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CONTRIBUTIONS OF THE ORNL PIPING PROGRAM TO NUCLEAR
PIPING DESIGN CODES AND STANDARDS*

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Summary

The ORNL Piping Program was conceived and established to develop basic information on the structural behavior of nuclear power plant piping components, or products, and to prepare this information in forms suitable for use in design analysis and codes and standards. One of the objectives was to develop and qualify stress indices and flexibility factors for direct use in Code-prescribed design analysis methods.

In January 1967, when the Laboratory was first asked to participate in this developmental effort, work had been underway for several years under the B31.7 Committee of the American Standards Association** to produce a nuclear piping system code. Up to that time, nuclear piping had been designed according to the rules of ASA B31.1 for pressure piping.¹ Like earlier pressure vessel codes the piping code was based largely on the concept of "design by rule," with a major emphasis placed on prevention of fatigue failure from cyclic expansion stresses. When the ASME nuclear pressure vessel code² was issued in 1965, however, there was a great deal of pressure to produce a comparable code for nuclear system piping; especially that portion of the piping that was judged to be critical for the safe operation of the plant.

In parallel with the ASME nuclear vessel code, the new nuclear piping code was to be based on the concept of "design by analysis," which in principle enables a designer to limit the maximum stresses everywhere in the structure.³ To implement this philosophy one must perform a rather detailed stress analysis, and for pressure vessel design the code provides rules and design criteria that enables the designer to do the required analyses. The cost for this type of stress analysis is considerably higher than required under the old rules, but since one knows more about the stresses in the structure, greater assurance for a safe design can be achieved even with higher allowable stresses.

To apply the philosophy of design by analysis to piping systems, however, introduced several unique problems. First, because many piping system components like tees and elbows are geometrically complicated, the state-of-the-art for performing the analysis was less well advanced than for pressure

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vessel components. Second, piping systems are made up of many parts whose individual cost is small relative to the total cost of the piping system, and a detailed stress analysis for each component could easily cost more than the initial purchase price. Third, the concept of design by analysis was almost completely foreign to most of the designers who would be required to implement a new code.

There was a clear need for a prescribed stress analysis method that was simple to use, cost effective, and if not entirely accurate was at least conservative. To satisfy these requirements the B31.7 Committee adapted the stress-limit criteria of the vessel code to piping system design, shown graphically in Fig. 1, and introduced the simplified or "stress-index method" of analysis. Conservative algebraic equivalents to the stress limits of the so-called hopper diagram of Fig. 1 are shown in Fig. 2. Code Eq. (9), for example, represents the allowable stress limit ($1.5S_m$) on the sum of primary membrane plus primary bending stress intensity, where stress intensity is defined as the absolute value of the difference between the maximum and minimum principal stresses. Each term in the equations represents a nominal stress multiplied by a coefficient or "stress index." The B, C, and K's are unique stress indices associated with each type of piping component, and represent the maximum stress intensity anywhere in the component due to a particular type of loading. Loadings considered most important for piping system design are internal pressure P, external bending moments M_i applied by the connecting pipe, and thermal gradients either through the wall thickness ΔT or between components ($T_a - T_b$). The assumption that the terms add directly, even though the maximum stress intensities from the different loadings may not occur at the same position in the component or be oriented in the same direction, guarantees a certain degree of conservatism.

When Oak Ridge was brought into the program, the greatest need was to provide information needed for the development of the stress indices; and two important facts made the job feasible. First, the general shape and dimensions of a number of commonly used piping products are more or less standardized. For many years piping products had been manufactured according to dimensional standards developed by the American National Standards Institute (ANSI) and by the Manufacturers Standards Society (MSS). Although these standards do not give dimensional requirements for some of the details that are important for stress analysis, they do provide overall dimensions as illustrated in the upper part of Fig. 3 for a concentric reducer, so that ranges of important parameters can be studied (such as those shown in the lower part of Fig. 3).

Second, a significant body of literature existed that could be used in the development of stress indices. For some types of fittings the literature was extensive, while for others it was virtually nonexistent. To collect and evaluate this literature we initiated a literature survey study which was published as a AEC document in 1970 (Ref. 4). Over 800 references were identified and evaluated. Using this study as background, we selected the components listed in Fig. 4 for analytical studies. Extensive experimental data and/or analytical development was required for other components.

While the program work was getting underway, however, the B31.7 Committee was under heavy pressure to issue a Code document, and the analysis section required the use of stress indices. Working under subcontract to ORNL, Mr. E. C. Rodabaugh of Battelle Memorial Institute put together a set of about 90 stress indices for the most commonly used component, as shown in Fig. 5, in less than 6 months; and the B31.7 code⁵ was issued for trial use and comment in February 1968.

These early stress indices were based largely on engineering judgment, and a large portion of the ORNL Piping Program work since then has been directed toward insuring that the stress indices are adequate but not overly conservative, as well as providing stress indices and methods of analysis for components not originally covered. Subsection NB of the present ASME Code⁶ now contains 126 stress indices (see Fig. 6) for the simplified stress-index analysis, as well as indices for more detailed analysis of elbows and branch connections. Most of these are now supported by detailed studies of the type described in the previous paper.

Figure 6 is from the latest published Addenda⁷ to the Code. Since then the Code has adopted new indices for concentric reducers that were developed under the ORNL Piping Program.⁸ The indices C_1 and K_1 for pressure loading and C_2 and K_2 for moment loading that are currently in use are given as constants to represent conservative upper bounds. The ORNL study, however, showed that for certain dimensional parameters the current indices are unconservative, while for others; including the most commonly used reducers, the indices are overly conservative. The new indices were developed as relatively simple parametric equations, and will be given in the Code as footnotes to Table NB-3683.2-1.

A more recent development is a simplified method of analysis for integral attachments (or lugs) to straight pipe.^{9,10} For these components, transverse shear and thrust loads are important, and it was therefore necessary to expand the relatively simple equations of the Code as well as to supply new stress indices. This analysis method is currently working its way through the ASME Code committees, and if adopted, will be issued as a Code Case early next year.

In addition to the simplified methods of analysis, the ORNL Piping Program has also provided qualified methods for more detailed stress analysis under the rules of Paragraph NB-3200 of the Code. Under some conditions, elbows or tees may not pass the Code stress criteria using the more conservative stress-index analysis methods. For these cases, computer codes such as ELBOW,¹¹ CURT-II,¹² CORTES,¹³ and LUGS⁹ may enable the designer to calculate more accurate stresses and flexibilities, and thus qualify the design. These computer codes are now available through the Argonne Code Center.

Future work now being conducted under NRC-RSR sponsorship includes development of improved stress indices and flexibility factors for elbows, tees, and branch connections; development of Code rules for socket-welding fittings; and publication of ten reports on work essentially completed (see Fig. 7).

References

1. American Standard Code for Pressure Piping, ASA B31.1-1955, American Society of Mechanical Engineers, New York, 1955.
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3. Criteria of Section III of the ASME Boiler and Pressure Vessel Code for Nuclear Vessels, American Society of Mechanical Engineers, New York, 1963.
4. E. C. Rodabaugh and A. G. Pickett, Survey Report on Structural Design of Piping Systems and Components, TID-25553, December 1970.
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9. W. G. Dodge, Secondary Stress Indices for Integral Attachments to Straight Pipe, ORNL-TM-3476, June 1973; also in Welding Research Council Bulletin 198, September 1974.
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12. R. C. Gwaltney, CURT-II - A Computer Program for Analyzing Curved Tubes or Elbows and Attached Pipes with Symmetric and Unsymmetric Loadings, ORNL-TM-4646, October 1974.
13. A. N. Gantayat and G. H. Powell, Stress Analysis of Tee Joints by the Finite Element Method, University of California Report UC-SESM-73-6, ORNL-Sub-3193-1, February 1973.

TABLE F-104. STRESS CATEGORIES AND LIMITS OF STRESS INTENSITY

STRESS CATEGORY	PRIMARY			SECONDARY		PEAK
	GENERAL MEMBRANE	LOCAL MEMBRANE	BENDING	EXPANSION	MEMBRANE PLUS BENDING	
DESCRIPTION (FOR EXAMPLES SEE TABLE F-103)	AVERAGE PRIMARY STRESS ACROSS SOLID SECTION. EXCLUDES EFFECTS OF DISCONTINUITIES AND CONCENTRATIONS, PRODUCED BY PRESSURE AND MECHANICAL LOADS.	AVERAGE STRESS ACROSS ANY SOLID SECTION. CONSIDERS EFFECTS OF DISCONTINUITIES BUT NOT CONCENTRATIONS, PRODUCED BY PRESSURE AND MECHANICAL LOADS, INCLUDING INERTIA EARTHQUAKE EFFECTS.	COMPONENT OF PRIMARY STRESS PROPORTIONAL TO DISTANCE FROM CENTROID OF SECTION. EXCLUDES EFFECTS OF DISCONTINUITIES AND CONCENTRATIONS, PRODUCED BY PRESSURE AND MECHANICAL LOADS, INCLUDING INERTIA EARTHQUAKE EFFECTS.	STRESSES WHICH RESULT FROM THE CONSTRAINT OF FREE END DISPLACEMENT AND THE EFFECT OF ANCHOR POINT MOTIONS RESULTING FROM EARTHQUAKES. CONSIDER EFFECTS OF DISCONTINUITIES BUT NOT LOCAL STRESS CONCENTRATION.	SELF-EQUILIBRATING STRESS NECESSARY TO SATISFY CONTINUITY OF STRUCTURE. OCCURS AT STRUCTURAL DISCONTINUITIES. CAN BE CAUSED BY PRESSURE, MECHANICAL LOADS, OR BY DIFFERENTIAL THERMAL EXPANSION. EXCLUDES LOCAL STRESS CONCENTRATIONS.	(1) INCREMENT ADDED TO PRIMARY. A SECONDARY STRESS BY A CONCENTRATION (NOTCH). (2) CERTAIN THERMAL STRESSES WHICH MAY CAUSE FATIGUE BUT NOT DISTORTION.
SYMBOL	P_m	P_L	P_b	P_e	Q	F
COMBINATION OF STRESS COMPONENTS AND ALLOWABLE LIMITS OF STRESS INTENSITIES	<p>LEGEND</p> <p>○ ALLOWABLE VALUE</p> <p>□ CALCULATED VALUE</p> <p>— DESIGN LOADS</p> <p>- - - - - OPERATING LOADS</p> <p>NOTE 1: When the secondary stress is due to a temperature transient at the point at which the stresses are being analyzed or to restraint of free end deflection, the value of S_m shall be taken as the average of the tabulated S_m values for the highest and the lowest temperatures of the metal during the transient. Then part or all of the secondary stress is due to mechanical load, the value of S_m shall not exceed the value for the highest temperature of metal during the transient.</p> <p>NOTE 2: The stresses in category Q are those parts of the total stress that are produced by thermal gradients, structural discontinuities, etc., and they do not include primary stresses that may also exist at the same point. However, it should be noted that a detailed stress analysis frequently gives the combination of primary and secondary stresses directly, and when appropriate, the calculated value represents the total of $P_m + P_b + Q$ and not Q alone. Similarly, if the stress in category F is produced by a stress concentration, the quantity F is the additional stress produced by the notch over and above the nominal stress. For example, if a point has a nominal stress intensity, P_m, and has a notch with a stress concentration factor, K, then $P_m \leq S_m$, $P_b = Q$, $Q = 0$, $F = P_m(K - 1)$, and the peak stress intensity equals $P_m + P_m(K - 1) = KP_m$. However, P_L is the total membrane stress that results from mechanical loads, including discontinuity effects, rather than a stress increment. Therefore, the P_L value always includes the P_m contribution.</p> <p>NOTE 3: S_d is obtained from the fatigue curves, Figs. F-106(a), F-106(b) and F-106(c). The allowable stress intensity for the full range of fluctuations is $2S_d$.</p> <p>NOTE 4: The symbols P_m, P_L, P_b, P_e, Q, and F do not represent single quantities but sets of six quantities representing the six stress components σ_1, σ_2, σ_3, τ_{12}, τ_{13}, and τ_{23}.</p> <p>NOTE 5: Special rules for exceeding $3S_m$ are provided in F-105.4 and F-105.2.7.</p>					

Table of Equations^a for the simplified design-
analysis procedures of the Code

Design stress formulas	Code equation No.
$B_1 \frac{PD_o}{2t} + B_2 \frac{D_o}{2I} \bar{M}_1 \leq 1.5S_m$	(9)
$S_n = C_1 \frac{P_o D_o}{2t} + C_2 \frac{D_o}{2I} M_1 +$ $\frac{1}{2(1-\nu)} E\alpha AT_1 + C_3 E_{ab} \alpha_a T_a - \alpha_b T_b \leq 3S_m$	(10)
$S_p = K_1 C_1 \frac{P_o D_o}{2t} + K_2 C_2 \frac{D_o}{2I} M_1 +$ $\frac{1}{2(1-\nu)} K_3 E\alpha AT_1 + K_3 C_3 E_{ab} \alpha_a T_a - \alpha_b T_b $ $+ \frac{1}{1-\nu} E\alpha AT_2 $	(11)
$S_e = C_2 \frac{D_o}{2I} M_1' \leq 3S_m$	(12)
$C_1 \frac{P_o D_o}{2t} + C_2 \frac{D_o \bar{M}_1}{2I} + C_3 E_{ab} \alpha_a T_a - \alpha_b T_b \leq 3S_m$	(13)
$S_{alt} = \frac{K}{n} S_p$	(14)

where

$$K_e = 1 \quad (S_n \leq 3S_m),$$

$$K_e = 1 + \frac{(1-n)}{n(m-1)} \left(\frac{S_n}{3S_m} - 1 \right) \quad (3S_m < S_n < 3mS_m),$$

$$K_e = 1/n \quad (S_n \geq 3mS_m),$$

and m and n are material parameters given in NB-3226.3(b).

^aAbstracted from paragraph NB-3650 of the Code; see "Nomenclature" and the Code for symbol definitions.

Figure 2

Examples of extreme contours of concentric reducers that are acceptable under ANSI B16.9 standard requirements

Nomenclature sketch for inclusion in NB-3683.2-1.

Figure 3

SELECTED COMPONENTS FOR ANALYTICAL STUDIES
BASED ON EXISTING INFORMATION

1. Straight Pipe
(out-of-roundness, flat spots, peaks)
2. Circumferential Welds
(reinforcement, mismatch, shrinkage)
3. Transition Joints
(inside, outside, balanced tapers)
4. Flanged Joints
5. Local Attachments on Straight Pipe
(lugs, supports, etc.)
6. Socket Welding and Threaded Fittings
7. Concentric and Eccentric Reducers

Figure 4

TABLE D-201. STRESS INDICES FOR USE WITH EQUATIONS 9, 10, AND 11 OF DIVISION 1-703

Component	Internal Pressure			Moment Loading ⁽⁵⁾			Thermal Loading	
	K_1	C_1	K_2	B_2	C_2	K_3	C_3	K_4
Straight pipe, remote from welds or other discontinuities	0.5	1.0	1.0 ⁽¹⁾	1.0	1.0	1.0	0	1.0
Girth butt weld between straight pipe or between pipe and butt-welding components ⁽²⁾								
(a) flush	0.5	1.0	1.1 ⁽¹⁾	1.0	1.0	1.1	0	1.1
(b) as welded	0.5	1.1	1.2 ⁽¹⁾	1.0	1.0	1.2	0	1.2
Girth filler weld to socket weld fittings, slip-on flanges, or socket-welding flanges ⁽²⁾	0.5	2.0	3.0	1.0	1.5	2.0	1.5	3.0
Longitudinal butt welds in straight pipe ⁽²⁾								
(a) flush	0.5	1.0	1.1 ⁽¹⁾	1.0	1.0	1.1	0	1.1
(b) as welded	0.5	1.1	1.2 ⁽¹⁾	1.0	1.2	1.3	0	1.2
Tapered transition joints per Subpar. 1-727.4.2(c) and Fig. 1-727.3.1	0.5	1.4	1.5	1.0	1.2	1.8	0	1.5
Branch connections per Subdiv. 1-704.3 ⁽³⁾	1.0	2.0	1.7	(7)	(7)	1.0	1.8	1.7
Curved pipe or butt-welding elbows per USAS B16.9, USAS B16.28, or MSS SP48 ⁽¹⁰⁾	1.0	$\frac{2R-r}{2(R-r)}$ ⁽⁴⁾	1.0 ⁽¹⁾	(8)	(8)	1.0	0	1.0
Butt-welding tees per USAS B16.9 or MSS SP48 ⁽¹⁰⁾	1.0	1.5	4.0	(9)	(9)	1.0	1.0	1.0
Butt-welding reducers per USAS B16.9 or MSS SP48 ⁽¹⁰⁾	1.0	1.5	4.0	1.0	1.3	1.0	0	1.0

(1) The values of K_1 shown for these components are applicable for components with circular cross section. If the cross section is out-of-round such that the cross-section shape is appreciably elliptical, the value of K_1 may be obtained by the equation:

$$K_1 = 1 + \frac{D_{\max} - D_{\min}}{D_{\min}} \left[\frac{1.5}{1 + 0.43 \left(\frac{D_{\max} - D_{\min}}{D_{\min}} \right)^2} \right]$$

where $D_{\max}$ = maximum outside diameter of cross section, in.

$D_{\min}$ = minimum outside diameter of cross section, in.

t = nominal wall thickness, in.

D_o = nominal outside diameter, in.

P = internal pressure, psi

E = modulus of elasticity of component material, psi.

If the cross section contains flat spots or peaks, particularly at or near longitudinal welds in the component, the designer shall make a suitable theoretical or experimental analysis (Appendix 2) to determine the stresses at such irregularities.

(2) Welds in accordance with the requirements of this Code for Class 1 piping. In addition, "flush" welds are defined as those welds which have been ground on both interior and exterior surface to remove weld irregularities and abrupt changes in contour due to misalignment. Thickness of weld reinforcement shall not exceed one-half of the values tabulated in Par. 1-724.3.1(1). No concavity on the exterior side is permitted. The finished contour shall neither have a slope (angle measured from tangent to surface of pipe) greater than 7 degrees. "As welded" is defined as welds not meeting the special requirements for "flush welds".

(3) The values given are limited to branch connections in straight pipe and to connections with (a) d/D not over 1/2, (b) D/t not over 100, and (c) branch pipe normal to the surface of the run pipe, d = nominal outside diameter of branch pipe, D = nominal outside diameter of run pipe, t = nominal thickness of run pipe.

(4) R = curved pipe or elbow radius, in.

r = mean radius of cross section, in.

t = $(D_o - t)/2$, where t = nominal wall thickness.

(5) The values of the moment M_1 shall be obtained from an analysis of the piping system in accordance with Div. 1-719. M_1 is defined as the range of moment loading applied during the specified operating cycle.

Straight Through Components

M_1 = moment at Point A

$$M_1 = \sqrt{M_2^2 + M_3^2 + M_4^2}$$

Curved Pipe or Welding Elbow

M_1 = moment at Point A

$$M_1 = \sqrt{M_2^2 + M_3^2 + M_4^2}$$

Branch Components

Moments calculated for point at intersection of run and branch centerlines

M_1 = larger of:

$$(a) \sqrt{(M_1 + M_2)^2 + (M_3 + M_4)^2 + (M_5 + M_6)^2}$$

$$\text{or } (b) \sqrt{M_2^2 + M_3^2 + M_4^2}$$

(6) The K_2 indices for tapered transition joints are for such joints where a girth butt weld is made at the thin end of the taper.

(7) $C_2 = \frac{1.8}{h_1/2}$, but not less than 2.0; $B_2 = 0.75 C_2$

$$h_1 = \frac{3t}{2}, \text{ where } t = \text{nominal run pipe wall thickness}$$

$$r = \text{mean run pipe radius}$$

$$= (D_o - t)/2.$$

(8) $C_2 = \frac{1.95}{h_2}$, but not less than 1.5; $B_2 = 0.75 C_2$

$$h_2 = \frac{tR}{r}, \text{ where } t = \text{nominal pipe wall thickness}$$

$$R = \text{bend radius of curved pipe or elbow}$$

$$r = \text{mean pipe radius}$$

$$= (D_o - t)/2.$$

(9) $C_2 = \frac{1.8}{h_3/2}$, but not less than 2.0; $B_2 = 0.75 C_2$

$$h_3 = \frac{4.4t}{r}, \text{ where } t = \text{nominal run pipe wall thickness}$$

$$r = \text{mean run pipe radius}$$

$$= (D_o - t)/2.$$

(10) The C and K indices given for fittings per USAS B16.9, USAS B16.28, or MSS SP48 apply only to seamless fittings with no connections, attachments, or other extraneous stress raisers on the bodies thereof. For fittings with longitudinal butt welds, the K indices shown shall be multiplied by the 1.1 for "flange" welds as defined in Note (2); by 1.2 for welds not meeting the requirements for flange welds.

TABLE NB-3683.2-1
STRESS INDICES FOR USE WITH EQUATIONS 9, 10, AND 11 of NB-3650

Component	Internal Pressure			Moment Loading ⁽¹⁾			Thermal Loading		
	B_1	C_1	K_1	B_2	C_2	K_2	C_3	K_3	C_4
Straight pipe, remote from welds or other discontinuities	0.5	1.0	1.0 ⁽¹⁾	1.0	1.0	1.0	1.0	1.0	...
Girth butt weld between straight pipe or between pipe and butt-welding components ⁽²⁾									
(a) flush	0.5	1.0	1.1 ⁽¹⁾	1.0	1.0	1.1	1.0	1.1	0.5
(b) as welded $t > 3/16"$	0.5	1.1	1.2 ⁽¹⁾	1.0	1.0	1.8	1.0	1.7	0.5
(c) as welded $t \leq 3/16"$	0.5	1.1	1.2 ⁽¹⁾	1.0	1.4	2.5	1.0	1.7	0.5
Girth fillet weld to socket weld fittings slip-on flanges, or socket-welding flanges ⁽²⁾	0.5	2.0	3.0	1.0	1.5	2.0	1.8	3.0	1.0
Longitudinal butt welds in straight pipe ⁽²⁾									
(a) flush	0.5	1.0	1.1 ⁽¹⁾	1.0	1.0	1.1	1.0	1.1	...
(b) as welded $t > 3/16"$	0.5	1.1	1.2 ⁽¹⁾	1.0	1.2	1.3	1.0	1.2	...
(c) as welded $t \leq 3/16"$	0.5	1.4	2.5 ⁽¹⁾	1.0	1.2	1.3	1.0	1.2	...
Tapered transition joints per NB-3661.2 and Fig. NB-4233-1 ⁽³⁾	0.5	1.4	1.5	1.0	1.2	1.8	1.0	1.5	1.0
Branch connections per NB-3643 ⁽³⁾	1.0	2.0	1.7	(7)	(7)	(7)	1.8	1.7	1.0
Curved pipe or butt-welding elbows per ANSI B16.9, ANSI B16.38 or MSS SP48 ^(1,4)	1.0	$\frac{2R-r}{2(R-r)}$	1.0 ⁽¹⁾	(8)	(8)	1.0	1.0	1.0	0.5
Butt-welding tees per ANSI B16.9 or MSS SP48 ^(1,6)	1.0	1.5	4.0	(8)	(8)	1.0	1.0	1.0	0.5
But-welding reducers per ANSI B16.9 or MSS SP48 ^(1,6)	1.0	1.5	2.0	1.0	1.3	1.0	1.0	1.0	0.5

PIPING PROGRAM

Follow-On Studies
(FY 1976)

- TASK 1: Information Surveys
Publish Report on Dimensional Study of Piping Components
- TASK 2: Straight Pipe, In-Line Configurations, and Attachments
Publish Three Reports on Design Analysis of Flanged Joints
- TASK 3: Thin-Walled Tees and Branch Connections
Publish Fourth Report on Idealized Thin-Walled Tees
Publish Report on Flexibility Factors for Branch Connections
Conduct Limited Parametric Study of Approximately 20 Nozzle-to-Cylindrical Shell Attachment Models
- TASK 4: Elbows and Curved Pipe
Complete Analytical Studies and Develop Stress Indices and Flexibility Factors to Account for End Effects
Publish Report on Experimental Study of Four Machined Elbows
Publish Results of Pressure Fatigue Test on Ovalled Elbow
- TASK 5: ANSI Standard B16.9 Tees
Summarize Results of Tests on B16.9 Tees
Make Operational on ORNL Computers and Check-Out Finite Element Computer Program for B16.9 Tees
- TASK 6: Limit Loads
Publish Report on Available Limit Load Data for Elbows
Publish Report on Available Limit Load Data for Branch Connections
Make Operational on ORNL Computers and Check-Out Finite Element Computer Program for B16.9 Tees

Figure 7