Nonlinear Thermal Analysis, Stress Analysis and Code Verification of SNR-300 Heat Exchanger Nozzle and Suspension Structure

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Abstract

The intermediate heat exchanger between the primary and the secondary sodium loop of the German SNR-300 fast breeder facility is connected with a degasification pipe and a suspension structure for transportation. The distribution of temperatures and stresses have been analysed for a variety of thermal and mechanical transients. The structural integrity was investigated by code verifications including primary and secondary stress, progressive deformation and fatigue analyses.

1. Introduction

The present analyses refer to an intermediate heat exchanger between the primary and the secondary sodium loop of the German SNR-300 fast breeder facility. A large number of normal and accidental high temperature transients must be considered for structural integrity of the sodium boundary and components. In this particular case a nozzle of the degasification pipe and a suspension structure for transportation have been analyzed. These structures were analysed by MOTOR-COLUMBUS Consulting Engineers Inc. under a contract from NERATOOM.

The distribution of temperatures and stresses are considerably influenced by complex heat transfer mechanisms between the vessel wall and the sodium. Temperature dependent heat transfer properties of the structural steel must be represented since temperature gradients of more than 100 ^{o} C may occur. Furthermore, these temperature gradients require a representation of temperature dependent mechanical properties for the analyses of deformation and stress.

The nozzle and suspension structures are connected eccentrically to the heat exchanger so that three-dimensional computational models are necessary for the accurate representation of temperature and stress fields (see Fig. 1 and 2). The ANSYS Finite Element computer program has been used for these large size time dependent thermal analyses. Due to the extraordinary high bandwidth of the system of equations, the NASTRAN Finite Element program has been more suitable for the stress analysis on the computer available.

The code and design specification verification procedure required basically the following steps:

- Reduction of approximately 100 transient or steady state thermal load cases to 5 transient and some steady state load cases.
- Selection of critical time points with respect to extreme stresses for every transient.
- Superposition of thermal and mechanical stresses. Approximately 40 basic loads yielded about 80 load combinations.
- Separation of stresses according to the ASME-Code Section NB into membrane, bending and peak stresses.
- Verification of stresses in accordance with the
  . ASME-Code Section NB
  . Code Cases 1331-4 and 1331-6 of ASME
  . SNR-300 design specifications

  For this purpose, a computer program ABSI has been developed by MOTOR-COLUMBUS Consulting Engineers Inc.

2. Heat Transfer Mechanisms

The surface heat transfer coefficients have been computed in accordance with the following relations (see Fig. 1 and 2):

= Nu * l/D: Heat transfer coefficient

for region 1: $Nu = b_1 + c_1 \cdot (Pe) \exp d_1$

for regions 2 and 3: $Nu = b_2 + c_2 \cdot (R * Pe) \exp d_2$

with:

Nu = Nusselt number
l = Conductivity of sodium
D = Hydraulic diameter
R = Function of E and Pr
b, c, d = Constants
Pe = Peclet number, function of l and M
M = Mass flow, time dependent
Pr = Prandtl number
E = Eddy diffusion

This means that the heat transfer coefficients depend on sodium and wall temperatures and on the sodium mass flow. Furthermore, the steel conductivity depends on the temperatures. This required a nonlinear analysis algorithm for the thermal field calculation.

3. Selection of Critical Time Points

A stress analysis for hundreds of time increments for models of this size is a prohibitive task with respect to computer time and data management. Therefore, temperature criteria have been selected for the determination of time points with extreme stresses. Time points with extreme temperature differences between different locations yield extreme strains and hence extreme stresses.

The following criteria had to be considered:

- Differences between averaged teperatures of different sections
- Differences of temperatures between inside and outside of the shell
- Thermal strains in the whole heat exchanger due to different temperatures in the central tubes and the vessel wall
- Strains due to internal pressure

The thermal differences have been evaluated for a variety of sections in and around the nozzle, the support structure and the intersection of the central tube with the vessel wall, see Fig. 1 and 2. Fig. 4 shows the variation with time of some differences of averaged section temperatures and of inside-outside temperatures.

4. Temperature and Stress Distribution

The temperature and stress intensity distribution for a characteristic time point of one of the transients are shown in Fig. 5 and 6.

5. Verification of ASME and SNR-300 Design Specifications

Due to high temperature (546/520 ^{o} C) in the primary and secondary sodium loops, the requirements of the ASME Code Section III Subsection NB have been extended. The ASME Code Cases 1331-4 and 1331-6 had to be considered.

This means that a temperature dependent curve for the design fatique strength S_a in accordance with the ASME Code Case 1331-4 has to be applied for the evaluation of the cumulative damage. A sample of the fatigue analysis table produced by the program ABSI is shown in Fig. 3.

The effect of creep had to be evaluated in accordance with the ASME Code Case 1331-6. This means that the so called "Use Fraction Requirements" for membrane stress and for membrane plus bending stress had to be evaluated. Specific requirements of the SNR-300 Design Specification for the determination of the allowable stress range were included in the analyses.

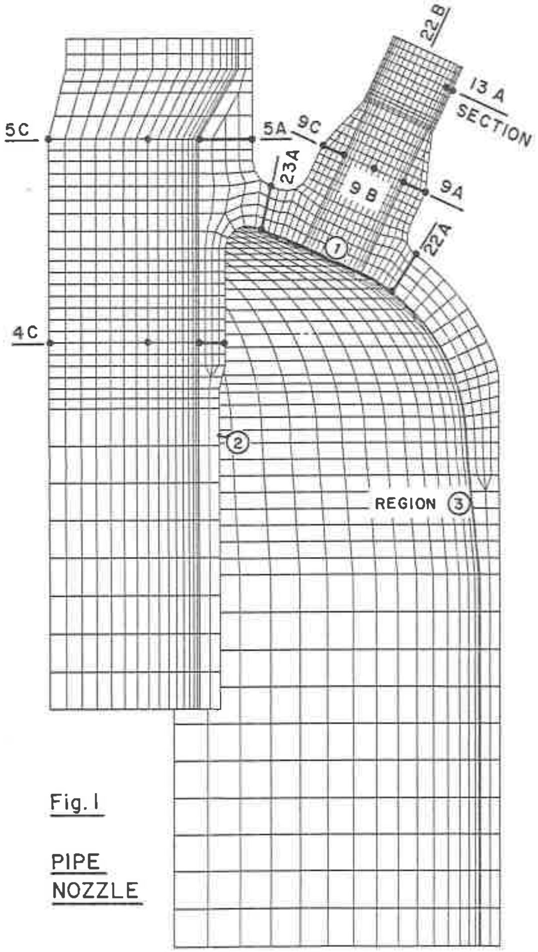

Fig. 1

PIPE NOZZLE

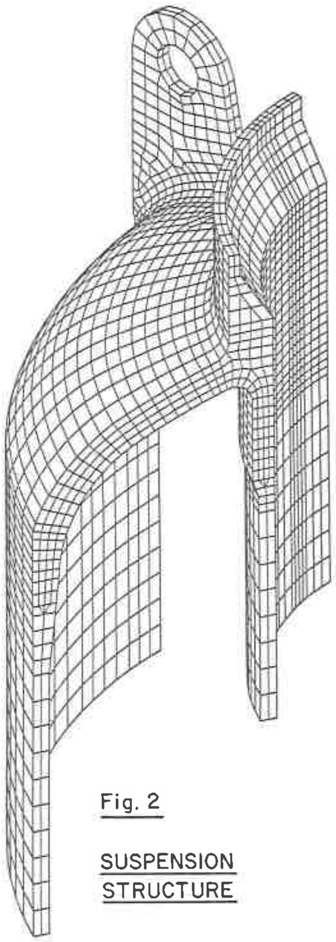

Fig. 2

SUSPENSION STRUCTURE

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FATIGUE ANALYSIS TABLE

FATIGUE ANALYSIS AT SECTION 25, FACE 1

LOAD CASE PAIR I	J	SALT (N/M**2)	OCCURENCES NI	NJ	NUMBER USED	SET ELIMINATED	NO. CYCLES TO FAILURE	USAGE FACTOR
132	81	0.20926E 09	7 0	9436 9431	7	13	2668	0.26237E-02
132	113	0.18646E 09	0 0	260 260	0	13	4055	0.00000E 00
171	132	0.17904E 09	20000 20000	0 0	0	13	4857	0.00000E 00
51	132	0.16611E 09	0 0	0 0	0	5,13	6635	0.00000E 00
132	91	0.13710E 09	0 0	9165 9165	0	13	22833	0.00000E 00
132	112	0.12054E 09	0 0	260 260	0	13	65147	0.00000E 00
112	81	0.89046E 08	260 0	9431 9171	260	11	>1000000	0.26000E-03
91	81	0.72108E 08	9165 0	9171 6	9165	9	>1000000	0.91651E-02
113	112	0.66467E 08	0 0	0 0	0	11,11	>1000000	0.00000E 00
171	112	0.58880E 08	20000 20000	0 0	0	11	>1000000	0.00000E 00
113	91	0.49395E 08	0 0	0 0	0	11, 9	>1000000	0.00000E 00
51	112	0.48144E 08	0 0	0 0	0	5,11	>1000000	0.00000E 00
171	91	0.41946E 08	20000 20000	0 0	0	9	>1000000	0.00000E 00
51	81	0.41212E 08	0 0	6 6	0	5	>1000000	0.00000E 00
51	91	0.31091E 08	0 0	0 0	0	5, 9	>1000000	0.00000E 00
171	81	0.30247E 08	20000 19994	6 0	6	8	>1000000	0.60001E-05

USAGE FACTOR = 0.12055E-01

Fig. 3

TEMPERATURE DIFFERENCES

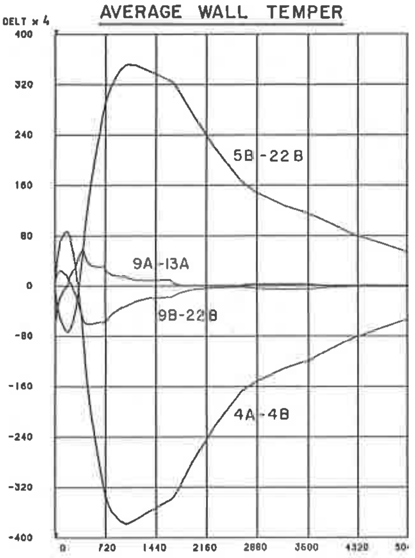

Fig. 4A

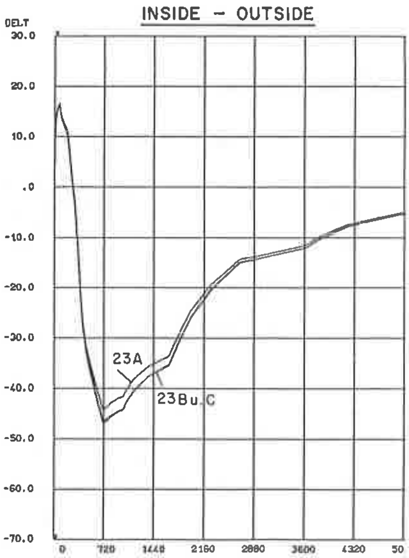

Fig. 4B

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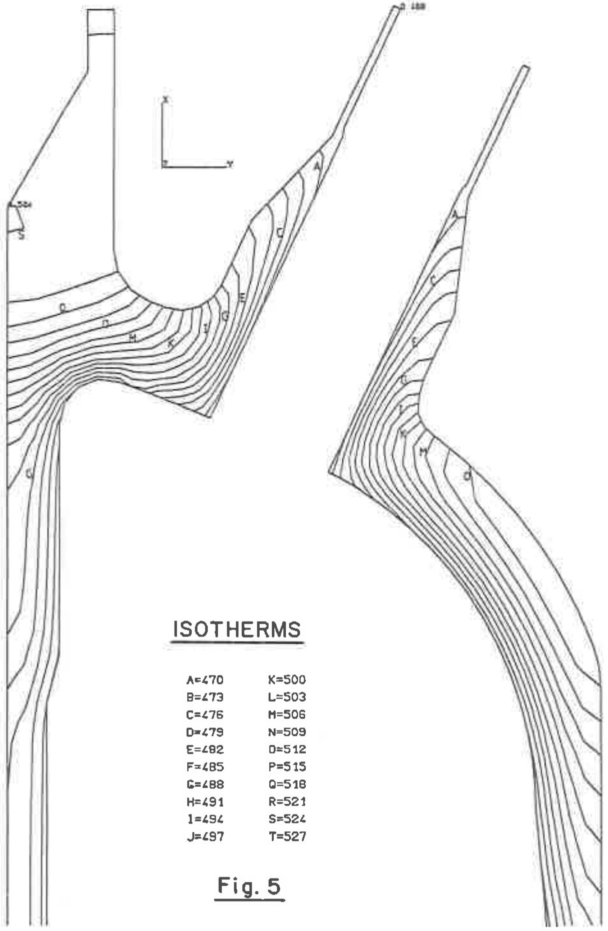

Fig. 5

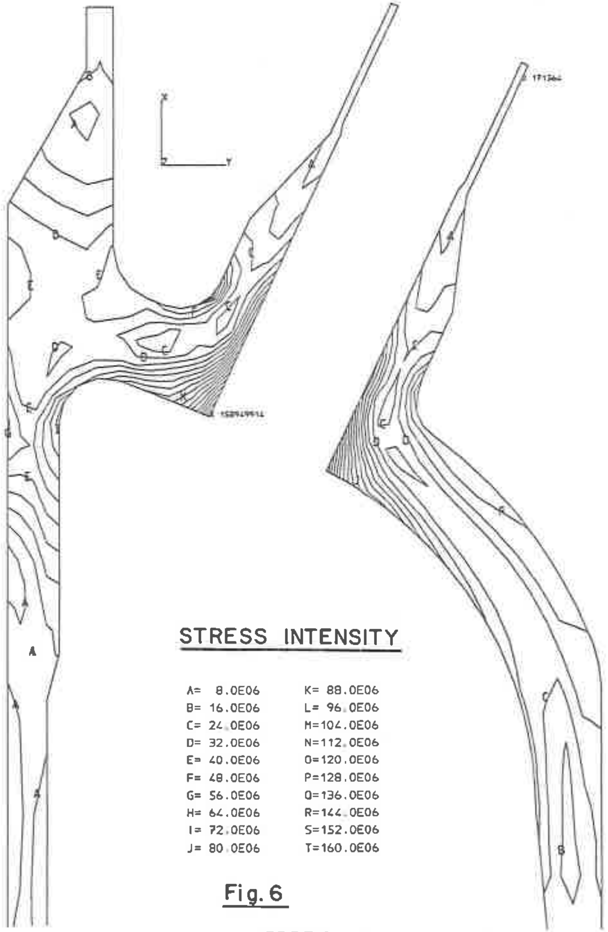

Fig. 6

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