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STRUCTURAL FAILURE ANALYSIS OF REACTOR VESSELS DUE TO MOLTEN CORE DEBRIS

by

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ABSTRACT

Maintaining structural integrity of the reactor vessel during a postulated core melt accident is an important safety consideration in the design of the vessel. This paper addresses the failure predictions of the vessel due to thermal and pressure loadings from the molten core debris depositing on the lower head of the vessel. Different loading combinations were considered based on a wet or dry cavity and pressurization of the vessel based on operating pressure or atmospheric (pipe break). The analyses considered both short term (minutes) and long term (days) failure modes. Short term failure modes include creep at elevated temperatures and plastic instabilities of the structure. Long term failure modes are caused by creep rupture that lead to plastic instability of the structure. The analyses predict the reactor vessel will remain intact after the core melt has deposited on the lower vessel head.

1 INTRODUCTION

The paper addresses the failure prediction of the vessel due to thermal and pressure loadings from molten core debris. The core debris are collected on the bottom head of the reactor vessel. The finite element computer program STRAW was employed to perform structural analyses of common reactor vessels. STRAW (Kulak, et al. 1978) is a nonlinear structural-fluid and thermomechanical finite element program. Structural failure can occur by two mechanisms. They are plastic instability of the structure and creep rupture. Plastic instability occurs through thermal degradation of the elastic-plastic stress-strain response. Essentially the effective stress state becomes larger than the saturation (ultimate) stress. This causes the stress-strain response to become unstable (i.e., equilibrium is unobtainable). Creep rupture is the final stage of a metal material being exposed to a long-time loading of stress at an elevated temperature. Primary and secondary creep are modeled through the creep constitutive relationship. Creep rupture is modeled through a Larson-Miller creep rupture curve (Larson and Miller, 1952) and damage is accumulated through a "life fraction" relationship based on the stress and temperature of an integration point through time in the structure.

2 REACTOR VESSEL MODELS

All analyses of the reactor vessels were axisymmetric. The reactor vessel model includes the cylindrical shell and torispherical lower head which is welded to the cylindrical shell. All penetrations were neglected in the model. A schematic of the vessel is shown in Fig. 1.

A viscoplastic constitutive model for 316 stainless steel was used to model the stress-strain behavior and creep response. The plastic flow behavior of annealed, unirradiated type 316 stainless steel is described by the Voce equation, which has the form of

$$\sigma = \sigma_s - (\sigma_s - \sigma_y)\exp(-\varepsilon_p/\varepsilon_c) \tag{1}$$

where σ_y is the yield stress of fully annealed, unirradiated material; and σ_s is the saturation stress approached by the flow stress σ as ε_p increases and ε_c is a material parameter dependent on σ_s and σ_y. The quantity ε_p is the hardness parameter which is equal to the accumulated plastic strain. Both σ_s and σ_y are temperature and strain rate dependent functions chosen so that at low strain rate, Eq. 1 reduces to the familiar power law of thermally activated creep. Details of these functional dependencies are summarized in the appendix of Dimelfi and Kramer (1980). Above 2500°F the material is assumed to have melted and essentially gives a zero stress response to any strain value. The values of Poisson's ratio equal to 0.3 and coefficient of thermal expansion equal to 11×10^{-6} in/in/°F were used and both are assumed to be temperature independent.

Failure due to creep rupture at various temperatures is given in Fig. 2 for stress levels versus time to rupture. The curve fits are based on creep rupture data by Larson and Miller (1952) for 18-8 Cr-Mo stainless steel. The time to rupture, t(hr) is:

$$t = 10^{\left[(C_1 \log_{10}\sigma + C_2)/T - 20\right]} \tag{2}$$

where σ is the stress level in psi, T is the absolute temperature in °R and C_1 and C_2 are constants dependent on the stress level. Under constant stress and temperature the time to failure can easily be established. However, since most structural elements are not subjected to either constant stress or constant temperature, a creep-rupture damage criteria is needed to predict time to rupture. One method is the "life fraction" rule based on the total life at elevated temperature is independent of all other fractions, thus rupture occurs when

$$\sum \frac{t_i}{t_{Ri}} = 1 \tag{3}$$

where t_i is the time at temperature i and t_{Ri} is the creep rupture time at temperature i. When rupture does occur, the stresses at the integration point are set to zero.

3 LOADING CASES AND RESULTS

A failure analysis of different thermal and pressurizations were investigated. Two thermal load cases were utilized and are obtained from a core melt on the bottom head. The first thermal load case was obtained from nucleate boiling heat transfer on the bottom head. A steady state temperature distribution is obtained in about ten hours (35285 sec) after the melt comes in contact with the bottom head. The temperature distribution is given in Fig. 3. The second thermal load case was obtained from film boiling heat transfer on the bottom head. A steady state temperature distribution is obtained after about 111 minutes. The temperature distribution is based on a heat transfer coefficient of 50 BTU/hr-ft^2-F on the outside of the vessel and is given in Fig. 4. Two pressure cases were considered for each thermal case. The first case is an internal loading of 75 psi based on the operating pressure of the system. The second case is an internal loading pressure of 0 psi assuming a pipe break and thus relieving the internal pressure. Other loadings on the vessel wall include the melt mass and the outer cavity water head. The water level of the cavity is indicated in Fig. 1. The maximum outer water pressure on the reactor vessel is about 8.7 psi at the center of the bottom head. The outer cavity water head is present for the first thermal load case only. In the second thermal load case, a dry cavity was assumed. Nodalization of the reactor vessel model is given in Fig. 5. The model is comprised of thirty-two nodes and thirty-one axisymmetric shell elements. The closure head and upper flange were not modeled because they are in the far-field from potential failure locations. Thus, the top node 32 was assumed to be fixed against translation and rotation. Four different static analyses were performed with a total simulation time of 240 hrs. with 2400 time steps of 360 sec each.

3.1 Thermal Load Case One

Initially the whole vessel is assumed to be at 150 F operating temperature. Mesh displacement plots for load cases 1 and 2 are given in Fig. 6. The dashed lines indicate the original position (undeformed) of the mesh. In both load cases the vessel remains intact up to at least 240 hours. The plastic strains that arise at 240 hours are shown in Fig. 7 for load case 2. The largest plastic strain is about 2.7% at a temperature of 2014°F. At this temperature the failure strain is estimated to be 30%, thus the lower head is plastically stable, and failure of the vessel due to plastic instability will not occur. Steady state thermal conditions were assumed up to 240 hours. In reality the pool will begin to cool after a few hours from the initial formation. As the pool begins to cool, the potential failure of plastic instability in the vessel head will be mitigated.

The vertical displacement of the vessel at the bottom center (node 1 of Fig. 5) is shown in Fig. 8 for both pressures. The displacement plots indicate both primary and secondary creep behavior after a steady state thermal condition is reached at ten hours. An indication of relative failure based on creep rupture is depicted in Fig. 9 for load case 2. This figure shows the creep rupture accumulation based on the stress and temperature history for the vessel. The location of the most critical location is at the bottom center of the vessel at the inner most layer (layer 5, inside of vessel wall). At the end of 240 hours, the layer has used about 35% of its life for load case 2. An estimation of the time to failure of the vessel based on creep rupture can be made at the critical location (i.e. highest creep rupture values). The estimated time to failure for each layer based on the stress levels at ten hours (initial steady state thermal conditions reached) and at 240 hours for load case 2 is given in Table 1. The most significant result is that the stresses have been reduced substantially from ten hours to 240 hours. This occurs due to the stress relaxation of the thermal stresses. From an analyses with large time steps it was found that a conservative value of time to failure could be estimated from the stress levels at 240 hours based on the projected time to failure of the third layer. Thus for load case 2 the time to failure of the vessel would be 1.4×10^{8} hours or about 15,000 years, assuming that the temperature field remains constant. Load case 1 has an estimated time to failure of the vessel of 3.7×10^{8} hours or about 42,000 years. Obviously, the vessel will not fail due to creep rupture, because the pool will have cooled off in this time period.

3.2 Thermal Load Case Two

Initially, the whole vessel is assumed to be at 150 F operating temperature. In both cases, the vessel remains intact up to at least 240 hours. The largest plastic strain is about 1.6% at a temperature of 2062°F which is below the estimated failure strain of 30%, and failure of the vessel will not occur. Load case 3 has an estimated time to failure of 1.9×10^5 hours or about 21 years. Load case 4 has an estimated time to failure of 1.9×10^6 hours or about 216 years.

4 CONCLUSIONS

The reactor vessels were assessed for failure after the molten core had deposited on the lower head of the vessel. Four different load combinations were analyzed. The results of the analyses indicate that the vessel would survive for each loading case. Some slight damage to the vessel wall would occur near the centerline of the bottom head, but structural integrity would remain. Currently the STRAW finite element scheme does not include the possible effects of chemical attack of the vessel wall from the core melt. Dissolving of the vessel wall could easily reduce the time to structural failure of the vessel.

ACKNOWLEDGMENTS

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Table 1. Load case 2 rupture times

Layer	Stress (psi)	Temperature (°F)	Life Fraction	Time to Rupture (Hr)
Values at 10 Hours				
1	42641	300	0.0000	5.7×10^{24}
2	6476	644	0.0000	1.9×10^{21}
3	-17912	1150	0.0000	1.2×10^5
4	-3555	1654	0.0031	1007
5	-1008	1998	0.0489	37
Values at 240 Hours				
1	30080	300	0.0000	1.8×10^{28}
2	-5010	644	0.0000	2.9×10^{22}
3	-6763	1150	0.0000	1.4×10^8
4	-965	1654	0.0074	1.4×10^5
5	-274	1998	0.3481	1128

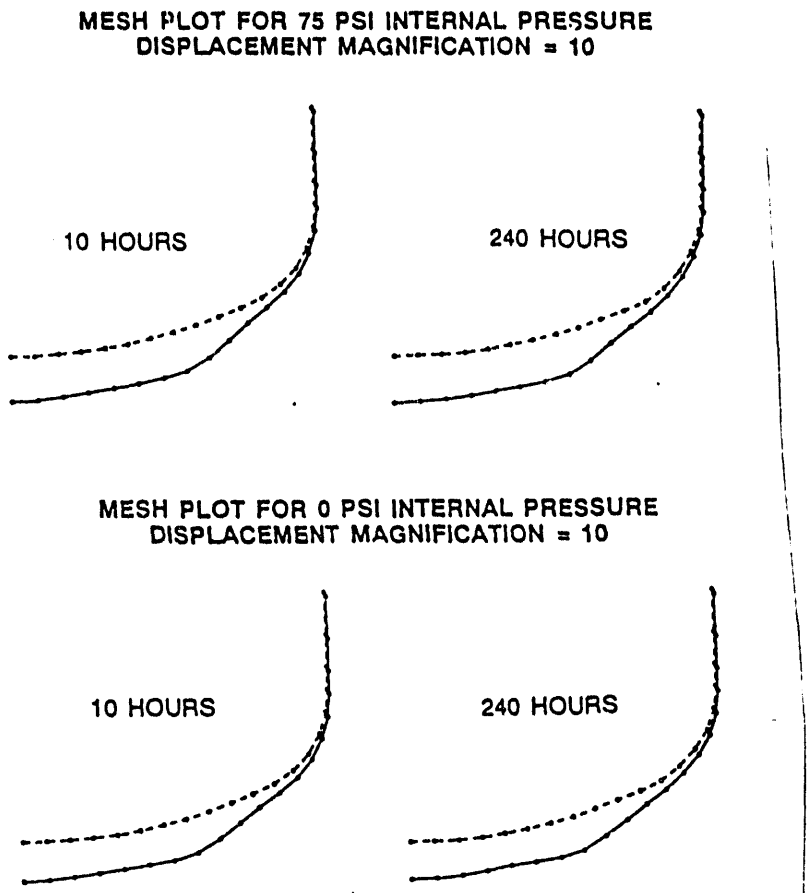

Figure 6 Deformed Mesh Plots for Load Cases 1 and 2

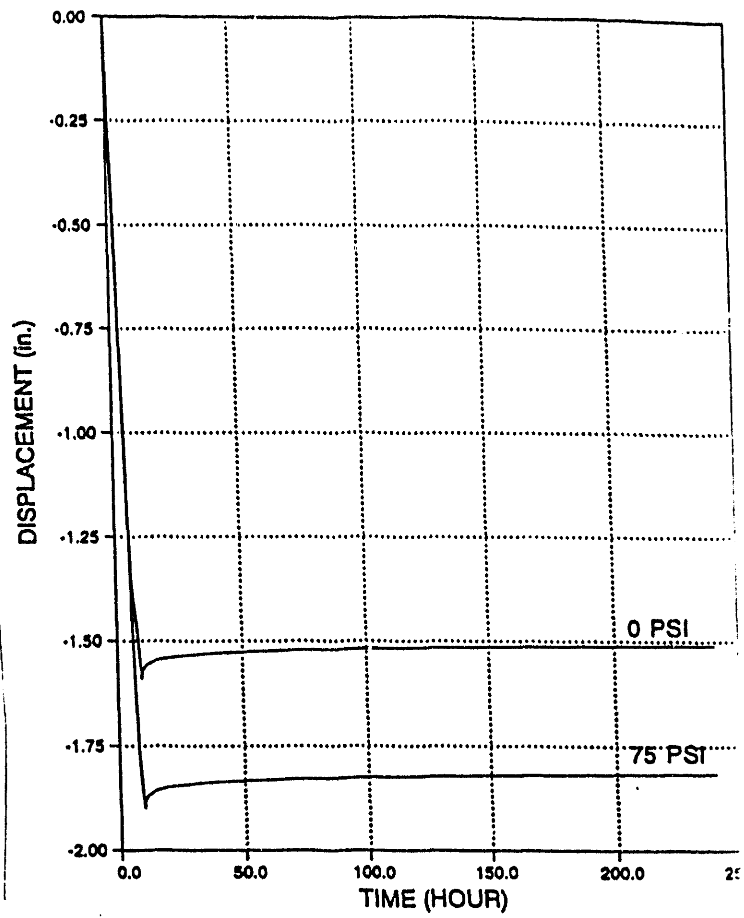

Figure 8. Vertical Displacement at the Bottom Cent of the Vessel for Load Cases 1 and 2

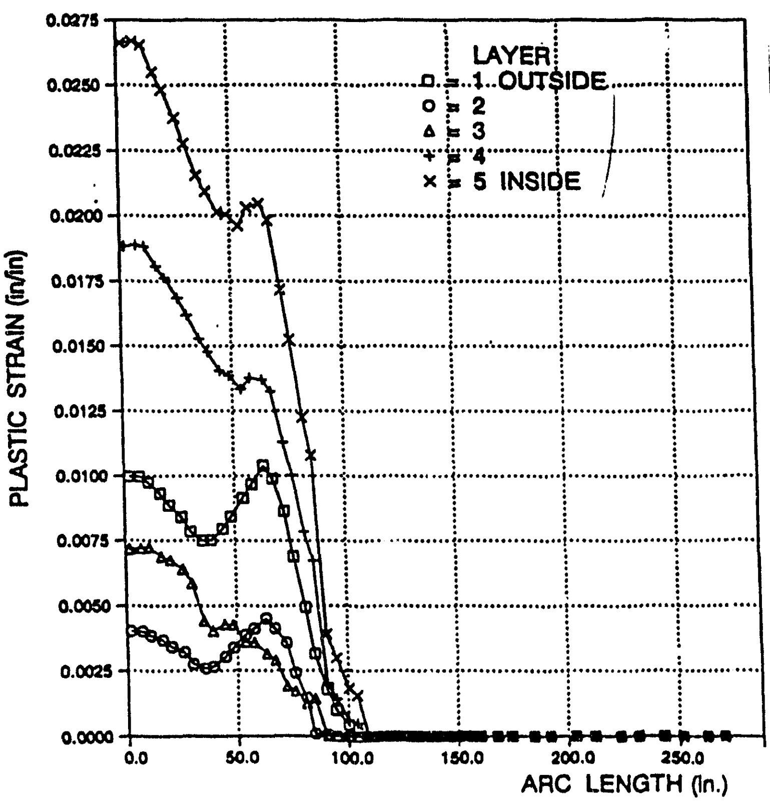

Figure 7. Effective Plastic Strain Profile for Load Case 2

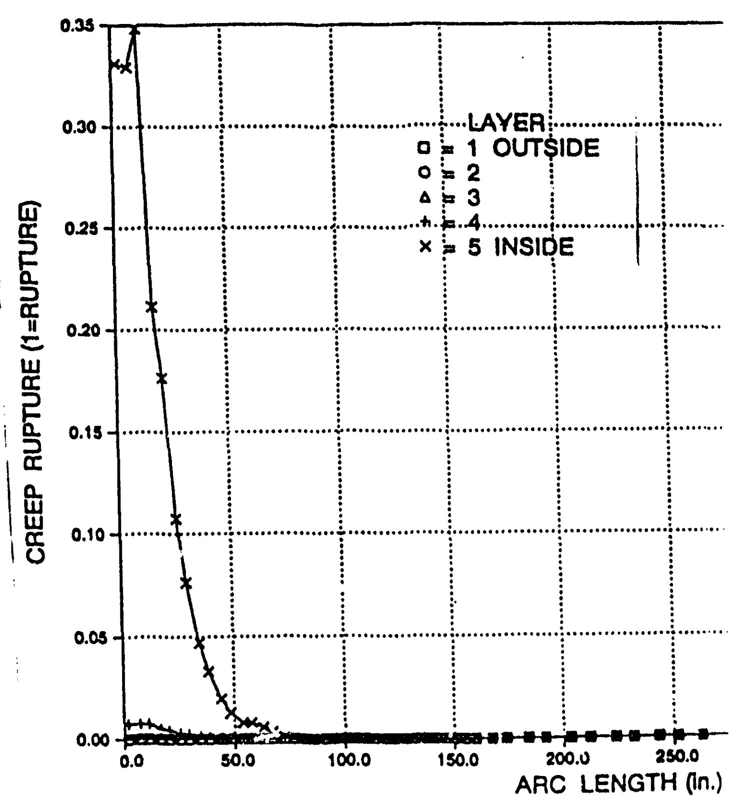

Figure 9. Creep Rupture Profile for Load Case 2

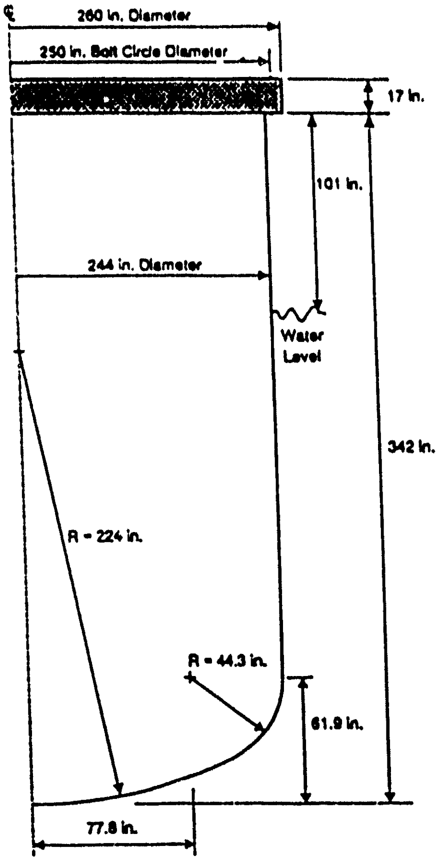

Figure 1. Design Configuration of a Reactor Vessel

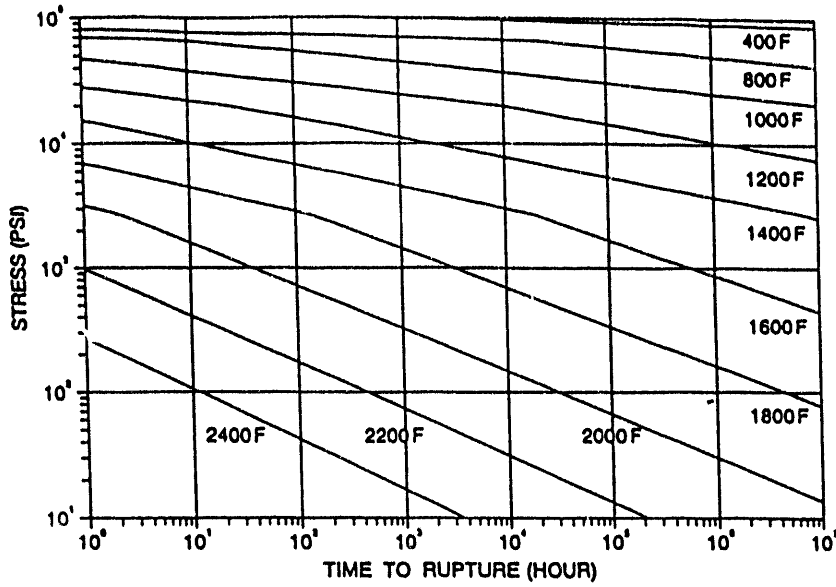

Figure 2 Creep Rupture Curves at Various Temperatures for 316 SS

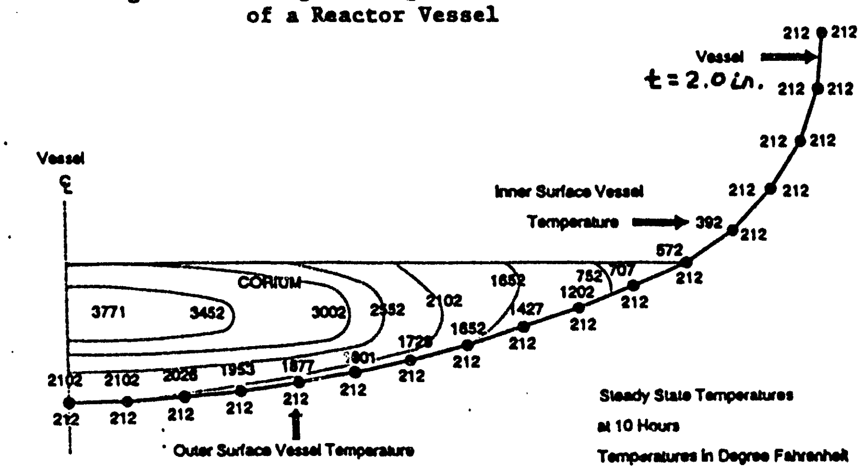

Figure 3 Temperature Distribution for Nucleate Boiling Heat Transfer

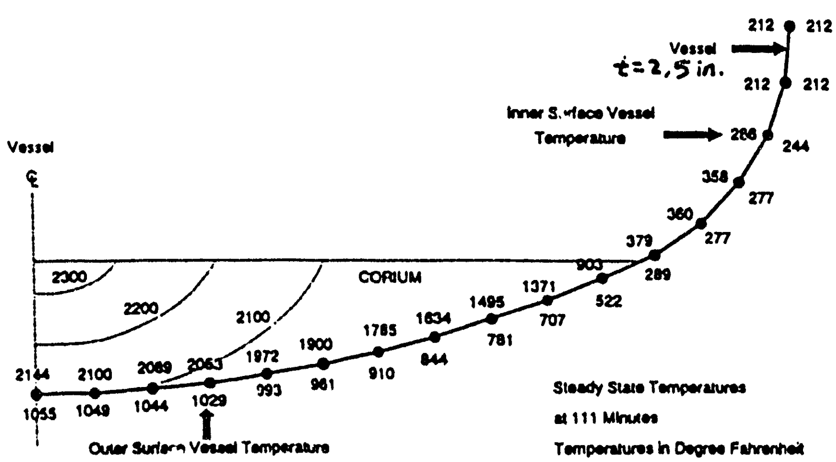

Figure 4 Temperature Distribution for Film Boiling Heat Transfer

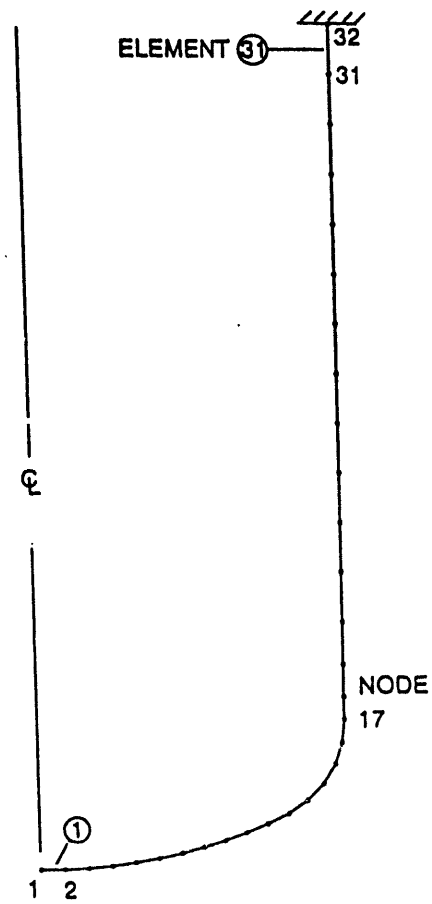

Figure 5 Finite Element Mesh of Reactor Vessel

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