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EXPERIMENTAL STRESS ANALYSIS FOR FOUR 24-IN.
ANSI STANDARD B16.9 TEES*

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ABSTRACT

This paper describes the experimental stress analysis and low cycle fatigue tests of four tees tested by Combustion Engineering, Inc. (C-E) under subcontract to Union Carbide Nuclear Division. These tests are part of the ORNL Design Criteria for Piping and Nozzles Program which is being conducted for the development of design criteria for nuclear power plant service piping components.

The test assemblies were fabricated at C-E from commercially obtained ANSI B16.9 tees and matching diameter steel pipes welded to the tees, with suitable and closures and fixtures for applying the loads. The tees tested and discussed in this report are described below:

<u>Tee Number</u>	<u>Material</u>	<u>Nominal Size</u>			
T-11	carbon steel	24"	X 24"	X 24"	sch 160
T-12	carbon steel	24"	X 24"	X 10"	sch 40
T-13	carbon steel	24"	X 24"	X 10"	sch 160
T-16	stainless steel	24"	X 24"	X 24"	sch 10

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Each tee test assembly was instrumented with approximately 240 rectangular strain gage rosettes for determining elastic stress distributions, and four linear variable displacement transducers for determining flexibility factors. Elastic-response tests were conducted for 12 loading conditions consisting of internal pressure and pure bending moments and direct force loads applied individually to the branch pipe extension and to one end of the run pipe. The other run pipe extension was fixed rigidly to the loading frame. Automatic data handling equipment and data reduction techniques were used to process the strain gage readings. For each loading condition, stress distributions were determined and the locations and magnitudes of the maximum stresses were identified. Test results are presented and compared with appropriate design formulas of the ASME Boiler and Pressure Vessel Code, Section III. In comparing the experimentally determined peak stress indices with the ASME Code values (Section III, Division 1, Nuclear Power Plant Components) the code was conservative in all instances for the particular loading conditions tested with the exception of the moment loading applied to the branch of the T-11 tee.

After the elastic-response tests were completed three of the tees were low cycle fatigue tested by pressure cycling using transformer oil. The T-11 and T-13 tees were pressurize cycled from 100 psig (790 kPa) to 7000 psig (48 360 kPa); whereas, the T-12 tee was pressure cyclied from 0 (100 kPa) to 1800 psig (12 510 kPa). A low cycle fatigue test was performed on the T-16 tee assembly by applying a bending moment to the branch pipe in the plane of the tee with the tee pressurized to a constant internal pressure of 300 psig (2170 kPa). All low cycle fatigue tests were performed until a through-the-wall fatigue crack occurred as evidenced by a leak.

Section NB-3653.6 of ASME Code, Section III, Division 1, Nuclear Power Plant Components was used to calculate the fatigue life. With the exception

of one tee the present code procedure is conservative in predicting fatigue life; however, the elastic-response data for all the tees discussed here indicate that substantial change in the code stress index values may be in order.

INTRODUCTION

The work reported in this paper was performed in the Components Engineering Test Laboratory, Combustion Engineering, Inc., Chattanooga Division, under Union Carbide Corporation Nuclear Division Subcontract No. 3310 as part of the ORNL Design Criteria for Piping and Nozzles Program, S. B. Moore, Manager.

This program is funded by the U. S. Nuclear Regulatory Commission under the Division of Reactor Safety Research (RSR) as part of a cooperative effort with industry to develop and verify analytical methods for assessing the safety of pressure-vessel and piping-system design. The cooperative effort is coordinated through the Pressure Vessel Research Committee of the Welding Research Council.

The study described in this report was conducted under the general direction of W. L. Greenstreet, Technical Director of Solid Mechanics Department, Reactor Division, ORNL; and is a continuation of work supported in prior years by the Division of Reactor Research and Development, U. S. Energy Research and Development Administration (formerly the USAEC).

In early 1969, the Oak Ridge National Laboratory (ORNL) issued a contract to Combustion Engineering to conduct experimental stress analysis and low cycle fatigue tests of four 24-in (610 mm) diameter ANSI B16.9 carbon steel tees. Two 24-in. (610 mm) diameter ANSI B16.9 stainless steel tees were subsequently added to this contract.

The Combustion Engineering tests are for tees number T-10 through T-13, T-16 and T-17 supplied by the Oak Ridge National Laboratory from a series of

17 ANSI B16.9 tees being studied under the Piping Program (1). The tees in the C-E test series are as follows:

<u>Tee Number</u>	<u>Material</u>	<u>Nominal Size</u>
T-10	carbon steel	24"(610 mm) X 24"(610 mm) X 24"(610 mm) sch 40
T-11	carbon steel	24"(610 mm) X 24"(610 mm) X 24"(610 mm) sch 16
T-12	carbon steel	24"(610 mm) X 24"(610 mm) X 10"(254 mm) sch 40
T-13	carbon steel	24"(610 mm) X 24"(610 mm) X 10"(254 mm) sch 16
T-16	stainless steel	24"(610 mm) X 24"(610 mm) X 24"(610 mm) sch 10
T-17	stainless steel	24"(610 mm) X 24"(610 mm) X 10"(254 mm) sch 10

The test results from a T-10 tee were previously reported (2). Test results for T-11, T-12, T-13, and T-16 tees are presented here. A detailed description of the test procedures, test equipment, test tee assembly, elastic response tests, computer programs, data acquisition equipment and low cycle fatigue tests is also discussed. A comparison is made between the normalized stress intensities determined from the test data and the design values tabulated in the current issue of the ASME Boiler and Pressure Vessel Code, Section III, Nuclear Power Plant Components (3).

In regard to the fatigue test, a comparison is also made between the actual number of cycles at which a fatigue failure with the number of allowable design cycles calculated, using the Simplified Elastic-Plastic Discontinuity Analysis in Section III of the ASME Code and the Section III, Design Curve.

LABORATORY EQUIPMENT

Load Frame. The test frame consists of an assembly of wide flange beams bolted to foundation anchor points at eight places (4). The test frame was designed for the following loading conditions:

Bending moment	9,600,000 in-lbs (1 085 000 N·m)
Torsional moment	9,600,000 in-lbs (1 085 000 N·m)
Axial Load	800,000 lbs (3 559 000 N)

The foundation consists of four large rectangular beams of steel reinforced

¹ Numbers in brackets designate References at end of paper.

concrete arranged in a "rectangular donut" configuration. Approximately 126 cubic yards (96 m^3) of concrete and 7300 lbs (3310 kg) of reinforcing steel were utilized in the foundation. Each anchor point was designed to resist a load combination of 57.1 kips (6450 N·m) upward or downward and 50 kips (5650 N·m) horizontal in perpendicular directions.

To apply bending moments, torsional moments, and axial loads, three load cylinders were designed with large rectangular flanges located at one end. These load cylinders were bolted to special lab joint flanges welded to the outside diameter of the piping components. Figure 1 shows a load frame and the T-13 tee test assembly.

Various hydraulic jack assemblies are used to apply the different loads to the test assembly. Most of the jack assemblies were provided with swivels containing ball bearings at each end. Each jack assembly has been calibrated on a tensile machine. A hydraulic system capable of producing accurate pressures up to 10,000 psig (69 050 kPa) were employed to provide the necessary pressure for all jacks. Special ball bearing and roller bearing type supports were designed to support the tee test assembly.

Data Acquisition and Processing Equipment. A computer controlled data acquisition system was employed for reading the strain gages, thermocouple, and LVDT instrumentation (4). This system consists of an Astrodata Model 2000 analog-to-digital converter and an IBM 1620 data processing system. The Astrodata Model 2000 unit is a special purpose random access multiplexer and data measuring instrument which is automatically controlled by the IBM 1620 computer or manually controlled by its own front panel switches. The system is designed to measure the output signal from any of 2000 channels.

During a typical test, all test results are punched on cards with a limited number of the more important test results displayed on the 1620 typewriter.

At the conclusion of a test the punched cards are transmitted to the Corporate computer center via an IBM 7711 tape receiver and telephone link. The test data is then processed on an IBM 370-165 computer.

When it is desired to plot specific data, a magnetic tape X-Y drum plotting system is utilized in Windsor. This permits complete automatic plotting of all desired information.

Fatigue Test Equipment. The fatigue test equipment utilized for pressurizing the tees consists of an MTS closed-loop servo control system, hydraulic power supply, five intensifiers, Heise pressure gage, and a pressure transducer. The MTS system is primarily designed for structures and materials testing. It is a single channel system that utilizes one Servo Controller (SERVAC). The system employs a closed loop that is a continuous path of interacting elements. The basic components in the system are a Servo Controller, Servo-Valve, command input module, function generator, counter hydraulic power supply, and pressure transducer. The hydraulic power supply consists of a variable volume pump capable of delivering up to 35 gpm (2.21 l/sec) of hydraulic oil. It is designed for providing a hydraulic pressure of 3000 psig (20 790 kPa). For the tee tests five oil to oil intensifiers were used with the MTS system to provide sufficient oil volume to achieve the desired 7000 psig (48 360 kPa) pressure in one stroke of the intensifiers. The intensifiers have an intensification ratio of 3.31 and were manufactured by Ortman-Miller. BLH pressure transducers were used for control of the fatigue tests.

TEST MODELS

All the tees to be tested were provided by ORNL. "As built" dimensions and critical contours of the tees are shown in Figures 2 through 5.

Each of the tees were wrought ANSI B16.9 standard tees manufactured in accordance with ASTM spec. A-234 which is required by the ANSI B16.9 standard. Pertinent fabrication information relative to each tee is provided below:

T-11 & T-13 Tees - These tees were fabricated from ASTM-A-105 grade 2 forgings. Specimens were taken from the forgings used in fabrication of the tees and supplied to C-E by the vendor. Samples were heat treated at 1150°F (621°C) for 3-3/4 hours to simulate the same heat treatment provided for the tee assemblies. Average physical properties obtained from C-E tests of these specimens are listed below:

Yield Strength - 44,100 psi (304 060 kPa)
Ultimate Strength - 74,100 psi (510 900 kPa)
Elongation - 36%
Reduction in Area - 66.7%

T-12 Tee - This tee was fabricated from ASTM-A-515 grade 70 plate. Physical properties of the material were obtained from the plate mill tests report and are listed below:

Yield Strength - 50,600 psi (348 870 kPa)
Tensile Strength - 78,000 psi (537 790 kPa)
Elongation - 23%

Specimens which were taken from the plate used in fabrication of the tee were supplied to C-E by the tee vendor. Physical properties obtained from C-E test on these specimens are listed below:

Yield Strength - 49,800 psi (343 360 kPa)
Tensile Strength - 78,400 psi (540 550 kPa)
Elongation - 30%
Reduction of Area - 68.8%

T-16 Tee - This tee was fabricated from ASTM-A-240-70, 304L stainless steel plate. Physical properties of the material were obtained from the plate mill test report and are listed below:

Yield Strength - 38,000 psi (262 000 kPa)
Tensile Strength - 83,000 psi (57 226 kPa)
Elongation - 53%

Before assembly of the tees to the piping, plaster of paris casts were made of the inside and outside of the tees. The surfaces on the tees which were to be instrumented were polished and the center lines of the strain gages established. For future reference, the X-Y-Z coordinates of each strain gage center line were established. This was accomplished by first establishing the center lines of the tees and then machining the weld preps perpendicular to the center lines. By using the weld prep to position the tee on a marble table, the desired coordinates could be readily acquired using a vernier height gage.

Pipe extensions of SA-106 grade B material were welded to the carbon steel tees, T-11, T-12, and T-13. The pipe extensions for the T-16 tee were fabricated of SA-312 type 304 stainless steel material. All pipe extensions were closed with ellipsoidal caps attached. In order to install the inside surface gages it was necessary to attach one of the pipe assemblies after the remainder of the tee assembly had been completed and all the internal instrumentation had been installed. All welding procedures were qualified in accordance with Section IX of the ASME Boiler and Pressure Vessel Code and all the critical pipe to tee joints were nuclear quality welds. The root passes were made using the gas tungsten arc welding method. Both the qualification welds and the actual pipe welds were examined by magnetic particle tests and by radiography. In addition, the qualification welds were subjected to tensile tests, bend tests, and Charpy impact tests.

Special lap joint flanges were welded to the outside diameter of each carbon steel piping extension to make provision for application of the test loads, to the tee assembly. Welding neck flanges were used for the stainless steel tee. The mating surface of the flange (load application point) was positioned 75-1/2 in. (1917.7 mm) from the center line of the tee to fit properly in the load

frame. Nozzles were provided in the pipe extensions for filling, venting, and pressurizing the tee. Nozzles were also provided for special glands used for sealing approximately 1000 lead wires connected to the internal strain gages. Special anchor pads were also provided for attaching LVDT hardware for determining displacements and flexibility factors. The completed carbon steel tee sub-assemblies and piping sub-assemblies were stress relieved at 1150°F (621°C).

The strain gage glands were prepared by installing polythermalese coated 26 gage copper wire in special pipe fittings and potting the glands with an epoxy material. The glands were hydrostatically tested to the maximum anticipated test pressure before being installed in the tee assembly.

ELASTIC RESPONSE TEST

Elastic data were obtained for twelve loading conditions; internal pressure, six pure bending moments and five direct force loadings.

Instrumentation. Two basic types of instrumentation were used; strain gages to measure stress distribution and LVDT's to measure flexibility.

Approximately 240 three gage foil type rosette strain gages of constantan material (Micro-Measurements EA-06-125RA-120) with a grid length of 0.125 in. (3.175 mm) were installed with Eastman 910 cement on the tee assemblies. Two diagonally opposite quadrants of each tee were instrumented on both the inside and outside surfaces. The instrumentation for the full outlet tees (T-11 & T-16) were arranged in each quadrant in five rows as shown in Figures 6 and 7. The first row of gages was located on the run-branch center line at the top of the tee. The remaining rows of strain gages were located on radial planes extending from the run and branch piping center lines. The rows were located in 22-1/2° (0.3927 rad) increments from the vertical plane through the tee to a horizontal plane through the tee, with the tee lying on its side as shown

In Figure 1. The instrumentation for the reduced outlet tees (T-12 & T-13) were arranged in each quadrant in six rows as shown in Figures 8 and 9. The first row was located on a vertical plane through the branch center line. The second, third, fifth, and sixth rows were located on planes extending from the branch center line. These plans were located in $22\text{-}1/2^\circ$ (0.3927 rad) increments from the vertical plane through the branch center line to a horizontal plane through the branch center line. The fourth row was located midway between the third and fifth rows on the run.

All strain gages were moisture proofed with polyurethane coating (Micro-Measurement M Coat A). A three lead wire system was employed in wiring the strain gages to the data acquisition equipment to prevent temperature changes in the lead wire from causing inaccuracies in the strain gage data.

As stated earlier, one pipe assembly for each of the tees was attached after installing the internal strain gages. During the welding operation the temperature of the tee was monitored to ensure that the material in the region where the strain gages were located did not exceed 150°F (66°C) and thereby destroy the strain gage cement. Since it was not possible to stress relieve this weld, all loads were applied with one pipe extension of the tee in an "as welded" condition.

Six LVDT's with special support hardware were employed to measure relative displacement and rotations of the run and branch ends of the tee. These data were utilized to calculate flexibility factors for each type of loading. The instrumentation and data acquisition equipment can determine displacements to the nearest 0.0001 in. (0.00254 mm). Figure 10 shows the T-13 tee in the load frame with the strain gage and LVDT instrumentation installed.

Test Procedure. The loadings imposed on the tees consisted of internal pressure plus the twelve mechanical loadings shown in Figure 11 where the

"right hand rule" is used to designate the direction of the moment vector. The mechanical loadings may be visualized by considering one of the run ends of the tee extension piping as built in. Three orthogonal moments and three orthogonal direct forces were then applied individually to either the end of the branch or the free end of the run of the tee for a total of twelve mechanical loadings. All of these loadings were imposed separately on the tees except F3X which was omitted due to limitations on the strength of the test frame. Superposition may then be used to obtain any combination of mechanical loadings and internal pressure.

Initially, a sufficient number of load-unload cycles was imposed on the tees for each of the twelve elastic response tests to assure "shakedown" to linear elastic behavior as evidenced by 98 percent of the strain gages returning to zero within acceptable limits. The components were then loaded in four incremental steps which were repeated in the unloading process, providing a total of nine sets of data for each load cycle. To assure repeatable application of load and measurement of test data, a minimum of two load cycles were applied for each of the twelve elastic response tests and the results compared for consistency. The most highly stressed strain gages were monitored during the loading process to assure that the yield strength of the tee was not exceeded.

DATA ACQUISITION AND EVALUATION

Figure 12 illustrates the six steps involved in the data acquisition and evaluation scheme. The actual data acquisition and monitoring of the most essential data is done in the first step. The remaining five steps, identified as Phases 1-5, are essentially the computation of all of the engineering parameters of interest, screening of the data for validity, and preparation of output as both hard copy listings for documentation and computer plots to facilitate rapid comprehension of the test results. The function

of each major phase is discussed below

At the time of data acquisition, the temperature, strain, stress, and deflections are computed on the IBM 1620 and all of the results punched on cards. The computer program permits input of limits on strain, normal stress, and shear stress which enables monitoring only the most significant results on the console typewriter. These limits are raised as the load is raised to keep output on the typewriter to an acceptable level. Additionally, specific instrumentation may be preselected and monitored on the typewriter irrespective of whether it exceeds the specified limits. The capability of a computer-controlled data processing system to allow real time evaluation of the most critical instrumentation is an invaluable aid in assuring a good test. All the remaining data processing is performed on the IBM 370-165 computer at corporate headquarters.

The Phase 1 program computes, sorts, and lists all of the results for all transducers. For strain gages, data corrections are made for desensitization of the Wheatstone bridge due to lead wire length and for transverse sensitivity. A listing is provided for uncorrected strain, corrected strain, maximum and minimum strain, principal stress, angle of principal stress, stress in direction of a perpendicular to the "ray" line, and shear stress. For LVDT's the displacements and flexibility factors are computed.

The Phase 2 program screens all of the strain gage data for linear response of strain relative to the applied load. It is essentially divided into two portions. The load adjusting portion uses a technique based on the assumption that all of the strains should be directly proportional to the applied load. Hydraulic jacks, previously calibrated on a tensile machine, were used to apply the load to the tees. Load cells were not used due to physical limitations of the frame. Therefore, there was a possibility of some slight inaccuracies in

application of the loads. On a statistical basis, the strains from a large number of strain gages are a more accurate reflection of the applied load and thus represented a logical means for adjusting the applied load to obtain the best linear relation between strain and applied load. Basically, the technique consists of "normalizing" the strain for each gage indicating significant strain, by dividing by the strain at maximum load. At each load increment an average is obtained for the normalized strains and this is used as the basis for adjusting the numerical value of the applied load. An iterative technique is used in which gages are excluded whose normalized strain differs significantly from the average normalized strain. The iteration is continued until the applied load adjustment between successive iterations is insignificant. The applied load adjustments are usually less than 2 percent.

The second portion of Phase 2 checks the linearity of strain readings against adjusted applied load for each gage for the nine data points in the load-unloaded sequence. A least square linear curvefit is used and a tolerance band is established above and below the curvefit line. If all data points lie within the tolerance band, the data are accepted. Otherwise, the datum point which falls farthest from the tolerance band is excluded and another linear curvefit performed. This procedure is continued until the data either pass the tolerance criteria or until three of the nine data points are excluded, which constitutes total rejection of the data for that gage. Usually, no more than five active strain gage elements were rejected out of the 700. The slopes for all the gages having an acceptable curvefit were retained for use in Phase 3.

The Phase 3 program uses the slopes from the linear curvefits of Phase 2 to compute the normalized stresses.

The Phase 4 program uses the output of Phase 3 and plots graphs for internal and external gages which completely describe the stress distribution along the

instrumented ray lines. The Phase 5 program also uses the output from Phase 3 and sorts on the absolute value of either the maximum normal stress or twice the maximum shear stress, whichever is greater, and orders the output from the most highly stressed gage to the least stressed gage.

TEST RESULTS

Elastic Data. A very large amount of computer data was acquired during the test program. To more easily visualize the stress distribution in the tees and to provide a basis for comparison of test results for various tee sizes, it was considered advantageous to normalize the stresses. The nominal stress to be used in the normalization is, to a large extent, arbitrary. For this program it was decided that the nominal principal stress would be established for the imposed loading condition by calculating the stress that would exist at the outermost fiber of the pipe size that would normally be used for attachment to that size tee. For pressure loading, the maximum stress intensities were normalized with regard to the run pipe by the factor $PD_o/2$, where D_o is the nominal outside diameter and t is the nominal wall thickness. For moment loadings on the branch and run, the normalizing factors are M/Z_b and M/Z_r , respectively, where Z_b and Z_r are nominal section moduli of the branch pipe and the run pipe. For perpendicular transverse force loadings, the moment loading was calculated by multiplying the force times the distance from the load application point to the branch-run center line intersection. For axial force loadings such as F3Y the normalizing factor was calculated by dividing the force by the area of the pipe where the load is applied.

Based on the aforesaid, the nominal stress intensity is calculated as twice the value of the maximum shear stress. This value is used as the nominal stress to provide correlation with the shear stress theory of failure used in the

ASME Nuclear vessel code. Specifically, the following three equations are used as definitions in presentation of results:

Normalized stress intensity

$$i = \frac{2\tau_{\text{meas}}}{2\tau_{\text{nom}}} = \frac{S_{\text{meas}}}{S_{\text{nom}}}$$

Normalized principal stress

$$i_{\text{max}} = \frac{(\sigma_{\text{max}})_{\text{meas}}}{S_{\text{nom}}}$$

$$i_{\text{min}} = \frac{(\sigma_{\text{max}})_{\text{meas}}}{S_{\text{nom}}}$$

Tables 1 through 4 show the maximum value of the normalized stress intensity, $(i_s)_{\text{max}}$, for ten loading conditions for each of the tees tested. These tables show the maximum value independent of whether it was in the tee or the weldments. The equations used for calculating the nominal stress intensity as well as the nominal pipe properties are also included in these tables. The results of the four remaining loadings are not included for the following reasons. As previously mentioned, the F3X test was not performed. The F3Z loading was applied 7.2 pipe diameters from the branch-run intersection producing an M3X moment. The stresses due to the bending moment were large compared to the stresses due to the shear force and the results were essentially the same as those obtained for the M3X moment loading. The F2Y and F2Z loadings were applied 173 inches (4394.2 mm) (7.2 pipe diameters) from the branch-run intersection producing M2Z and M2Y moments, respectively. Again the stresses due to the moment dominated and the results were essentially in agreement with the moment loadings. These values were therefore not listed in the tables.

Figures 13 through 25 show the stress distribution on the inside and outside surface of the tees for the ray of strain gages which include the highest normalized stress intensity from Tables 1 through 4. Plots are provided showing the maximum

normalized stress intensity for branch, run, and pressure loadings for each tee. The curves were essentially taken from computer plots developed by the Phase 4 computer program.

For easy visualization of the stress distribution the ordinate was plotted as the normalized principal stress. The abscissa established the physical location of the stresses on the tee as a non-dimensionalized distance ratio. They may be further clarified as follows:

Referring to Figure 13 the dashed line representing the intersection of the branch and run (the crotch line) is used as the origin. The surface distance ratio for the furthest gages on the run is -1. For points between the crotch line and the furthest gages on the run, the surface distance ratio is computed by dividing the surface distance from the crotch line to the gage by the surface distance from the crotch line to the furthest gage on the run for the particular ray line in question.

In a like manner, gages on the branch weld are identified by a surface distance ratio of +1. The surface distance ratio for gages between the crotch line and the branch weld is similarly computed by dividing the surface distance from the crotch line to the gage by the surface distance from the crotch to the branch weld for the particular ray in question. The actual surface distances are not measured. The surface distance ratios were established by using dividers. For additional clarity, the relative locations of the stresses have been graphically presented in Figures 13, 16, 19, and 22. This representation has not been repeated in the other figures but it is applicable to all the indicated curves.

Table 5 shows the maximum normalized stress intensity values for the same loadings on each of the tees for comparison purposes. The highest values for the weldments (inclosed in parenthesis) as well as for the body of the tees are listed in the table.

Flexibility Factors. Basically a flexibility factor is used to correct the deflection and rotation calculated with simple beam equations to actual deflection and rotation.

The load displacement relationships of a tee cannot be described by a single flexibility factor and as many as 42 nonzero independent flexibility factors for a symmetrically-fabricated tee have been hypothesized (5). However, for the purposes of this paper the definition of flexibility factor is the ratio of a relative rotation of the ends of a piping component due to a moment, M , and in the direction of the moment, M , to the nominal rotation due to moment, M . The relative rotation described is between weld lines of the fitting. However to make valid measurements the attachment point for the hardware must be removed far enough from discontinuities to assure that plane sections remain plane. The attachment point for the LVDT hardware used to make the rotation measurements was approximately midway between the weld line of the tee and the flange attachment to the extension piping representing the area least likely to be affected by either the local effects of the tee or the flange.

The flexibility factor applicable between weld lines on the fitting is computed from the rotation measured between the attachment points. This procedure is consistent with ASME code philosophy, paragraph NB3682, but is not identical with code definition. Flexibility factor is designed as follows:

$$k = \frac{\theta_{\text{meas}} - \theta_{\text{corr}}}{\theta_{\text{nom}}}$$

where

θ_{meas} is the measured rotation between the LVDT attachment points.

θ_{corr} is the rotation correction computed by simple beam theory for the length of pipe between the tee weld lines and the attachment point for the LVDT hardware. Actual pipe dimensions were used for this correction.

θ_{nom} is the nominal rotation computed by simple beam theory between weld lines on the tee using nominal dimensions

The subscript on the flexibility factor identifies the axis about which the rotation is taken and the two planes of relative rotation shown in Figure 11. For example, K_{X31} is the flexibility factor representing rotations about the x axis of the "3" plane with respect to the "1" plane. In all instances the "1" plane represents the built-in end and is used as the reference plane.

Tables 6 through 9 summarize the flexibility factors for each of the tees for six loading conditions. It is interesting to note that the flexibility factors are generally less than 1.0, indicating that in those cases, the actual tee flexibility was less than was predicted by simple beam theory. However, there are a few factors greater than 1.0.

LOW CYCLE FATIGUE TEST

T-11 & T-13 Tees. The T-11 and T-13 tees were fatigue tested with a cyclic internal pressure using lower and upper limits of 100 psig (790 kPa) and 7000 psig (48 360 kPa) respectively. The calculated cyclic peak stress amplitude based on experimental elastic response data was 133,000 psi (917 000 kPa) for the T-11 tee and 84,800 psi (584 680 kPa) for the T-13 tee. Transformer oil was used as the pressurizing fluid. For various reasons including the length of time required for a test and the performance requirements of the test equipment, the primary interest was a low number of cycles to failure.

The maximum pressure for these two tees was limited to less than would be required to yield the pipe in order to preclude the possibility of plastic ratchetting. An internal pressure of 7000 psig (48 360 kPa) gives a maximum stress in the pipe that is about 93% of the code minimum yield strength (35,000 psi) (241 320 kPa) for SA-106 grade B pipe used in the test.

Prior to the start of the fatigue tests ultrasonic inspections of the tees were performed to establish a base line. For the first 20 pressure cycles extensive strain gage data was acquired until "shakedown" was assured. An ultrasonic inspection of the T-11 tee was again performed at 2000 cycles; however, there were no apparent indications of crack initiation at this time. A through-the-wall crack occurred on the T-11 tee at 2875 cycles resulting in leakage of transformer oil. Figures 26 and 27 are photographs of the fatigue crack from the interior and exterior of the T-11 tee.

During the fatigue test of the T-13 tee much more frequent ultrasonic inspections were performed. This tee was ultrasonically inspected at cycle numbers 535, 1050, 1902, 2984, 3480, 4077, 4588, 5558, 6678, 7186, 7775, 8551, 9356, 10623, 11, 934, and 13,928. However, there were no apparent indications of crack initiation having occurred at any of these points even with very high sensitivity settings of the instrumentation. A through-the-wall crack occurred on the T-13 tee at 15,084 cycles.

T-12 Tee. This tee was subjected to a low cycle fatigue test (0 to 1800 psig) (100 kPa to 12 510 kPa) under internal pressure using transformer oil. The experimental value for C_1K_1 acquired during the elastic response test was 2.4. Using this value the cyclic peak stress intensity range at the highest stressed point was calculated to be 75,000 psi (517 110 kPa) following the procedure essentially as identified in the Elastic-Plastic Discontinuity Analysis from NB-36531 of reference (3). In pressurizing the tee to 1800 psig (12 510 kPa) in the first few cycles the apparent stress range was 86,500 psi (596 400 kPa) as compared to the predicted range of 75,000 psi (517 110 kPa) based on the elastic response data. Extensive strain gage data was acquired in the first 20 pressure cycles.

A through-the-wall crack developed in the tee at cycle number 76,620 in the crotch region of the tee. The crack was located in the run pipe adjacent to

the branch intersection essentially a horizontal plane through the tee assembly.

Of special interest in this test is the fact that approximately 9,000 cycles prior to the fatigue failure ultrasonic indications had indicated the initiation of a crack. Crack growth was readily monitored until it reached a length of 2-3/4 inches (69.85 mm) when failure occurred.

T-16 Tee. A low cycle fatigue of this tee was performed by applying a completely reversing displacement to the branch of the tee. The tee was pressurized to 300 psig (2170 kPa) throughout the fatigue test. Two actuators and a load beam were used to apply the alternating moment (M3Z) to the branch load cylinder. An LVDT was used for control purpose with the MTS closed loop servo-control system to control the displacement.

The magnitude of the loading was based on an expected fatigue failure within the range of 500 to 100,000 fully reversed controlled-displacement cycles. The loading was selected to produce a failure in approximately 7,000 cycles which is the log mean value between 500 and 100,000 cycles. The maximum stress amplitude was calculated to be 95,700 psi (659 830 kPa) using Markl's equation for austenitic stress at room temperature (6).

At 2355 cycles a through-the-wall crack developed with slight leakage occurring only when the bending moment was applied. The crack was approximately 2-1/2 inches (63.5 mm) long as measured from the exterior of the tee assembly. The crack occurred in the branch weld near the top of the tee assembly. This is near the neutral axis of the branch and opposite the fixed end of the tee.

No satisfactory explanation for why the tee failed in this location can be given. X-rays taken at the time the weld was made showed an area of porosity less than 1/32 inch (0.80 mm) in diameter in this region. This was acceptable with regards to code requirements. Similar indications were noted in a region approximately 90° away from the point where failure occurred. It should be noted

that although this tee was ordered as a Sch 10 tee, the vendor indicated that it is standard practice to manufacture these tees as Sch 20 tees and bore out the straight sections to mate with Sch 10 pipe.

It is assumed that metallographic examination of the fracture will provide insight as to why the failure occurred in this region.

During the performance of the fatigue test ultrasonic inspections were performed periodically. No significant indications were detected.

COMPARISON OF RESULTS WITH ASME CODE, SECTION III

The methods used to obtain the normalized stress intensity are consistent with the definition of stress indices in section NB-3682 of the Code. In the code the secondary stress indices are presented by "C" and the peak stress indices by the product "CK" where "K" is a local stress index. If the sensing element of the strain gage is small with respect to the strain gradients, as in the present tests, the gage indicates peak strains and it is not possible to separate the C and K indices without supplementary information. Therefore, it is appropriate to compare the maximum normalized stress intensity from the present tests with the CK product as shown in Tables 1 through 4.

For flexibility calculations the code states that the load-displacement relationship for ASA B16.9 tees shall be obtained by assuming that the run pipe and branch pipe extend to the intersection of the run pipe center line with the branch pipe center line. The imaginary junction is assumed to be rigid. This is equivalent to a flexibility factor as defined above equal to 1.0. The experimental flexibility factors can easily be compared to 1.0 by referring to Tables 6 through 9. It is interesting to note that the flexibility factors are generally less than 1.0 thus indicating that the tees are stiffer than the adjoining pipe.

Table 10 shows comparisons between the fatigue life determined in the test N_t ; the code-allowable design life N_c calculated by NB-3653.6 including the present code values for the stress indices; and an expected design life N_e calculated by the procedures of NB-3653.6, but using the normalized stress intensities of Tables 1 through 4 instead of the stress indices of the code. The ratios of N_t/N_c and N_t/N_e can be taken as safety factors for the two different methods of calculating the design life.

If one arbitrarily assumes that a safety factor of 20 on the allowable design cycles is adequate then it appears that the T-11 (full outlet) tee did not meet this criterion. Therefore, for this size tee the code calculation was not conservative. The relatively low value of N_t/N_c equal to 5 suggests that changes are needed in the code values for C_1 and K_1 .

CONCLUSIONS

1. Normalized Stress Intensity Values - All experimentally determined values of the CK for the four tees tested were less than the ASME Code CK index except as noted below:

Tee No.	Load	Normalized Stress Intensity	ASME Code CK Index
11	M3X	2.3	2.0
	M3Y	2.1	2.0
	M3Z	2.2	2.0
13	M2Z	2.1	2.0

The experimentally determined CK value for internal pressure loading was generally significantly lower than the ASME Code value as illustrated below:

Tee No.	Exper. Normalized Stress Intensity	ASME Code CK Index
11	3.7	6.0
12	2.4	6.0
13	2.4	6.0
16	2.2	6.0

The CK index values for the moment loadings for the T-16 tee were less than 1/2 the ASME Code values. However, it should be noted that T-16 was basically a schedule 20 tee which the ends of the tee machined for attachment to a schedule 10 pipe.

2. Flexibility Factors -

T-11 Tee. The flexibility factors reached a maximum value of 1.3 for loads which generate a moment about the Z axis at the intersection of the run-branch center lines (M2Z, F2Y, and M3Z). All of the other flexibility factors were determined to be less than 1.0 with the exception of one factor for the F2Y loading which also reached a magnitude of 1.3. Flexibility factors for the T-11 tee ranged from 0.2 to 1.3 for all loadings. Flexibility factors less than one indicate that the tee is more rigid than the adjoining pipe.

T-12 Tee. All flexibility factors for this tee were less than 1 with the exception of one flexibility factor for the M3X loading. K_{X31} was determined to be 1.8.

T-13 Tee. All flexibility factors for the T-13 tee were determined to be less than 1.0 with the exception of the flexibility factors for the F2Y loading. The flexibility factors for the F2Y loading were found to be equal to 1.0. Flexibility factors for the T-13 tee ranged from 0.2 to 1.0.

T-16 Tee. For this thin wall tee many of the flexibility factors were larger than one. Previously tested tees did not exhibit this behaviour. The values exceeding one are tabulated below:

Load	K Subscript	K Magnitude
M2Z	Z21	2.5
M2Z	Z31	2.5
M2Y	Z31	1.2
M3Z	Z21	2.4
M3Z	Z31	3.3

3. Low Cycle Fatigue - The Simplified Elastic-Plastic Discontinuity Analysis in Section III of the ASME Code was used to calculate the anticipated fatigue life using present code values of C_1 and K_1 as well as experimental $C_1 K_1$ values. If we assume that it is desirable to have a safety factor of 20 in comparing actual fatigue life to calculated fatigue life by the ASME Code then it may be concluded that for the T-11 tee the Code is not conservative. A safety factor of only 5 existed for this tee using Code values. Using experimental $C_1 K_1$ values the safety factor was determined to be 10.

For the T-13 (reduced outlet) tee the code calculation was conservative in providing an N_t/N_c equal to 27. The code calculations were conservative for predicting the fatigue life for the T-12, T-13, and T-16 tees using the current Code indices. However it is important to note that elastic response data presented in this paper suggest that the Code indices should be modified and thus the ratio N_t/N_c is perhaps a better measure of the safety factor. Values of N_t/N_c given in Table 10 range from 6.5 to 12.7 for tees T-11 through T-16.

4. Detailed experimental stress analysis data were acquired for this tee for numerous loading operations. The coordinates of each strain gage rosette were accurately established. The test data have been documented and organized in an orderly fashion for easy reference. This experimental data, therefore, should be quite beneficial in establishing the reliability of new analytical methods such as the three-dimensional finite element analysis for determining the stress distribution in tees.

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TABLE 1 Summary of Normalized Stress Intensity and Comparison With The ASME Code Stress Indices (T-11)

Load	Normalized Stress Intensity (i_s)max	Rosette No.	Nominal Stress Intensity ¹	ASME Code CK Index ²
1.M3X	2.3	8 (e) ³	M3X/Zb	2.
2.M3Y	2.1	7 (e)	M3Y/Zb	2.
3.M3Z	2.2	3 (e)	M3Z/Zb	2.
5.F3Y	0.7	1 (i)	F3Y/Ab	
7.M2X	1.8	3 (e)	M2X/Zr	2.
8.M2Y	1.2	2 (e)	M2Y/Zr	2.
9.M2Z	1.8	5 (i)	M2Z/Zr	2.
10.F2X	2.7	6 (i)	F2X/Ar	
13.P	3.7	4 (i)	PD ₀ /2t	6.0

¹ Nominal pipe properties using dimensions from ASA B36.10-1959 for 24 in. (610 mm) schedule 160 pipe

$$D_o = 24.000" (609.600 \text{ mm})$$

$$t = 2.344" (59.5376 \text{ mm})$$

$$Zb = Zr = 788.1 \text{ in}^3 (12\,914\,645.14 \text{ mm}^3)$$

$$Ab = Ar = 159.4 \text{ in}^2 (102\,838.50 \text{ mm}^2)$$

² Pressure

$$C_1 = 1.5$$

$$K_1 = 4.0$$

$$C_1 K_1 = 6.0$$

Moment $C2b = C2r = 0.67(R_m/T_r)^{2/3} = 1.86$, but not less than 2.0

$$K2b = K2r = 1.0$$

$$C2bK2b = C2rK2r = 1.86 \text{ (Use 2.0)}$$

³ Identifies whether high stress is on the exterior (e) or the interior (i) of the tee.

TABLE 2 Summary of Normalized Stress Intensity and Comparison With The ASME Code Stress Indices (T-12).

Load Case And Name	Normalized Stress Intensity (i_s) _{max}	Rosette No.	Nominal Stress Intensity ¹	ASME Code CK Index ²
1.M3X	2.0	6 (e) ³	M3X/Zb	4.40
2.M3Y	1.1	4 (e)	M3Y/Zb	4.40
3.M3Z	1.3	3 (e)	M3Z/Zb	4.40
5.F3Y	3.7	6 (e)	F3Y/Ab	
7.M2X	1.8	5 (i)	M2X/Zr	4.40
8.M2Y	1.1	1 (e)	M2Y/Zr	4.40
9.M2Z	2.4	6 (i)	M2Z/Zr	4.40
10.F2X	2.3	6 (i)	F2X/Ar	
13.P	2.4	2 (i)	PD _o /2t	6.0

¹ Nominal pipe properties using dimensions from ASA B36.10-1959 for 10 in. (254 mm) and 24 in. (610 mm) schedule 40 pipe

<u>Branch</u>	<u>Run</u>
$D_o = 10.75$ in. (273.050 mm)	$D_o = 24.0$ in. (609.600 mm)
$t_b = 0.365$ in. (9.271 mm)	$t_r = 0.687$ in. (17.450 mm)
$Z_b = 29.91$ in. (759.714 mm)	$Z_r = 285$ in. ³ (4 670 313.24 mm ³)
$A_b = 11.91$ in. (302.514 mm)	$A_r = 50.3$ in. ² (32 451.55 mm ²)

² Pressure $C_1 = 1.5$ Moment $C_{2b} = C_{2r} = 0.67 (R_m/T_r)^{2/3} = 4.40$
 $K_1 = 4.0$ $K_{2b} = K_{2r} = 1.0$
 $C_1 K_1 = 6.0$ $C_{2b} K_{2b} = C_{2r} K_{2r} = 4.40$

³ Identifies whether high stress is on the exterior (e) or the interior (i) of the tee.

TABLE 3 Summary of Normalized Stress Intensity and Comparison With The ASME Code Stress Indices (T-13)

Load	Normalized Stress Intensity (i) _s max	Rosette No.	Nominal Stress Intensity ¹	ASME Code CK Index ²
1.M3X	1.4	6 (e) ³	M3Z/Zb	2.0
2.M3Y	1.1	3 (e)	M3Z/Zb	2.0
3.M3Z	1.6	3 (e)	M3Z/Zb	2.0
5.F3Y	2.3	6 (e)	F3Y/Ab	
7.M2X	1.6	4 (i)	M2X/Zr	2.0
8.M2Y	1.2	1 (e)	M2Y/Zr	2.0
9.M2Z	2.1	6 (i)	M2Z/Zr	2.0
10.F2X	2.4	5 (i)	F2X/Ar	
13.P	2.4	2 (i)	PD _o /2t	6.0

¹ Nominal pipe properties using dimensions from ASA B36.10-1959 for 10 in. (254 mm) and 24 in. (610 mm) schedule 160 pipe

Branch

Run

$$D_o = 10.75 \text{ in. (273.050 mm)}$$

$$D_o = 24.000 \text{ in. (609.600 mm)}$$

$$t = 1.125 \text{ in. (28.575 mm)}$$

$$t = 2.344 \text{ in. (59.538 mm)}$$

$$Z_r = 74.3 \text{ in.}^3 (1\,217\,558.86 \text{ mm}^3)$$

$$Z_r = 788.1 \text{ in.}^3 (12\,914\,645.14 \text{ mm}^3)$$

$$A_r = 34.01 \text{ in.}^2 (21\,941.89 \text{ mm}^2)$$

$$A_r = 159.4 \text{ in.}^2 (102\,838.50 \text{ mm}^2)$$

² Pressure $C_1 = 1.5$

$$K_1 = 4.0$$

$$C_1 K_1 = 6.0$$

Moment $C_{2b} = C_{2r} = 0.67(R_m/T_r)^{2/3} = 1.86$, but less than 2.0

$$K_{2b} = K_{2r} = 1.0$$

$$C_{2b} K_{2b} = C_{2r} K_{2r} = 1.86 \text{ (Use 2.0)}$$

³ Identifies whether high stress is on the exterior (e) or the interior (i) of the tee.

TABLE 4 Summary of Normalized Stress Intensity and Comparison With The ASME Code Stress Indices (T-16)

Load Case And Name	Normalized Stress Intensity (i_s)max	I.D. No.	Nominal Stress Intensity ¹	ASME Code CK Index ²
1.M3X	3.2	1 (i) ³	M3X/Zr	8.75
2.M3Y	3.2	3 (i)	M3Y/Zr	8.75
3.M3Z	2.9	2 (i)	M3Z/Zr	8.75
5.F3Y	3.1	1 (i)	F3Y/Ar	
7.M2X	3.4	4 (i)	M2X/Zr	8.75
8.M2Y	1.1	5 (i)	M2Y/Zr	8.75
9.M2Z	2.5	5 (i)	M2Z/Zr	8.75
10.F2X	3.6	5 (i)	F2X/Ar	
13.P	2.2	6 (i)	PD o/2tr	6.0

¹ Nominal pipe properties using dimensions from ASA B36.10-1959 for 24 in. (610 mm) schedule 10 pipe

$$D_c = 24.0 \text{ in. (609.600 mm)}$$

$$t_r = 0.250 \text{ in. (6.350 mm)}$$

$$Z_r = 109.6 \text{ in.}^3 \text{ (1 796 122.21 mm}^3\text{)}$$

$$A_r = 18.7 \text{ in.}^2 \text{ (12 064.49 mm}^2\text{)}$$

² Pressure $C_1 = 1.5$ Moment $C = C_2 = 0.67(R_m/T_r)^{2/3} = 8.75$

$$K_1 = 4.0 \quad K = K_2 = 1.0$$

$$C_1 K_1 = 6.0 \quad C = C_2 K_2 = 8.75$$

³ Identifies whether high stress in on the exterior (e) or the interior (i) of the tee.

TABLE 5 Maximum Normalized Stress Intensities for B16.9 Tees^a

Tee No.	Internal Pressure Loading	Branch Moment Loadings			Run Moment Loadings		
		In Plane	Out of Plane	Torsional	In Plane	Out of Plane	Torsional
		(M3Z)	(M3X)	(M3Y)	(M2Z)	(M2Y)	(M2X)
T-10	2.9	3.8	3.7	3.6	3.1	1.6	3.6
T-11	3.7	2.2	2.3	2.1	1.8	1.2	1.8
T-12	2.4(1.2) ^c	1.3(1.2) ^c	2.0(1.2) ^b	0.9(1.1) ^c	2.4(0.9) ^c	0.8(1.1) ^b	1.8
T-13	2.4(1.9) ^c	1.6(1.1) ^c	1.4(1.0) ^c	1.2(1.1) ^c	2.1(1.0) ^b	.9(1.2) ^b	1.6
T-16	2.2(1.8) ^b	2.9(3.1) ^b	3.2(5.1) ^c	3.2(2.9) ^b	2.5(3.0) ^b	1.1(1.9) ^b	3.4

^a The maximum stress intensities were located on the inside surface for all the numbers in the tables that are marked with an asterisk; otherwise the maximum value was on the outside surface of the tee. The terms in parentheses are the highest stress intensities at welded joints.

^b On run to extension pipe weld.

^c On branch to extension pipe weld.

TABLE 6 Summary of Flexibility Factors (T-11)

<u>Load</u>	<u>RUN</u>		<u>BRANCH</u>	
	K Subscript	K Magnitude	K Subscript	K Magnitude
M2X	X21	---	X31	0.3
M2Y	Y21	0.8	Y31	0.8
M2Z	Z21	1.3	Z31	1.2
M3X	X21	---	X31	0.5
M3Y	Y21	0.7	Y31	0.3
M3Z	Z21	1.2	Z31	1.2

TABLE 7 Summary of Flexibility Factors (T-12)

Load	<u>RUN</u>		<u>BRANCH</u>	
	K Subscript	K Magnitude	K Subscript	K Magnitude
M2X	X21	-0.4	X31	-0.5
M2Y	Y21	0.7	Y31	0.6
M2Z	Z21	0.9	Z31	0.8
M3X	X21	-0.5	X31	1.8
M3Y	Y21	0.5	Y31	-0.3
M3Z	Z21	0.8	Z31	0.9

TABLE 8 Summary of Flexibility Factors (T-13)

Load	<u>RUN</u>		<u>BRANCH</u>	
	K Subscript	K Magnitude	K Subscript	K Magnitude
M2X	X21	0.2	X31	0.3
M2Y	Y21	0.8	Y31	0.8
M2Z	Z21	0.9	Z31	0.9
M3X	X21	0.2	X31	0.5
M3Y	Y21	0.6	Y31	0.3
M3Z	Z21	0.9	Z31	0.4

TABLE 9 Summary of Flexibility Factors (T-16)

Load	<u>RUN</u>		<u>BRANCH</u>	
	K Subscript	K Magnitude	K Subscript	K Magnitude
M2X	X21	.7	X31	0.55
M2Y	Y21	.4	Y31	0.42
M2Z	Z21	2.5	Z31	2.5
M3X	X21		X31	1.2
M3Y	Y21	.4	Y31	1.0
M3Z	Z21	2.4	Z31	3.3

TABLE 10 B16.9 Tee Fatigue Test Results and
Calculated Allowable Design Cycles

Tee	N_t^a	N_c^b	N_t/N_c	N_e^c	N_t/N_e
T-10	18,532	19	975	50	371
T-11	2,875	550	5	280 ^d	10
T-12	76,620	750	102	6000 ^e	12.77
T-13	15,084	550	27	2250 ^f	7
T-16	2,344	5	469	360	6.5

- ^a N_t is the number of cycles at which failure occurred in the test.
- ^b N_c is the code-allowable design life based on paragraph NB-3653.6 and the stress indices of Table NB-3683.2-1 of ASME-III-1974.
- ^c N_e is the expected design life based on the procedures of NB-3653.6 and the maximum elastic stress amplitude imposed during the tests, that is using the experimentally determined normalized stress intensities instead of the code values for the stress intensities.
- ^d This value of N_e for the cyclic pressure test of T-11 was calculated using experimental stress index values of $C_1K_1 = 3.7$ and $K_1 = 1.2$ from the photoelastic tests of T-7.
- ^e This value of N_e for the cyclic pressure tests of T-12 was calculated using experimental stress index values of $C_1K_1 = 2.4$ and $K_1 = 1.0$ from the photoelastic tests of T-9.
- ^f This value of N_e for the cyclic pressure tests of T-13 was calculated using experimental stress index values of $C_1K_1 = 2.4$ and $K_1 = 1.0$ from the photoelastic test of T-9.

NOTE:

CROTCH SECTIONS
TRACED FROM
MOLDING PLASTER
MOLDS.

CROTCH SECTION
END "A"

TABLE			
ALL DIMENSIONS IN MM			
LOC.	END "A"	END "B"	BRANCH
T ₁	74.3	64.5	75.8
T ₂	70.4	70.6	69.8
T ₃	64.5	73.7	74.9
T ₄	71.1	71.1	68.3

CROTCH SECTION
END "B"

TYPICAL SECTION
15 INCHES FROM ϵ

FIG. 2 AS BUILT DIMENSIONS OF T-II TEE

NOTES:

FIGURES SHOWN ARE C.E. MEASUREMENTS.
CONTOURS TRACED FROM PLASTER OF
PARIS CAST TAKEN FROM CENTER LINE
LOCATIONS OF TEE.

CROTCH SECTION
END "A"

CROTCH SECTION
END "B"

TABLE			
ALL DIMENSIONS IN MM			
LOC.	END "A"	END "B"	BRANCH
T ₁	25.4	24.6	15.1
T ₂	23.4	25.2	14.9
T ₃	24.6	26.0	15.1
T ₄	26.0	25.5	14.8

FIG. 3 AS BUILT DIMENSIONS OF T-12 TEE

TABLE			
ALL DIMENSIONS IN MM			
LOC	END "A"	END "B"	BRANCH
T ₁	63.1	65.4	32.4
T ₂	68.2	69.2	32.6
T ₃	66.0	64.9	31.6
T ₄	69.0	68.7	31.6

TYPICAL CROTCH THROUGH
END "A" DRAWN REDUCED
SCALE

GENERAL NOTES

FIGURES SHOWN ARE C.E.
MEASUREMENTS (TYP).
SECTION IS 2" FROM EDGE FOR
ENDS AND 1" FROM EDGE FOR
BRANCH.

TYPICAL SECTION
VIED FROM OPENING

FIG. 4 AS BUILT DIMENSIONS OF T-13 TEE

NOTE:

ALL CONTOUR SECTIONS
TRACED FROM MOLDS
MADE OF MOLDING
PLASTER

FIG. 5 AS BUILT CONTOUR DIMENSIONS OF T-16 TEE

FIG. 6 TYPICAL INSTRUMENTATION FOR QUADRANT OF T-J TEE

Figure 7. Maximum Normalized Stress Intensity Locations For "T-16"

FIGURE 8 Maximum Normalized Stress Intensity Locations For "T-12"

Fig. 9 Typical Instrumentation For Quadrant of T-13 Tee

Fig. 11 Schematic View of Moment and Force Loadings for the Tees

Fig. 12 Block Diagram of Data Processing Scheme

Figure 13. Normalized Principle Stress for row 3, quadrant -X, +Y, -Z for M3X loading (T-11)

Figure 14. Normalized Principle Stress for row 1, quadrant -X, +Y, -Z for M22 loading (T-11)

Figure 15. Normalized Principle Stress for row 5, quadrant -X, +Y, -Z for internal pressure loading (T-11)

Figure 16. Normalized Principle Stress for row 1, quadrant +X, +Y, +Z for M3X loading (T-12)

Figure 17. Normalized Principle Stress for row 1, quadrant -X, +Y, -Z for M22 loading (T-12)

Figure 18. Normalized Principle Stress for row 6, quadrant +X, +Y, +Z for internal pressure loading (T-12)

Figure 19. Normalized Principle Stress for row 1, quadrant -X, +Y, -Z for M3X loading (T-13)

Figure 20. Normalized Principle Stress for row 1, quadrant -X, +Y, -Z for M22 loading (T-13)

Figure 21. Normalized Principle Stress for row 6, quadrant -X, +Y, -Z for internal pressure loading (T-13)

Figure 22. Normalized Principle Stress for row 1, quadrant +X, +Y, +Z for M3X loading (T-16)

Figure 23. Normalized Principle Stress for row 2, quadrant -X, +Y, -Z for M2X loading (T-16)

Figure 24. Normalized Principle Stress for row 2. quadrant -X, +Y, -Z for F2X loading (T-16)

Figure 25. Normalized Principle Stress for row 5, quadrant +X, +Y, +Z for internal pressure loading (T-16)

NOMENCLATURE

A	=	area of metal in pipe, in. ²
C	=	secondary stress index
CK	=	peak stress index
D _o	=	nominal outside diameter, in.
i _{max}	=	most positive normalized principal stress
i _{min}	=	least positive normalized principal stress
i _s	=	normalized stress intensity
k	=	flexibility factor
K	=	local stress index
M	=	bending moment, in.lb.
N _c	=	calculated code allowable design life
N _e	=	expected design life
N _t	=	fatigue life determined by test
P	=	pressure, psig
S	=	elastic stress amplitude in piping for fatigue consideration, psi; or stress intensity, psi
t	=	nominal wall thickness, in.
Z	=	nominal section modulus, in. ³
θ	=	rotation, radians
σ _{max}	=	most positive principal stress
σ _{min}	=	least positive principal stress
τ	=	shear stress

Subscripts

b	=	branch
r	=	run
1,2,3	=	planes for the three ends of the tee piping configuration