \varphi + 95160 \times 10^{-6}) - 2.93779\, \varphi + 89815 \times 10^{-6}$$

$$\Delta R_D = -3.0552\, \varphi + 86685 \times 10^{-6} \qquad (22)$$

I 8

EQUILIBRIUM OF OUTER RING – PER RADIAN –

$$11.8125\,M_B + 15.125\,M_D - 15.125 \times 3.3125\,Q_D - 16.5625\,M_E$$

$$+16.5625 \times 3.3125\,Q_E + 15.90625\,M_G = 0$$

512.249 −364215 −56.266 +282.391

$$11.8125(43.365\times10^6\varphi - 30833) + 15.125(-3.72009\times10^6\Delta R_D + 18.6705\times10^6\varphi$$

+4634935 −74.274 +186.382 +6118252

$$+306442) - 50.10156(1.48246\times10^6\Delta R_D - 3.72009\times10^6\varphi - 122117)$$

+19.650 +79.374 −2204353

$$-16.5625(-1.18643\times10^6\Delta R_E - 4.78998\times10^6\varphi + 133093)$$

+32.245 +65.091 −3617246

$$+54.86328(.58773\times10^6\Delta R_E + 1.18643\times10^6\varphi - 65932)$$

+313.54 −596039

$$+15.90625(19.7118\times10^6\varphi - 37472) = 0$$

$$1438.988\times10^6\varphi - 130.54\times10^6\Delta R_D + 51.895\times10^6\Delta R_E + 3971334 = 0$$

+399.826 −11.315530 185.255 +4.938328

$$1438.988\varphi - 130.54(-3.0552\varphi + 86685\times10^{-6}) + 51.895(3.5698\varphi + 95160\times10^{-6})$$

$$3.971334 = 0$$

$$2023.069\,\varphi = 2.406198 \qquad \varphi = .001189 = 1189\times10^{-6}$$

4244

From (21) $\Delta R_E = 3.5698(1189\times10^{-6}) + 95160\times10^{-6} = 99404\times10^{-6}$

−3633

From (22) $\Delta R_D = -3.0552(1189\times10^{-6}) + 86685\times10^{-6} = 83052\times10^{-6}$

51561

From (9) $M_B = 43.365(1189) - 30833 = 20728$

−117936 −5695

From (13) $M_E = -1.18643(99404) - 4.78998(1189) + 133093 = 9462$

58423 1411

From (14) $Q_E = .58773(99404) + 1.18643(1189) - 65932 = -6098$

−308961 22199

From (15) $M_D = -3.72009(83052) + 18.6705(1189) + 306442 = 19680$

123121 −4423

From (16) $Q_D = 1.48246(83052) - 3.72009(1189) - 122117 = -3419$

+23437

From (12) $M_G = 19.7118(1189) - 37472 = -14035$

I 9

CHECK THE EQUILIBRIUM EQUATION –

$$\overset{244150}{11.8125(20728)} + \overset{297660}{15.125(19680)} - \overset{+171297}{50.10156(-3419)} \overset{-156714}{-16.5625(9462)}$$

$$+ \overset{-334556}{54.86328(-6098)} + \overset{-223244}{15.90625(-14035)} = -707 \checkmark$$

$$\text{FROM (8)}\quad M_A = \overset{22690}{1.09465(20728)} - 11479 = 11211$$

$$\text{FROM (19)}\quad N_B = \overset{+2242}{-.65578(-3419)} \overset{+4395}{-.72029(-6098)} + 15945 = 22582$$

$$\text{FROM (7)}\quad N_A = \overset{25054}{1.10948(22582)} - 10502 = 14552$$

STRESSES – STEADY STATE THERMAL STRESS

TUBE AREA – (ROARK · P201 #25)

IN THE TUBE AREA THE BENDING STRESSES ARE GIVEN BY.–

$$\text{RADIAL STRESS} = S_R = \frac{6}{t^2(R_D^2 - R_A^2)}\left[R_D^2 M_D - R_A^2 M_A - \frac{R_B^2 R_A^2}{R^2}(M_D - M_A)\right]$$

$$\text{TANGENTIAL STRESS} = S_T = \frac{6}{t^2(R_D^2 - R_A^2)}\left[R_B^2 M_B - R_A^2 M_A + \frac{R_B^2 R_A^2}{R^2}(M_D - M_A)\right]$$

WHERE R IS THE RADIUS TO ANY POINT & OTHER TERMS ARE AS PREVIOUSLY DEFINED.

$$\frac{6}{t^2(R_B^2 - R_A^2)} = \frac{6}{(6.625)^2(11.8125^2 - 7.3125^2)} = .0015884$$

$$R_B^2 = (11.8125)^2 = 139.53515625 \qquad R_A^2 = (7.3125)^2 = 53.47265625$$

$$R_B^2 R_A^2 = 7461.315$$

AT THE INNERMOST LIGAMENT $R = 7.5625''$

$$\frac{R_B^2 R_A^2}{R^2} = \frac{7461.315}{(7.5625)^2} = 130.462$$

$S_R = .0015884\left[\overset{2892281}{139.535(20728)} - \overset{-599486}{53.473(11211)} - \overset{-1241607}{130.462(20728+11211)}\right]$

$S_R = 1670$ C ON TOP

$S_T = .0015884\left[2892281 - 598486 + 1241607\right] = 5614$ C ON TOP

AT THE OUTERMOST LIGAMENT $R = 11.5625''$

$$\frac{R_B^2 R_A^2}{R^2} = 55.8100$$

$S_R = .0015884\left[2892281 - 599486 - \overset{-531144}{55.81(9517)}\right] = 2798$ C ON TOP

$S_T = .0015884\left[2892281 - 599486 + 55.81(9517)\right] = 4486$ C ON TOP

THE NORMAL STRESSES ARE GIVEN BY – (ROARK P276 #27&28)

RADIAL STRESS = $S_R = \frac{N_A}{t}\frac{R_A^2}{R^2}\left(\frac{R_B^2-R^2}{R_B^2-R_A^2}\right) + \frac{N_B}{t}\frac{R_B^2}{R^2}\left(\frac{R^2-R_A^2}{R_B^2-R_A^2}\right)$

TANGENTIAL STRESS = $S_T = -\frac{N_A}{t}\frac{R_A^2}{R^2}\left(\frac{R_B^2+R^2}{R_B^2-R_A^2}\right) + \frac{N_B}{t}\frac{R_B^2}{R^2}\left(\frac{R^2+R_A^2}{R_B^2-R_A^2}\right)$

AT INNERMOST LIGAMENT $R = 7.5625''$

$\frac{R_A^2}{tR^2} = .14113 \qquad \frac{R_B^2}{tR^2} = .36827 \qquad \frac{R_B^2+R^2}{R_B^2-R_A^2} = 2.2859$

$\frac{R_B^2-R^2}{R_B^2-R_A^2} = .95679 \qquad \frac{R^2-R_A^2}{R_B^2-R_A^2} = .64321 \qquad \frac{R^2+R_A^2}{R_B^2-R_A^2} = 1.2859$

$S_R = (14552)\overset{1965}{(.14113)(.95679)} + (22582)\overset{359}{(.36827)(.04321)} = 2324$ T

$S_T = -(14552)\overset{-4655}{(.14113)(2.2859)} + (22582)\overset{10694}{(.36827)(1.2859)} = 5999$ T

AT THE OUTERMOST LIGAMENT $R = 11.5625''$

$$\frac{R_A^2}{tR^2} = .06037 \qquad \frac{R_B^2}{tR^2} = .15754 \qquad \frac{R_B^2 + R^2}{R_B^2 - R_A^2} = 3.1747$$

$$\frac{R_B^2 - R^2}{R_B^2 - R_A^2} = .06790 \qquad \frac{R^2 - R_A^2}{R_B^2 - R_A^2} = .93210 \qquad \frac{R^2 + R_A^2}{R_B^2 - R_A^2} = 2.1747$$

66 3316

$$S_R = (14552)(.06037)(.06790) + (22582)(.15754)(.93210) = 3376 \text{ T}$$

-2789 7737

$$S_T = -(14552)(.06037)(3.1747) + (22582)(.15754)(2.1747) = 4948 \text{ T}$$

TUBE AREA STRESSES BECOME— $\eta = .500$

INNER ROW

		$\frac{\sigma}{\lvert\sigma_{max}\rvert}$		
SHELL SIDE	$\sigma_R = 2324 + 1670 = 3994$	.344	K = 3.15	$\sigma_R = 12501$ T
(BOTTOM)	$\sigma_T = 5999 + 5614 = 11613$			$\sigma_T = 36581$ T
BARREL SIDE	$\sigma_R = 2324 - 1670 = 654$	.589	K = 2.75	$\sigma_R = 1798$ T
(TOP)	$\sigma_T = 5999 - 5614 = 385$			$\sigma_T = 1059$ T

OUTER ROW

SHELL SIDE	$\sigma_R = 3376 + 2798 = 6174$	.654	K = 2.65	$\sigma_R = 16361$ T
(BOTTOM)	$\sigma_T = 4948 + 4486 = 9434$			$\sigma_T = 25000$ T
BARREL SIDE	$\sigma_R = 3376 - 2798 = 578$	.799	K = 2.5	$\sigma_R = 1445$ T
(TOP)	$\sigma_T = 4948 - 4486 = 462$			$\sigma_T = 1155$ T

BARREL STRESSES – AT JUNCTION WITH TUBE SHEET

$$6/t^2 = 6/(3.25)^2 = .56805$$

$$\Delta R_D = 83052 \times 10^{-6}$$

$$\Delta R_D^{\circ} = (10.7 \times 10^{-6})(609 - 100) \begin{cases} (13.5) = 73525 \times 10^{-6} & \text{INSIDE} \\ (16.75) = 91226 \times 10^{-6} & \text{OUTSIDE} \end{cases}$$

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LONGITUDINAL STRESS

$$S_L = \frac{6\, M_0}{t^2} = (.56805)(19680) = 11179 \quad \begin{matrix} C \text{ OUTSIDE} \\ T \text{ INSIDE} \end{matrix}$$

CIRCUMFERENTIAL STRESS $= \dfrac{\Delta R - \Delta R_0}{R} E \pm \mu S_L$

$$\text{OUTER SURFACE } S_c = \frac{83052-91226}{16.75}\overset{-12005}{24.6} - \overset{3354}{(.3)(11179)} = 15359 \quad C$$

$$\text{INNER SURFACE } S_c = \frac{83052-73525}{13.5}\overset{17360}{24.6} + (.3)(11179) = 20714 \quad T$$

<u>SHELL STRESSES</u> - AT JUNCTION WITH TUBE SHEET

$$6/t^2 = 6/(2.125)^2 = 1.3287$$

$$\Delta R_s = 99404 \times 10^{-6}$$

$$\Delta R_s^{\circ} = (10.7 \times 10^{-6})(733-100) \begin{cases} \rightarrow 15.5 = 104983 \times 10^{-6} \text{ INSIDE} \\ \rightarrow 17.625 = 119376 \times 10^{-6} \text{ OUTSIDE} \end{cases}$$

LONGITUDINAL STRESS

$$S_L = \frac{6\, M_s}{t^2} = (1.3287)(9462) = 12572 \quad \begin{matrix} C \text{ OUTSIDE} \\ T \text{ INSIDE} \end{matrix}$$

CIRCUMFERENTIAL STRESS $= \dfrac{\Delta R - \Delta R^{\circ}}{R} E \pm \mu S_L$

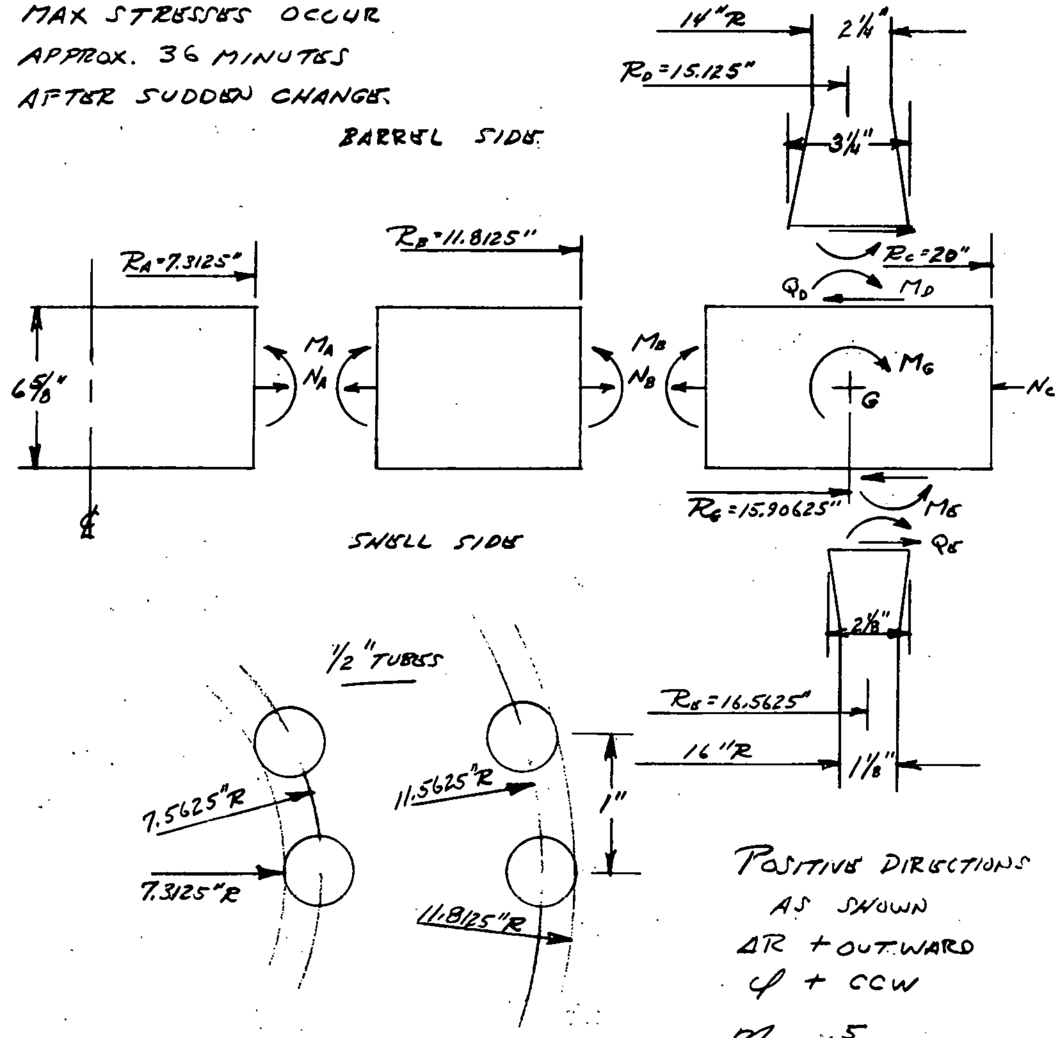
$$\text{OUTER SURFACE } S_c = \frac{99404-119376}{17.625}\overset{27876}{(24.6)} - \overset{3772}{(.3)(12572)} = 31648 \quad C$$

$$\text{INNER SURFACE } S_c = \frac{99404-104983}{15.5}\overset{8855}{(24.6)} + (.3)(12572) = 5082 \quad C$$

30 MW STEAM GENERATOR - LOWER TUBE SHEET

TRANSIENT TEMPERATURE STRESSES

SODIUM RISES FROM
775F TO 1175F
MAX STRESSES OCCUR
APPROX. 36 MINUTES
AFTER SUDDEN CHANGE.



POSITIVE DIRECTIONS
AS SHOWN
ΔR + OUTWARD
φ + CCW

$\eta = \frac{.5}{1.0} = .500$

PHYSICAL CONSTANTS USED —

TEMP. BASE = 600F

TUBE SHEET	$E = 24.6 \times 10^6$	$\alpha = 10.7 \times 10^{-6}$
SHELL	$E = 24 \times 10^6$	$\alpha = 10.9 \times 10^{-6}$
BARREL	$E = 25.2 \times 10^6$	$\alpha = 10.5 \times 10^{-6}$

$E^* = .4E$ $\mu = .3$ $\mu^* = .4$

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CORE - TEMPERATURES AS GIVEN IN TEMPERATURE CALCULATIONS - I 29 - I 33

$$T_{MEAN} = 1/4\left(\frac{657}{2}+687+741+814+\frac{914}{2}\right)$$

657 BARREL SIDE
687
741
814
914 SHELL SIDE

$$T_{MEAN} = 757\,°F$$

THERMAL MOMENT -

$657 \times .25 \times .5 = 82.125$
$687 \times 1 \times 1 = 687$ -
$741 \times 2 \times 1 = 1482$ -
$814 \times 3 \times 1 = 2442$ -
$914 \times 3.75 \times .5 = 1713.75$
6406.875
$757 \times 4 \times 2 = 6056$
$M_T = 350.875$

$$\Delta T = \frac{6M_T}{t^2} = \frac{(6)(350.875)}{(4)^2} = 132\,°F$$

$$\text{FREE EXPANSION} = (7.3125)(10.7\times10^{6})(757-600) = 12284\times10^{-6}$$

$$\text{FREE ROTATION} = \frac{(7.3125)(10.7\times10^{-6})(132)}{6.625/2} = 3118\times10^{-6}$$

FROM ROARK P.276 # 28 -

$$\Delta R_A = \frac{N_A R_A}{Et}(1-\mu) = \frac{7.3125\,N_A}{(24.6\times10^{6})(6.625)}(1-.3)$$

$$\Delta R_A = .031408\times10^{-6}N_A + 12284\times10^{-6} \qquad (1)$$

FROM ROARK P. 197 # 12 -

$$\theta_A = \frac{12(1-\mu)M_A R_A}{Et^3} = \frac{(12)(1-.3)(7.3125)M_A}{(24.6\times10^{6})(6.625)^3}$$

$$\theta_A = .008587\times10^{-6}M_A + 3118\times10^{-6} \qquad (2)$$

TUBE AREA-

$$T_{MEAN} = \frac{1}{4}\left(\frac{654}{2}+666+701+751+\frac{823}{2}\right)$$

$$T_{MEAN} = 714\,°F$$

654 BARREL SIDE
666
701
751
823 SHELL SIDE

THERMAL MOMENT

$$\begin{aligned} 654 \times .25 \times .5 &= 81.75 \\ 666 \times 1 \times 1 &= 666- \\ 701 \times 2 \times 1 &= 1402- \\ 751 \times 3 \times 1 &= 2253- \\ 823 \times 3.75 \times .5 &= \underline{1543.125} \\ & 5945.875 \\ 714 \times 4 \times 2 &= \underline{5712} \\ M_T &= 233.875 \end{aligned}$$

$$\Delta T = \frac{6M_T}{t^2} = \frac{(6)(233.875)}{(4)^2}$$

$$\Delta T = 88\,°F$$

FREE EXPANSION @ A $= (7.3125)(10.7\times10^{-6})(714-600) = 8920\times10^{-6}$

@ B $= (11.8125)(10.7\times10^{-6})(714-600) = 14409\times10^{-6}$

FREE ROTATION @ A $\dfrac{(7.3125)(10.7\times10^{-6})(88)}{6.625/2} = 2079\times10^{-6}$

@ B $\dfrac{(11.8125)(10.7\times10^{-6})(88)}{6.625/2} = 3358\times10^{-6}$

FROM ROARK P. 276 #27 & 28 —

$$\Delta R_A = -\frac{N_A R_A}{E^* t}\left(\frac{R_B^2+R_A^2}{R_B^2-R_A^2}+\mu^*\right)+\frac{N_B R_A}{E^* t}\,\frac{2R_B^2}{R_B^2-R_A^2}$$

$$= -\frac{7.3125\,N_A}{(9.84\times10^6)(6.625)}\left(\frac{11.8125^2+7.3125^2}{11.8125^2-7.3125^2}+.4\right)+\frac{7.3125\,N_B}{(9.84\times10^6)(6.625)}\frac{(2\times11.8125^2)}{(11.8125^2-7.3125^2)}$$

$$\Delta R_A = -.29643\times10^{-6}N_A + .36373\times10^{-6}N_B + 8920\times10^{-6} \qquad (3)$$

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$$\Delta R_B = -\frac{N_A R_B}{E^* t}\left(\frac{2 R_A^2}{R_B^2 - R_A^2}\right) + \frac{N_B R_B}{E^* t}\left(\frac{R_B^2 + R_A^2}{R_B^2 - R_A^2} - \nu^*\right)$$

$$= \frac{-11.8125\, N_A}{(9.84\times10^6)(6.625)}\left(\frac{2\times7.3125^2}{11.8125^2 - 7.3125^2}\right) + \frac{11.8125 N_B}{(9.84\times10^6)(6.625)}\left(\frac{11.8125^2 + 7.3125^2}{11.8125^2 - 7.3125^2} - .4\right)$$

$$\Delta R_B = -.22517\times10^{-6} N_A + .33389\times10^{-6} N_B + 14409\times10^{-6} \qquad (4)$$

FROM ROARK P.201 #25 & PLOT OF P.215 #25 -

$$\theta_A = \frac{R_B}{E^* t^3}\left(-19.1\times1.039\, M_A + 24\, M_B\right) = \frac{11.8125\left(-19.8449 M_A + 24 M_B\right)}{(9.84\times10^6)(6.625)^3}$$

$$\theta_A = -.081929\times10^{-6} M_A + .099083\times10^{-6} M_B + 2079\times10^{-6} \qquad (5)$$

$$\theta_B = \frac{R_B}{E^* t^3}\left(-15 M_A + 23.2\times.9485\, M_B\right)$$

$$\theta_B = -.061927\times10^{-6} M_A + .090848\times10^{-6} M_B + 3358\times10^{-6} \qquad (6)$$

COMBINING EQUATIONS OF CORE & TUBE AREA —

$$(1) = (3) \quad .031408\, N_A + 12284 = -.29643\, N_A + .36373\, N_B + 8920$$

$$N_A = \frac{1}{.327838}\left(.36373\, N_B - 3364\right) = 1.10948\, N_B - 10261 \qquad (7)$$

$$(2) = (5) \quad .008587\, M_A + 3118 = -.081929\, M_A + .099083\, M_B + 2079$$

$$M_A = \frac{1}{.090516}\left(.099083\, M_B - 1039\right) = 1.09465\, M_B - 11479 \qquad (8)$$

SUBSTITUTING (8) INTO (6) —

$-.06779 \qquad +.71$

$$\theta_B = -.061927\times10^{-6}\left(1.09465\, M_B - 11479\right) + .090848\times10^{-6} M_B + 3358\times10^{-6}$$

$$M_B = \frac{10^6}{.023060}\left(\theta_B - 4069\times10^{-6}\right) = 43.365\times10^6\, \theta_B - 176453 \qquad (9)$$

SUBSTITUTING (7) INTO (4) —

$-.24982 \qquad +2310$

$$\Delta R_B = -.22517\times10^{-6}\left(1.10948\, N_B - 10261\right) + .33389\times10^{-6} N_B + 14409\times10^{-6}$$

$$\Delta R_B = .08407\times10^{-6} N_B + 16719\times10^{-6} \qquad (10)$$

RING-

$$T_{MEAN} = \tfrac{1}{4}\left(\frac{670}{2} + 699 + 746 + 811 + \frac{896}{2}\right)$$

$$T_{MEAN} = 760\,^{\circ}F$$

670 BARREL SIDE
699
746
811
896 SHELL SIDE

THERMAL MOMENT

$$670 \times .25 \times .5 = 83.75$$
$$699 \times 1 \times 1 = 699 -$$
$$746 \times 2 \times 1 = 1492 -$$
$$811 \times 3 \times 1 = 2433 -$$
$$896 \times 3.75 \times .5 = 1680 -$$
$$6387.75$$
$$760 \times 4 \times 2 = 6080 -$$
$$M_T = 307.75$$

$$\Delta T = \frac{6M_T}{t^2} = \frac{(6)(307.75)}{(4)^2}$$

$$\Delta T = 115\,^{\circ}F$$

$$\text{FREE EXPANSION @ } B' = (11.8125)(10.7\times10^{-6})(760-600) = 20223\times10^{-6}$$

$$\text{FREE ROTATION} = \frac{(15.90625)(10.7\times10^{-6})(115)}{6.625/2} = 5909\times10^{-6}$$

FROM ROARK P.276 #27 & 28 -

$$\Delta R_{B'} = -\frac{N_B R_B}{Et}\left(\frac{R_C^2 + R_B^2}{R_C^2 - R_B^2} + \mu\right) - \frac{N_C R_B}{Et}\left(\frac{2R_C^2}{R_C^2 - R_B^2}\right)$$

$$= \frac{11.8125\,N_B}{(24.6\times10^6)(6.625)}\left(\frac{20^2 + 11.8125^2}{20^2 - 11.8125^2} + .3\right) - \frac{11.8125\,N_C}{(24.6\times10^6)(6.625)}\left(\frac{2\times20^2}{20^2 - 11.8125^2}\right)$$

$$\Delta R_B' = -.17188\times10^{-6} N_B - .22262\times10^{-6} N_C + 20223\times10^{-6} \qquad (11)$$

RESISTANCE OF RING TO ROTATION - ROARK P.231 -

$$\theta_G = \varphi = \frac{-12\,M_G R_C}{Et^3 \ln R_C/R_B} = \frac{-(12)(15.90625)M_G}{(24.6\times10^6)(6.625)^3 \ln \frac{20}{11.8125}} = .050731\times10^{-6} M_G$$

REARRANGED –

$$M_G = \frac{10^6}{.050731}\left(\varphi - 5909\times10^{-6}\right) = 19.7118\times10^{6}\,\varphi - 116477 \qquad (12)$$

<u>SHELL</u> – TREATED AS UNIFORM THICKNESS OF 1 5/8". MEAN TEMPERATURE TAKEN AS 1033°F –
AS A BEAM ON AN ELASTIC FOUNDATION –

$$\beta = \frac{1.285}{\sqrt{(16.5625)(1.625)}} = \frac{1.285}{5.187876} = .24769$$

$$.3025\,\frac{Et^2}{R} = (.3025)\,\frac{(24.0\times10^6)(1.625)^2}{16.5625} = 1.15749\times10^6$$

FREE EXPANSION = $\Delta R_E^\circ = (10.9\times10^{-6})(16.5625)(1033-600) = 78170\times10^{-6}$

$$M_E = -.3025\,\frac{Et^2}{R}\left(\Delta R_E - \Delta R_E^\circ + \theta_E/\beta\right)$$

$$M_E = -1.15749\times10^6\,\Delta R_E - 4.6731\times10^6\,\theta_E + 90481 \qquad (13)$$

$$Q_E = .3025\,\frac{Et^2}{R}\left[2\beta(\Delta R_E - \Delta R_E^\circ + \theta_E\right]$$

$$Q_E = .57340\times10^6\,\Delta R_E + 1.15749\times10^6\,\theta_E - 44822 \qquad (14)$$

<u>BARREL</u> – TREATED AS OF UNIFORM THICKNESS OF 2 3/4". TEMPERATURE AT A MEAN OF 630°F. AS A BEAM ON AN ELASTIC FOUNDATION –

$$\Delta R_D^\circ = (10.5\times10^{-6})(15.125)(630-600) = 4764\times10^{-6}$$

$$\beta = \frac{1.285}{\left[(15.125)(2.75)\right]^{1/2}} = \frac{1.285}{6.44932} = .19925$$

$$.3025\,\frac{Et^2}{R} = (.3025)\,\frac{(25.2\times10^6)(2.75)^2}{15.125} = 3.8115\times10^6$$

$$M_D = -3.8115\times10^6\,\Delta R_D + 19.1292\times10^6\,\theta_D + 18158 \qquad (15)$$

$$Q_D = 1.51888\times10^6\,\Delta R_D - 3.8115\times10^6\,\theta_D - 7236 \qquad (16)$$

$$N_c = \frac{15.125}{20}\varphi_D + \frac{16.5625}{20}\varphi_G = .75625\varphi_D + .828125\varphi_G \qquad (17)$$

SUBSTITUTING (17) INTO (11) —

$$\Delta R_B = -.17188\times10^{-6} N_B - .22262\times10^{-6}(.75625\varphi_D + .828125\varphi_G) + 20223\times10^{-6}$$

$$\Delta R_B = -.17188\times10^{-6} N_B - .16836\times10^{-6}\varphi_D - .18436\times10^{-6}\varphi_G + 20223\times10^{-6} \qquad (18)$$

$$(10) = (18)$$

$$.08407 N_B + 16719 = -.17188 N_B - .16836\varphi_D - .18436\varphi_G + 20223$$

$$N_B = \frac{1}{.25595}(-.16836\varphi_D - .18436\varphi_G + 3504)$$

$$N_B = -.65778\varphi_D - .72030\varphi_G + 13690 \qquad (19)$$

SUBSTITUTE (19) INTO (18) —

$$\overset{+.1130}{}\qquad\overset{-.1239}{}$$

$$\Delta R_B = -.17188\times10^{-6}(-.65778\varphi_D - .72030\varphi_G + 13690) - .16836\times10^{-6}\varphi_D$$
$$- .18436\times10^{-6}\varphi_G + 20223\times10^{-6}$$

$$\Delta R_B = -.05530\times10^{-6}\varphi_D - .06055\times10^{-6}\varphi_G + 17870\times10^{-6} \qquad (20)$$

$$\Delta R_D = \Delta R_B + (15.125 - 11.8125)(10.7\times10^{-6})(760-600) - \frac{6.625}{2}\varphi$$

$$= -.05530\times10^{-6}\varphi_D - .06055\times10^{-6}\varphi_G + 17870\times10^{-6} + 5350\times10^{-6} - 3.3125\varphi$$

$$\qquad -.09\ldots \qquad -.2107\ldots$$

$$= -.05530(1.51888\Delta R_D - 3.8115\varphi - 7236\times10^{-6}) + 23220\times10^{-6}$$

$$\qquad -.03472 \qquad -.07009 \qquad .27\ldots$$

$$- .06055(.57340\Delta R_G + 1.15749\varphi - 44822\times10^{-6}) - 3.3125\varphi$$

$$\Delta R_D = -.08399\Delta R_D - .03472\Delta R_G - 3.17181\varphi + 26334\times10^{-6}$$

$$\Delta R_D = -.03203\Delta R_G - 2.92605\varphi + 24294\times10^{-6}$$

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$$\Delta R_G = \Delta R_B + (16.5625 - 11.8125)(10.7 \times 10^{-6})(760 - 600) + \frac{6.625}{8} \varphi$$

$$= \Delta R_D + 8132 \times 10^{-6} - 5350 \times 10^{-6} + 6.625 \varphi$$

$$= -.03203 \Delta R_G - 2.92605 \varphi + 24294 \times 10^{-6} + 2782 \times 10^{-6} + 6.625 \varphi$$

$$= -.03203 \Delta R_G + 3.69895 \varphi + 27076 \times 10^{-6}$$

$$\Delta R_G = 3.58415 \varphi + 26236 \times 10^{-6} \qquad (21)$$

$$\overset{-.11480}{} \qquad \overset{-840}{}$$

$$\Delta R_D = -.03203(3.58415 \varphi + 26236 \times 10^{-6}) - 2.92605 \varphi + 24294 \times 10^{-6}$$

$$\Delta R_D = -3.04085 \varphi + 23454 \times 10^{-6} \qquad (22)$$

EQUILIBRIUM OF THE OUTER RING - PER RADIAN -

$$11.8125 M_B + 15.125 M_D - 15.125(3.3125) Q_D - 16.5625 M_G + 16.5625(3.3125) Q_G$$

$$+ 15.90625 M_6 = 0$$

$$\overset{512.249}{} \quad \overset{-2084351}{} \quad \overset{-57.649}{} \quad \overset{+259.317}{}$$

$$11.8125(43.365 \times 10^6 \varphi - 176453) + 15.125(-3.8115 \times 10^6 \Delta R_D + 19.1292 \times 10^6 \varphi$$

$$\overset{+274640}{} \quad \overset{-76.099}{} \quad \overset{+190.962}{} \quad \overset{+362.535}{}$$

$$+ 18158) - 50.10156(1.51888 \times 10^6 \Delta R_D - 3.8115 \times 10^6 \varphi - 7286)$$

$$\overset{+19.171}{} \quad \overset{+77.393}{} \quad \overset{-1498572}{} \quad \overset{+31.459}{}$$

$$-16.5625(-1.15749 \times 10^6 \Delta R_G - 4.6731 \times 10^6 \varphi + 90481) + 54.8638(.57340 \times 10^6 \Delta R_G$$

$$\overset{+63.504}{} \quad \overset{-2459083}{} \quad \overset{313.541}{} \quad \overset{-1252712}{}$$

$$+ 1.15749 \times 10^6 \varphi - 44822) + 15.90625(19.7118 \times 10^6 \varphi - 116477) = 0$$

$$1446.983 \times 10^6 \varphi - 133.747 \times 10^6 \Delta R_D + 50.630 \times 10^6 \Delta R_G - 7257563 = 0$$

$$\overset{+406.705}{} \quad \overset{-3.136902}{} \quad \overset{+181.466}{}$$

$$1446.983 \varphi - 133.747(-3.04085 \varphi + 23454 \times 10^{-6}) + 50.630(3.58415 \varphi$$

$$\overset{+1.328329}{}$$

$$+ 26236 \times 10^{-6}) - 7.257563 = 0$$

$$2035.154 \varphi = 9.066136 \qquad \varphi = .004455 = 4455 \times 10^{-6}$$

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FROM (21) $\Delta R_E = 3.58415(\overset{15967}{4455\times10^{-6}}) + 26236\times10^{-6} = 42203\times10^{-6}$

FROM (22) $\Delta R_D = -3.04085(\overset{-13547}{4455\times10^{-6}}) + 23454\times10^{-6} = 9907\times10^{-6}$

FROM (9) $M_B = 43.365(\overset{193191}{4455}) - 176453 = 16738$

FROM (13) $M_E = -1.15749(\overset{-48850}{42203}) - 4.6731(\overset{-20819}{4455}) + 90481 = 20812$

FROM (14) $Q_E = .57340(\overset{24199}{42203}) + 1.15749(\overset{5157}{4455}) - 44822 = -15466$

FROM (15) $M_D = -3.8115(\overset{-37761}{9907}) + 19.1292(\overset{85221}{4455}) + 18158 = 65618$

FROM (16) $Q_D = 1.51888(\overset{15048}{9907}) - 3.8115(\overset{-16980}{4455}) - 7236 = -9168$

FROM (12) $M_G = 19.7118(\overset{87816}{4455}) - 116477 = -28661$

SUBSTITUTING INTO MOMENT EQUATION —

$$11.8125(\overset{197718}{16738}) + 15.125(\overset{992472}{65618}) - 50.10156(\overset{+459331}{-9168}) - 16.5625(\overset{-344699}{20812})$$

$$+54.8633(\overset{-848516}{-15466}) + 15.90625(\overset{-455892}{-28661}) = 417$$

FROM (8) $M_A = 1.09465(\overset{18322}{16738}) - 11479 = 6843$

FROM (19) $N_B = -.65776(\overset{6030}{-9168}) - .72030(\overset{11140}{-15466}) + 13690 = 30861$

FROM (7) $N_A = 1.10948(\overset{34240}{30861}) - 10261 = 23979$

STRESSES — TRANSIENT TEMPERATURE STRESSES

TUBE AREA — IN THE TUBE AREA THE BENDING STRESSES ARE GIVEN BY —

RADIAL STRESS $= S_R = \dfrac{6}{t^2(R_B^2 - R_A^2)}\left[R_B^2 M_B - R_A^2 M_A - \dfrac{R_B^2 R_A^2}{R^2}(M_B - M_A)\right]$

TANGENTIAL STRESS $= S_T = \dfrac{6}{t^2(R_B^2 - R_A^2)}\left[R_B^2 M_B - R_A^2 M_A + \dfrac{R_B^2 R_A^2}{R^2}(M_B - M_A)\right]$

WHERE R IS RADIUS TO ANY POINT & OTHER TERMS AS PREVIOUSLY DEFINED.

I 22

$$\frac{6}{t^2(R_B^2-R_A^2)} = \frac{6}{(6.625)^2(11.8125^2-7.3125^2)} = .0015884$$

$$R_B^2 = (11.8125)^2 = 139.53515625 \qquad R_A^2 = (7.3125)^2 = 53.47265625$$

$$R_B^2 R_A^2 = 7461.315$$

AT THE INNERMOST LIGAMENT $R = 7.5625''$

$$\frac{R_B^2 R_A^2}{R^2} = 130.462$$

$$S_R = .0015884\left[\overset{2335537}{139.535(16738)} - \overset{-365916}{53.473(6843)} - \overset{-1290921}{130.462(16738-6843)}\right]$$

S_R = 1078 C ON TOP

$S_T = .0015884\left[2335537-365916+1290921\right] = 5179$ C ON TOP

AT THE OUTERMOST LIGAMENT $R = 11.5625''$

$$\frac{R_B^2 R_A^2}{R^2} = 55.8100$$

$S_R = .0015884\left[2335537-365916-\overset{-552240}{55.81(9895)}\right] = 2251$ C ON TOP

$S_T = .0015884\left[2335537-365916+55.81(9895)\right] = 4006$ C ON TOP

THE NORMAL STRESS IS GIVEN BY—

RADIAL STRESS $= S_R = \dfrac{N_A}{t}\dfrac{R_A^2}{R^2}\left(\dfrac{R_B^2-R^2}{R_B^2-R_A^2}\right) + \dfrac{N_B}{t}\dfrac{R_B^2}{R^2}\left(\dfrac{R^2-R_A^2}{R_B^2-R_A^2}\right)$

TANGENTIAL STRESS $S_T = -\dfrac{N_A}{t}\dfrac{R_A^2}{R^2}\left(\dfrac{R_B^2+R^2}{R_B^2-R_A^2}\right) + \dfrac{N_B}{t}\dfrac{R_B^2}{R^2}\left(\dfrac{R^2+R_A^2}{R_B^2-R_A^2}\right)$

AT INNERMOST LIGAMENT — $R = 7.5625''$.

$$\frac{R_A^2}{tR^2} = .14113 \qquad \frac{R_B^2}{tR^2} = .36827 \qquad \frac{R_B^2+R^2}{R_B^2-R_A^2} = 2.2859$$

$$\frac{R_B^2-R^2}{R_B^2-R_A^2} = .95679 \qquad \frac{R^2-R_A^2}{R_B^2-R_A^2} = .043210 \qquad \frac{R^2+R_A^2}{R_B^2-R_A^2} = 1.2859$$

$$S_R = \overset{3238}{(23979)(.14113)(.95679)} + \overset{491}{(30861)(.36827)(.04321)} = 3729 \ T$$

$$S_T = \overset{-7735}{-(23979)(.14113)(2.2859)} + \overset{14614}{(30861)(.36827)(1.2859)} = 6878 \ T$$

AT THE OUTER MOST LIGAMENT $R = 11.5625''$

$$\frac{R_A^2}{c R^2} = .06037 \qquad \frac{R_B^2}{c R^2} = .15754 \qquad \frac{R_B^2 + R^2}{R_B^2 - R_A^2} = 3.1747$$

$$\frac{R_B^2 - R^2}{R_B^2 - R_A^2} = .06790 \qquad \frac{R^2 - R_A^2}{R_B^2 - R_A^2} = .93210 \qquad \frac{R^2 + R_A^2}{R_B^2 - R_A^2} = 2.1747$$

$$S_R = \overset{98}{(23979)(.06037)(.06790)} + \overset{+4532}{(30861)(.15754)(.93210)} = 4434 \ T$$

$$S_T = \overset{-4596}{-(23979)(.06037)(3.1747)} + \overset{+10573}{(30861)(.15754)(2.1747)} = 5977 \ T$$

<u>TUBE AREA STRESSES</u> BECOME-

<u>INNER ROW</u> $\eta = .500$ $\dfrac{\sigma}{|\sigma_{MAX}|}$

SHELL SIDE (BOTTOM)

$\sigma_R = 3729 + 1078 = 4807$ .399 $K = 3.0$ $\sigma_R = 14421 \ T$

$\sigma_T = 6878 + 5179 = 12057$ $\sigma_T = 36171 \ T$

BARREL SIDE (TOP)

$\sigma_R = 3729 - 1078 = 2651$ .641 $K = 2.65$ $\sigma_R = 7025 \ T$

$\sigma_T = 6878 - 5179 = 1699$ $\sigma_T = 4502 \ T$

<u>OUTER ROW</u> $\sigma / |\sigma_{MAX}|$

SHELL SIDE (BOTTOM)

$\sigma_R = 4434 + 2251 = 6685$ .670 $K = 2.6$ $\sigma_R = 17381 \ T$

$\sigma_T = 5977 + 4006 = 9983$ $\sigma_T = 25956 \ T$

BARREL SIDE (TOP)

$\sigma_R = 4434 - 2251 = 2183$ .903 $K = 2.4$ $\sigma_R = 5239 \ T$

$\sigma_T = 5977 - 4006 = 1971$ $\sigma_T = 4730 \ T$

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BARREL STRESSES - AT JUNCTION WITH TUBE SHEET (TRANSIENT TEMPERATURE STRESSES).

$$6/t^2 = \frac{6}{(3.25)^2} = .56805$$

$$\Delta R_D = 9907 \times 10^{-6}$$

$$\Delta R_D^\circ = (10.5 \times 10^{-6})(630-600) \begin{cases} \nearrow (13.5) = 42525 \times 10^{-6} \text{ AT INSIDE} \\ \searrow (16.75) = 527625 \times 10^{-6} \text{ AT OUTSIDE} \end{cases}$$

LONGITUDINAL STRESS

$$S_L = \frac{6 M_D}{t^2} = .56805(65618) = 37274 \quad \begin{matrix} \text{C OUTSIDE} \\ \text{T INSIDE} \end{matrix}$$

CIRCUMFERENTIAL STRESS $S_C = \frac{\Delta R - \Delta R^\circ}{t} \pm \mu S_L$

$$\text{OUTER SURFACE } S_C = \frac{(9907-5276)}{16.75}\overset{6967}{(25.2)} - \overset{11182}{(.3)(37274)} = 4215 \text{ C}$$

$$\text{INNER SURFACE } S_C = \frac{(9907-4252)}{13.5}\overset{[illegible]}{(25.2)} + (.3)(37274) = 21738 \text{ T}$$

SHELL STRESSES – AT JUNCTION WITH TUBE SHEET (TRANSIENT TEMP. STRESS)

$$6/t^2 = 6/(2.125)^2 = 1.3287$$

$$\Delta R_v = 42203 \times 10^{-6}$$

$$\Delta R_v^\circ = (10.9 \times 10^{-6})(1033-600) \begin{cases} \nearrow 15.5 = 73155 \times 10^{-6} \text{ INSIDE} \\ \searrow 17.625 = 83185 \times 10^{-6} \text{ OUTSIDE} \end{cases}$$

LONGITUDINAL STRESS

$$S_L = \frac{6 M_v}{t^2} = (1.3287)(20812) = 27653 \quad \begin{matrix} \text{C OUTSIDE} \\ \text{T INSIDE} \end{matrix}$$

CIRCUMFERENTIAL STRESS $S_C = \frac{\Delta R - \Delta R^\circ}{R} t \pm \mu S_L$

$$\text{OUTER SURFACE } S_C = \frac{42203 - 83185}{17.625}\overset{[illegible]}{(24)} - \overset{-8296}{(.3)(27653)} = 64101 \text{ C}$$

$$\text{INNER SURFACE } S_C = \frac{42203 - 73155}{15.5}\overset{-47926}{(24)} + \overset{8296}{(.3)(27653)} = 39630 \text{ C}$$

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30 MW STEAM GENERATOR

STEADY STATE & TRANSIENT TEMPERATURE CALCULATIONS

LOWER TUBE SHEET

THE LOWER TUBE SHEET IS SHIELDED WITH SST PLATES UP TO A HEIGHT OF 5 1/4" ABOVE THE TUBE SHEET, SODIUM BETWEEN THE PLATES. THE EQUIVALENT THICKNESS OF SOLID SST IS - (10 - 1/4" PLATES)

$$10 \times 1/4 + (5\tfrac{1}{4} - 10 \times 1/4)/4 = 3.1875''$$

THEN TOTAL THICKNESS OF TUBE SHEET PLUS SHIELD BECOMES 6.625 + 3.1875 = 9.8125" & THE TUBE SHEET REPRESENTS APPROXIMATELY 70% OF THE TOTAL THICKNESS.

THE TIME FOR THE WORST TEMPERATURE GRADIENT IS CALCULATED ON THE FOLLOWING PAGE.

THE SODIUM FILM COEFFICIENT IS TAKEN AS $h = 4000$.

THE TRANSIENT IS A 400°F RISE (775 - 1175°F) IN A SHORT TIME; THE EXACT TIME FOR THE TRANSIENT TO OCCUR BEING NOT IMPORTANT AS LONG AS IT IS SMALL RELATIVE TO THE LENGTH OF TIME REQUIRED TO REACH WORST TEMPERATURE CONDITION.

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STEADY STATE TEMPERATURES

THE TEMPERATURE THRU THE STRAIGHT PORTION OF THE SHELL (1 1/8" THICK) IS UNIFORMLY AT 775°F

SECTION F (CORE AREA) 775-600°F (175° ΔT)

		775	
SODIUM h=4000	.00025	774	-1
3.1875" SHIELD K=13	.02043	719	-55
TUBE SHEET 6 5/8" K=13	.04247	604	-115
1/8" INCONEL K=16.5	.00063	602	-2
WATER h=1000	.00100	600	-2
	.06478		

ΔT THRU TUBE SHEET = 115°F

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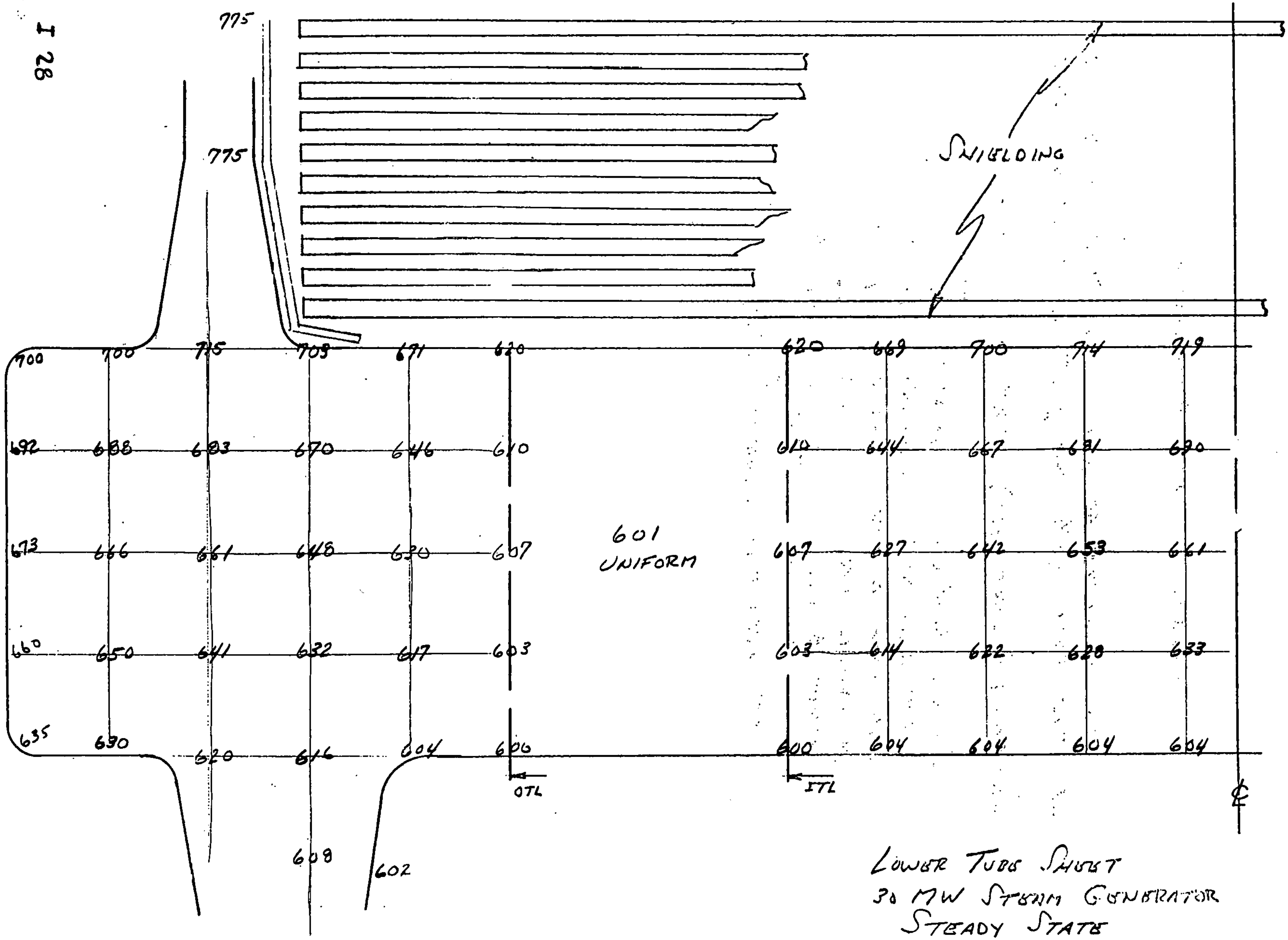

Lower Tube Sheet
30 MW Steam Generator
Steady State

30 MW STEAM GENERATOR - TRANSIENT TEMPERATURES
FOR A SUDDEN UNIT RISE IN SODIUM TEMPERATURE (400°/40SEC)
AT LOWER TUBE SHEET

0-.7 TUBESHEET .7-1.0 IN SHIELD

POINT	N_{F_0} =.070 τ =1021		N_{F_0} =.100 τ = 1459		N_{F_0} = .150 τ = 2188		N_{F_0} =.200 τ =2918	
0	.014		.049	165	.133	449	.225	759
.1	.019		.057	342	.143	858	.234	1404
.2	.033		.079	395	.170	850	.261	1305
.3	.060		.119	476	.216	864	.305	1220
.4	.107		.178	534	.281	843	.366	1098
.5	.178		.260	00560	.363	726	.443	886
.6	.280		.367	.00367	.464	.00464	.534	.00534
.7	.416		.496	62	.580	73	.637	80
Σ				.02901		.05127		.07286
M_N			.189	.04631	.283	.06934	.366	.08967
Δ			.307	.01730	.297	.01807	.271	.01681
ΔT								

↑ MAXIMUM CONDITION

$$N_{Bi}^{-1} = \frac{(12)(13)}{(4000)(9.8125)} = .004$$

$$N_{F_0} = \frac{.0066\tau}{(9.8125)^2} = .000068546\tau$$

TEMPERATURE GRADIENTS IN TUBE SHEET
36 MINUTES AFTER TRANSIENT (400°-40 SEC)

SECTION B (CORE)

$\bar{X} = 9.8125"$

$$N_{Bi}^{-1} = \frac{(12)(13)}{(4000)(9.8125)} = .004$$

$$N_{Fo} = \frac{(.0066)(2160)}{(9.8125)^2} = .148$$

USE .150

POINT	TEMP.	ΔT
0	.133	53
.1	.143	57
.2	.170	68
.3	.216	86
.4	.281	112
.5	.363	144
.6	.464	185
.68		222
.7	.580	231
.8	.710	283
.9	.849	338
1.0	.993	395

.68 - 1.0 IN SHIELD

SECTION A (SHELL WALL)

$\bar{X} = 1.28125"$

$$N_{Bi}^{-1} = \frac{(12)(13)}{(4000)(1.28125)} = .030$$

$$N_{Fo} = \frac{(.0066)(2160)}{(1.28125)^2} = 8.68$$

POINT	TEMP.	ΔT
0	1.0 ↑	400 ↑
.1		
.2		
.3		
.4		
.5		
.6		
.7		
.8		
.88		
.9		
1.0	↓ 1.0	↓ 400

0 - .88 SHELL WALL

POINT	TEMP.	ΔT
0	.050	20
.1	.057	23
.2	.079	32
.3	.119	48
.4	.179	72
.5	.261	104
.6	.368	147
.7	.498	199
.75	.575	230
.8	.650	260
.9	.818	327
1.0	.995	398

SECTION C (OUTER RING)

$\bar{X} = 11.625$

$TS = 8.75/11.625 = 75\%$

$$N_{Bi}^{-1} = \frac{(12)(13)}{(4000)(11.625)} = .003$$

$$N_{Fo} = \frac{(.0066)(2160)}{(11.625)^2} = .105$$

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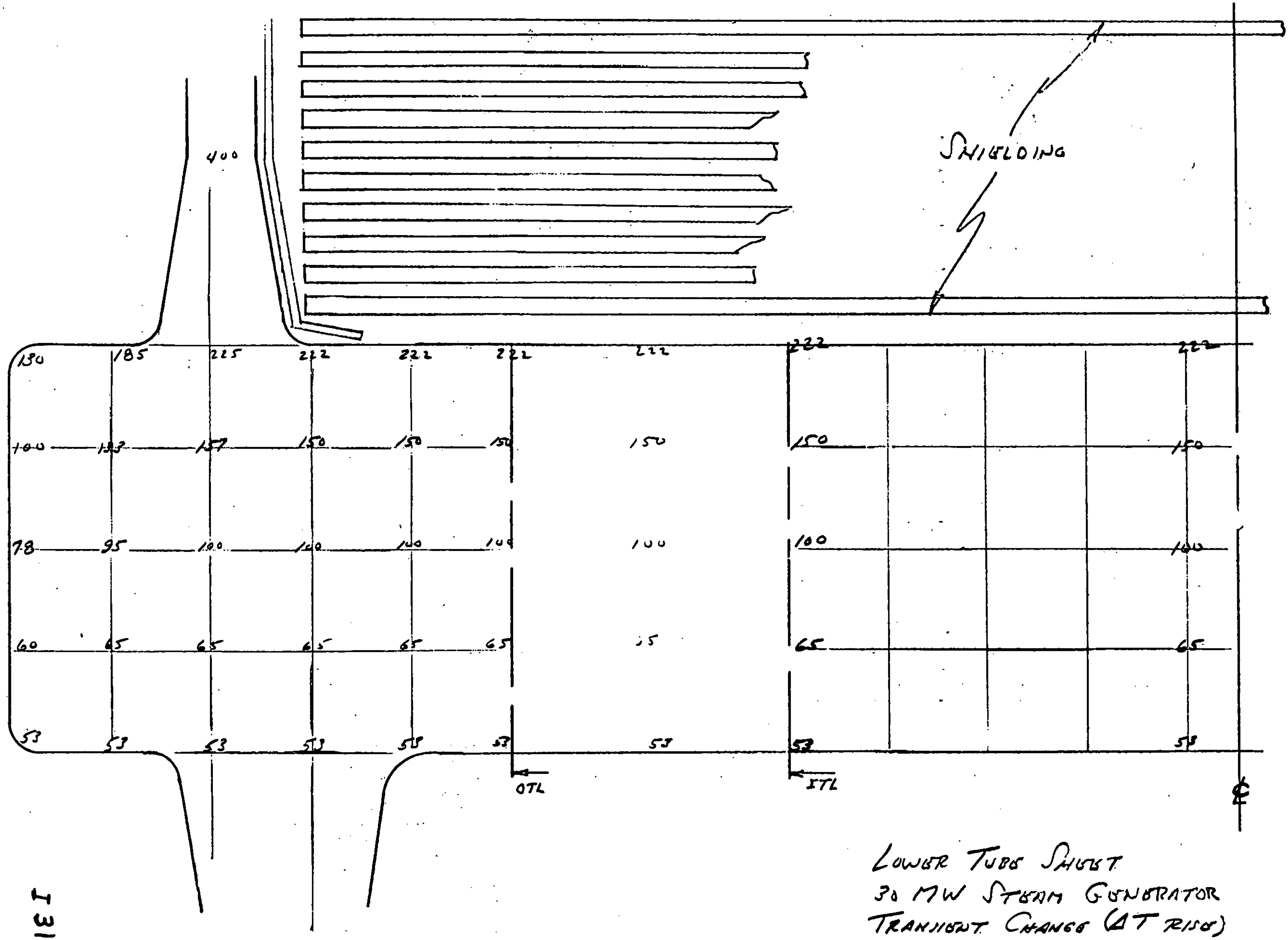

LOWER TUBE SHEET
30 MW STEAM GENERATOR
TRANSIENT CHANGE (ΔT RISE)
36 MIN AFTER 400° ΔT

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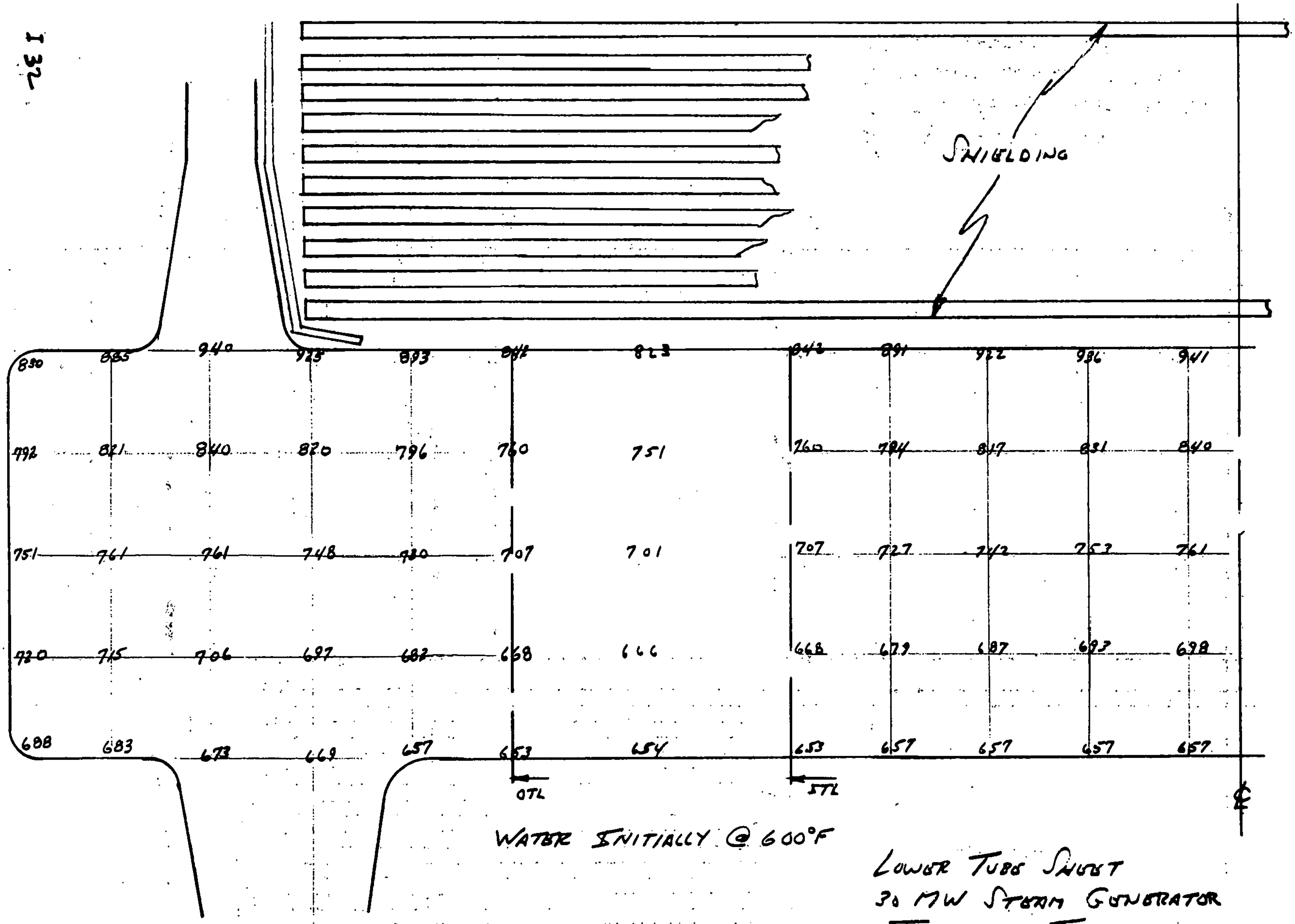
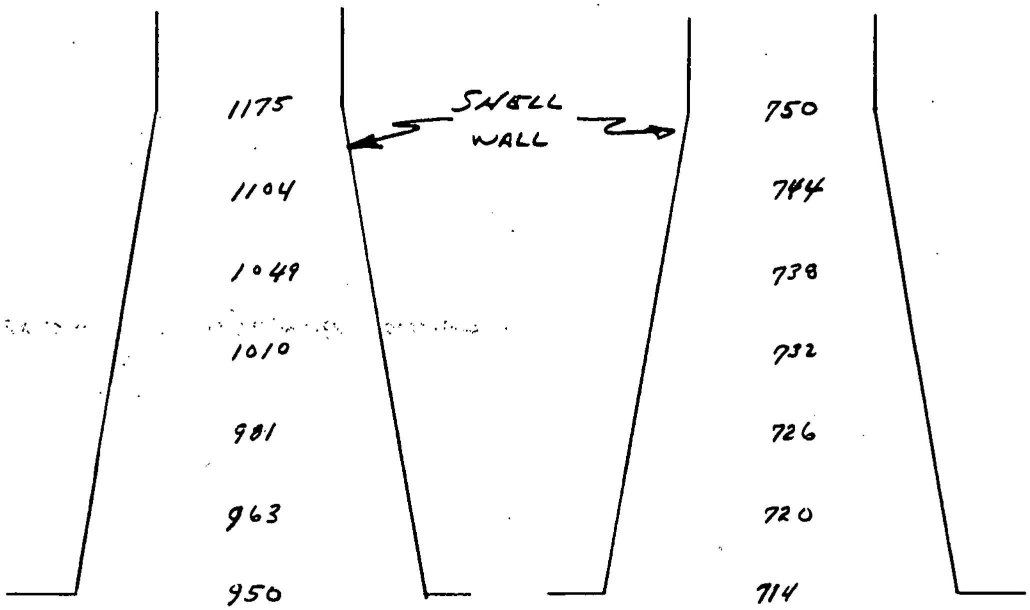


830	885	940	925	893	842	823	842	891	922	936	941
792	821	840	820	796	760	751	760	794	817	831	840
751	761	761	748	730	707	701	707	727	742	753	761
720	715	706	697	682	668	666	668	679	687	693	698
688	683	673	669	657	653	654	653	657	657	657	657

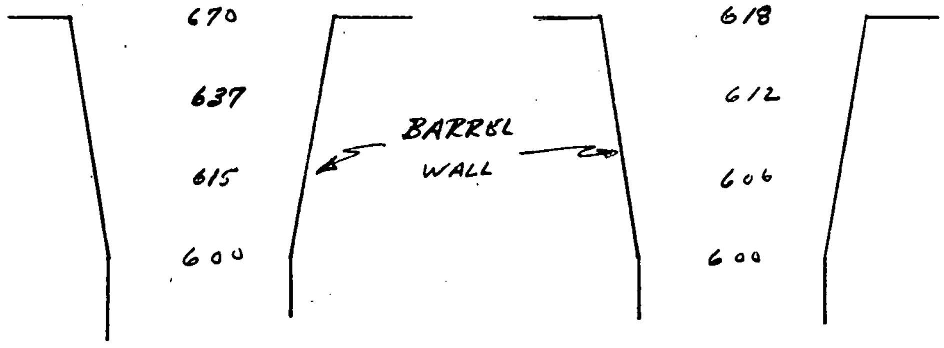
WATER INITIALLY @ 600°F

LOWER TUBE SHEET
30 MW STEAM GENERATOR
TRANSIENT TEMPERATURES
36 MINUTES AFTER TRANSIENT



TRANSIENT

STEADY-STATE



TRANSIENT

STEADY-STATE

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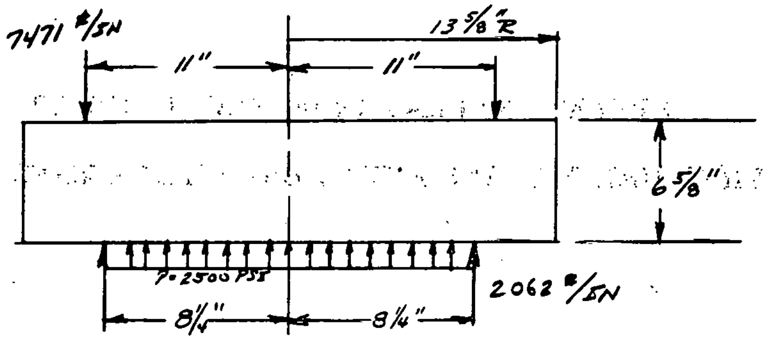
STEAM GENERATOR MANHOLE COVER

PRESSURE & TRANSIENT THERMAL STRESSES 4J

30 MW STEAM GENERATOR
MANHOLE COVER – PRESSURE STRESSES



MANHOLE COVER @ DESIGN CONDITIONS   MAT'L. 316 SST
2500 PSI @ 1100°F

BOLT FORCE (ASME CODE UPV SECTION VIII)

$F = .785 G^2 P + 2b\pi G m P$ $b_0 = \frac{w}{8} = \frac{1/2}{8} = .0625 = b$

$= (.785)(16.5)^2(2500) + (2)(.0625)(\pi)(16.5)(6.50)(2500)$

$F = 534291 + 105292 = 639583$

BOLT LOAD $= \frac{639583}{2\pi(13.625)} = 7471$ #/IN

GASKET LOAD $= \frac{105292}{2\pi(8.25)} = 2062$ #/IN

FROM ROARK P. 194 #2 STRESS DUE TO INTERNAL PRESSURE –

AT CENTER $S_Z = S_T = MAX.$

$$S = \frac{3W}{2\pi m t^2}\left[m + (m+1)\ln\frac{A}{R_0} - (m-1)\frac{R_0^2}{4A^2}\right]$$

$$= \frac{(3)(2500)(\cancel{\pi})(8.25)^2}{2\cancel{\pi}(6.625)^2}\left[1 + (1+.3)\overset{.6526}{\ln\frac{13.625}{8.25}} - (1-.3)\overset{.06416}{\frac{8.25^2}{4(13.625)^2}}\right]$$

$S = 9237$ PSI

J2

FROM ROARK P. 195 #3 - STRESS DUE TO GASKET FORCE -

AT $R < R_0$ $S_R = S_T$

$$S = \frac{3W}{2\pi t^2}\left[\tfrac{1}{2}(1-\mu) + (1+\mu)\,\mathrm{Ln}\frac{A}{R_0} - (1-\mu)\frac{R_0^2}{2A^2}\right]$$

$$= \frac{3(105292)}{2\pi(6.625)^2}\left[\overset{.35}{\tfrac{1}{2}(.7)} + (1.3)\,\mathrm{Ln}\overset{.6526}{\underset{.97056}{\frac{13.625}{8.25}}} - .7\overset{.03209}{\frac{8.25^2}{2 \times 13.625^2}}\right]$$

S = 1112 PSI

MAX BENDING STRESS = 9237+1112 = 10349 PSI

SHEAR STRESS = $\frac{7471}{6.625}$ = 1128 PSI

THE ABOVE BENDING STRESS ASSUMES A NEGLIGIBLE THICKNESS TO RADIUS RATIO WHICH IS NOT TRUE IN THIS CASE. CORRECTING FOR THIS RATIO, (SEE: HANDBUCH DER PHYSIKALISCHEN UND TECHNISCHEN MECHANIK VOL. 3 P. 170) THE STRESS BECOMES -

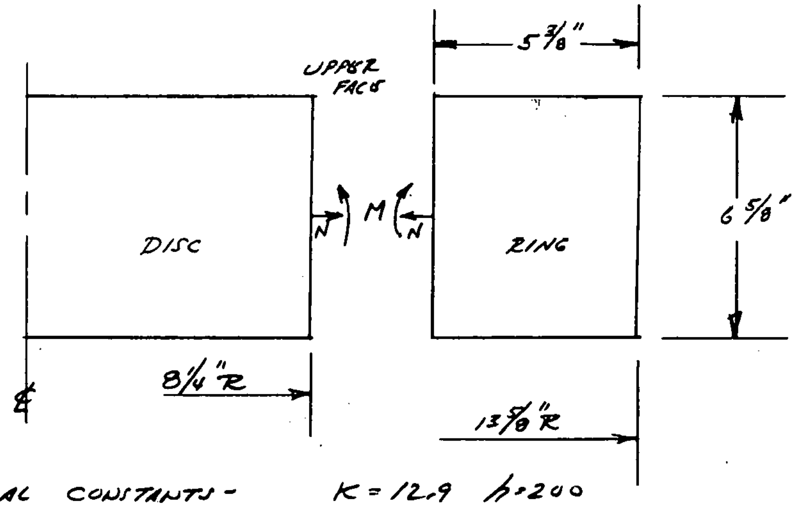
$$S_{MAX} = S\left(1+.0923\frac{t^2}{R^2}\right) = S\left(1+.0923\overset{.0218}{\frac{6.625^2}{13.625^2}}\right) = 1.0218\,S$$

INNER (LOWER) FACE S = 10575 PSI C

OUTER (UPPER) FACE S = 10575 PSI T

30 MW STEAM GENERATOR
MANHOLE COVER - THERMAL STRESSES

THE MAXIMUM BENDING IN A PLATE OF THIS THICKNESS OCCURS APPROXIMATELY 5 MINUTES AFTER A SUDDEN CHANGE IN FLUID TEMPERATURE. TAKING THE TRANSIENT TO BE A 400°F SUDDEN DROP FROM 1050° TO 650°F, THE TEMPERATURES ARE AS GIVEN IN TABLE BELOW.



PHYSICAL CONSTANTS - $K = 12.9$ $h = 200$

$$N_{Bi}^{-1} = \frac{12K}{h\mathrm{I}} = \frac{(12)(12.9)}{(200)(6.625)} = .117 \text{ (USE .100)}$$

$$N_{Fo} = \frac{.0066t}{\mathrm{I}^2} = \frac{.0066(300)}{(6.625)^2} = .045$$

POINT	ΔT	MOMENT
0	.001	.00005
.1	.001	.00008
.2	.004	.00028
.3	.010	.00060
.4	.025	.00150
.5	.055	.00275
.6	.110	.00440
.7	.203	.00609
.8	.342	.00684
.9	.529	.00529
1.0	.757	.00095
Σ		.02883
M_N	.164	.08200
M		.05317

$$\Delta T = \frac{6M}{t^2} = \frac{6(.05317)}{(1)^2}$$

$$\Delta T = .31962$$

$$\Delta T = .31902 \times 400 = 128°F$$

J4

TO SIMPLIFY THE CALCULATIONS ASSUME THAT THE COMPUTED GRADIENT IS AS GIVEN IN THE TABLE & EXTENDS OUT TO GASKET, & BEYOND THE GASKET NO TEMPERATURE CHANGE HAS OCCURRED. THIS IS AN EXTREME TEMPERATURE CONDITION TO ASSUME & IF THE STRESSES ARE UNREASONABLE CORRECTIONS WILL BE MADE TO GIVE A MORE REALISTIC TEMPERATURE PICTURE.

DISC –

FREE SLOPE = $\frac{\alpha \Delta T}{t/2} = \frac{(11.1)(10^{-6})(128)(2)}{6.625} = 429 \times 10^{-6}$

INCREASE IN RADIUS $= \Delta R^{\circ} = -(11.1 \times 10^{-6})(8.25)(.164)(400) = -6007 \times 10^{-6}$

FROM ROARK P.197 #12 –

$$\Theta = -\frac{12(1-\mu)MR}{Et^3} = \frac{(12)(.7)(8.25)M}{23\times10^6\,(6.625)^3} = -.01036\times10^{-6}M + 429\times10^{-6} \qquad (1)$$

FROM ROARK P.276 # 28

$$\Delta R = \frac{N}{t}\,\frac{R}{E}(1-\mu) = \frac{8.25N}{(6.625)(23\times10^6)}(1-.3) = .03790\times10^{-6}N - 6007\times10^{-6} \qquad (2)$$

RING –

$$\Theta = \frac{12 R_c M_c}{Et^3 \,Ln \frac{R_o}{R}} \cdot \frac{(12)(10.9375)M}{(23\times10^6)(6.625)^3\, Ln \frac{13.625}{\underset{.502}{8.25}}}\;\frac{8.25}{10.9375} = .02949\times10^{-6}M \qquad (3)$$

$$\Delta R = -\frac{N}{t}\,\frac{R}{E}\left(\frac{R_o^2+R^2}{R_o^2-R^2}+\mu\right) = \frac{8.25N}{(23\times10^6)(6.625)}\left(\overset{2.45776}{\frac{13.625^2+8.25^2}{13.625^2-8.25^2}}+.3\right)$$

$$\Delta R = -.13307\times10^{-6}N \qquad (4)$$

$(1) = (3) \quad -.01036\,M + 429 = .02949\,M$

$.04885M = 429 \qquad M = 8782$

J5

$(2) = (4) \quad .03790N - 6007 = -.13307N$

$.17097N = 6007 \quad N = 35135$

BENDING STRESS $= \dfrac{6M}{t^2} = \dfrac{(6)(8782)}{(6.625)^2} = 1201$ PSI C ON TOP
T ON BOTTOM

RADIAL STRESS $= \dfrac{N}{t} = \dfrac{35135}{6.625} = 5303$ PSI T

COMBINED STRESSES

$S = 5303 \pm 1201 =$ 4102 PSI T ON TOP
6504 PSI T ON BOTTOM

RESIDUAL STRESS – THE MAXIMUM RESIDUAL STRESS IS AT THE LOWER SURFACE, THE RESIDUAL BEING THE RESULT OF THE DIFFERENCE BETWEEN THE LINEARIZED TEMPERATURE & THE TRUE TEMPERATURE AT THE LOWER SURFACE.

$$S_{RES.} = \frac{E\alpha\Delta T}{1-\nu} = \frac{(11.1)(23)}{.7}\left[.757\times400 - \overset{109}{(.164)(400)} - 128\right]$$

$S = 39754$ PSI T

THE MAXIMUM STRESS AT THE LOWER SURFACE BECOMES –

$S_{MAX} = 6504 + 39754 = 46258$ PSI T

AT THE UPPER SURFACE THE RESIDUAL IS

$$\frac{(11.1)(23)}{.7}\left[-(.001)(400) - \overset{62}{(.164)(400)} + 128\right] = 22612 \text{ PSI T}$$

AT THE UPPER SURFACE THE TOTAL STRESS IS –

$4102 + 22612 = 26714$ PSI T

J6

30 MW STEAM GENERATOR
MANHOLE COVER - STRESSES
SUMMARY

	PRESSURE STRESS	THERMAL STRESS	TOTAL PSI
UPPER SURFACE	10575 T	26714 T	37289 T
LOWER SURFACE	10575 C	46258 T	35683 T

@ 650F THE ALLOWABLE FOR 500 CYCLES IS ± 66000 PSI
& FOR 2500 CYCLES IS ± 45000 PSI

J7