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AN ENGINEERING APPROACH TO FINITE ELEMENT ANALYSIS OF NUCLEAR COMPONENTS

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SUMMARY

The practical aspects of three dimensional stressing of nuclear components to ASME Code III are discussed. The method of modelling and some typical analytical and experimental results are presented. General bounds on model complexity and computational costs are discussed.

In general, the peak stresses of components with thick sections will be temperature dependent, whereas thin wall components will be more dependent upon earthquake loads.

1. INTRODUCTION:

Much has been written on the theory of finite elements. [1] to [3]. What perhaps, has not been so well documented concerns their application to practical problems. In particular, their use in finding the stresses in large complex structures can represent a significant part of the total cost of that item. It then becomes important to consider carefully each step in the process to ensure not only maximum efficiency, but also that the results are really the ones needed.

The authors' experience in the use of this method has been, to a large degree, related to applications in the nuclear energy field. This paper deals with some typical examples that illustrate the compromises needed to get answers with satisfactory accuracy, at reasonable cost, and within an acceptable time scale.

Canadian reactors are required to comply with the ASME Nuclear Power Plant Components Code [4]. Among other things this specifies the operating conditions that must be investigated and also defines a set of allowable stresses. A useful stress analysis, of course, consists of more than a catalogue of the stresses existing in a structure. The ASME Code breaks the stresses down into a number of categories called primary, secondary and peak stresses. (For a complete description, the reader is referred to the definitions in the Code.) For present purposes, it is enough to know that each category has its own allowable value which depends, in turn, on the operating condition being dealt with.

When account is taken of the various loads that can exist on a piece of equipment, not only during normal operation, but also under a variety of abnormal conditions, it becomes clear that the quantity of numbers that may be produced can become a problem in itself. Unless adequate provision is made for dealing with this flood of data, the results could well be of no practical use.

2. METHOD OF ANALYSIS

2.1 Stress Analysis

The finite element method of structural analysis has been used to analyse nuclear components for mechanical and thermal stresses in three dimensions. The method involves idealizing a component as an assemblage of discrete elements, comprising either plates and beam elements or three dimensional solid elements. Components which may be classified as thick walled pressure vessels and subjected to hydrostatic strain will normally be modelled using tetrahedral elements, assembled in the more convenient hexahedron and pentahedron forms. Nuclear pumps, gate valves and Y-fittings fall within this category. Boilers, pressurizers and similar components will, on the other hand, more appropriately be modelled using plate and beam elements.

2.2 Thermal Analysis

In order to minimize the work, the thermal analysis of the components should be carried out using the same idealized model as for the stress analysis program. The same node numbers and co-ordinates can be used, and the temperatures at the centre of gravity of the elements calculated as a function of time, for various thermal transients of the fluid. These temperatures can then be used directly in the stress analysis program to calculate internal thermal stresses in the component.

The boundary conditions for the thermal model are the external temperatures and heat transfer coefficients. These can vary with time depending on the transients considered. The element temperatures can then be computed using a relaxation technique. The matrix can be set up so that only non-zero elements are stored, and in this way it is possible to analyse all structures on a computer of about 54K capacity without using secondary storage.

3. MODELLING

The modelling of most structures using three dimensional structural elements will present problems with regard to model sophistication, computer capacity and run time costs. A balance has to be achieved, between which model will give adequate solutions and a computer bill that will not seem too excessive.

The size of subdivision necessary to obtain a reasonable solution is not obvious. Figures 1 and 2 indicate that where there are no structural discontinuities and the strains are predominantly of a hydrostatic nature, a very coarse subdivision will suffice.

When a sophisticated model is required in order to adequately represent a nuclear component, then the capacity of computer systems and programming methods will have to be assessed during all stages of modelling.

The following nuclear components have been stressed analysed using the above precepts.

3.1 Pump Bowl

Figure 3 represents the general arrangement of a pump casing and figure 4 the finite element model. A mathematical split [5] was introduced in order to reduce the numbering difference and to keep the core requirement within the capacity of a 320K CDC 6600 computer. There are 592 Hexahedral and 66 Pentahedral elements in the model. The numbering difference is 68.

A comparison between the results of an axisymmetric program and a three dimensional one at a section of the bowl are shown in figure 5. Figures 6 and 7 compare the three dimensional results with some measured values from a pressure test.

3.2 Gate Valve

The modelling of half a gate valve is shown in figure 8. There are 44 Pentahedral and 410 Hexahedral elements in the model with a numbering difference of 72. Some of the stress intensities, at a meridional section, during a sudden change in system temperature, are shown in figure 9.

3.3 Y-Fittings

The model of a Y-fitting is shown in figure 10. There are 408 Pentahedral and 48 Hexahedral elements in the model and a numbering difference of 81. The radial stresses due to a pressure of 1600 psi for a centre line section are shown in figure 11.

3.4 Steam Drum Nozzle

The model of a Steam Drum Nozzle, using plate elements is shown in figure 12. There are 416 rectangular and 36 triangular elements in the model. The numbering difference is 38. A free-free body support condition is imposed. Forces and moments due to pressure, thermal, earthquake and other loads are ensured in balance with respect to the dimensions of the model.

Some stress results are shown in figure 13. The two computer programs were used in this instance to verify the order of stresses obtained.

4. SUBSTANTIATION OF RESULTS

The analytical results have been confirmed using separate computer codings, figures

5 and 13. The stresses in figures 6 and 7, however, show difference between analytical and experimental results. These differences are attributed to (a) bending moment which the tetrahedron element is not capable of absorbing, (b) differences in the model as originally drawn compared with the model actually made, (c) the simplified support conditions used in the model.

The output from the stress analysis program consists of stress components for each element of the model, for each of the loads of the operating and design conditions. Maximum stress intensities were then computed and compared to the Code [4].

Areas of high stresses were substantiated further by applying the method of "Convergence" [5]. This technique is essentially the setting up of a volume of the original structure in very great detail, maintaining the integrity of boundary forces and displacements of the volume and recalculating for stresses in the required areas.

5. APPLICATION OF CODE RULES

Reference [4] lays down a set of rules describing the various load cases to be considered, and indicating how, for each load condition the stresses are to be compared with the allowable limits. This fairly straightforward approach is complicated by two things:

a) In general, the analysis of a component will have to cover similar items at different locations in the plant. This will involve a different set of piping loads (consisting of dead weight, thermal and earthquake loads) for each location of the component.

b) The thermal expansion loads of the component itself will vary with time. It is necessary to select the worst combination of thermal expansion loads with all other mechanical loads to carry out a correct stress comparison.

It is assumed that a component has two locations within the plant, a typical total number of load cases would be as follows:

Type of Loading	Number of Cases	Total
Internal Pressure	1	1
Piping Dead Weight	1	2
Piping Thermal Expansion	1	2
Piping Seismic	2	4
Piping Burst Condition	2	4
Internal Thermal Expansion Normal	4	4
Internal Thermal Expansion Upset	4	4
		21

The above load cases have to be added up in various combinations to find the maximum stress intensities for the specified load conditions as follows

Loading Condition	Load Case (Number of Cases)		Maximum Number	Probable Number
Design	Pressure (1) + Dead Weight (2)	=	2	2
Normal plus Upset	Pressure (1) + Dead Weight, Pipe Thermal and Seismic (2) + Internal Thermal (8)	=	16	8
Emergency	Pressure (1) + Dead Weight (2) + Seismic (2)	=	4	2
Faulted	Pressure (1) + Dead Weight (2) + Seismic (2) + Burst Pipe (4)	=	16	4
			38	16

Since it becomes very expensive to run all possible combinations of loads some judgement has to be exercised to reduce the computing cost. Hence a look at the various temperature gradients can indicate that probably the number of cases for which stresses are required can be reduced from, say, 8 to 4. This may be true also for the various pipe mechanical loads, particularly the burst and seismic cases. Hence there are two columns showing the maximum number and probable number. The maximum, of course, could be a lot larger.

The overall problem of straight data processing becomes considerable when a typical structure with, say 500 elements, is considered. This structure would produce 3000 stresses per load case, and for 16 combinations this would be 48,000 stress components that have to be reviewed. To reduce the amount of labour involved, the results of each individual load case are dumped on file after computation. Then subsequently the combination of the load cases, required for each loading condition, are generated by adding the individual results in the proportions required. The elements of the structure are then sorted in order of maximum stress intensity for each load combination. This immediately highlights the areas of maximum interest, and also ensures no high stress areas are overlooked. If required, further analysis of these high stress areas can be carried out using the method of "Convergence" outlined in [5].

6. COMPUTATIONAL COSTS

The computer costs control to a large extent the degree of model sophistication which may be considered. Figure 14 shows that the number of elements for a given structure soon reaches an uneconomical level. Other factors which would slightly modify the costs in Figure 14 are numbering difference and number of nodes.

In order to reduce the cost of analysis for additional load cases, facilities for storing the stiffness matrix in modified form have been included in the computer programs used. This allows additional load cases to be processed at approximately a 20th of the cost of the initial run.

7. DISCUSSION OF RESULTS

A summary of the maximum stress intensities for the various components is given as follows.

Summary of Maximum Stress Intensities

	Design Condition-	Operating Condition Without Earthquake	Operating Condition With Earthquake
Pump	18,000	33,000	34,000
Valve	10,000	35,000	35,000
Y Piece	13,000	19,000	23,000
Steam Drum Nozzle*	12,000	29,000	52,000

*These results are only preliminary.

It can be seen that the stress intensities for the design condition are much lower than the operating values. This is because the design condition only considers internal pressure and external mechanical loads that are not self relieving. The operating condition includes all possible mechanical loads plus the effects of temperature and seismic loads. The code allows the maximum stress intensities for the operating condition to be three times as high as the design condition.

It is interesting to note that where high thermal stresses exist, in general the effect of an earthquake is small. This is because the high thermal stresses are due to thick wall sections, which are not affected significantly by earthquake loads. This can be seen clearly in the results for the pump and the valve. For components with lower thermal stress, the effect of earthquake loads tend to predominate, as shown by the results for the Y piece and the steam drum nozzle.

8. RECAPITULATION

1. A stress analysis must cover all expected operating conditions. The results of such an analysis must not exceed the allowable values specified by the appropriate jurisdictional authority.

2. The modelling of any structure has to be considered simultaneously with computer capacity. The program should contain the steps for processing further loading conditions without having to regenerate the stiffness matrix each time.

3. Examples have been given of structural items, the modelling of which shows sufficient sophistication while retaining a reasonable computational cost.

4. For thin walled vessels the effects of external loads tend to predominate. On the other hand thermal effects are of more significance for thick walled vessels.

REFERENCES

[1] O.C. Zienkiewicz and G.S. Holister, Stress Analysis, John Wiley & Sons Ltd. 1965.

[2] J.S. Campbell, The Finite Element Stress Analysis of Plane and Axi-symmetric Structures, Nuclear Science Abstracts (1969).

[3] J.S. Przemieniecki, Theory of Matrix Structural Analysis, McGraw Hill.

[4] ASME Boiler and Pressure Vessel Code, Section III, Nuclear Power Plant Components, 1971 Edition.

[5] E.E. Remedios, J.D. Lovatt and R. Bell, The Stress Analysis of a Heat Transport Pump for a Nuclear Power Generating Station, Study No. 7, Applications of Solid Mechanics, University of Waterloo.

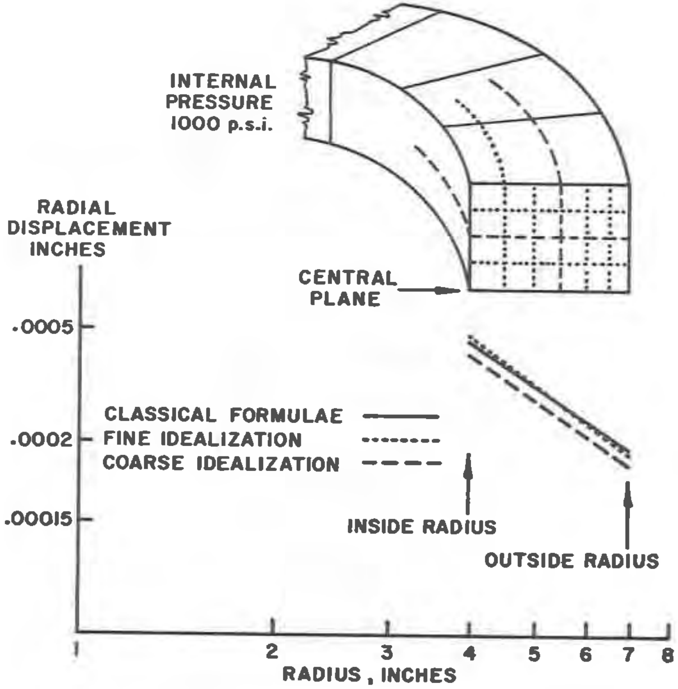


Figure 1 Idealization of Thick Walled Cylinder Using Tetrahedral Elements

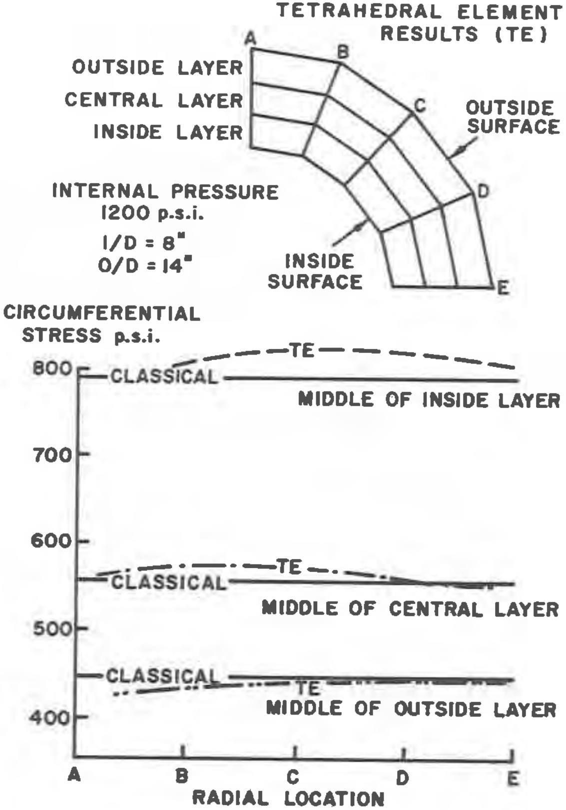


Figure 2 Model of a Hollow Sphere Using Tetrahedral Elements

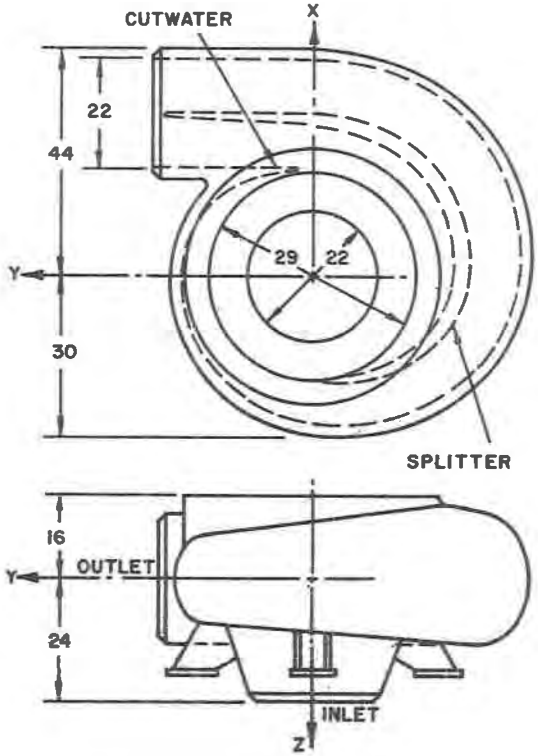
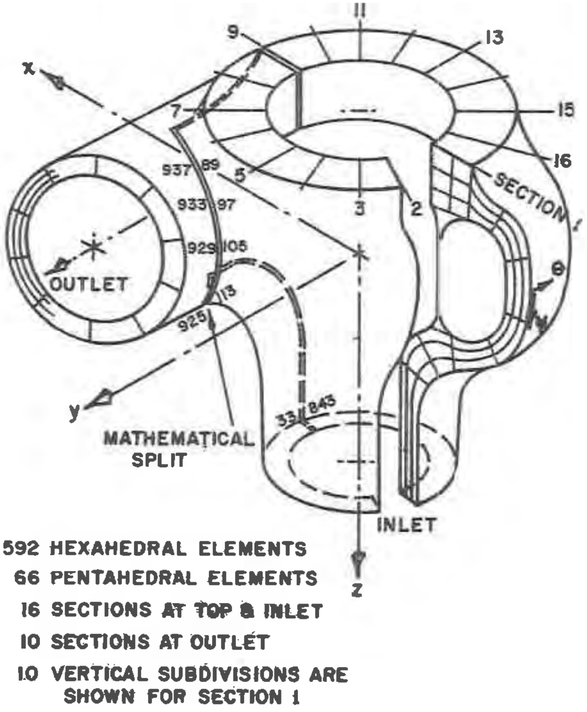


Figure 3 Pump - General Arrangement



592 HEXAHEDRAL ELEMENTS
66 PENTAHEDRAL ELEMENTS
16 SECTIONS AT TOP & INLET
10 SECTIONS AT OUTLET
10 VERTICAL SUBDIVISIONS ARE SHOWN FOR SECTION 1

Figure 4 Modelling of Pump Bowl

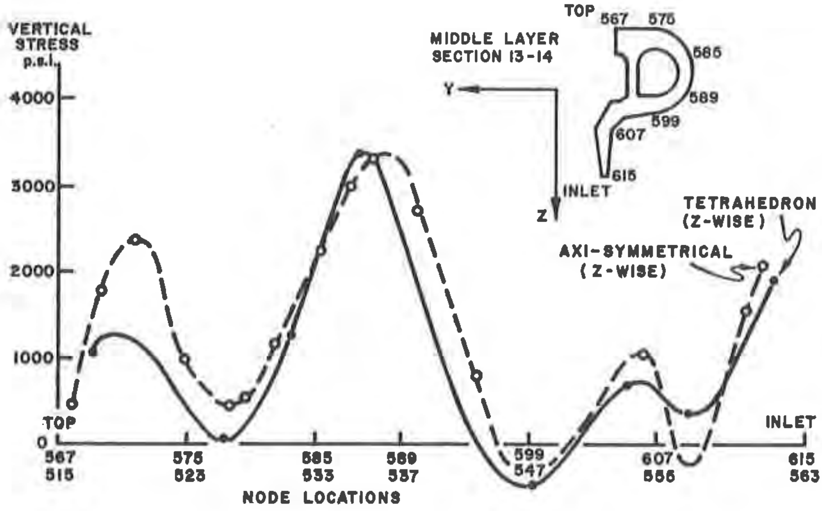


Figure 5 Verification of Results. Tetrahedron and Axi-Symmetric Models

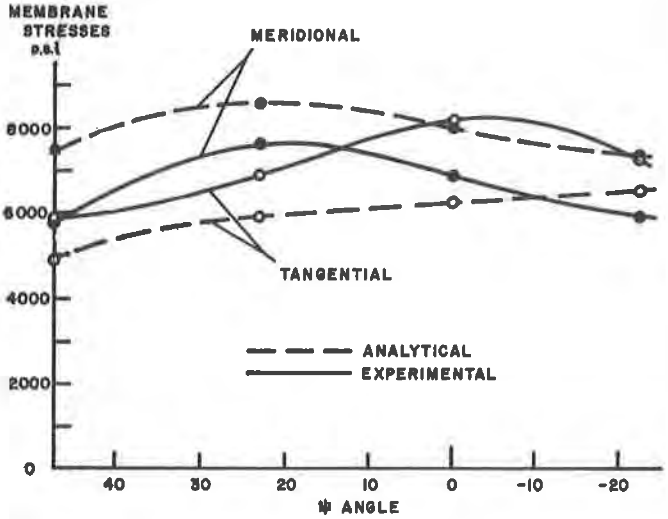


Figure 6 Membrane Stresses on Section 1

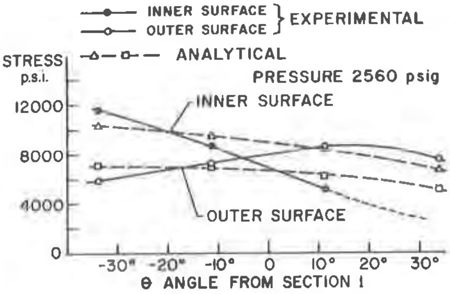


Figure 7 (a) Pump Casing Meridional Stresses on Horizontal Centre Line

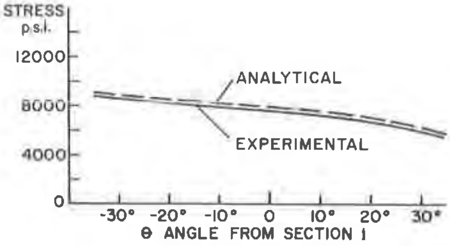


Figure 7 (b) Mean Stresses on Horizontal Centre Line

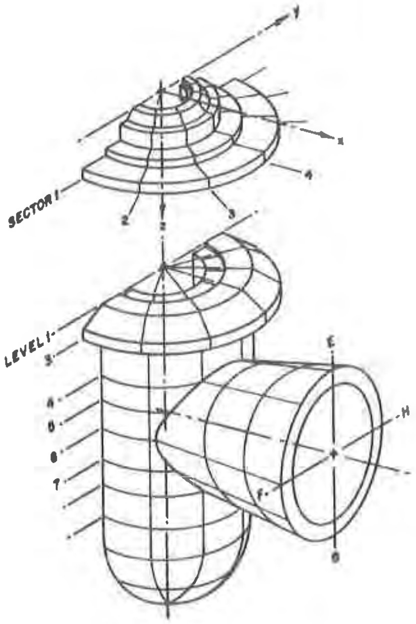


Figure 8 Overall Structural Idealization of Valve Body

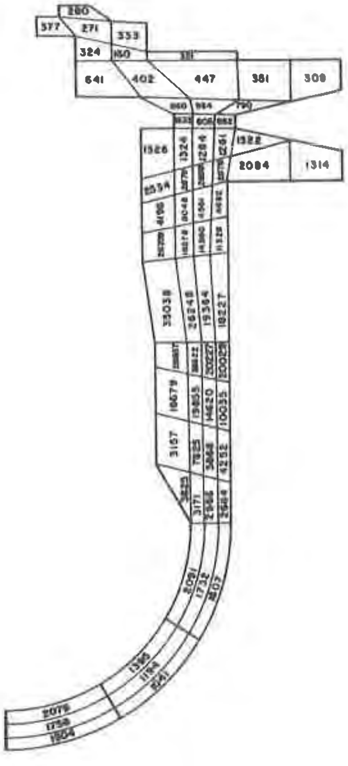


Figure 9 Stress Intensities for Abnormal Thermal Cycle

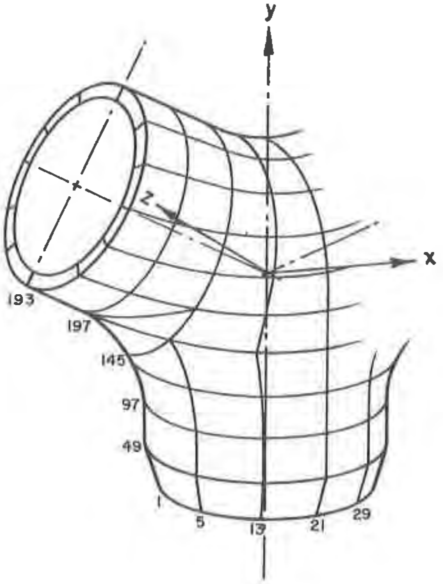


Figure 10 Structional Idealization of Y-Fittings

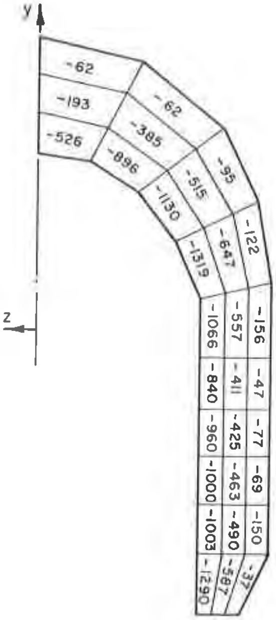


Figure 11 Radial Stresses Due to Pressure 1600 psi

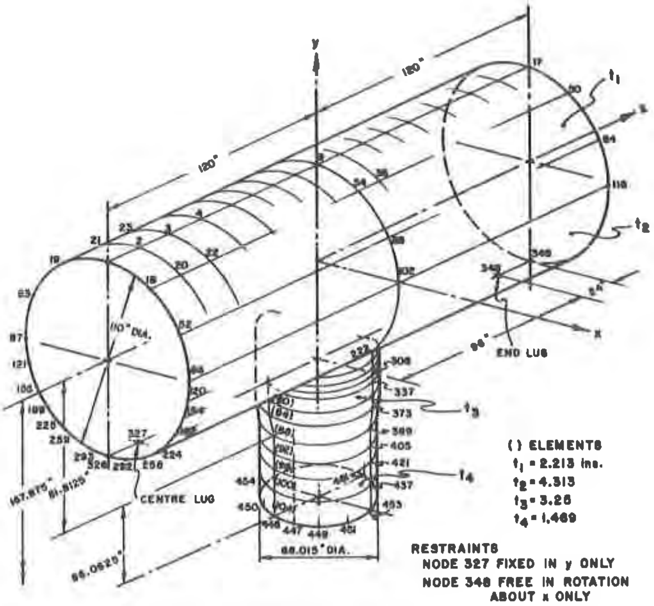


Figure 12 Model of Steam Drum Nozzle

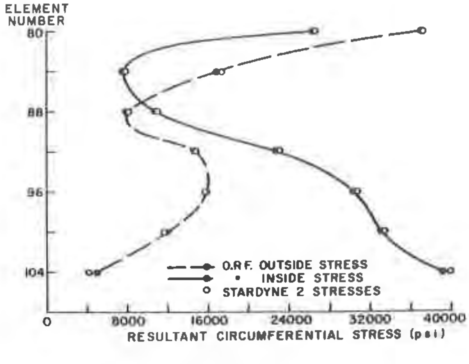


Figure 13 Circumferential Stresses.

BERESHL (ORF) vs Stardyne 2

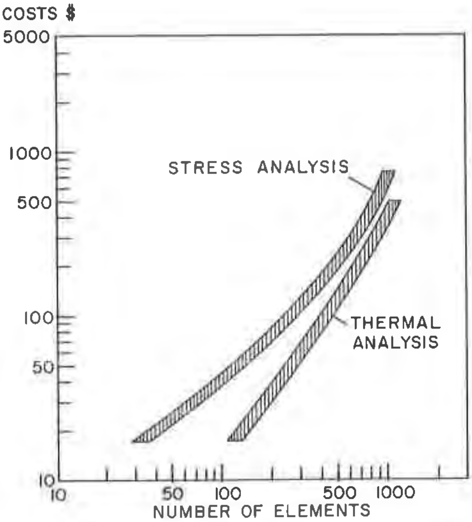


Figure 14 Approximate Computer Costs