**Stresses in Reinforced Nozzle
Attachments Under Internal Pressure
Loading Analyzed by the Finite-Element
Method—A Parameter Study**

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PRESSURE LOADING ANALYZED BY THE FINITE-ELEMENT METHOD —
A PARAMETER STUDY

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FOREWORD

The work reported here was performed at the Oak Ridge National Laboratory (ORNL) in support of the ORNL Design Criteria for Piping and Nozzles Program. This program is sponsored by the Division of Reactor Safety Research (RSR), Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission. E. K. Lynn of the Metallurgy and Materials Branch is the cognizant RSR engineer, and S. E. Moore, ORNL Engineering Technology Division (formerly Reactor Division), is the program manager.

Activities under the program are coordinated with other safety-related piping and pressure-vessel research through the Design Division, Pressure Vessel Research Committee (PVRC) of the Welding Research Council, and through the ASME Boiler and Pressure Vessel Code Committee as part of a cooperative effort with industry to confirm and/or improve the adequacy of design criteria and analytical methods used to assure the safe design of nuclear power plants.

The study of stresses at reinforced nozzle penetrations in cylindrical pressure vessels described in this report is part of a continuing study of stress analysis methods and design rules being coordinated by the PVRC Subcommittee on Reinforced Openings and External Loadings, W. L. Greenstreet, Chairman. Results from these studies are used by appropriate ASME code groups in drafting new and improved design rules.

Previous reports in this series are:

A. J. Edmondson, *Stress Analysis of a Radial Nozzle Attached to a Cylindrical Shell Under Internal Pressure*, ORNL/TM-4269 (May 1974).

E. C. Rodabaugh, *Phase Report 117-1 - Elastic Stresses in Nozzles in Pressure Vessels with Internal Pressure Loading*, Battelle-Columbus Laboratories (April 1969).

E. C. Rodabaugh, *Phase Report 117-8 - Applicability of Axisymmetric Geometry Analytic Methods to Nozzles in Cylindrical Shells with Internal Pressure Loading*, Battelle-Columbus Laboratories (July 1973).

J. L. Mershon and E. C. Rodabaugh, *Phase Report 117-10 - Preliminary Evaluation of Closely Spaced Reinforced Openings in a Cylindrical Pressure Vessel Under Internal Pressure Loading*, ORNL/Sub/3131-10, Battelle-Columbus Laboratories (June 30, 1975).

J. M. Corum et al., *Theoretical and Experimental Stress Analysis of ORNL Thin-Shell Cylinder-to-Cylinder Model No. 1*, ORNL-4553 (October 1972).

R. C. Gwaltney, S. E. Bolt, and J. W. Bryson, *Theoretical and Experimental Stress Analyses of ORNL Thin-Shell Cylinder-to-Cylinder Model 2*, ORNL-5021 (October 1975).

R. C. Gwaltney et al., *Theoretical and Experimental Stress Analyses of ORNL Thin-Shell Cylinder-to-Cylinder Model 3*, ORNL-5020 (June 1975).

R. C. Gwaltney, S. E. Bolt, and J. W. Bryson, *Theoretical and Experimental Stress Analyses of ORNL Thin-Shell Cylinder-to-Cylinder Model 4*, ORNL-5019 (June 1975).

STRESSES IN REINFORCED NOZZLE-CYLINDER ATTACHMENTS
UNDER INTERNAL PRESSURE LOADING ANALYZED BY THE
FINITE-ELEMENT METHOD — A PARAMETER STUDY

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ABSTRACT

A parameter study was conducted on stresses in reinforced nozzle-to-cylinder attachments under internal pressure loading as analyzed by the finite-element method. Twenty-five models with branch-to-run diameter ratios $0.08 < d/D < 0.50$ and run diameter-to-thickness ratios $10 < D/T < 100$ were investigated. A three-dimensional finite-element program, CORTES-SA, which was developed at the University of California at Berkeley specifically for analyzing tee-joint configurations, was used in the study.

Two of the recommended nozzle reinforcement designs given in Subsection NB-3338.2, Section III of the ASME Boiler and Pressure Vessel Code were examined: nozzle thickening, or so-called "standard" reinforcement (S1 models), and 30° triangular pad reinforcement (P30 models). Essentially unreinforced models (U models) were also included for comparison. Although these design configurations have been recommended by the Code for many years, very little specific stress analysis information exists by which the adequacy or relative safety margins of the Code design rules can be judged. Results from the parameter studies reported here provide some of the needed information.

It was concluded from the study that both of the reinforcement designs investigated significantly reduce maximum stresses relative to configurations having little or no reinforcement. For internal pressure loading, neither of the reinforcement designs offered a significant advantage over the other in that both types of reinforcement gave very nearly the same maximum stresses.

Keywords: stress analysis, pressure vessels, pressure vessel nozzles, ASME BPVC, design rules, ORNL Nozzles Analysis Program

1. INTRODUCTION

Nozzles attached to cylindrical shells are common configurations in the pressure vessel and piping industry. For pressure vessel design,

branch-to-run diameter ratios d/D up to 0.5 cover almost all nozzles; however, for piping, d/D ratios up to 1.0 are fairly common. Cylindrical shell diameter-to-thickness ratios D/T may be as high as 1000 for steel containment vessels (e.g., large oil storage tanks) but are generally less than 100 for nuclear vessels. Most of the stress analysis data available in the literature for nozzle-to-cylinder attachments are limited to either flush unreinforced connections or models having very small fillet radius reinforcements. Very little experimental or analytical data are available in the open literature on reinforced connections, particularly for nozzle-to-cylinder attachments having the reinforcement designs given in Subsections NB-3330 through NB-3339, Section III, of the ASME Boiler and Pressure Vessel Code.*

Additional data are needed in order to confirm and/or improve the design rules and safety criteria specified in the Code for the qualification of reinforced nozzle design. The stress analysis parameter study for 25 isolated nozzle-to-cylinder attachments under internal pressure loading described in this report was conducted to provide some of the needed information. A three-dimensional finite-element computer program, which was developed under subcontract at the University of California, Berkeley, specifically for analyzing tee-joint configurations, was used in the study. The program, CORTES-SA, features an automatic mesh-generation package with a number of input-variable options which enable the user to model a wide variety of nozzle-attachment designs using a minimum amount of input data.

The parameter study consisted of 25 models having dimensionless parameters within the ranges $10 \leq D/T \leq 100$ and $0.08 \leq d/D \leq 0.50$. Three types of models were examined: 6 which were minimally reinforced by a small fillet radius at the junction as specified by the Code; nozzle thickened, or the so-called "standard" reinforcement (S1) models; and 30° triangular pad (P30) models. Nineteen of the models analyzed were of the latter two types. These reinforcement designs are given in Subsection NB-3338.2, Section III, of the Code.

*Henceforth, "the Code" refers to the ASME Boiler and Pressure Vessel Code, Section III, Subsections NB-3330 through NB-3338.

The basic nozzle-to-cylindrical-shell configuration is shown in Fig. 1. In the finite-element idealization for all the models in the study, one end of the run pipe was clamped, while the free ends of the run and the branch were capped with stiff end diaphragms. These diaphragms were represented by finite elements that were assigned an artificially large elastic modulus.

The objective of this report is to summarize and present the more important and relevant results of the parameter study. No attempt is made here to relate these results to the design rules of Subsections NB-3330 through NB-3339, Section III, of the Code. We plan to address this subject in a follow-up document that will include recommendations for improved design rules for nozzles in pressure vessels and branch connections in piping. It should also be pointed out that future work under the Design Criteria Program will be to run the orthogonal set of force and moment loadings applied to the branch and free end of the run for these same 25 models.

Parameter study reports or other reports dealing with large quantities of data are particularly difficult to prepare since they require an unusual

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Fig. 1. Basic nozzle-to-cylindrical shell attachment.

amount of discrimination in choosing which data to present and an effective format. The results of this study are given in both graphical and tabular formats; the graphs present stresses in and normal to the X-Y (0°) and Y-Z (90°) planes (see Fig. 1) of the configurations, and the tables give the displacements and principal stresses and their direction cosines for each nodal point on the outside and inside surfaces. In order to minimize the size of this report, the tables are printed on microfiche and included in the envelope on the back cover. Three appendices, one for each type of model design, contain the graphical presentation of the results and also include isometric and cross-sectional views of the finite-element meshes for each of the models.

The following chapters discuss the finite-element computer program used in the study, the checkout and verification of the program, the parameter study, and the results and conclusions. The largest principal stresses and their locations are tabulated in Chapter 5.

2. THE COMPUTER PROGRAM

The finite-element computer program CORTES-SA¹ (California, Oak Ridge Tee S - Stress Analysis) used in the study was developed earlier at the University of California, Berkeley. It is one of a five-program package designed specifically for the analysis of piping tee joints subjected to a variety of mechanical and thermal loadings. The other programs in the package include CORTES-THFA (Transient Heat Flow Analysis), -SHFA (Steady-state Heat Flow Analysis),² -TSA (Thermal Stress Analysis), and -EPA (Elastic-Plastic Analysis). These programs are available upon request from the Argonne Code Center, Argonne National Laboratory. They were originally developed for the analysis of ANSI B16.9 standard tees but are also applicable to a wider range of joint geometries, including the reinforcement configurations discussed here.

Two of the more prominent features of CORTES-SA include the use of a relatively economical finite element and the capability to automatically generate the input data. In addition, peripheral plotting software has been developed at ORNL for analyzing and interpreting the output and for preparing report-grade figures. These features are discussed below.

2.1 The Finite Element

The finite element used in CORTES-SA is the ZIB8R9 element originated by Irons and Zienkiewicz.³ It is an 8-node isoparametric brick element with additional deformation modes and is the same element that is used in the general-purpose computer program SAP.⁴ The added deformation modes allow the element edges to deform quadratically rather than imposing linear displacement variations. However, by doing so, displacement compatibility along the element edges is violated. The element is more flexible than a linear isoparametric brick element and thus behaves much better in bending; however, certain problems with regard to convergence and bounding of the solution are introduced.

The displacement expansions for the ZIB8R9 element are given by

$$u = \sum_{i=1}^8 N_i u_i + \alpha_1(1 - r^2) + \alpha_2(1 - s^2) + \alpha_3(1 - t^2) ,$$

$$v = \sum_{i=1}^8 N_i v_i + \beta_1(1 - r^2) + \beta_2(1 - s^2) + \beta_3(1 - t^2) ,$$

$$w = \sum_{i=1}^8 N_i w_i + \gamma_1(1 - r^2) + \gamma_2(1 - s^2) + \gamma_3(1 - t^2) ,$$

where u_i , v_i , and w_i are nodal displacements; α , β , and γ represent generalized displacements associated with the added deformation modes; and N_i represents the shape functions given by

$$N_i = \frac{1}{8} (1 + rr_i)(1 + ss_i)(1 + tt_i) .$$

Figure 2 shows the local and global coordinates for the element. When the strain energy within the element is minimized with respect to the α , β , and γ values, nine additional equations are obtained which permit these terms to be eliminated. The resulting (condensed) stiffness matrix is therefore 24×24 . A more detailed discussion of the element and the finite-element method in general may be found in Ref. 1.

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Fig. 2. Local and global coordinates for ZIB8R9 element.

The modified 8-node brick element has given results comparable to the 20-node element for plates and shells with moderately fine element subdivisions.¹ Its inherent simplicity makes it more economical than the 20-node element since it requires less computational effort.

2.2 Mesh-Generation Capability

The input for most finite-element computer programs without mesh-generation capability usually consists of a rather large number of cards which describe the element connectivity and give the global (or local) coordinates of the nodes. CORTES-SA can require as few as ten cards to generate a mesh for a tee connection; this is a great advantage to the user, particularly if many problems requiring different meshes (such as a parameter study) are to be solved.

The program uses a "pentagonal" scheme for mesh generation; that is, a quarter section of a tee is divided into five main parts or "quadrilaterals" that are joined at a common "control node." These quadrilaterals are further subdivided into "quadrilateral elements." For internal pressure loading, only a quarter section, or a quadrant, of a tee need be considered because of symmetry. The five quadrilaterals connect with each other along five axes which emanate from the control node (see Figs. 3 and 4). The user specifies the number of elements or divisions along each axis for each quadrilateral, the lengths of the tee from the branch and run centerlines to the ends of the branch and run, and fillet radii in the X-Y and Y-Z planes (X-axis coincident with the run centerline and Y-axis coincident with the branch centerline). Additional input data define the tee and pipe extension regions and the material properties. The program internally numbers the nodes and elements; this numbering scheme is illustrated in Fig. 5.

Since it is necessary to define corresponding meshes on both the outer and inner surfaces of the joint, two options for outer and inner surface mesh generation are provided. The first option generates both surfaces using specified lengths, fillet radii, and other necessary dimensions. The second option generates the inside surface by projecting from the outer surface using thicknesses at specified nodes supplied by the user. As many as five layers of elements can be specified through the wall thickness.

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Fig. 3. Pentagonal system.

Fig. 4. Finite-element mesh.

Fig. 5. Node numbering scheme.

The mathematical relationships which describe the fillet and junction region of the branch and run connection are discussed in Ref. 1.

Data for the mesh generation and program execution of a sample tee joint are shown in Fig. 6. As may be seen, only a few cards are needed to run the program.

2.3 Plotting Routines

ORNL has devoted much effort to the development of peripheral output and plotting software for the CORTES programs. A plotting package called GRFPAK³ has been developed which greatly facilitates analyzing, interpreting, and presenting CORTES results.

One of the quickest and easiest ways to examine finite-element program input for errors is to plot the original or undeformed mesh. The first routine plots both the outside and inside surface meshes as viewed from any specified exterior point in space. It is also necessary to examine the

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EXAMPLE DATA - THIN SHELL CYLINDER TO CYLINDER CONNECTION

	5.		10.		0.75		0.1		5.		3.5		20.		20.
2	2	10	20	6	16	6	16	1		1.3		1.5			
	50.														
2	6	50.	1.25		5.		10.						0.01		0.01
2	6	50.	1.25		4.9		9.8						0.01		0.01
<p>00000000. 0.3</p> <p>5 10 5 7 12</p>															

Fig. 6. Sample input data for mesh generation using computer program CORTES-SA.

generated mesh layout through the thickness, that is, to look at cross sections of the model when working with solid elements. This same routine has the capability for examining such cross sections. Figures 7 and 8 illustrate these types of plots. The routine is also capable of plotting the deformed configuration of cross sections to an exaggerated scale as specified by the user.

A second routine gives a projected stress vs length parameter plot along any specified line or stringer of nodes. Figure 9, which illustrates this type of plot, shows stresses in and normal to the 0° section (see Fig. 7). Numbers on the abscissa represent projected values of the nodal coordinates as illustrated in Fig. 10.

A third routine gives a three-dimensional stress plot which shows the value of the desired stress at every node on a surface of the tee. Figures 11 and 12 show sample plots for the branch. The lower left edge of the figures is the junction of the branch with the run. Figure 12 shows the same results as Fig. 11, but the "knobs" have been connected with straight lines to form a "stress surface." Figures 13 and 14 show similar plots for the run.

Fig. 7. Isometric mesh plot.

Fig. 8. Mesh cross-sectional plots of tee symmetry sections.

Fig. 9. Projected plot of stress vs length parameter XP.

Fig. 10. Length parameter XP for projective plot program.

Fig. 11. Stress stick plot on outer surface of branch.

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LOAD CASE 1

TMAX

1 IN. = 1.8782E 03 PSI

Fig. 12. Stress surface plot on outer surface of branch.

Fig. 13. Stress stick plot on outer surface of run.

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Fig. 14. Stress surface plot on outer surface of run.

3. COMPUTER PROGRAM CHECKOUT

The first step in a computer program parameter study is the selection and evaluation of the program to be used. As stated earlier, the CORTES programs were developed specifically for the analysis of ANSI B16.9 standard tees, for which the branch-to-run diameter ratio d/D generally ranges from 0.5 to 1.0 but may be as small as 0.3. Since the range of d/D in the parameter study is from 0.08 to 0.5, there was an initial concern as to whether the CORTES programs would give satisfactory results for small d/D ratios. Another concern was whether the program would adequately predict the stress distributions over the wide range of run diameter-to-thickness ratios ($10 \leq D/T \leq 100$).

In order to satisfy these concerns, we compared analytical results from CORTES-SA with available experimental data falling within the d/D and D/T ranges of the parameter study. The experimental models listed in Table 1 all have d/D and D/T ratios within these ranges ($0.08 \leq d/D \leq 0.5$, $10 \leq D/T \leq 100$). The first three models were tested photoelastically at Westinghouse Research Laboratories.⁶⁻⁸ The other models are all strain-gaged steel models tested either at or under subcontract to ORNL.⁹⁻¹² Three models from Table 1 were selected for comparison purposes; ORNL-1 (Ref. 9), ORNL-3 (Ref. 10), and WC-12D (Ref. 8). Two of the three were ORNL models, primarily because the authors were more familiar with them. Model WC-12D was selected because it is relatively thick, but more importantly, because it has a "standard" reinforcement design of the type to be investigated in the parameter study.

Model ORNL-1 is an idealized thin-shell structure consisting of two circular cylindrical shells intersecting at right angles and has no transitions, reinforcements, or fillets in the junction region. The outside diameters of the run and the branch are 254 mm (10.0 in.) and 127 mm (5.0 in.), respectively. The thicknesses of the run and the branch are 2.54 mm (0.1 in.) and 1.27 mm (0.05 in.), respectively. A detailed discussion of model fabrication, strain-gage layout, and testing is given in Ref. 9. The appropriate model dimensions were input into CORTES-SA. Since the program requires that a fillet radius be specified, an arbitrarily small value

Table 1. Experimental models within d/D and D/T ranges of parameter study (1 in. = 25.4 mm)

Model	D/T^a	d/D	Type of reinforcement ^b
C-2A ^c	12.1	0.129	Fillet, $r_0/T = 0.56$
WC-12D ^c	12.25	0.129	Standard shape
WC-2AQ ^c	99.1	0.129	Fillet, $r_0/T = 0.50$
ORNL-1 ^d	100.0	0.500	None
ORNL-3 ^d	50.0	0.129	Extra wall in nozzle
ORNL-4 ^d	50.0	0.129	None
ORNL-T8 ^e	34.0	0.52	ANSI B16.9 tee, 12 × 12 × 6 in. sched 40
ORNL-T15 ^e	34.0	0.52	ANSI B16.9 tee, 12 × 12 × 6 in. sched 40

^a D and d are inside surface dimensions for models tested at Westinghouse Research Laboratories; they are outside surface dimensions for all other models.

^bSee Subsections NB-3330 through NB-3339, Section III, of the Code.

^cPhotoelastic models tested at Westinghouse Research Laboratories.⁶⁻⁸

^dTested at ORNL.⁹⁻¹¹

^eTested at Southwest Research Institute under subcontract to ORNL.¹²

[0.254 mm (0.01 in.)] was used. One through-the-wall-thickness element was used. There were a total of 1226 nodes, 613 on each surface. The internal pressure loading [0.345 MPa (50 psi)] was the same as that used for the experimental model.

An isometric view of the mesh generated for the outside surface of the model is shown in Fig. 15, and cross-sectional views for 0 and 90° sections are shown in Fig. 16. Comparisons of experimental and calculated stress distributions along 0 and 90° sections are shown in Figs. 17 and 18, where longitudinal and transverse stress distributions are given for the outside and inside surfaces of both the run and the branch. Longitudinal stresses

Fig. 15. Isometric view of outside surface for ORNL-1 generated mesh and definition of stresses for 0 and 90° sections.

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Fig. 16. Cross-sectional views for ORNL-1 generated mesh.

Fig. 17. Comparisons of experimental and theoretical stress distributions for 0° section of ORNL-1, internal pressure loading = 50 psi. (1 in. = 25.4 mm).

Fig. 18. Comparisons of experimental and theoretical stress distributions for 90° section of ORNL-1, internal pressure loading = 50 psi. (1 in. = 25.4 mm).

are those in the plane of the section along the node stringer, while transverse stresses are normal to the section (see Fig. 15). The comparisons of calculated and experimental values for both longitudinal and transverse stresses were generally very good for the 0° section. The calculated values were slightly below the experimental values near the junction except on the inside surface of the branch; however, the overall trends or shapes of the curves were very similar. Good comparisons were obtained at the 90° section, except on the run near the junction where the calculated values were somewhat below the experimental ones.

Model ORNL-1 represents limiting cases for the parameter study in two respects: it is an idealized cylinder-to-cylinder connection with no reinforcing or transition region and has a d/D ratio of 0.5, which is the upper bound of the study; it is also a very thin model. Thus the comparisons of experimental and theoretical results indicate that CORTES-SA gives stress distributions similar to those obtained experimentally for a thin, flush tee having a d/D ratio of 0.5. The maximum principal stresses for this model were 135 and 164 MPa (19.52 and 23.8 ksi) (a difference of 17%) for the calculated and experimental results, respectively. Both of these maximums occurred on the outside surface at the junction of the 0° section. The experimental value was obtained by a linear extrapolation to the junction (see Ref. 9).

Model ORNL-3 was the second model for which experimental and calculated stress comparisons were made. Like ORNL-1, this model is an idealized structure with no transitions, reinforcements, or fillets in the junction region, but it has a smaller d/D ratio, 0.129, and is relatively thicker, $D/T = 50$. The outside diameter of the run is 254 mm (10.0 in.) and the thickness 5.08 mm (0.2 in.); the outside diameter of the branch is 32.9 mm (1.29 in.) and the wall thickness 4.27 mm (0.168 in.). Comparisons of experimental and calculated results were made for this model primarily to investigate the capability of the computer program to predict stress distributions for models with small d/D ratios. As stated previously, the CORTES programs were initially developed to analyze ANSI B16.9 tees, which have relatively thick walls and generally have d/D ratios ranging from 0.5 to 1.0.

Figure 19 is an isometric view of the mesh generated for ORNL-3. Two elements were used through the thickness. Figure 20 shows cross-sectional views of the mesh for the 0 and 90° sections, and Figs. 21 and 22 show comparisons between calculated and experimental results for this model. Generally very good agreement between calculated and experimental stress distributions was obtained at both 0 and 90° sections. The maximum principal stresses for this model were 127 and 121 MPa (18.4 and 17.5 ksi) for the calculated and experimental results, respectively. Both of these maximums occurred on the inside surface at the junction of the 0° section. Again, the experimental value represents an extrapolated stress (see Ref. 10).

Both models, ORNL-1 and -3, are flush cylinder-to-cylinder connections with no reinforcing or fillet in the transition region. In order to investigate the capability of the computer program to predict stress distributions for tees with a reinforced transition region, comparisons between experimental and theoretical results were also made for model WC-12D, a photoelastic model that was tested by Leven⁹ at Westinghouse Research Laboratories. It has the same relative nozzle size ($d/D = 0.129$) as ORNL-3 but has the so-called standard reinforcement (see Fig. 23) as prescribed by the Code. In addition, the vessel is relatively thick-walled with a diameter-to-thickness ratio $D/T = 12.0$. The outside diameter of the run is 187 mm (7.364 in.) and the wall thickness is 13.4 mm (0.526 in.); the outside diameter of the branch is 24 mm (0.951 in.) and the wall thickness is 1.73 mm (0.068 in.).

Comparisons between experimental and calculated results are shown in Figs. 24 and 25. Good agreement between the two was obtained at both the 0 and 90° sections. The calculated results were obtained using material properties of $E = 206.8$ GPa (30×10^6 psi) and $\nu = 0.3$. An internal pressure of 1.061 MPa (153.9 psi) was used for a nominal stress of $S = 6.895$ MPa (1000 psi). Both the experimental and calculated maximum stresses occurred on the inside surface at the junction of the 0° section. The calculated maximum was 18.6 MPa (2.7 ksi) while the experimental result was 19.3 MPa (2.8 ksi).

In-depth comparisons of experimental and calculated results for three other reinforced models were made by the authors; a discussion of these

Fig. 19. Isometric view of outside surface for ORNL-3 generated mesh.

Fig. 20. Cross-sectional views of the ORNL-3 mesh for the 0 and 90° sections.

Fig. 21. Comparisons of experimental and theoretical stress distributions for 0° section of ORNL-3, internal pressure loading = 300 psi. (1 in. = 25.4 mm).

Fig. 22. Comparisons of experimental and theoretical stress distributions for 90° section of ORNL-3, internal pressure loading = 300 psi. (1 in. = 25.4 mm).

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Fig. 23. ASME Code standard reinforcement design.

models and the ones presented here may be found in Ref. 13. The comparisons for these additional models were equally good. Other comparisons may be found in Ref. 1, which is the summary report and user's manual for the CORTES package of programs. Reference 1 also gives preliminary results of a mesh-refinement study using CORTES-SA as well as background information that led to the selection of the particular finite element used in the program. In light of the results given here and in Ref. 13, CORTES-SA appears to give good comparisons with experimental data over the parameter ranges ($0.08 \leq d/D \leq 0.5$ and $10 \leq D/T \leq 100$) of this study. In addition, the mesh-generation feature of the program, the minimal amount of input required, and the extensive graphics software for both pre- and post-processing make CORTES-SA the only economically feasible analytical tool for a parameter study of this magnitude.

Fig. 24. Comparisons of photoelastic and calculated stress distributions for 0° section of WC-12D, internal pressure loading = 153.9 psi.

Fig. 25. Comparisons of photoelastic and calculated stress distributions for 90° section of WC-120, internal pressure loading = 153.8 psi.

4. THE PARAMETER STUDY

The parameter study consisted of the 25 models, shown in Table 2, all of which are within the parameter ranges $10 \leq D/T \leq 100$ and $0.08 \leq d/D \leq 0.5$. All the nozzles were designed according to one of the sketches shown in Fig. 26, which was abstracted from paragraph NB-3338.2 of the ASME Boiler and Pressure Vessel Code. The 6 U models listed in Table 2 were essentially unreinforced except for the minimum fillet (r_2) at the junction, as shown in Fig. 26a. The 14 S1 models (so-called standard reinforced) depicted in Fig. 26b and the 5 P30 models (30° pad reinforced) depicted in Fig. 26c were fully reinforced in accordance with the rules of paragraphs NB-3332 through NB-3334. All 25 models were analyzed for internal pressure loading. The primary emphasis of the study was placed on the S1 models because the standard reinforcement is most widely used at present for both nuclear pressure vessels and piping. The U and P30 models provide a relative measure of the effect of reinforcement and the shape of the reinforcement on the calculated stress distributions when compared with the appropriate S1 model results.

4.1 U Models

The U models (Table 2) were essentially unreinforced, except that a small outside fillet of radius $r_2 = T/2$ as required by paragraph NB-3338.2 was used (see Fig. 26a). This radius was taken as constant around the junction zone.

An inside diameter of 254 mm (10 in.) was chosen for these models as well as for all the other models of the study. The other dimensional quantities were then determined from the parameter ratios (see Table 3). The nozzle thickness was determined from the relation $t = (d/D)T$ or $s/S = 1$ for all the models; $s = pd/2t$ and $S = pD/2T$ are the nominal circumferential membrane stresses in the branch and run, respectively.

Models UA through UE have d/D ratios of 0.50 and D/T ratios from 10 to 100. Model UF has d/D and D/T values of 0.08 and 10, respectively.

At the outset of the study, it was realized that a multitude of finite-element meshes could be used for any one model. No detailed mesh-

Table 2. Dimensionless parameters for the study of isolated nozzles in cylindrical vessels

D/T^a	d/D^b			
	0.08	0.16	0.32	0.50
10	(0.2530) ^c UF ^d S1N ^d P30E ^d	(0.5060) S1K	(1.0119) S1H P30D	(1.5811) UE S1E e
20	(0.3578)	(0.7155)	(1.4311) P30C	(2.2361) UD S1D e
40	(0.5060)	(1.0119)	(2.0239) P30B	(3.1625) UC S1C e
80	(0.7155)	(1.4311)	(2.8622)	(4.4721) UB S1B e
100	(0.8000)	(1.600)	(3.2000) P30A	(5.0000) UA S1A e

^a D/T is the inside diameter-to-thickness ratio of the cylindrical vessel.

^b d/D is the ratio of the inside diameters in the nozzle and cylindrical vessel.

^cNumbers given in parentheses are values for the parameter $(d/D) \sqrt{D/T}$.

^dU, S1, and P30 refer to nozzle designs shown in Figs. 26a, 26b, and 26c, respectively.

^eP30 models are geometrically impossible for these parameter values.

Isometric and cross-sectional views for the 0 and 90° sections for the U models along with computer plots of stresses along and transverse to the 0 and 90° sections are given in Appendix A. The results for the U models are tabulated and discussed in Chapter 5.

Nozzle-thickening reinforcement (depicted in Figs. 26b and 27) is one of the most widely used reinforcement configurations for pressure vessel

Table 3. Dimensional parameters^a for U models (1 in. = 25.4 mm)

Model (D/T, d/D)	D (in.)	d (in.)	T (in.)	t (in.)	L _c (in.)	L _b (in.)	r ₁ (in.)	r ₂ (in.)
UA (100, 0.50)	10	5	0.1	0.05	20	20	0.05	0.05
UB (80, 0.50)	10	5	0.125	0.0625	20	20	0.0625	0.0625
UC (40, 0.50)	10	5	0.25	0.125	20	20	0.125	0.125
UD (20, 0.50)	10	5	0.50	0.25	20	20	0.25	0.25
UE (10, 0.50)	10	5	1.0	0.5	20	20	0.5	0.5
UF (10, 0.08)	10	0.8	1.0	0.08	20	20	0.5	0.5

^aD = inside diameter of the run; same for all 25 models.

d = inside diameter of the branch.

T = wall thickness of the run.

t = wall thickness of the branch.

L_c = length of the run from the intersection of the run and branch axes.

L_b = length of the branch from the intersection of the run and branch axes.

r₁ = inner transition radius (see Fig. 26a).

r₂ = outer fillet radius (see Fig. 26a).

Fig. 27. Parameters for S1 standard reinforcement designs.

design. Fourteen models of this type were investigated; the dimensions are given in Table 4 and these dimensions or parameters are identified in Fig. 27.

The rules of paragraphs NB-3332 through NB-3334 of the Code require that the total cross-sectional area of reinforcement A in any given plane for a vessel under internal pressure shall not be less than

$$A = dTF ,$$

(1)

Table 4. Dimensional parameters^a for S1 models (1 in. = 25.4 mm)

Model (D/T, d/D)	D (in.)	d (in.)	T (in.)	t (in.)	L _c (in.)	L _b (in.)	L _n (in.)	t _n (in.)	r ₁ (in.)	r ₂ (in.)
S1A (100, 0.50)	10	5	0.1	0.05	20	20	0.651	0.434	0.05	0.217
S1B (80, 0.50)	10	5	0.125	0.0625	20	20	0.7123	0.5012	0.0625	0.251
S1C (40, 0.50)	10	5	0.25	0.125	20	20	0.9487	0.7838	0.125	0.392
S1D (20, 0.50)	10	5	0.5	0.25	20	20	1.2834	1.224	0.25	0.612
S1E (10, 0.50)	10	5	1	0.5	20	20	1.7658	1.9158	0.5	0.958
S1F (40, 0.32)	10	3.2	0.25	0.08	20	20	0.7143	0.64	0.125	0.32
S1G (20, 0.32)	10	3.2	0.5	0.16	20	20	0.9662	0.988	0.25	0.494
S1H (10, 0.32)	10	3.2	1	0.32	20	20	1.9324	1.5236	0.5	0.762
S1I (40, 0.16)	10	1.6	0.25	0.04	20	20	0.4658	0.4694	0.125	0.235
S1J (20, 0.16)	10	1.6	0.5	0.08	20	20	0.6321	0.7128	0.25	0.356
S1K (10, 0.16)	10	1.6	1	0.16	20	20	0.8707	1.0788	0.5	0.539
S1L (40, 0.08)	10	0.8	0.25	0.02	20	20	0.3081	0.3446	0.125	0.172
S1M (20, 0.08)	10	0.8	0.5	0.04	20	20	0.4203	0.5158	0.25	0.258
S1N (10, 0.08)	10	0.8	1	0.08	20	20	0.6213	0.7238	0.5	0.5

^aD = inside diameter of the run.

d = inside diameter of the branch.

T = wall thickness of the run.

t = wall thickness of the branch.

L = total length of the run from the intersection of the run and branch axes.

L_c = total length of the branch from the intersection of the run and branch axes.

L_b = reinforced length in junction zone (see Fig. 27).

t_n = reinforced thickness in junction zone (see Fig. 27).

r₁ = inner transition radius (see Fig. 26b).

r₂ = outer fillet radius (see Fig. 26b).

where F is a correction factor which compensates for the variation in pressure stresses on different planes with respect to the axis of a pressure vessel. A chart for determining the value of F for any plane is given in paragraph NB-3332.2. A value of $F = 1.0$ was used in the parameter study. In terms of t_n , L_n , and t (see Fig. 27), Eq. (1) then becomes

$$A = dT = 2L_n(t_n - t) \quad (2)$$

The values for t_n and L_n were selected so that Eq. (2) was satisfied in the 0° (X-Y) plane. In other planes, L_n remained at the same distance above the vessel as in the 0° plane. Therefore, the reinforcement area was somewhat more than required in these other planes.

Paragraph NB-3334 imposes an additional restriction on L_n and hence on the shape of the reinforcement. This limitation is given by

$$2L_n \leq \sqrt{0.5(d + t_n)t_n} + r_2 \quad (3)$$

where $r_2 = \max(T/2, t_n/2)$ and is constant in all planes. Taking the upper limit on L_n , we thus have two equations involving the two unknowns, t_n and L_n , for any particular model. Equations (2) and (3) can be solved simultaneously using an iteration scheme for the values of t_n and L_n ; the results are given in Table 4 for each of the S1 models.

Appendix B gives isometric as well as cross-sectional views for the 0 and 90° sections for the S1 models. It might be pointed out here that one limitation of the CORTES-SA mesh-generation routines is that the same number of elements used through the thickness of the reinforcement region must also be used through the branch and run thicknesses. This necessarily leads to a coarser mesh in the reinforcement region than in the immediate branch and run regions, as can be seen from an examination of the figures in Appendix B. Another limitation of the program is that there is no provision for generating a fillet radius r_1 on the reinforcement top corner (see Fig. 26a). In other words, $r_1 = 0$ was used for all the S1 models in the study. Computer plots of stresses in and normal to the 0 and 90° sections are also given in Appendix B.

4.3 P30 Models

Five 30° pad reinforced models (see Figs. 26c and 28) were included in the study to investigate the influence of reinforcement shape. Four of these models have d/D ratios of 0.32, and their results can be compared directly to the corresponding S1 models. None of these models were run for d/D = 0.5 because they were geometrically impossible.

For the 30° pad models, the required reinforcement in the 0° plane [i.e., Eq. (1)] is given by the following in terms of the dimensions X and Y shown in Fig. 28:

$$A = dT = XY = 1.732X^2, \quad (4)$$

since $\theta = 30^\circ$ and $F = 1$. The height of the reinforcement triangle remained at the same distance above the vessel in the 0° plane; hence for these models the reinforcement was also somewhat more than required in the other planes. As for the S1 models, $r_2 = \max(T/2, t_n/2)$, where

$$t_n = t + \frac{2}{3}X, \quad (5)$$

and $r_3 = 0$. Radius r_2 was constant in all planes. Table 5 gives X and Y values as well as other dimensions for the triangular pad models.

Isometric views of the generated meshes for the triangular pad models are given in Appendix C. The fact that the same number of elements must be used through the thickness for the entire nozzle-to-shell attachment region led to relatively coarse, elongated elements in the triangular reinforcement region, particularly near the base of the pad. These models violated most seriously the authors' attempt to maintain "cubic" elements throughout the tees. Appendix C also gives cross-sectional views of the meshes along 0 and 90° sections and plots of longitudinal and transverse stresses for these sections. The results for these models as well as for all the models used in the study are discussed in Chapter 5.

Fig. 28. Parameters for 30° pad reinforcement designs.

Table 5. Dimensional parameters^a for P30 models (1 in. = 25.4 mm)

Model (D/T, d/D)	D (in.)	d (in.)	T (in.)	t (in.)	L _c (in.)	L _b (in.)	Y (in.)	X (in.)	r ₁ (in.)	r ₂ (in.)
P30A (100, 0.32)	10	3.2	0.1	0.032	20	20	0.7444	0.4298	0.05	0.1593
P30B (40, 0.32)	10	3.2	0.25	0.08	20	20	1.1771	0.6796	0.125	0.2665
P30C (20, 0.32)	10	3.2	0.5	0.16	20	20	1.6646	0.9611	0.25	0.4003
P30D (10, 0.32)	10	3.2	1.0	0.32	20	20	2.3543	1.3593	0.5	0.6131
P30E (10, 0.08)	10	0.8	1.0	0.08	20	20	1.1771	0.6796	0.5	0.5

^aD = inside diameter of the run.

d = inside diameter of the branch.

T = wall thickness of the run.

t = wall thickness of the branch.

L = length of the run from the intersection of the run and branch axes.

L_c = length of the branch from the intersection of the run and branch axes.

Y^b = height of reinforcement triangle (see Fig. 28).

X = base of reinforcement triangle (see Fig. 28).

r₁ = inner transition radius (see Fig. 26c).

r₂ = outer fillet radius (see Fig. 26c).

5. RESULTS AND CONCLUSIONS

This parameter study was undertaken as a first step in the assessment of existing design safety criteria and the development of improved Code rules for reinforced isolated and closely spaced nozzles in cylindrical pressure vessels. As stated earlier, the objective of this report is to summarize and present the more important and relevant results of the study. A follow-up document will relate these results to present design rules and include recommendations for improved design safety criteria for nozzles and branch connections.

The 25 models fall within the parameter ranges $0.08 \leq d/D \leq 0.50$ and $10 \leq D/T \leq 100$, ranges which include most reactor pressure vessel nozzles. The emphasis of the study was on S1, or so-called standard reinforcement designs, since these are the most widely used; P30, or 30° triangular pad reinforcement, designs were investigated in order to examine the relative effects of reinforcement shape. The U or unreinforced models were included because much of the available experimental data in the literature are for flush, unreinforced nozzle-to-cylindrical-shell attachments.

Table 6 is a summary of the algebraically largest and smallest principal stresses obtained on the outside and inside surfaces for each of the models and their locations. Table 7 gives the maximum stress intensity ($\bar{\sigma}_{\max}$) obtained on the outer and inner surfaces for each model and its location. The stress intensity at any particular node on either surface represents twice the maximum shear stress ($2\tau_{\max}$) and is given by

$$\bar{\sigma} = \max(|\sigma_1 - \sigma_2|, |\sigma_2 - \sigma_3|, |\sigma_1 - \sigma_3|),$$

where σ_1 and σ_2 represent principal stresses in a plane tangent to the surface at the particular node and σ_3 is zero for the outside surface and the negative of the internal pressure loading for the inside surface.

The internal pressure loadings were chosen such that the run hoop stress, $\sigma_h = PD/2T$ (thin shells), would equal 6.8948 MPa (1 ksi) in regions removed from the junction. Hence, the values in the tables represent normalized values. A Young's modulus of 206.8 GPa (30×10^6 psi) and a Poisson's ratio of 0.3 were used for all models. The locations of the maximum and minimum stresses are given both in terms of the number of

Table 6. Summary of largest and smallest principal stresses
(1 psi = 6.895 × 10³ Pa; 1 ksi = 6.895 MPa)

Model (D/T, d/D) ^{a,b}	No. elements through thickness	Internal pressure load (psi)	Outside surface			Inside surface		
			$\sigma_{\max}$ (ksi)	$\sigma_{\min}$ (ksi)	Location ^c	$\sigma_{\max}$ (ksi)	$\sigma_{\min}$ (ksi)	Location
UA (100, 0.50)	1	20	7.547	-0.796	5-0-0-0-0 (2.565, 5.115, 0.0) 0-0-0-1-3 (2.655, 4.599, 2.206)	5.036	-3.206	5-0-0-0-0 (2.515, 5.015, 0.0) 5-1-0-0-0 (2.501, 5.176, 0.0)
UB (80, 0.50)	1	25	6.943	-0.707	5-0-0-0-0 (2.582, 5.144, 0.0) 0-0-0-1-3 (2.660, 4.621, 2.218)	4.891	-3.124	5-0-0-0-0 (2.519, 5.019, 0.0) 5-1-0-0-0 (2.501, 5.179, 0.0)
UC (40, 0.50)	2	50	4.953	-0.562	5-0-0-0-0 (2.662, 5.187, 0.0) 0-4-5-0-0 (0.0, 5.519, 2.625)	4.630	-1.660	5-0-0-0-0 (2.537, 5.037, 0.0) 0-1-5-0-0 (0.0, 4.617, 2.501)
UD (20, 0.50)	2	100	3.179	-0.463	5-0-0-0-0 (2.824, 5.574, 0.0) 0-4-5-0-0 (0.0, 6.260, 2.751)	4.374	-1.477	5-0-0-0-0 (2.575, 5.074, 0.0) 0-1-5-0-0 (0.0, 4.789, 2.502)
UE (10, 0.50)	4	200	2.188	-0.218	0-0-1-0-0 (0.480, 5.263, 3.027) 0-4-5-0-0 (0.0, 7.077, 3.001)	4.567	-1.016	5-0-0-0-0 (2.649, 5.118, 0.0) 0-2-5-0-0 (0.0, 5.576, 2.502)
UF (10, 0.08)	4	200	1.168	0.054	0-0-0-1-2 (0.674, 5.975, 0.557) 3-0-0-0-0 (0.614, 6.145, 0.122)	3.303	-0.252	4-1-0-0-0 (0.407, 5.423, 0.0) 0-2-1-0-0 (0.0, 5.717, 0.401)
S1A (100, 0.50)	1	20	1.693	-0.711	0-0-3-2-0 (0.915, 3.975, 3.200) 0-6-5-0-0 (0.0, 6.200, 2.550)	2.381	-0.452	5-0-0-0-0 (2.516, 5.016, 0.0) 0-8-5-0-0 (0.0, 6.803, 2.500)
S1B (80, 0.50)	1	25	1.773	-0.731	0-0-3-2-0 (0.937, 3.949, 3.270) 0-6-5-0-0 (0.0, 6.300, 2.563)	2.503	-0.433	5-0-0-0-0 (2.519, 5.020, 0.0) 0-0-1-1-0 (1.477, 4.386, 2.106)
S1C (40, 0.50)	2	50	1.906	-0.623	0-0-5-2-0 (0.0, 3.787, 3.641) 0-6-5-0-0 (0.0, 6.900, 2.625)	2.773	-0.302	5-0-0-0-0 (2.538, 5.038, 0.0) 0-0-2-2-0 (1.145, 4.029, 2.966)
S1D (20, 0.50)	3	100	2.057	-0.458	0-0-5-1-0 (0.0, 3.875, 3.909) 2-5-0-0-0 (2.779, 7.388, 1.416)	2.994	-0.259	5-0-0-0-0 (2.575, 5.075, 0.0) 0-0-3-3-0 (0.784, 3.583, 3.493)
S1E (10, 0.50)	4	200	2.054	-0.306	0-0-5-1-0 (0.0, 3.833, 4.624) 1-5-0-0-0 (2.908, 8.587, 2.113)	3.165	-0.114	5-0-0-0-0 (2.550, 5.149, 0.0) 0-0-2-0-0 (1.170, 4.533, 2.297)
S1F (40, 0.32)	2	50	1.551	-0.625	0-0-3-2-0 (0.708, 4.513, 2.687) 2-5-0-0-0 (1.636, 6.368, 0.834)	2.733	-0.133	5-0-0-0-0 (1.638, 5.038, 0.0) 0-0-1-2-0 (0.957, 4.518, 2.147)
S1G (20, 0.32)	3	100	1.553	-0.445	0-0-5-1-0 (0.0, 4.689, 2.882) 2-5-0-0-0 (1.836, 6.993, 0.936)	2.872	-0.063	5-0-0-0-0 (1.675, 5.075, 0.0) 0-0-2-0-0 (0.750, 4.835, 1.472)
S1H (10, 0.32)	4	200	1.607	-0.301	0-0-5-1-0 (0.0, 4.918, 3.443) 0-5-0-0-0 (1.656, 8.111, 1.656)	3.049	-0.111	5-0-0-0-0 (1.749, 5.149, 0.0) 0-0-2-0-0 (0.771, 4.876, 1.515)

Table 6 (continued)

Model (D/T, d/b) ^{a,b}	No. elements through thickness	Internal pressure load (psi)	Outside surface			Inside surface		
			σ_{max} (ksi)	σ_{min} (ksi)	Location ^d	σ_{max} (ksi)	σ_{min} (ksi)	Location
SII (40, 0.16)	2	50	1.320	-0.517	0-0-1-2-0 (0.735, 5.046, 1.454) 2-5-0-0-0 (0.868, 6.046, 0.359)	2.598	-0.028	1-0-0-0-0 (0.838, 5.038, 0.0) 0-1-3-0-0 (0.156, 5.166, 0.786)
SIJ (20, 0.16)	3	100	1.321	-0.371	0-0-2-2-0 (0.607, 5.170, 1.880) 1-5-0-0-0 (0.883, 6.583, 0.590)	2.706	-0.030	4-0-0-0-0 (0.875, 5.074, 0.0) 0-1-4-0-0 (0.0, 5.279, 0.801)
SIK (10, 0.16)	4	200	1.312	-0.249	0-0-4-1-0 (0.0, 5.584, 2.204) 0-5-0-0-0 (0.891, 7.489, 0.891)	2.878	-0.124	4-0-0-0-0 (0.948, 5.148, 0.0) 0-1-4-0-0 (0.0, 5.477, 0.802)
SIL (40, 0.08)	2	50	1.265	-0.361	0-0-1-2-0 (0.438, 5.170, 0.919) 1-5-0-0-0 (0.422, 5.795, 0.282)	2.509	-0.046	4-0-0-0-0 (0.437, 5.037, 0.0) 0-1-4-0-0 (0.0, 5.156, 0.401)
SIM (20, 0.08)	3	100	1.210	-0.263	0-0-2-2-0 (0.374, 5.365, 1.219) 1-5-0-0-0 (0.484, 6.254, 0.323)	2.619	-0.071	4-0-0-0-0 (0.474, 5.074, 0.0) 0-1-4-0-0 (0.0, 5.259, 0.401)
SIN (10, 0.08)	4	200	1.247	-0.179	0-0-4-1-0 (0.0, 5.847, 1.365) 0-5-4-0-0 (0.0, 7.074, 0.671)	2.976	-0.129	4-1-0-0-0 (0.402, 5.474, 0.0) 0-1-4-0-0 (0.0, 5.447, 0.402)
P30A (100, 0.32)	1	20	2.037	-0.692	0-0-5-3-0 (0.0, 4.150, 2.970) 3-5-0-0-0 (1.623, 5.715, 0.527)	2.574	-0.174	5-0-0-0-0 (1.615, 5.016, 0.0) 0-0-3-0-0 (0.498, 4.772, 1.532)
P30B (40, 0.32)	2	50	1.945	-0.529	0-0-5-2-0 (0.0, 4.169, 3.196) 3-4-0-0-0 (1.821, 6.021, 0.592)	2.860	-0.109	5-0-0-0-0 (1.638, 5.038, 0.0) 0-0-3-0-0 (0.502, 4.784, 1.546)
P30C (20, 0.32)	3	100	1.989	-0.434	0-0-5-1-0 (0.0, 4.200, 3.556) 2-4-0-0-0 (1.877, 6.565, 0.956)	2.935	-0.027	5-0-0-0-0 (1.675, 5.075, 0.0) 0-0-2-0-0 (0.750, 4.835, 1.472)
P30D (10, 0.32)	4	200	1.652	-0.275	0-0-5-1-0 (0.0, 3.956, 4.517) 1-4-0-0-0 (1.973, 7.455, 1.434)	3.009	-0.042	5-0-0-0-0 (1.749, 5.149, 0.0) 0-0-1-0-0 (1.002, 4.920, 1.380)
P30E (10, 0.08)	4	200	1.195	-0.188	0-0-4-1-0 (0.0, 5.818, 1.475) 4-3-0-0-0 (0.813, 6.601, 0.0)	3.058	-0.170	4-1-0-0-0 (0.404, 5.453, 0.0) 0-2-4-0-0 (0.0, 5.776, 0.401)

^aD and d are inside diameters of run and branch, respectively.

^bYoung's modulus E = 206.8 GPa (30 × 10⁶ psi); Poisson's ratio ν = 0.3 for all models.

^cPressure load used such that the run hoop stress σ_h = PD/2T = 1 ksi.

^dLocation is given by A1-A2-A3-A4-A5 (X, Y, Z), where A1 through A5 represent the number of divisions along each of the respective axes and X, Y, and Z are the global coordinates of the model point (see text).

Table 7. Summary of maximum stress intensities^a

Model (D/T, d/D)	No. elements through thickness	Internal pressure load (psi)	Outside surface		Inside surface	
			$\sigma_{\max}$ (ksi)	Location	$\sigma_{\max}$ (ksi)	Location
UA (100, 0.50)	1	20	7.547	5-0-0-0-0 (2.565, 5.115, 0.0)	8.221	5-1-0-0-0 (2.501, 5.176, 0.0)
UB (80, 0.50)	1	25	6.943	5-0-0-0-0 (2.582, 5.114, 0.0)	7.877	5-1-0-0-0 (2.501, 5.179, 0.0)
UC (40, 0.50)	2	50	4.953	5-0-0-0-0 (2.662, 5.287, 0.0)	5.583	5-1-0-0-0 (2.501, 5.190, 0.0)
UD (20, 0.50)	2	100	3.179	5-0-0-0-0 (2.824, 5.574, 0.0)	4.474	5-0-0-0-0 (2.575, 5.074, 0.0)
UE (10, 0.50)	4	200	2.188	0-0-4-0-0 (0.480, 5.263, 3.027)	1.567	5-0-0-0-0 (2.649, 5.148, 0.0)
UF (10, 0.08)	4	200	1.168	0-0-0-1-2 (0.674, 5.975, 0.557)	3.503	4-1-0-0-0 (0.407, 5.423, 0.0)
S1A (100, 0.50)	1	20	1.693	0-0-3-2-0 (0.915, 3.975, 3.200)	2.401	5-0-0-0-0 (2.516, 5.016, 0.0)
S1B (80, 0.50)	1	25	1.773	0-0-3-2-0 (0.937, 3.949, 3.270)	2.528	5-0-0-0-0 (2.519, 5.020, 0.0)
S1C (40, 0.50)	2	50	1.906	0-0-5-2-0 (0.0, 3.787, 3.641)	2.823	5-0-0-0-0 (2.538, 5.038, 0.0)
S1D (20, 0.50)	3	100	2.057	0-0-5-1-0 (0.0, 3.875, 3.909)	3.094	5-0-0-0-0 (2.575, 5.075, 0.0)
S1E (10, 0.50)	4	200	2.054	0-0-5-1-0 (0.0, 3.833, 4.624)	3.165	5-0-0-0-0 (2.650, 5.149, 0.0)
S1F (40, 0.32)	2	50	1.551	0-0-3-2-0 (0.708, 4.513, 2.687)	2.783	5-0-0-0-0 (1.638, 5.038, 0.0)
S1G (20, 0.32)	3	100	1.553	0-0-5-1-0 (0.0, 4.689, 2.882)	2.972	5-0-0-0-0 (1.675, 5.075, 0.0)
S1H (10, 0.32)	4	200	1.607	0-0-5-1-0 (0.0, 4.918, 3.443)	3.249	5-0-0-0-0 (1.749, 5.149, 0.0)
S1I (40, 0.16)	2	50	1.390	0-0-1-2-0 (0.735, 5.046, 1.454)	2.648	4-0-0-0-0 (0.838, 5.038, 0.0)
S1J (20, 0.16)	3	100	1.321	0-0-2-2-0 (0.607, 5.170, 1.380)	2.806	4-0-0-0-0 (0.875, 5.074, 0.0)
S1K (10, 0.16)	4	200	1.312	0-0-4-1-0 (0.0, 5.584, 2.204)	3.078	4-0-0-0-0 (0.948, 5.148, 0.0)
S1L (40, 0.08)	2	50	1.265	0-0-1-2-0 (0.438, 5.170, 0.919)	2.559	4-0-0-0-0 (0.437, 5.037, 0.0)
S1M (20, 0.08)	3	100	1.210	0-0-2-2-0 (0.374, 5.365, 1.219)	2.719	4-0-0-0-0 (0.474, 5.074, 0.0)
S1N (10, 0.08)	4	200	1.247	0-0-4-1-0 (0.0, 5.847, 1.365)	3.176	4-1-0-0-0 (0.402, 5.474, 0.0)
P30A (100, 0.32)	1	20	2.037	0-0-5-3-0 (0.0, 4.150, 2.970)	2.594	5-0-0-0-0 (1.615, 5.016, 0.0)
P30B (40, 0.32)	2	50	1.945	0-0-5-2-0 (0.0, 4.169, 3.196)	2.910	5-0-0-0-0 (1.638, 5.038, 0.0)
P30C (20, 0.32)	3	100	1.989	0-0-5-1-0 (0.0, 4.200, 3.556)	3.035	5-0-0-0-0 (1.675, 5.075, 0.0)
P30D (10, 0.32)	4	200	1.652	0-0-5-1-0 (0.0, 3.956, 4.517)	3.209	5-0-0-0-0 (1.749, 5.149, 0.0)
P30E (10, 0.08)	4	200	1.195	0-0-4-1-0 (0.0, 5.818, 1.475)	3.258	4-1-0-0-0 (0.404, 5.453, 0.0)

^aSee Table 6 for conversions to SI units.

divisions along axes A1 through A5 and the global coordinates (see Figs. 1 and 4). The first identification locates the node with respect to the isometric views of the meshes given in Appendices A, B, and C; the latter determines the relative location of the node on the model when used in conjunction with the dimensional data for each model.

Table 7 indicates that the largest values of stress intensity were found on the inside surface of the 0° section either at or very near the junction for every model in the study. This result was anticipated at the outset of the study since the 0° section represents the sharpest geometric transition. For the reinforced S1 and P30 models, the maximum stress intensities generally increased with smaller D/T values for a given d/D value. The opposite trend holds for the unreinforced U models; the maximum stress intensities decreased with smaller D/T values for the only d/D value (0.50) investigated. A further examination of the S1 models in Table 7 reveals that the maximum stress intensities decreased somewhat with decreasing d/D values for a given D/T value.

The highest stress intensity obtained in the study was 56.684 MPa (8.221 ksi) for the unreinforced model UA ($D/T = 100$, $d/D = 0.50$). For the reinforced S1 and P30 models, the highest stress intensities obtained were 22.402 MPa (3.249 ksi) and 22.464 MPa (3.258 ksi), respectively. These values were obtained for models S1H ($D/T = 10$, $d/D = 0.32$) and P30E ($D/T = 10$, $d/D = 0.08$).

The effects of reinforcement can be observed by comparing the results for the S1 and P30 models with the corresponding U models. A 71% reduction in the maximum stress intensity was obtained for model S1A relative to model UA. This trend is observed for all the S1 models, although the percentage reduction is not as great. In fact, only 31% reduction was obtained for model S1E relative to model UE. There appears to be little difference, less than 5%, in the maximum stress intensities obtained for corresponding S1 and P30 models.

The results of this parameter study indicate that the reinforcement designs of Subsections NB-3330 through NB-3338, Section III, of the Code significantly reduce the maximum stresses in nozzle-to-cylinder attachments under internal pressure loading. However, it is not apparent from these results that standard reinforcement offers a significant advantage

over 30° pad reinforcement. For the models investigated, both types of reinforcement gave very nearly the same maximum stresses.

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P. G. Fowler, Computer Sciences Division, UCC-ND, wrote all the plotting routines for the CORTES package of programs. The help of B. D. Nelson, also of the Computer Sciences Division, in generating input and executing the computer program is very much appreciated.

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APPENDICES

INTRODUCTION

The results of the parameter study are presented graphically in three appendices, one for each type of model design, and also in tabular format on microfiche. Appendices A, B, and C contain isometric and cross-sectional views of the meshes used for each model and plots of longitudinal and transverse stresses on the outside and inside surfaces for the 0 and 90° sections (see Fig. 15) for the U, S1, and P30 models, respectively. The nodal coordinates, principal stresses and their direction cosines, stress intensity, and displacements for each node on the outside and inside surfaces are tabulated on microfiche.

The results for the models are presented in the appendices in the order given in Table 6. Isometric views of the outside surface for each model are presented first, followed by both undeformed and deformed cross-sectional views in the X-Y (0°) and Y-Z (90°) planes. The deformed cross-sectional views have been greatly exaggerated so that the displacement configuration may be clearly seen. The maximum X, Y, or Z component of displacement obtained on the model was set equal to 25.4 mm (1 in.), and all other components of displacement for each node on the model were multiplied by a factor determined from the above. Only corresponding nodes on the outside and inside surfaces are shown in the deformed sections; the interior nodes have been omitted for clarity. Also, only the junction regions of the models are shown. The cross-sectional views are followed by plots of longitudinal and transverse stresses on the outside and inside surfaces for these same cross sections. The reference points A through F appearing on these figures are identified on the preceding isometric mesh plots. For the X-Y (0°) section, the abscissa XP is a projected value (see Fig. 10); for the Y-Z (90°) section, the abscissa Y is the global coordinate value.

A hard-copy tabulation of all data obtained in the study would be impractical due to cost and size of the report. Therefore, microfiche was used, and only the coordinates, principal stresses (psi) and their direction cosines, the stress intensity (psi), and the displacements (in.) for each nodal point on the outer and inner surfaces are given. All quantities

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tabulated and plotted in the appendices represent normalized values (see Table 6). The stress intensity reported here represents twice the maximum shear stress ($2\tau_{\max}$) and is defined by

$$\bar{\sigma} = \max (|\sigma_1 - \sigma_2|, |\sigma_2 - \sigma_3|, |\sigma_1 - \sigma_3|) ,$$

where $\sigma_1 = \sigma_{\max}$, $\sigma_2 = \sigma_{\min}$, and $\sigma_3 = 0$ on the outside surface and $-P$ on the inside surface. The results are tabulated in ascending nodal order according to the node numbering scheme illustrated in Fig. 5. In addition, a five-column identification (A1-A2-A3-A4-A5), each of which gives the number of divisions along the respective axis, is provided for each node (see Fig. 4). Results for nodes located on the end caps are not given, since an artificially large modulus of elasticity was assigned to the end cap elements to represent stiff diaphragms.

Appendix A

U MODELS

ORNL-DWG 78-11336

MODEL UA (100,0.5), INTERNAL PRESSURE

OUTER SURFACE

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

MODEL UA 0 DEG

ORNL-DWG 78-11381A

MODEL UA 90 DEG

ORNL-DWG 78-11283A

MODEL UA 90 DEG

ORNL-DWG 76-11264R

MODEL UB (80,0.5) . INTERNAL PRESSURE

OUTER SURFACE

ORNL-DWG 76-1773

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

MODEL UB 0 DEG

ORNL-DWG 78-1138R

ORNL-DWG 76-1138A

MODEL UB 0 DEG

MODEL UB 90 DEG

ORNL-DWG 78-11387A

MODEL UB 90 DEG

ORNL-DWG 78-11388R

ORNL-DWG 76-11338

MODEL UC (40.0.5), INTERNAL PRESSURE

OUTER SURFACE

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

MODEL UC 0 DEG

ORNL-DWG 78-11389A

MODEL UC 0 DEG

ORNL-DWG 76-11370R

MODEL UC 90 DEG

ORNL-DWG 78-11271R

ORNL-DWG 78-11372R

MODEL UC 90 DEG

ORNL-DWG 76-1133B

MODEL UD (20,0.5), INTERNAL PRESSURE

OUTER SURFACE

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

MODEL U7 0 DEG

ORNL-ORR 78-11772R

MODEL UD 90 DEG

ORNL-SDO 73-1170R

ORNL-DWG 76-11360

MODEL UE (10,0.5), INTERNAL PRESSURE

OUTER SURFACE

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

DAHL-CRAG 76-112000

ORNL-DWG 78-11341

MODEL UF (10,0.08), INTERNAL PRESSURE

OUTER SURFACE

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

MODEL UF 0 DEG

ORNL-DWG 78-11382R

MODEL UP 90 DEG

ORNL-DWG 78-11284R

Appendix B**S1 MODELS**

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ORNL-DWG 78-11342

MODEL S1A (100,0.5), INTERNAL PRESSURE

OUTER SURFACE

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

CNAI-DWG 76-1128A

MODEL S1A 0 DEG

ORNL-ORNL 75-11200A

MODEL S1A

90 DEG

ORNL-DWG 70-11287A

MODEL S1A

90 DEG

ORNL-SWS 75-11288R

ORNL-DWG 78-11343

MODEL S18 (80,0.5), INTERNAL PRESSURE

OUTER SURFACE

ORNL-DWG 76-17740

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

MODEL S18

0 DEG

ORNL-DWG 75-11259

GRAPH - CARD 76-11200A

MODEL S1B

90 DEG

ORNL-DWG 78-11801R

ORNL-DWG 78-11344

MODEL S1C (40.0.5), INTERNAL PRESSURE

OUTER SURFACE

ORNL-DWG 76-17741

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

CIVIL-800 76-11-0000

MODEL SIC 0 DEG

MODEL SIC

0 DEG

ORNL-DWG 78-11384R

MODEL S1C

90 DEG

ORNL-DWG 76-11888

CMM-000 76-11200A

MODEL S10 (20.0.5), INTERNAL PRESSURE

OUTER SURFACE

ORNL-DWG 76-17742

UNDEFORMED AND DEFORMED CROSS-SECTIONA. WS

MODEL S1D

0 DEG

ORNL-DWG 78-11287A

ORNL-DWG 78-1120A

MODEL S1D

90 DEG

ORNL-DWG 78-11380A

MODEL S1D 90 DEG

ORNL-DWG 78-11489R

ORNL-DWG 76-11348

MODEL S1E (10.0.5), INTERNAL PRESSURE

OUTER SURFACE

ORNL-DWG 76-17743

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

ORNL-CORR 75-11401R

MODEL S1E

0 DEG

ORNL-DWG 78-11482R

CONE-000 75-11000

MODEL S1E 90 DEG

MODEL S1E

90 DEG

ORNL-DWG 78-11494R

ORNL-DWG 78-11347

MODEL S1F (40,0.32), INTERNAL PRESSURE

OUTER SURFACE

ORNL-DWG 76-17744

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

MODEL S1F

0 DEG

ORNL-DWG 70-114850

MODEL S1F

90 DEG

ORNL-DWG 78-11487A

MODEL S1F

90 DEG

OANL-DWG 76-11408A

MODEL S1G (20.0.32) . INTERNAL PRESSURE

OUTER SURFACE

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS'

MODEL SIG

0 DEG

ORNL-DWG 75-11459R

MODEL SIG

90 DEG

ORNL-DWG 78-114119

MODEL SIG

90 DEG

ORNL-DWG 78-114129

MODEL S1H (10,0.32), INTERNAL PRESSURE

OUTER SURFACE

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

MODEL S1H

0 DEG

ORNL-DWG 78-11413A

ORNL-DWG 78-1114R

MODEL S1H 0 DEG

MODEL S1H

90 DEG

ORNL-DWG 76-11410A

MODEL S11 (40,0.16), INTERNAL PRESSURE

OUTER SURFACE

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

OAKL-DRG 70-11417A

ORNL-OWB 78-11418R

MODEL S11 0 DEG

MODEL S11

90 DEG

ORNL-DWG 71-11498

ORNL-CR-70-11000

MODEL S11 90 DEG

MODEL S1J (20.0.16), INTERNAL PRESSURE

OUTER SURFACE

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

ORNL-DWG 76-17748

ONAL-8888 74-114338

MODEL SLJ 90 DEG

ORNL-DWG 78-11034R

MODEL SIJ 90 DEG

MODEL S1K (10,0.16), INTERNAL PRESSURE

OUTER SURFACE

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

0.00E+00 1.00E-01 1.00E-03

ORNL-DWG 78-11628R

MODEL SIK 0 DEG

CONV-DWG NO-11427R

MODEL S1K 90 DEG

ORNL-CONF PG-1143M

MODEL S1K 90 DEG

MODEL S1L (40,0.08), INTERNAL PRESSURE

OUTER SURFACE

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

CONT-STEP 75-11000

MODEL S1L 0 DEG

CONT.-SHEET 25-114077A

MODEL S1L 90 DEG

MODEL S1L

90 DEG

ORNL-DWG 78-11422R

MODEL S1M (20,0.08), INTERNAL PRESSURE

OUTER SURFACE

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

MODEL SIM

0 DEG

ORNL-DWG 76-11433R

MODEL SIM

0 DEG

ORNL-DWG 78-11434R

MODEL SIM

90 DEG

ORNL-DWG 78-11438A

MODEL SIN (10,0.08), INTERNAL PRESSURE

OUTER SURFACE

ORNL-DWG 76-17752

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

MODEL SIN

0 DEG

ORNL-DWG 75-11407R

MODEL SIN

0 DEG

ORNL-DW8 78-114280

DRAST-ONE 78-114000

MODEL S1N 90 DEG

MODEL S1N

90 DEG

ORNL-DWG 78-11400A

Appendix C

P30 MODELS

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MODEL P30A (100,0.32), INTERNAL PRESSURE

OUTER SURFACE

ORNL-DWG 76-17753

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

MODEL P30A

0 DEG

ORNL-ORW 79-11441A

MODEL P30A

0 DEG

ORNL-DWG 78-1142A

MODEL P30A

90 DEG

ORNL-DWG 76-11443R

MODEL P30A

90 DEG

ORNL-DWG 78-11444R

ORNL-DWG 78-11357

MODEL P308 (40,0.32), INTERNAL PRESSURE

OUTER SURFACE

ORNL-DWG 76-17754

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

ORNL-DWG 78-1146A

MODEL P30B 0 DEG

ORNL-DWG 78-11446A

MODEL P308 0 DEG

MODEL P308

90 DEG

ORNL-DWG 78-11448R

ORNL-DWG 76-11358

MODEL P30C (20,0.32), INTERNAL PRESSURE

OUTER SURFACE

ORNL-DWG 76-17755

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

MODEL P30C

0 DEG

ORNL-ORW 78-11440R

MODEL P30C

0 DEG

ORNL-DWG 78-11460A

MODEL P30C

90 DEG

ORNL-DWG 78-11481A

MODEL P300 (10,0.32), INTERNAL PRESSURE

OUTER SURFACE

ORNL-DWG 76-17756

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

MODEL P300

0 DEG

ORNL-DWG 78-11464A

MODEL P300

90 DEG

ORNL-DWG 70-11480A

MODEL P300

90 DEG

ORNL-DWG 78-11468A

ORNL-DWG 78-11380

MODEL P30E (10,0.08), INTERNAL PRESSURE

OUTER SURFACE

ORNL-DWG 76-17757

UNDEFORMED AND DEFORMED CROSS-SECTIONAL VIEWS

MODEL P30E

0 DEG

ORNL-DWG 78-11487R

MODEL P30E

0 DEG

ORNL-DWG 78-11488A

MODEL P30E

90 DEG

ORNL-DWG 76-11488R