COMPUTERIZED THERMAL INPUT FOR STEAM GENERATOR STRESS ANALYSIS

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SUMMARY

In order to perform structural analyses of the CRBRP steam generators which include the effects of various system thermal hydraulic transients, detailed thermal profiles must be developed and transmitted to the stress analyst in a usable form. A unique, semi-automated computer system has been developed to optimally accomplish this task.

The transient data are given in the specification in the form of sodium and water (steam) flow, temperature and pressure at the inlet of the steam generator as a function of time. The transients occur over a period of one to two thousand seconds. The steam generator is divided into fourteen distinct zones each consisting of several subzones. As a result, masses of thermal data must be generated to provide temperature distributions in each subzone as a function of time.

A simplified nodal model of the entire steam generator is used to translate the specification transient data into boundary conditions for the detailed subzone models. This is accomplished by the SETS (Superheater-Evaporator Transient Simulation) program. The data are stored on tape and selected parameters are machine plotted as CRT output.

A one to one correlation between the stress and thermal models has been set up to enhance accuracy and simplify data transmittal. The stress analyst develops a finite element model to the degree of detail required by the MARC computer code. The same basic nodal model is used for thermal analysis. Nodes are added to this model to include adjacent structures or boundary conditions which are not included in the stress model. Thermal model development is accomplished using STAMP (Stress to Thermal Adaption Model Program). The output (network admittances, form factors, nodal volumes, and convection surface areas) is then combined with the appropriate heat transfer parameters and boundary nodes to complete the thermal model.

Thermal analysis is then accomplished using a finite difference code — TAP (Thermal Analyzer Program). The SETS tape is used to provide the boundary conditions, and the resulting nodal temperatures are stored on tape. Significant temperatures and temperature differences are output on CRT. Isotherms are also output at selected times. These data are used as visual scans to scope possible stress problems. TEMPOS (Temperature Postprocessor) is then used to extract the thermal data from tapes and present the results in such a manner that the maximum stress intensity range may be calculated. The thermal distributions at selected times are fed into the corresponding stress models and stress intensities are calculated.

This method has enabled very rapid analyses of complex thermal stress problems. For scoping purposes, simplified models have been used to determine the worst transients thus minimizing detailed analysis. The method has also permitted rapid analysis of the effect of design changes. While the method was developed for steam generator analysis, it is being applied, in full or part, to thermal stress analysis of other components resulting in significant engineering cost and time savings.

1. INTRODUCTION

The steam generators in the Clinch River Breeder Reactor Plant (CRBRP) are the basic heat removal elements in the overall system. Since all reactor systems are subject to power swings, both by intent and accident, the steam generators are subjected to a variety of transients. Flow and temperature variations of both the heat carrying fluid (sodium) and the heat removal fluid (water/steam) have been calculated for different plant operating conditions by the overall plant contractor — Westinghouse Advanced Reactor Division (WARD) — using a simplified plant model.

Approximately 100 different plant transients have been identified by WARD covering normal, upset, emergency and faulted events. To reduce the number of analyses required by the steam generator supplier, Atomics International (AI), these plant transients have been umbrellaed into 36 steam generator transients by the steam generator system contractor, General Electric (GE).

Considering approximately 18 zones of interest (Figure 1) in the steam generator unit (which can be used either as an evaporator or superheater) and the 36 umbrellaed transients, it was seen that a formidable analytical task would be required to insure structural integrity of the units. During the preliminary design phase, the computerized system of thermal/stress analysis described herein was instituted to simplify this task. It has continually been modified and improved to the point where it is readily adaptable to any system/component requiring thermal input for stress analysis.

2. STEAM GENERATOR OPERATIONAL CHARACTERISTICS

The plant heat transport systems each consist of a primary heat transfer system, an intermediate heat transfer system and a steam generator system. Three systems are used to attain the required plant capacity using a single reactor. The unplanned plant transient events can be generated by reactor trips, pump failures in any or all subsystems, pipe breaks, etc.

2.1 Steam Generator System Description

The steam generator system, shown in Figure 2, operates with an intermediate steam drum between two evaporators and a single superheater. Steam leaves the evaporators at about 60% quality. Saturated steam is separated in the drum to provide superheater input. The superheater output is used to drive turbogenerators. A recirculation ratio of 2:1 returns half the evaporator output to the evaporators; the other half is made up by feedwater. The total sodium flow passes through the superheater and is then split equally between the two evaporators.

The steam generators are shell and tube heat exchangers of the AI "hockey stick" design. The 90° bend in the tubes takes up differential thermal expansion. Sodium flow is through the straight cylindrical section only. The sodium in the hockey stick is essentially stagnant with a small vent flow used for leak detection. An auxiliary relief system is provided to accommodate a very unlikely major sodium-water reaction.

2.2 Transient Characteristics

The 36 transients analyzed are divided into normal, emergency, upset and faulted events. For each of the transients, the steam generator equipment specification defines boundary parameters as a function of time for the superheater and the evaporator. These include sodium and water/steam flow rates and inlet temperatures and pressures. The boundary parameters arè used to calculate the steam generator structural and fluid temperature distribution.

Normal transients include controlled events, such as heatup or cooldown of the system, startup and shutdown, load swings, etc. The nature of these transients is generally mild, and therefore, they do not cause excessive thermal gradients in the structure. However, the frequency of occurrence of some of the normal transients throughout the life of the units is relatively high. This factor is evaluated by the stress analyst.

Upset, emergency and faulted events are generally uncontrolled, resulting in steep changes in the boundary parameters. A typical upset condition is illustrated in Figure 3. The majority of these transients show an initial increase of the sodium inlet temperature from about 950 to 1000° F, followed by a decrease to about 600° F. Steam/water temperatures tend to follow the sodium temperature. In some cases these conditions are reversed. The steep fluid temperature ramp rates and substantial changes in temperature levels cause extremely severe thermal gradients in the structure. The thin wall waterside structure responds rapidly to the temperature change. The massive pressure boundary structures on the other hand respond very slowly.

2.3 Structural Considerations

The Steam Generators are structurally evaluated for the effects of thermal gradients in accordance with the ASME Boiler & Pressure Vessel Code, Section III, "Nuclear Power Plant Components,"[1] Supplementary Elevated Temperature Criteria Code Case 1592-4, [2] RDT Supplements F9-4, [3] and E15-2NBT.[4] At elevated temperatures, consideration is given to creep effects. The code considers secondary stresses such as those induced by thermal gradients or which occur at geometric discontinuities. Secondary stresses are always evaluated in combination with primary stresses, whereas primary stresses have independent mandatory limitations.

One of the perplexing problems facing the stress analyst is determining stress intensity extremes during one or more transients in order to assess code requirements. While it is theoretically possible to calculate the thermal stress at every time slice for various locations, in practice it is economically unfeasible since the inherent nature of the governing heat transfer equations requires small time steps to yield a stable solution. An alternative is to seek out the time when certain thermal stress indicators are at extreme values, e.g., nodal temperature differences, nodal linearized temperature differences, and bulk temperature differences. It is reasonable to expect that the extreme values of the thermal stress and that of the time parameters happen near the same time slice at a specified location. Therefore, this alternative technique was adopted for the computerized system and the code TEMPOS was prepared to do the searching.

3. ANALYSIS METHODOLOGY

The major objective of the computerized system is to simplify the analysis to the greatest extent possible. Therefore, the system was set up to permit a maximum of screening techniques. This involves the use of simplified models, tape searching and graphical output with examination of intermediate results prior to taking the next step in the overall analysis.

3.1 Thermal/Stress Interfacing

Figure 4 shows the interfacing between thermal and stress analysis. The modeling is initially set up by the stress analyst since a finer nodal breakdown is normally required for stress work. However, the thermal analyst is consulted frequently during this phase to insure model compatibility.

Simultaneously, a simplified model is set up with a network only as fine as is required to obtain rough approximations of both thermal and stress distributions. These simplified models are used to screen the transients using the boundary conditions calculated by the SETS Code. In this manner, the analytical effort is limited to a few transients with a high degree of assurance that the maximum stresses which the component will experience will be evaluated.

The thermal model is then developed using the STAMP Code. Nodes are added to the stress model as required to represent heat sinks, heat sources and flowing fluids. The TAP Code is then used to calculate temperature distributions based on the boundary conditions stored on tape from SETS runs. The resultant histories are stored on tape for use by the stress analyst. CRT plots of nodes of interest are also generated to provide visual inspection. Isotherm plots are also developed. A subsidiary code, CONGO, is available to read tapes and provide plots of nodes not originally selected if this is deemed necessary after the visual inspection.

At this point the stress analyst has all the thermal data required. A tape editing code, TEMPOS, is used to search the TAP output tape to determine the time at which maximum thermal gradients occur. The MARC or APSA Code is then used to calculate thermal stresses which are combined with mechanical loads to determine combined stresses. The output, both graphical and printed, is then evaluated. If stress levels exceed allowables, design changes are made to alleviate the problem and the process is iterated by a revision of the original model.

3.2 Transient Screening

An attempt at grouping the transients to enable the analysts to assess the potential impact of the transient groups in each of the 18 major structural zones analyzed was unsuccessful. The high number of boundary conditions and their complex relationship made it extremely difficult to go beyond an overall assessment of the transients and their effect on the structure. Therefore, a method was devised to screen, rank and select the most severe transients for detailed analysis.

The method developed consisted of setting up simplified thermal and stress computer models representing each of the structural zones. A typical simplified model is shown in Figure 5. These models are relatively inexpensive to set up and run on the computer. All 36 transients were analyzed using the simplified models. The results were used to rank and select the most severe transients for each zone. The selected transients were then analyzed in the detailed thermal and stress computer models. Excellent agreement was obtained between the results of the simplified and detailed models, substantiating the adequacy of the screening method.

4. DESCRIPTION OF CODES USED

The codes used in the system described are, in the most part, AI generated or AI modifications of adopted codes. The following descriptions are brief and primarily describe the function of the code with a simple description of the methods involved. All the codes have been verified by comparison of solutions to analytical problems or equivalent codes.

4.1 Thermal Analyzer Program (TAP)

The TAP Code is an AI proprietary code. It is a general, finite difference, lumped parameter code which can be used to solve steady-state or transient problems for any physical system which can be represented by an equivalent electrical network. Its primary application is in the solution of heat transfer problems.

A network is set up as data input to the program representing the physical system. The equations used in the analysis are built into the code and are called in the order required by use of "key" data input. Special equations may also be input. The program includes a variety of auxiliary functions. For example, thermal radiation paths between elements of the network are computed automatically if the surface areas and effective view factors are given. Conductances, capacitances, internal heat generation rates, and boundary temperatures may be either fixed values, tabular functions, or algebraic functions of any other parameter in the system. This makes possible the solution of problems involving variable material properties, phase changes, ablation, variable fluid flow, etc. It also makes possible the simultaneous solutions of temperature distributions, mass distributions, and thermal stresses in a body.

The method used to compute temperatures is to treat each time increment as a steady-state solution at an average temperature. A heat balance is attained such that the heat into a node equals the heat out plus the heat absorbed to change temperature. The solution is necessarily iterative; the accuracy is dependent on the convergency criteria used and the linearity of the transient. The code is extremely flexible in output and is easily modified for special applications by adding subroutines.

4.2 Stress to Thermal Adaptation Model Program (STAMP)

STAMP is a digital computer program which generates a two-dimensional thermal model using stress model data. The input data consist of a deck of cards defining the model nodal coordinates and material thermal properties. Most of the input is taken directly from the stress model, which uses the stress analyzer MARC-IBM or APSA Code. The thermal analyst then adds the boundary and structural nodes required to complete the thermal network, and the thermal properties.

The STAMP program output consists of punched cards which form the bulk of the input data required by the TAP Code. These cards provide data that define the thermal network, node coordinates, element volumes and surface areas, and conductance form factors. STAMP also generates CRT mosaic sketches depicting the model geometry which is used to verify that the modeling is correct.

4.3 Superheater - Evaporator Transient Simulation(SETS)

The SETS Code is primarily a network developed for input to the TAP Code previously described. The only change made to the basic TAP Code was a revision of one subroutine to account for the two phase water characteristics of the evaporator.

Figure 6 shows the network used. A single tube representation is adequate since the flow distribution through the bundle is quite uniform. Since SETS is used to determine boundary conditions, lumping the shroud, shell and stagnant sodium nodes is also an adequate representation. The heat into the node due to convection is based on the average of the upstream and downstream nodes. This increases accuracy and is the reason for the staggered connection between tube and fluid nodes.

4.4 Conversion of Numerical to Graphical Output (CONGO)

CONGO is a plotting program which was created to obtain CRT plots beyond the capability of SETS and TAP. Presently, these two programs can generate up to 5 CRT plots (20 curves) of any parameter being calculated. CONGO can provide up to 20 plots

(120 curves). In order to use CONGO, it is only required that the SETS or TAP output be stored in magnetic tape.

CONGO can perform operations with the data being read and calculate and plot the results. Examples of the output CRT plots of the program are nodal temperatures, arithmetic average of nodal temperatures, capacitance weighted bulk temperatures, temperature differentials, etc. The CRT plots are similar to those generated by TAP and SETS.

4.5 Temperature Post Processing (TEMPOS)

TEMPOS was developed to search the nodal temperature history data tape for the time slices when any one or any combination of the following temperature parameters is maximized or minimized:

1) The linear temperature gradient across a specified section
2) The temperature difference between specified nodal pairs
3) The thermal capacitance weighted average bulk temperature difference of pairs of adjoining regions.

These three parameters serve as a guide for selecting the time-temperature distribution at which the thermal stress is to be calculated during the transient.

Since the node temperature data tape is not directly usable to the stress analysis program (MARC-IBM or APSA), TEMPOS generates an element temperature data tape compatible with the stress analysis program input requirements. The program also has the options of plotting the temperature parameters as a function of time throughout the transient, punching a card deck of element temperature data at selected time slices and checking and printing the input tape data at specified nodes.

4.6 MARC-IBM/APSA

Both MARC-IBM and APSA are general purpose stress analysis codes. The MARC-IBM is a qualified three-dimensional nonlinear finite element computer program and may be used for elastic and inelastic analysis. The program contains general three-dimensional beam elements, plane isoparametric elements (plane stress and plane strain), axisymmetric constant strain element, axisymmetric isoparametric elements, doubly-curved shell element, curved pipe element and plane or axisymmetric isoparametric two-dimensional heat elements.

The code includes cyclic thermal and mechanical loads analyses capability with the optional use of isotropic hardening or Prager's kinematic hardening in full stress space. It can include primary and secondary creep response using a time-hardening or strain-hardening basis. This code allows the user to input his own creep formulation. Interim constitutive equations for 2-1/4 Cr - 1 Mo ferritic steel received from Oak Ridge (ORNL) have been programmed at AI in anticipation of performing inelastic analysis. Arbitrary histories for mechanical and thermal loadings can be applied.

APSA is an AI developed, two-dimensional axisymmetric, finite element computer program and may be used for elastic or elastic - plastic analyses. For the steam generator application, only elastic analysis is performed since the proper constitutive equations for the 2-1/4 Cr - 1 Mo ferritic steel have not yet been coded. The program allows for orthotropic, temperature-dependent material properties under thermal and mechanical loads. Both MARC-IBM and APSA provide visual displays of the finite element results. Contour plots, grid plots and graphical plots of stresses and strains can be obtained.

5. TYPICAL ANALYSIS

In order to illustrate the implementation of the system, a typical example — analysis of the superheater upper tubesheet — will be described from the generation of the stress model through the results of the stress analysis.

5.1 Stress Model

The axisymmetric finite element stress model of the superheater steam outlet includes the tubesheet, steam head studs and cylindrical and conical shells (Figure 7). The model is extensive and contains 1102 nodes and 988 elements. During thermal transients, there are very small axial and radial gradients in the central portion of the tubesheet since the ligaments respond very quickly to the steam temperature. Consequently, a relatively gross modeling of this section of the tubesheet was required. A finer mesh was prepared at the outer perforations, outer rim and sodium side fillet where maximum stress intensities were anticipated.

The perforated tubesheet was considered a homogenous material with adjusted Young's Modulus of Elasticity and Poisson's Ratio to account for reduced stiffness in accordance with the procedure of Appendix A-8000 of the Code. The effect of the holes on the stresses is determined by applying stress intensification factors to the calculated stress components.

Stud holes in the tubesheet rim and steam head were modeled as rings with special anisotropic material properties which provided zero hoop capability. The studs were overlaid on the tubesheet/steam head and connected at appropriate nodes to provide the shear reaction in the rim and bearing loads in the steam head. A preload may be simulated in the studs by proper adjustment of the coefficient of expansion or the input of a special temperature differential.

5.2 Thermal Model

Figure 7 illustrates the simplicity of adding nodes to the stress model to form a total thermal model. On the steam head side of the tubesheet it is only necessary to add a single node representing the steam flow. On the sodium side, it is necessary to add a significant number of nodes to represent the stagnant sodium in the annulus around the tube bundle and the steel baffles protecting the tubesheet. This is necessary since significant thermal gradients occur across these elements, thus, directly affecting the shell and tubesheet thermal response. A single node is sufficient to describe the tube bundle and sodium within the shroud since this area is essentially isothermal at any given time. Note that the exterior is considered adiabatic since the heat loss through the insulation is small and this treatment adds a small amount of conservatism.

5.3 SETS Output

The SETS output consists of the steam generator internal boundary conditions which are imposed on the detailed TAP models of the structural components. For each of the zones in in which the steam generator SETS model is divided, the internal boundary parameters: (water/steam and sodium temperatures heat transfer coefficients, water/steam pressures and quality, and bulk metal temperatures) are calculated. A typical output is presented in Figure 8. Key parameters which are input are also plotted with the calculated parameters to facilitate checking the program results. Figure 8 shows SETS results plots for some of the major steam generator zones.

5.4 TAP Output

Figure 9 shows the time variant temperature response of various nodes in the model. These nodes have normally been preselected by the stress analyst such that by simple inspection of such a graph, significant temperature gradients can be readily detected, thus assisting in the overall analysis of the stress results. This output is also quite helpful in determining the areas requiring design changes to reduce excessive gradients.

Figure 10 shows isotherms across the model. The particular example shows the result of a sodium inlet temperature down ramp with steam flow continuing through the unit. The large mass of metal in the tubesheet rim has responded slowly resulting in a significant radial temperature gradient. The perforated section responds rapidly. This combination results in high ligament stresses and the isotherm plot again assists the analysis in the same manner as the time temperature plots.

5.5 MARC/APSA Output

Figure 11 is an APSA plot of isostress intensity contours. The transient used for this analysis was an inadvertent opening of the relief valve on a superheater resulting in a relatively mild transient. Figure 12 is a similar plot in three dimensional format. These plots are helpful in locating the region of maximum stress. However, stress values selected for decomposition and manipulation for code requirements are taken from the printed output at present. Since the data are stored on tapes, additional add-on programs may be written to perform the necessary steps for Code comparisons or other purposes.

6. GENERAL APPLICATION OF TECHNIQUE

While the description of the technique in this paper centers on analysis of a sodium heated steam generator using codes in the most part unique to AI, the principles can be applied to the analysis of any piece of equipment subject to thermal stresses. Typical nuclear plant components to which the technique could be applied include reactor structures, pumps, heat exchangers, storage vessels, and cold traps. Certain elements of the technique such as the simplified model screening and the SETS analysis may or may not be required.

The primary objectives of the technique — rapid, computerized transfer of data between steps, minimization of duplication of effort by stress and thermal analysts, capability of handling massive amounts of data with a minimal chance of error and ease of iterating on design changes — can be met by any compatible set of programs properly linked by tape and card input and output.

REFERENCES

1. "Nuclear Power Plant Components," ASME Boiler and Pressure Vessel Code, Section III, Division I, Class 1, American Society of Mechanical Engineers, 345 East 47th Street, New York, N. Y. 10017

2. "Class 1 Components in Elevated Temperature Service," Cases of ASME Boiler and Pressure Vessel Code, Case 1592-4, American Society of Mechanical Engineers, 345 East 47th Street, New York, N. Y. 10017

3. "Requirements for Construction of Nuclear System Components at Elevated Temperatures," RDT F9-4T, RDT Standards Office, Oak Ridge National Laboratory, Post Office Box X, Oak Ridge, Tennessee 37830

4. "Class 1 Nuclear Components," RDT E15-2NBT, RDT Standards Office, Oak Ridge National Laboratory, Post Office Box X, Oak Ridge, Tennessee 37830

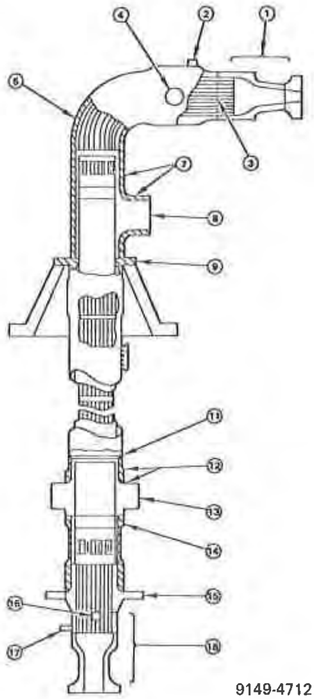

Figure 1. Steam Generator Unit

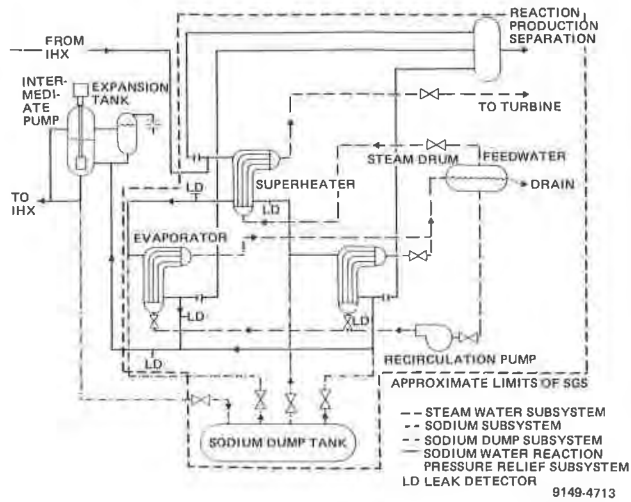

Figure 2. Steam Generator System

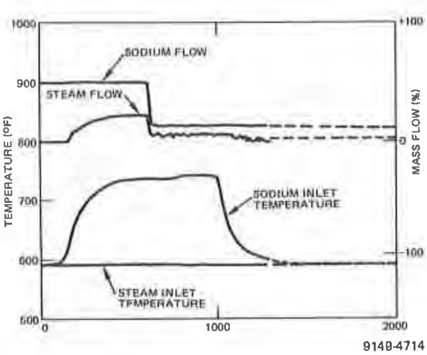

Figure 3. Typical Transient Data

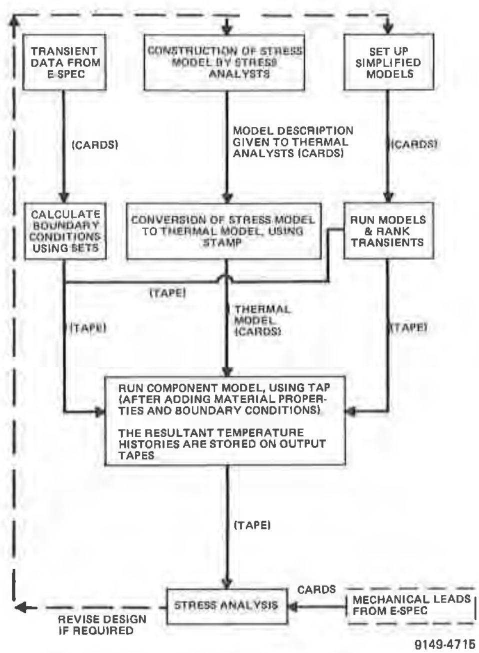

Figure 4. Procedures in Analyzing the Components

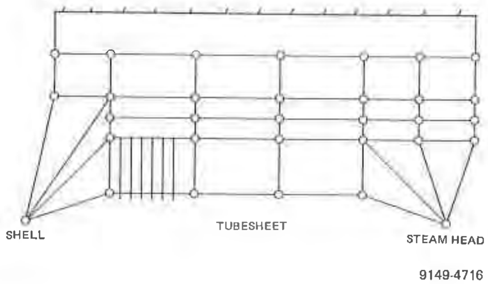

Figure 5. Typical Simplified Model

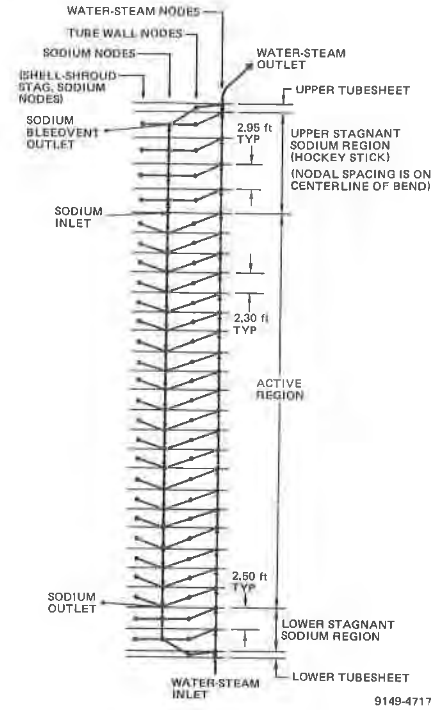

Figure 6. SETS ~~Nodal Geometry Description~~

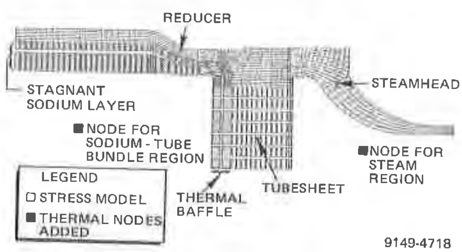

Figure 7. Typical Thermal/Stress Model

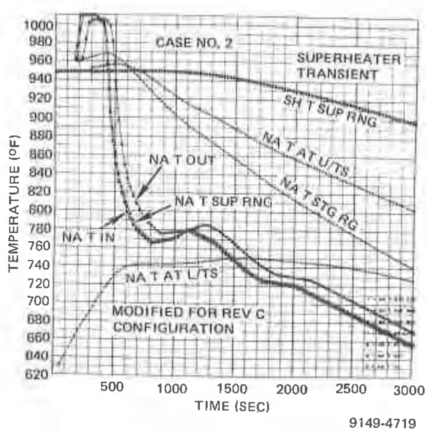

Figure 8. Typical SETS Output

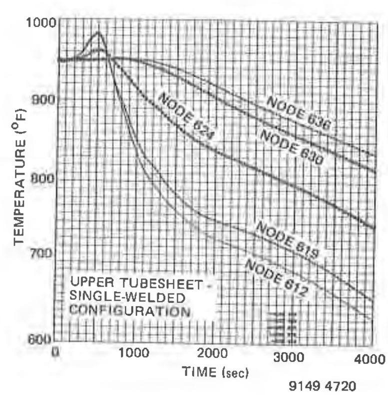

Figure 9. Typical TAP Temperature Profile

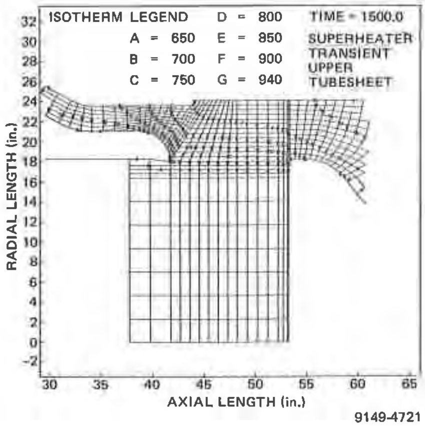

Figure 10. Typical TAP Isotherm

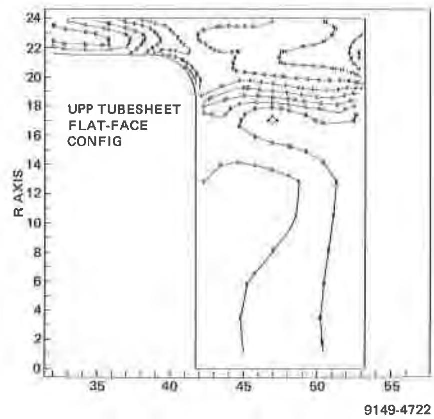

Figure 11. Typical 2D Stress Intensity Plot

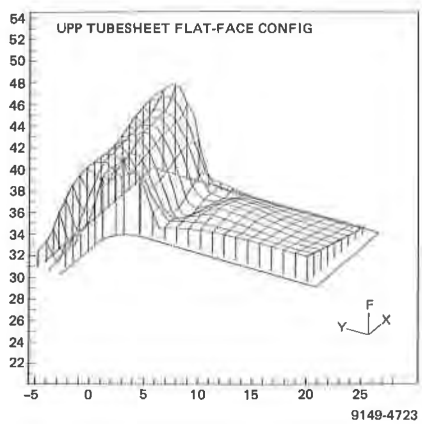

Figure 12. Typical 3D Stress Intensity Plot