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TEST REPORT ON EXPERIMENTAL STRESS ANALYSIS OF A 24 INCH DIAMETER TEE (ORNL T-16)

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COMBUSTION ENGINEERING, INC.
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DEPARTMENT

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by D. R. Henley

June 1975

SUBCONTRACT NO. 3310
FOR
OAK RIDGE NATIONAL LABORATORY
OAK RIDGE, TENN.

FOREWARD

The work reported here was done in the Nuclear Components Department Testing Laboratory, Combustion Engineering, Inc., Chattanooga Works, under Union Carbide Corporation Nuclear Division Subcontract No. 3310 as part of the ORNL Piping Program - Design Criteria for Piping, Pumps, and Valves. This program is being carried out for the U.S. Energy Research and Development Administration (ERDA) by the Oak Ridge National Laboratory under the direction of W. L. Greenstreet, Technical Director, Solid Mechanics Department; and S. E. Moore, Program Coordinator. Ben Wei of the ERDA Division of Reactor Research and Development is the Cognizant Engineer.

The ORNL Piping Program is funded by the Division of Reactor Research and Development as the ERDA supported portion of a cooperative effort with industry for the development of design criteria for Nuclear power plant piping components, pumps, and valves. This cooperative effort is coordinated by the Pressure Vessel Research Committee (PVRC) of the Welding Research Council.

ABSTRACT

This report describes the experimental stress analysis and low cycle fatigue test of one 24" X 24" X 24" schedule 10 stainless steel, ANSI B16.9 tee performed by Combustion Engineering, Inc. The tee was instrumented with 230 rectangular strain gage rosettes. Elastic data was obtained for 12 loading conditions consisting of internal pressure and orthogonal pure moments and orthogonal direct forces applied individually to the free branch and run ends of the tee. One of the run ends of the tee was "built in" throughout the test. All loads were applied through pipe extensions welded to the tee. The tee was fatigue tested to failure by applying a cyclic in-plane moment to the branch of the tee assembly. A through-the-wall fatigue crack occurred at 2344 cycles. Significant test results are summarized and compared with design values tabulated in the ASME Boiler and Pressure Vessel Code, Section III, 1971.

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NOMENCLATURE

C	=	primary plus secondary stress index
D_o	=	outside diameter, in.
K	=	local stress index
S	=	elastic stress amplitude in piping for fatigue consideration, psi; or stress intensity, psi
Z	=	nominal section modulus, in.
τ	=	shear stress
θ	=	rotation, radians
σ_{max}	=	most positive principal stress, psi
σ_{min}	=	least positive principal stress, psi
i_{max}	=	normalized principal stress (most positive)
i_{min}	=	normalized principal stress (least positive)
i_s	=	normalized stress intensity

Subscripts

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

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LIST OF TABLES AND FIGURES

1.0 INTRODUCTION

In early 1969 the Oak Ridge National Laboratory (ORNL) issued a contract to Combustion Engineering, Inc. to conduct experimental stress analyses and low cycle fatigue tests on four 24-inch diameter ANSI B16.9 carbon steel tees. This experimental work is part of the ORNL piping program to develop design criteria for nuclear service piping components. The program is the U.S. Energy Research and Development Administration supported portion of a joint ERDA-Industry program to develop design information for nuclear service piping components, pumps, and valves. ORNL later added two 24-inch diameter ANSI B16.9 tees to the contract.

The Combustion Engineering tests are for tees numbered 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 ORNL Piping Program (1).[1] The tees in the C-E test series are as follows:

Tee Number	Nominal Size
T-10 (carbon steel)	24" X 24" X 24" sch 40
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
T-17 (stainless steel)	24" X 24" X 10" sch 10

The test results from the T-10 tee, T-11 tee, T-13 tee, and the T-12 tee are presented in Ref. (2), Ref. (3), Ref. (4), and Ref. (5), respectively. In this report the test results from the T-16 tee, which was the fifth tee to be tested, are presented. Also covered is 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. A comparison is made between the normalized stress intensities determined from the test data and the design values tabulated in the ASME Boiler and Pressure Vessel Code, Section III, 1971.

[1] Numbers in brackets designate References at end of paper.

In regard to the fatigue test, a comparison is also made between the actual number of cycles that caused a fatigue failure and the number of cycles calculated using the Simplified Elastic-Plastic Discontinuity Analysis in Section III of the ASME Code (6).

2.0 LABORATORY EQUIPMENT

2.1 Load Frame. The test frame consists of an assembly of wide flanged beams bolted to foundation anchor points at eight places (7). The test frame was designed for the following loading conditions:

Bending moment	9,600,000 in-lbs
Torsional moment	9,600,000 in-lbs
Axial load	800,000 lbs

The foundation consists of four large rectangular beams of steel reinforced concrete arranged in a "rectangular donut" configuration. Approximately 126 cu. yds. of concrete and 7300 lbs. of reinforcing steel were utilized in the foundation. Each anchor point was designed to resist a load combination of 57.1 kips upward or downward and a resultant force of 70.7 kips horizontally.

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 are bolted to special 24-inch weld neck flanges welded to the outside diameter of the run piping components. Figure 1 shows a tee in the load frame.

Various hydraulic jack assemblies are used to apply the different loads to the test tee assembly. Most of the jack assemblies were provided with swivels containing ball bearings at each end (Fig. 2). Each jack assembly has been calibrated on a hydraulic universal testing machine. A hydraulic system capable of accurate pressures up to 10,000 psi is employed to provide necessary pressure for all jacks. Special ball bearing and roller bearing type supports were designed to support the test tee assembly (Fig. 3).

2.2 Data Acquisition and Processing Equipment. A computer controlled data acquisition system was employed for the strain gages, thermocouple, and LVDT instrumentation (7). 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 computer or manually controlled by its own front panel switches. The system is designed to measure the output signal for any of 2000 channels.

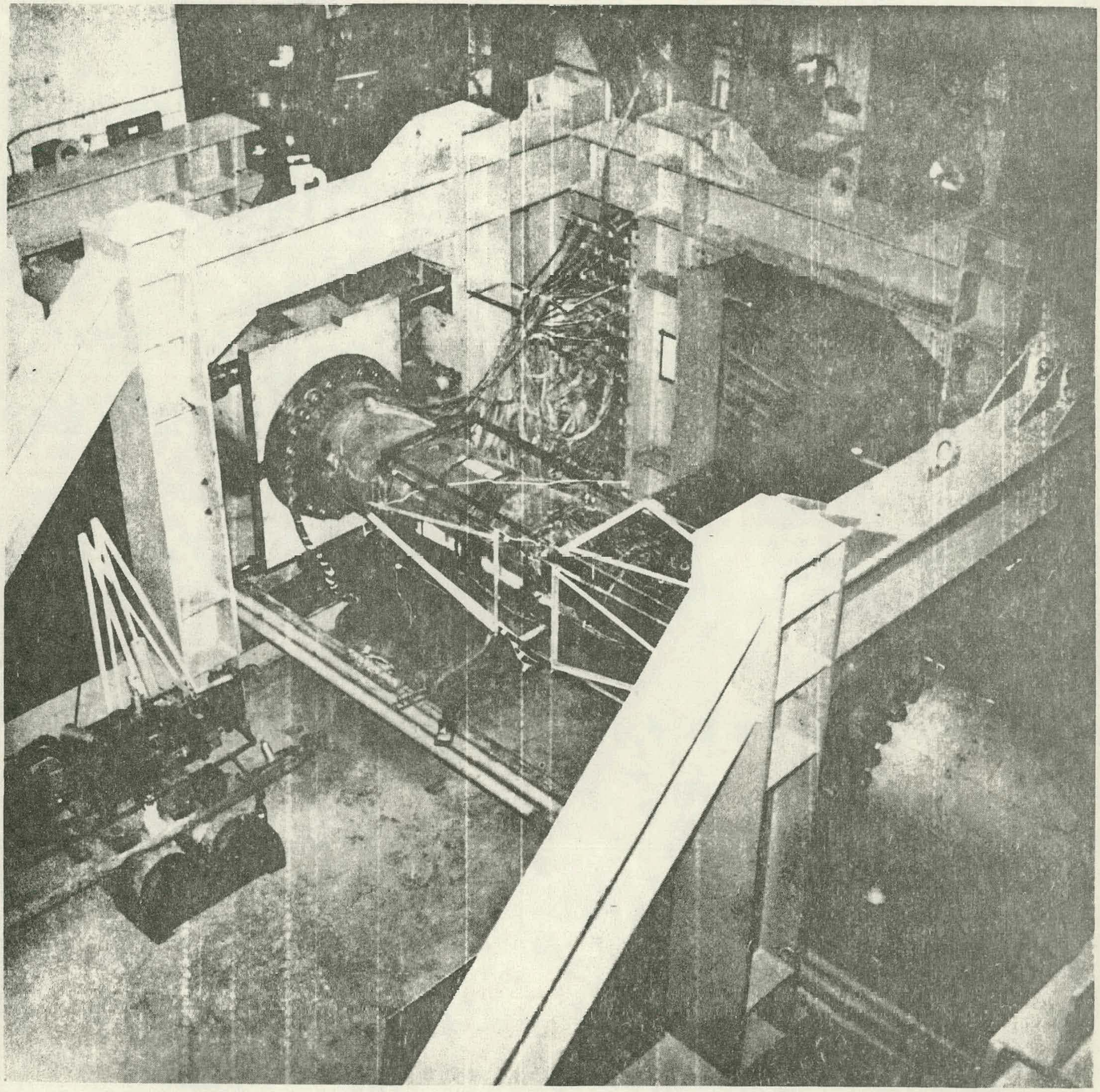

Fig. 1 View of a Tee in the Load Frame

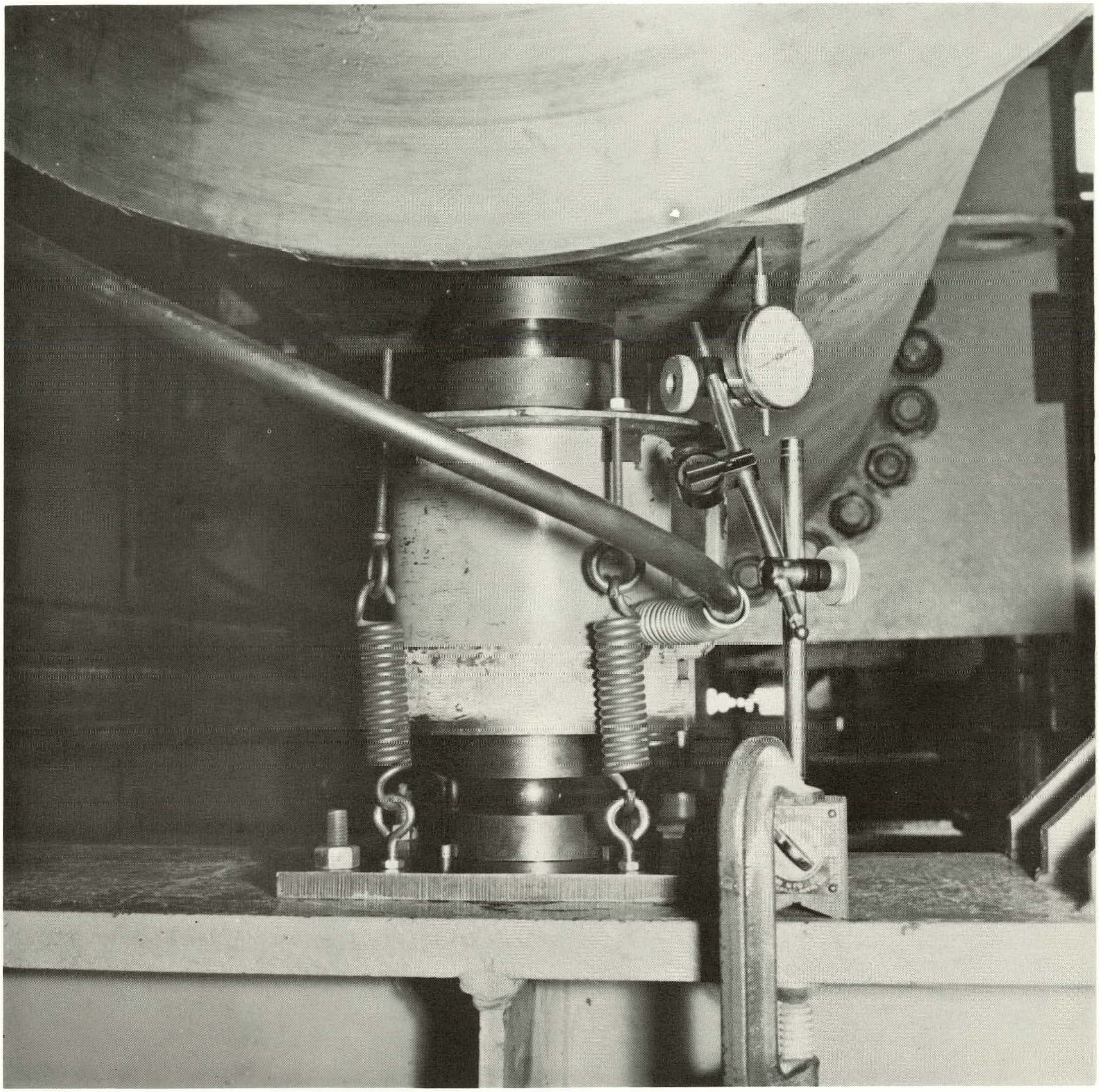

Fig. 2 View of 100 Ton Jack Assembly with Swivels

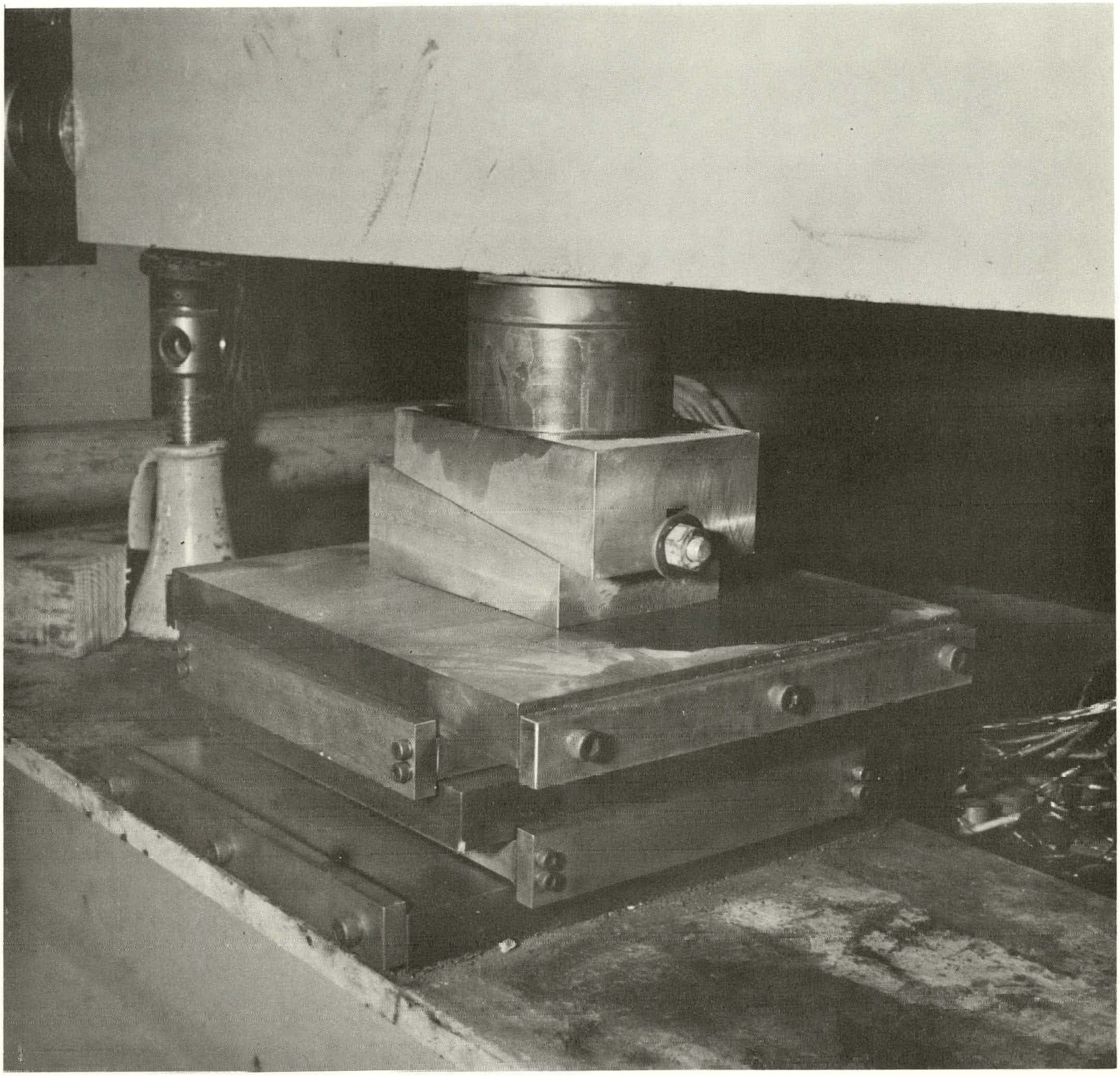

Fig. 3 View of Roller Bearing Supports

During a typical test, all tests 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 completely automatic plotting of all desired information.

2.3 Fatigue Test Equipment. The fatigue test equipment utilized for pressurizing the tee consists of an MTS closed-loop servo control system, a hydraulic power supply, five intensifiers, a Heise pressure gage and a pressure transducer. Title to the MTS system, hydraulic power supply, and the five intensifiers is vested in the U.S. Government. The arrangement of the fatigue test equipment is shown in Figure 17. A brief description of some of these items will be presented below:

MTS System - This system is primarily designed for structure 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.

With this system it is possible to apply pressure to the test components at various cyclic rates, depending on the capacity of the hydraulic system, and using different functions. An "inverted haversine" function is generally used for pressure cyclic tests. The MTS System has various interlocks to ensure proper test program operation. These are listed below:

(A) Limit Detector (prevent excess pressure rise)
(B) Low Amplitude Measurement (prevent undershoot during pressure cycle)
(C) Pressure Relief Valve on Hydraulic Power Supply (can be adjusted to limit maximum pressure attainable by MTS System)

Hydraulic Power Supply - The hydraulic power supply consists of a variable volume pump capable of delivering up to 35 gpm of hydraulic oil. It is a self-contained unit, containing an oil reservoir, oil-water heat exchanger, safety relief valve, pressure regulator, various indicators, and filters. It is designed for providing a hydraulic pressure of 3000 psi.

Intensifiers - One to five oil to oil intensifiers are used with the MTS System to provide sufficient oil volume to achieve the desired pressure in one stroke of the intensifiers. The intensifiers have an intensification ratio of 3.31 and were manufactured by Ortman-Miller.

Pressure Transducer - A BLH General Purpose pressure cell type GP is used for fatigue tests. It has a maximum pressure of 20,000 psi.

3.0 TEST MODEL

3.1 Fabrication Details of Tee. The test tee was provided by ORNL. The tee is considered a wrought fitting fabricated from ASTM A-240-70, 304L stainless steel plate. The lot number and mill heat number of the material are P-6453 and 500281-1A respectively. The tee was fabricated in accordance with ASTM Specification A-234 which is required by the ANSI B16.9 specification for wrought fittings. Physical properties of the material were obtained from the plate mill test report and are listed below:

Yield Strength - 38,000 psi
Tensile Strength - 83,000 psi
Percent Elongation - 53.0

3.2 "As-Built" Dimensions of Tee. Before welding pipe extensions to the tee, plaster of paris casts were made of the inside and outside of the tee. Several contours traced from these casts are shown on C-E Dwg. E-62873-003 in Appendix "A".

The surfaces on the tee which were to be instrumented were polished and the centerlines of the strain gages established. For future reference the X-Y-Z coordinates of each strain gage centerline were established. This was accomplished by first establishing centerlines for the tee and then machining the weld preps perpendicular to these centerlines. By using the weld prep to position the tee on a marble table, the desired coordinates would be readily acquired using a vernier height gage.

The actual measurements which were made are shown on C-E Dwg. B-62675-041 in Appendix "A". Also, the equations which were used to establish the X-Y-Z coordinates from the centerline of the tee are shown on this drawing.

The X-Y-Z coordinate dimensions for the center of each strain gage rosette are tabulated on data sheets in Appendix "A". The dimensions not shown on the data sheets could not be established since these strain gage rosettes were located at the weld centerlines. After the welds were made it was not feasible to establish these dimensions.

3.3 Test Assembly. Fifty-inch long pipe extensions of SA-312 Type 304 stainless steel material, with ellipsoidal caps attached, were welded to the tee. It was necessary to weld the extension run piping assembly after the remainder of the tee assembly had been completed and all internal instrumentation had been installed. All welding procedures were qualified in accordance with Section 9 of the ASME Boiler and Pressure Vessel Code and all welds were of nuclear quality. 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 weld neck flanges were welded to each piping extension to make provision for the application of load to the tee assembly. The mating surface of the flange was positioned 75½-inches from the centerline of the tee to fit properly in the load frame. Nozzles were provided in the pipe extension for filling, venting, and pressurizing of the tee. Nozzles were also provided for special glands used for sealing approximately 1000 lead wires connected to the internal strain gage instrumentation. Special anchor pads were also provided for attachment of LVDT hardware used for determining flexibility factors. The completed tee and pipe extension sub-assembly and the extension run piping sub-assemblies and final tee assembly were heat treated at 1150°F. See Dwgs. SE-11559 and SD-11558 in Appendix "B" for drawings of the sub-assemblies and final tee assembly.

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 before being installed in the tee assembly.

4.0 ELASTIC RESPONSE TEST

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

4.1 Instrumentation. Two basic types of instrumentation were used; strain gages to measure strain distributions and LVDT's to measure displacements.

Approximately 230 Micro-Measurement Type EA-09-125RA-120 rectangular rosette strain gages with a grid length of 0.125-inch were cemented on the tee assembly. Coordinate axes from the tee were assigned as follows:

The X axis coincided with the run centerline. The positive Y axis coincided with the branch centerline. The Z axis was mutually perpendicular to the X and Y axes and the positive direction was chosen such as to provide a conventional right-handed system as shown in Figure 4. The tee was heavily instrumented in the +Z, +Y, +Z region and the -X, +Y, -Z region on both the inside and outside surfaces. The instrumentation in each of these regions was arranged in five rows as shown in the instrumentation drawings in Appendix "B".

To establish the row lines $22\frac{1}{2}^{\circ}$ increments were marked off on inside and outside diameters of all three ends of the tee. The tee was then positioned with the weld prep on one of the runs of the tee flat on a marble table. As indicated in Section 3.2 the weld preps were all machined perpendicular to the axis of the tee. Then, using the $22\frac{1}{2}^{\circ}$ increments, row lines were constructed by scribing appropriate horizontal lines on the branch and vertical lines on the run. The "crotch line" was constructed by connecting the intersections of these horizontal and vertical lines.

Gage location on each row line were determined by using dividers. Thus the true surface distance between gages may vary. This was not considered detrimental as actual X, Y, and Z coordinates of each gage were measured. In addition to the gages that were on the row lines four gages were mounted on the "crotch line" midway between adjacent rows.

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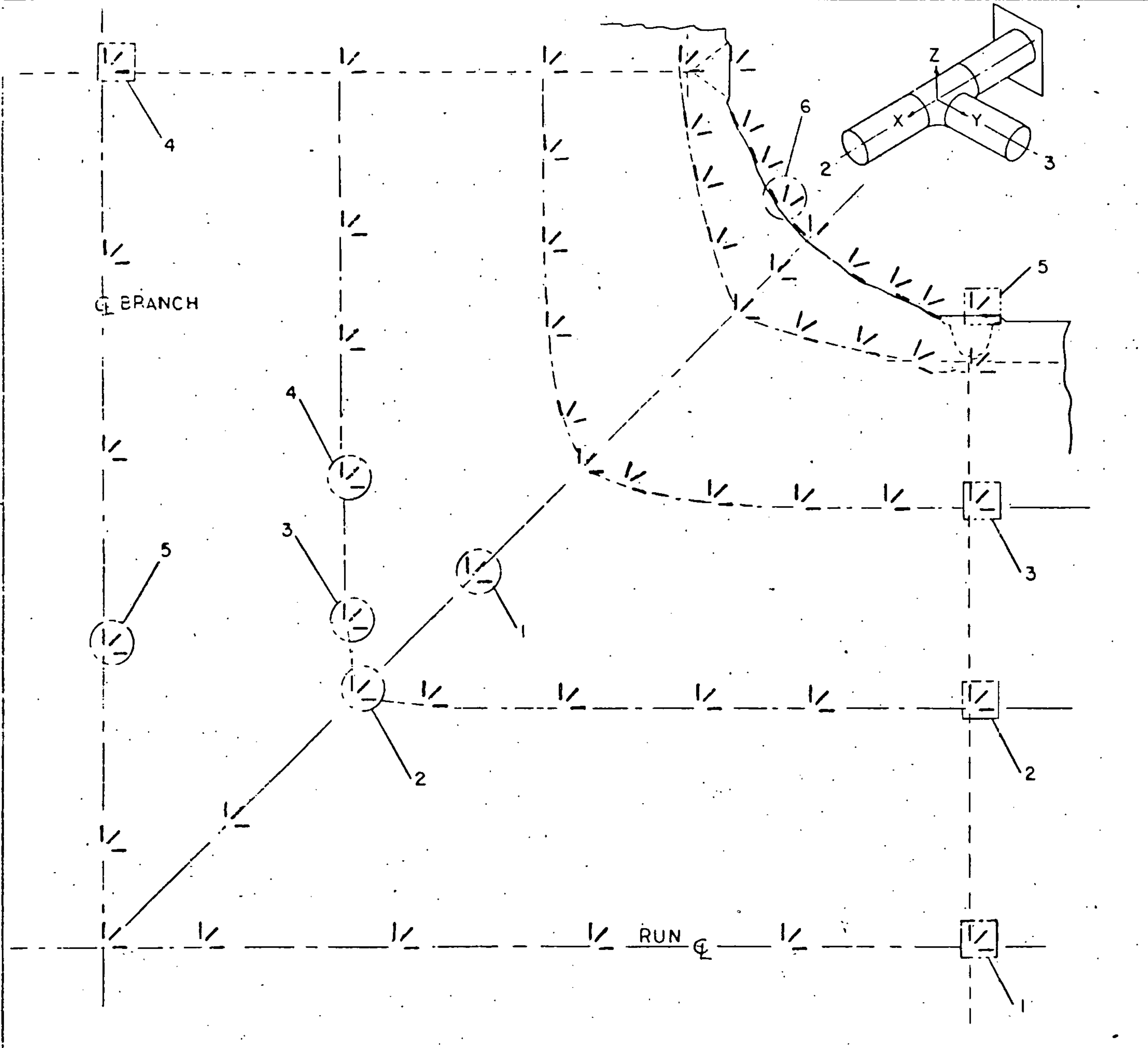
REVISIONS 1/ ADDED * ℄ LOAD "P" 1-24-74 D.R.H. 2/ M3Z [3] WAS 4 2-11-74 F3Z [4] WAS 3 D.R.H.



LOAD	MAXIMUM NORMALIZED STRESS INTENSITY ON TEE * FOR INTERNAL	ON TEE LOCATION	ON WELD * FOR INTERNAL	ON WELD LOCATION
M_3X	3.2*	(1)	5.1	[4]
M_3Y	3.2*	(3)	2.9	[1]
M_3Z	2.9*	(2)	3.1	[3]
F_3Y	3.1*	(1)	7.4	[3]
F_3Z	3.3*	(1)	4.2	[4]
M_2X	3.4*	(4)	2.5	[3]
M_2Y	1.1*	(5)	1.9	[2]
M_2Z	2.5*	(5)	3.0	[2]
F_2X	3.6*	(5)	4.8	[2]
F_2Y	2.7*	(5)	3.4	[2]
F_2Z	1.3	(3)	1.2	[2]
P	2.2*	(6)	1.8	[5]

MAXIMUM NORMALIZED STRESS INTENSITY LOCATIONS FOR "TEE 16" ORNL TEE TEST

SCALE — DATE —
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COMP. CODE — FIGURE 4

DRAWING NO. B-62873-069-2

Figure 4. Maximum Normalized Stress Intensity Locations For "T-16"

This same procedure was used to lay out both the inside and outside surfaces of the two regions that were heavily instrumented. Because of the method employed in locating the gages, corresponding gages on the inside and outside of the tee may not be exactly opposite each other.

Once the tee was laid out in this manner the actual "X, Y, and Z" coordinates for each gage were measured and are tabulated in Appendix "A". Five instrumentation drawings showing the locations of the inside and outside strain gage instrumentation are provided in Appendix "B".

Figure 4 shows a typical arrangement of instrumentation in one quadrant of the tee. The highest stressed rosettes for particular loadings have been identified in this view. All strain gages were moisture proofed. 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, the pipe assembly for the run of the tee was welded after installation of internal strain gages. The temperature of the tee was monitored during the welding operation by utilizing three chromel-alumel thermocouples which were located adjacent to the rosette strain gages nearest the weld. The thermocouples were read frequently to ensure that the temperature of the material in the region where the strain gages were located did not exceed 150 degrees F.

Six LVDT's with special support hardware were employed to measure the relative displacements 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 inch. Fig. 5 shows the arrangement of the LVDT support hardware. Specific dimensions at assembly, LVDT numbers, and LVDT support arrangements, and physical locations, utilized in the test program are shown on C-E Dwg. D-62874-027 in Appendix "B". Complete computer listings of all the measured displacements, the rotations calculated from these displacements and the calculated flexibility factors have been sent to ORNL.

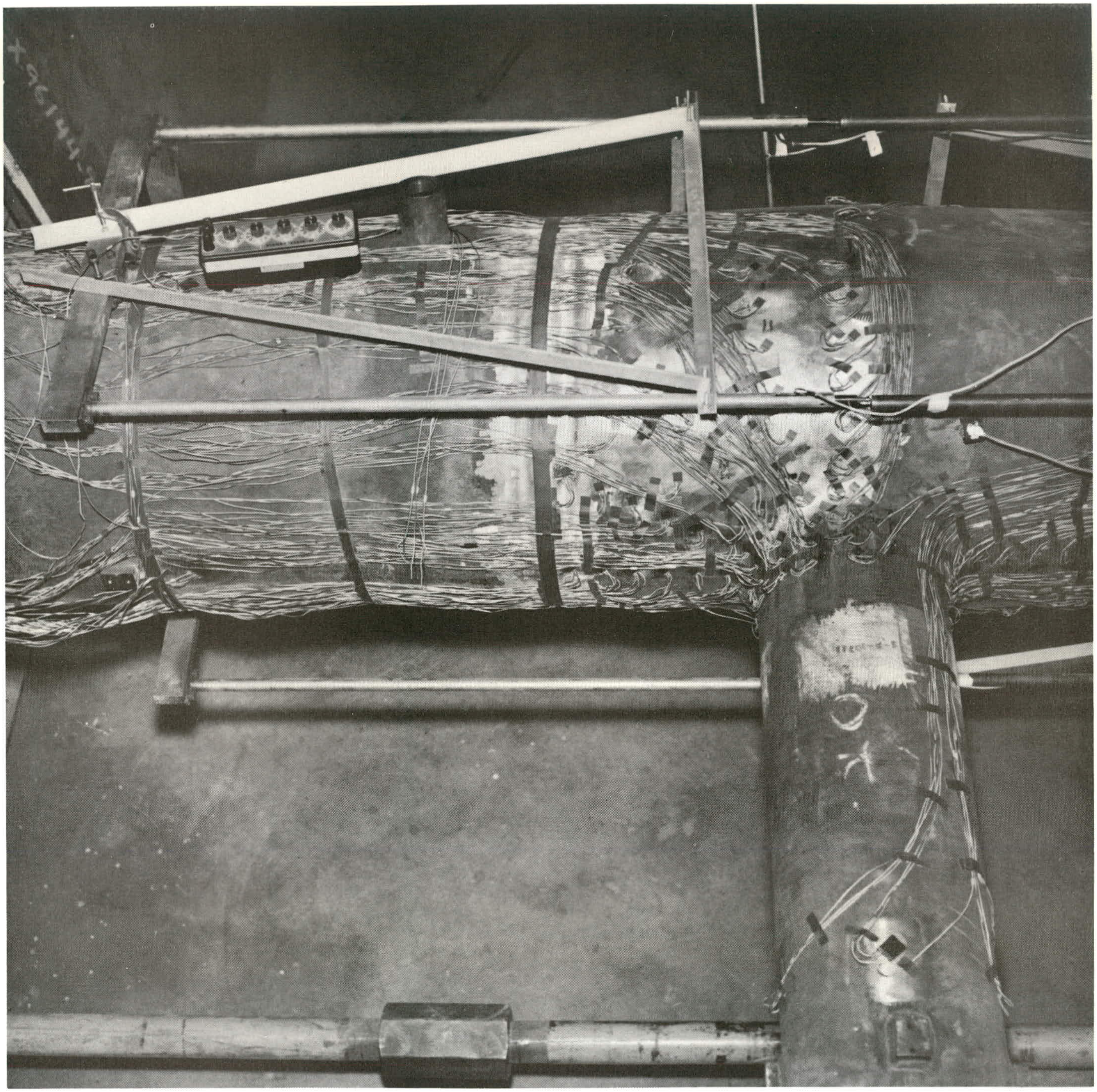


Fig. 5 View of LVDT Support Arrangement

4.2 Test Procedure. It is possible to load a tee with any of the twelve mechanical loadings shown in Fig. 6 or with internal pressure. The "right hand rule" is used as the moment vector convention in Fig. 6. The mechanical loadings may be visualized by considering one of the run ends of the tee extension piping as built in. Three orthogonal pure moments and three orthogonal direct forces may then be applied individually to either the free branch end or the free run end to create the total of twelve mechanical loadings. Superposition may then be used to obtain any combination of mechanical loadings and internal pressure. All of these loadings were imposed separately on the tee except F3X which was omitted due to limitations on the strength of the test frame. Table 1 provides a summary of the maximum applied loads and resulting stresses.

Initially, a sufficient number of load-unload cycles was imposed on the tee 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 ±20 microin./in. The component was 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.

4.3 Data Acquisition and Evaluation. Fig. 7 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 herein as Phase 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 company program permits input of limits on strain, normal stress, and shear stress which enables monitoring only the most significant results on

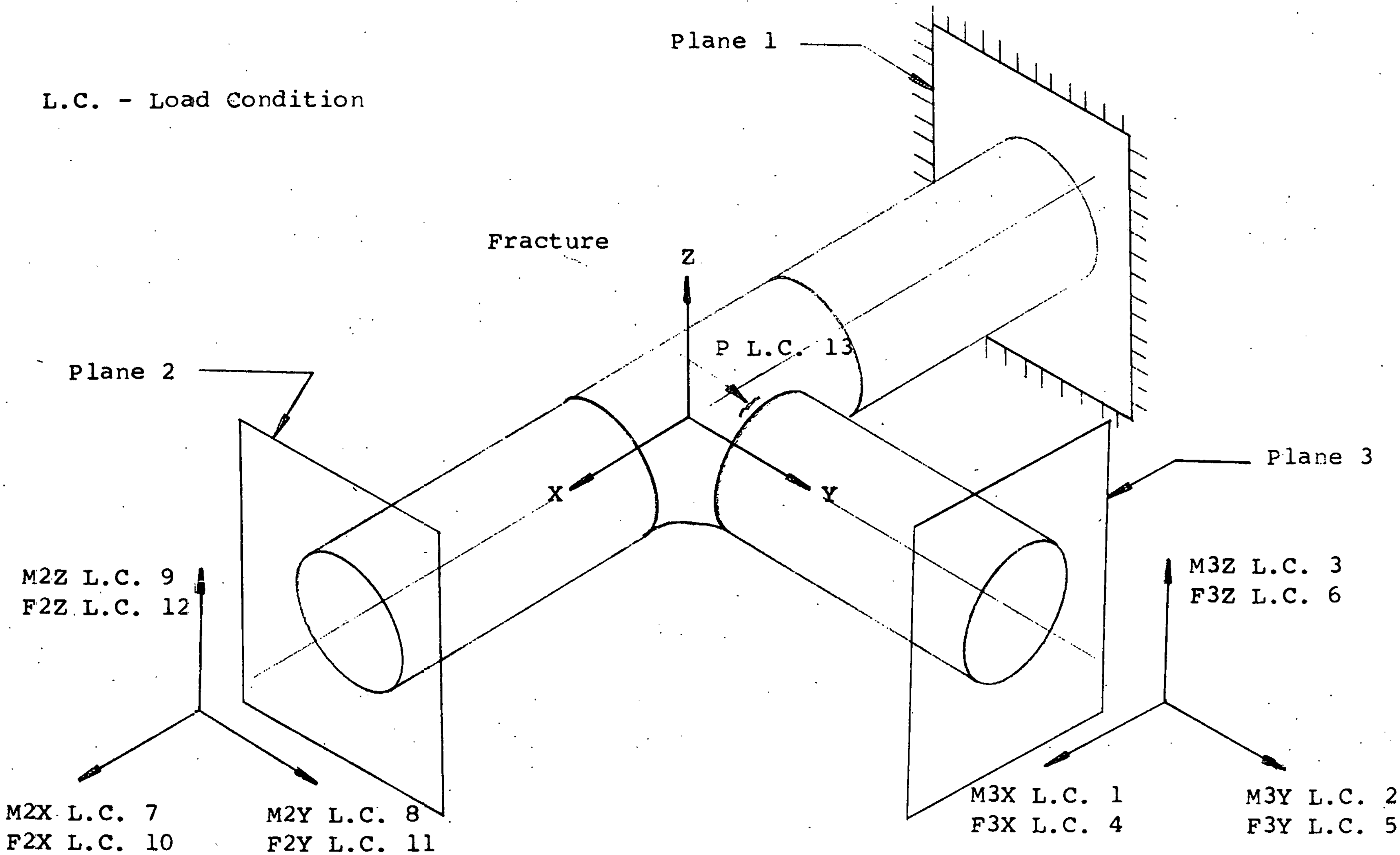


Figure 6 Schematic View of Moment and Force Loadings for Tee Test Model

TABLE 1 Summary of Maximum Loads and Stresses

Load Condition		Maximum[1] Applied Load	Nominal Pipe Stress	Maximum Stress Intensity in Tee
1.	M3X	518.874 in-kips	4.7 ksi	15.2 ksi
2.	M3Y	772.070 in-kips	7.0 ksi	22.5 ksi
3.	M3Z	748.000 in-kips	6.8 ksi	19.8 ksi
5.	F3Y	24.000 kips[2]	1.3 ksi	4.0 ksi
6.	F3Z	7.720 kips	5.4 ksi	17.9 ksi
7.	M2X	444.672 in-kips	4.1 ksi	13.8 ksi
8.	M2Y	1200.997 in-kips	11.1 ksi	12.1 ksi
9.	M2Z	518.784 in-kips	4.7 ksi	11.8 ksi
10.	F2X	-64.339 kips	-3.4 ksi	-12.4 ksi
11.	F2Y	3.088 kips	4.9 ksi	13.2 ksi
12.	F2Z	10.723 kips	16.9 ksi	22.0 ksi
13.	P	120 psi	5.8 ksi	12.7 ksi

1 Because the maximum stress intensities were limited to 35 ksi loads were selected to achieve a maximum stress intensity in the tee of approximately 30 ksi.

2 The stress intensity in the tee was small for this load. The magnitude of the load was limited due to the strength of the load frame.

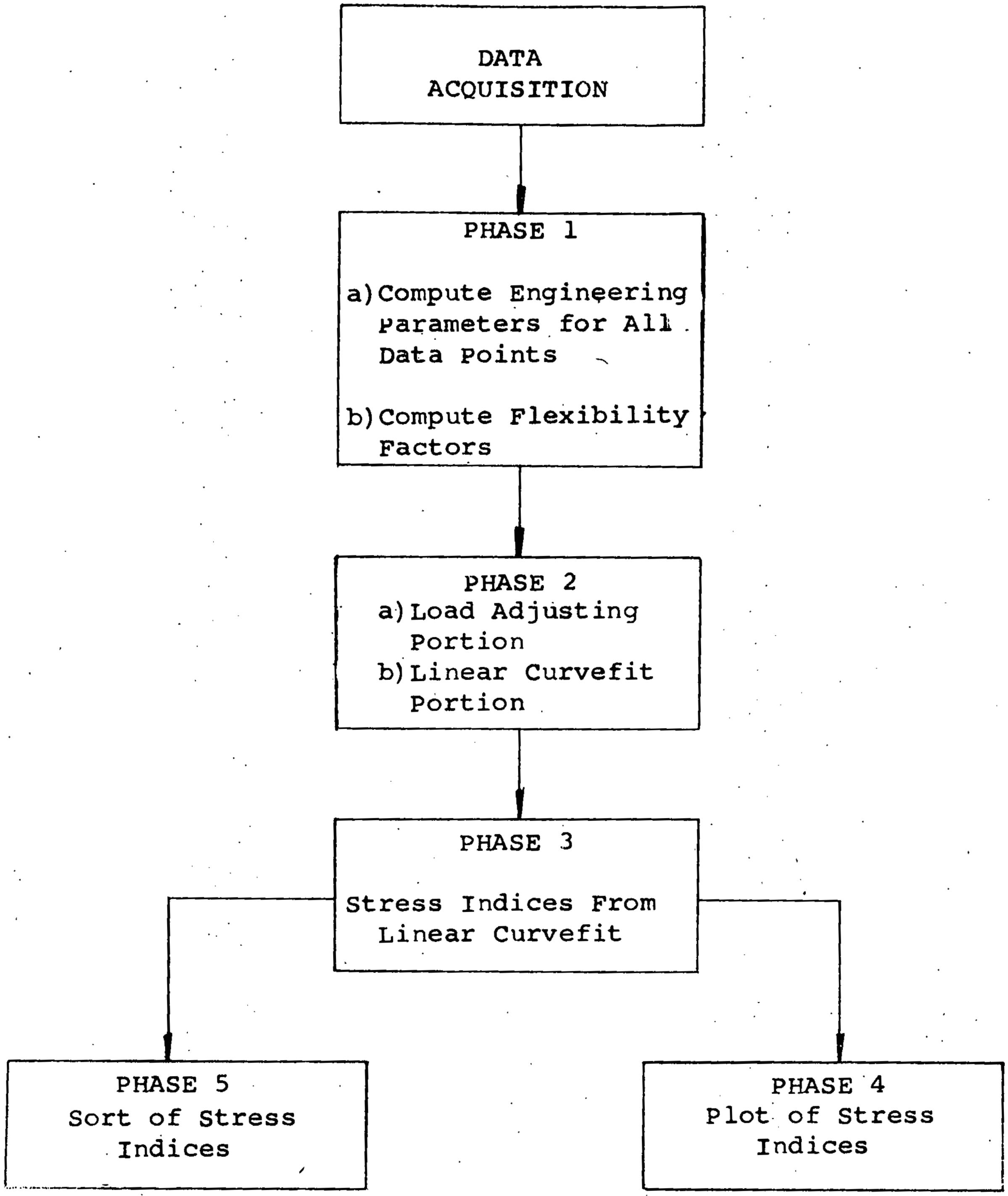


Figure 7 Block Diagram of Data Processing Scheme

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 I 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 and perpendicular to "ray" line, and shear stress. For LVDT's the displacements and flexibility factors are computed.

The Phase II program screens all of the strain gage data for linear response of strain to 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 (8).

Hydraulic jacks, previously calibrated on a hydraulic universal testing machine, were used to apply the load to the tee. Load cells are 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 were a more accurate reflection of the applied load and 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 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 II 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. The "tolerance band criteria" limits the data points to a deviation of ± 20 microin./in. for strains up to 300 microin./in. The data points having strains larger than 300 microin./in. are limited to a deviation of 6.66 percent of the strain. If all data points lie within the tolerance band, the data are accepted. Otherwise, the datum point which falls farthest outside 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 three active strain gage elements were rejected out of the 700 total using this procedure. Gages which were constantly rejected as the test program progressed were changed to an inactive status. At the conclusion of the test program these gages numbered approximately 21 out of 700. The slope for all gages having an acceptable curvefit was retained for use in Phase III.

The Phase III program uses the slopes from the linear curvefits of Phase II to compute the normalized stresses.

The Phase IV program uses the output of Phase III and plots 24 graphs (twelve for internal gages and twelve for external gages) which completely describe the stress distribution along the 20 instrumented ray lines for each load case. For easy visualization of the stress distribution the normalized principal stresses and twice the shear stress were plotted. The abscissa established the physical location of the stresses on the tee as a non-dimensional distance ratio. They may be further clarified as follows:

Referring to Fig. 4, the dashed line representing the intersection of the branch and run is used as the origin. The distance ratio for gages on the run which are furtherest from the dashed line is -1. For points between the dashed line and the furtherest gages on the run the surface distance ratio is computed by dividing the surface distance from the dashed line to the gage by the surface distance from the dashed line to furtherest gage 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 dashed line and the branch weld is similarily computed by dividing the surface distance from the dashed line to the gage by the surface distance from the dashed line to the branch weld for the particular ray in question. As noted in paragraph 4.1 actual surface distances are not measured. Surface distance ratios were established by using dividers.

One typical plot of "Normalized Principal Stresses vs Surface Distance Ratio" for the M3X loading is shown in Fig. 8. For additional clarity the relative locations of the stresses have been graphically presented in this figure. This is typical for all plots generated for this tee test program.

The Phase V program also uses the output from Phase III 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.

4.4 Elastic Data Test Results

Stress Data. A very large amount of computer data was acquired during the test program. To more easily visualize the stress distribution in the tee 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 all loadings by calculating the stress that would exist at the outermost fiber of an idealized 24-in. sch 10 pipe. For transverse force loadings the pipe was assumed to have a length from the load application point to the branch-run centerline intersection.

Based on the aforesaid, the nominal stress intensity is calculated as twice the value of the nominal shear stress. This value is used as the nominal stress to provide correlation with the shear stress theory of failure generally used for ductile materials. Specifically, the following

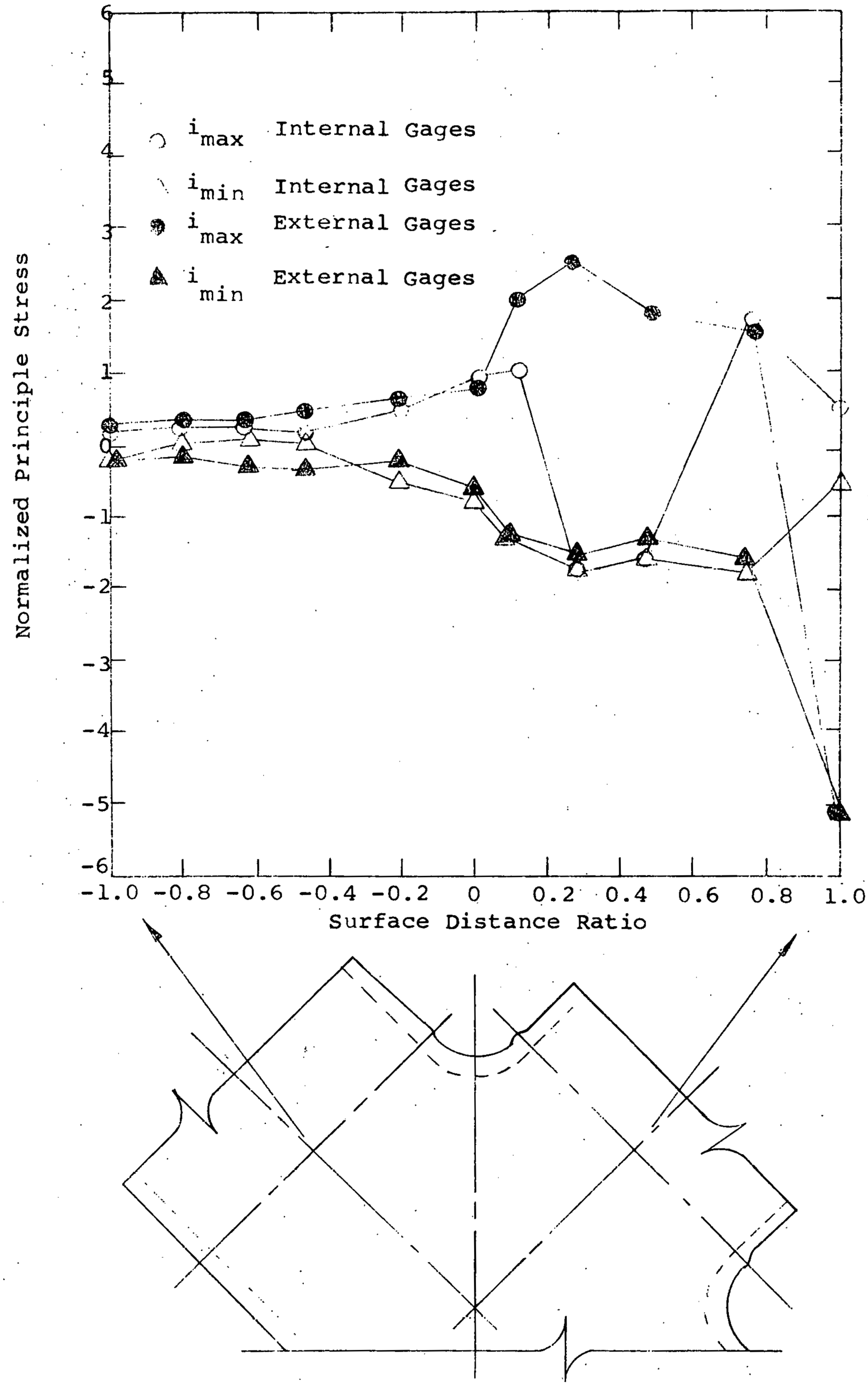


Figure 8 Normalized Principle Stress for row 1, quadrant +X, +Y, +Z for M3X loading

three equations are used as definitions in the presentation of results:

$$i_s = \frac{2\tau_{meas}}{2\tau_{nom}} = \frac{S_{meas}}{S_{nom}}$$

Normalized principle stress

$$i_{min} = \frac{(\sigma_{min})^{meas}}{S_{nom}}$$

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

Table 2 shows the maximum value of the normalized stress intensity, (i_s) max, for twelve loading conditions. The nominal stress intensity and nominal pipe properties are also included in Table 2. As previously mentioned, the F3X test was not performed. The F3Z loading was applied 77 in. (3.2 pipe dia.) from the branch-run intersection producing an M3X moment. The stresses due to the bending force and the results were essentially in agreement with those for the M3X moment loading. The F2Y and F2Z loadings were applied 173 in. (7.2 pipe dia.) 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.

For reference purposes all of the plots generated for each load case are included in Appendix "B".

Figs. 9 through 16 show the stress distribution on the inside and outside surface for the ray which includes the highest normalized stress intensity from Table 2. These curves were essentially traced from the computer plots developed by Phase IV computer program. The curves for the F3Z and F2Z loadings are not presented because they are essentially identical to the curves for M3X and M2Y loadings, respectively.

Flexibility Factors. Basically a flexibility factor is a relationship used to correlate deflections and rotations calculated using nominal pipe dimensions and elementary

TABLE 2 Summary of Normalized Stress Intensity and Comparison with the ASME Code Stress Indices

Load Case and Name		Applied Loads	Norm. Stress Inten. $(i_s)_{max}$	Strain Gage no.	I.D.[5] No.	Nominal Stress Intensity[1]	ASME Code CK Index
1.	M3X	5.19×10^5 in-lb	3.2	694	1(i)[4]	$M3X/Z_r$	8.75
2.	M3Y	-7.72×10^5 in-lb	3.2	535	3(i)	$M3Y/Z_r$	8.75
3.	M3Z	7.48×10^5 in-lb	2.9	541	2(i)	$M3Z/Z_r$	8.75
5.	F3Y	2.40×10^4 lb	3.1	694	1(i)	$F3Y/A_r$	
6.	F3Z(M3X)[3]	7.72×10^3 lb	3.3	694	1(i)	$77(F3Z)/Z_r$	8.75
7.	M2X	4.45×10^5 in-lb	3.4	535	4(i)	$M2X/Z_r$	8.75
8.	M2Y	-1.20×10^6 in-lb	1.1	502	5(i)	$M2Y/Z_r$	8.75
9.	M2Z	5.19×10^5 in-lb	2.5	502	5(i)	$M2Z/Z_r$	8.75
10.	F2X	-6.43×10^4 lb	3.6	502	5(i)	$F2X/A_r$	
11.	F2Y(M2Z)[3]	3.09×10^3 lb	2.7	537	5(i)	$173(F2Y)/Z_r$	8.75
12.	F2Z(M2Y)[3]	1.07×10^4 lb	1.3	214	3(e)	$173(F2Z)/Z_r$	8.75
13.	P	120 psi	2.2	463	6(i)	$PD_o/2t_r$	6.0

[1] Nominal pipe properties using dimensions from ASA B36.10-1959 for 24 in. schedule 10 pipe

$$D_o = 24.0 \text{ in.}$$

$$t_r = 0.250 \text{ in.}$$

$$Z_r = 109.6 \text{ in.}^3$$

$$A_r = 18.7 \text{ in.}^2$$

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

$K_1 = 4.0$ $K = K_2 = 1.0$

$C_1K_1 = 6.0$ $C = C_2K_2 = 8.75$

[3] These forces produce moments indicated in parenthesis.

[4] Identifies whether high stress in on the exterior (e) or the interior (i) of the tee

[5] See Figure 4 for location

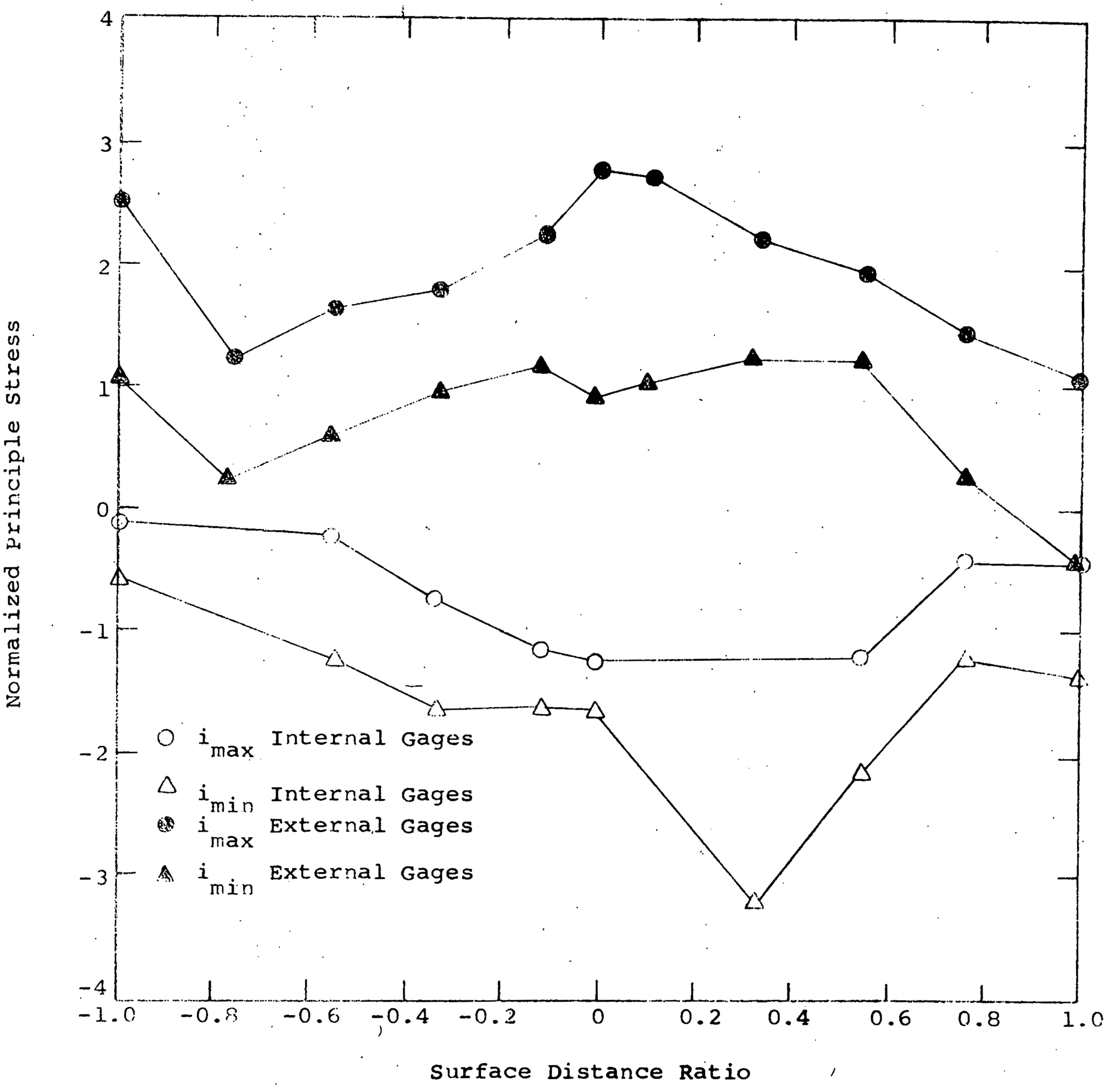


Figure 9 Normalized Principle Stress for row 2, quadrant -X, +Y, -Z for M3Y loading

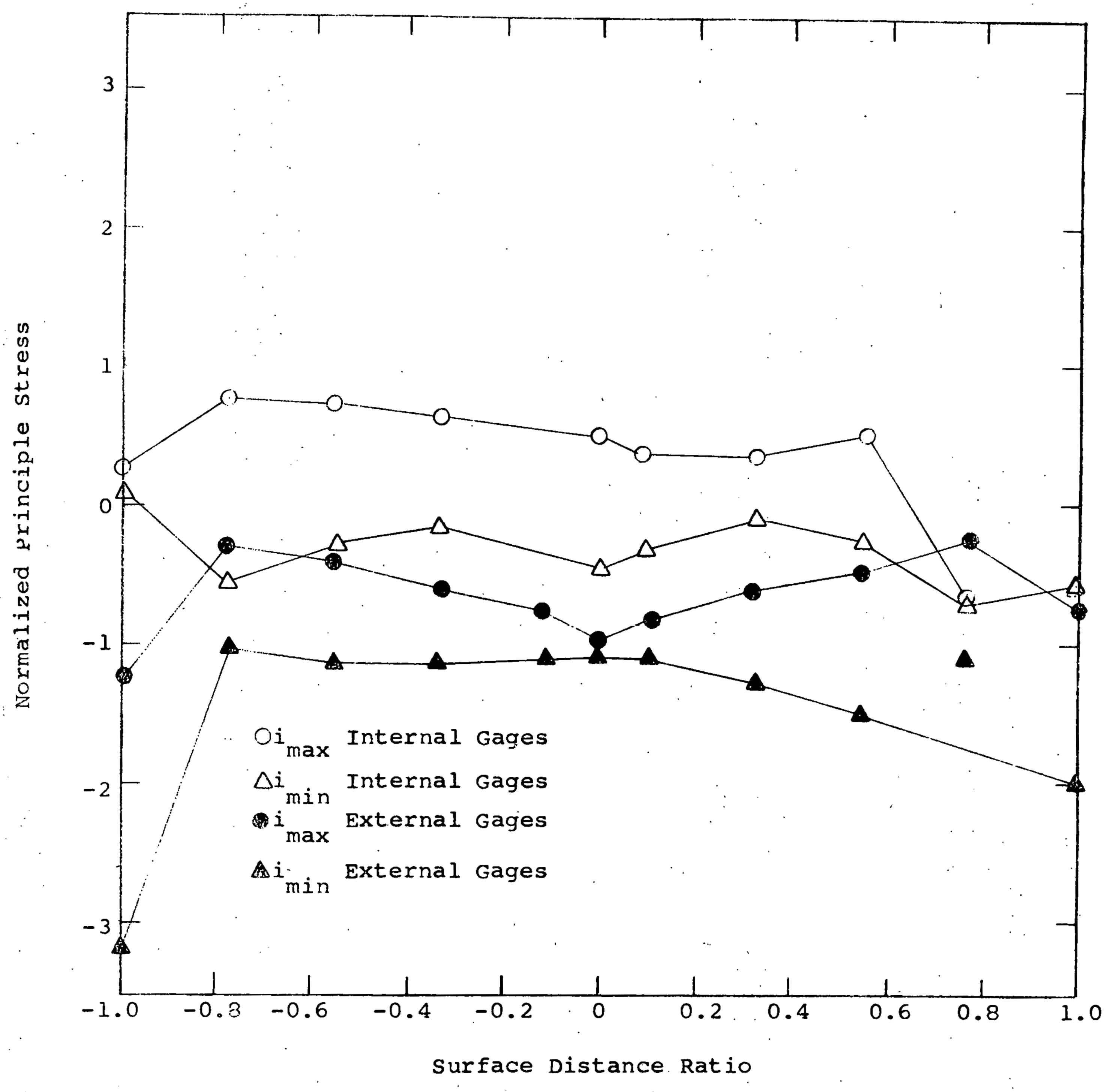


Figure 10 Normalized Principle Stress for row 3, quadrant -X, +Y, -Z for M3Z loading

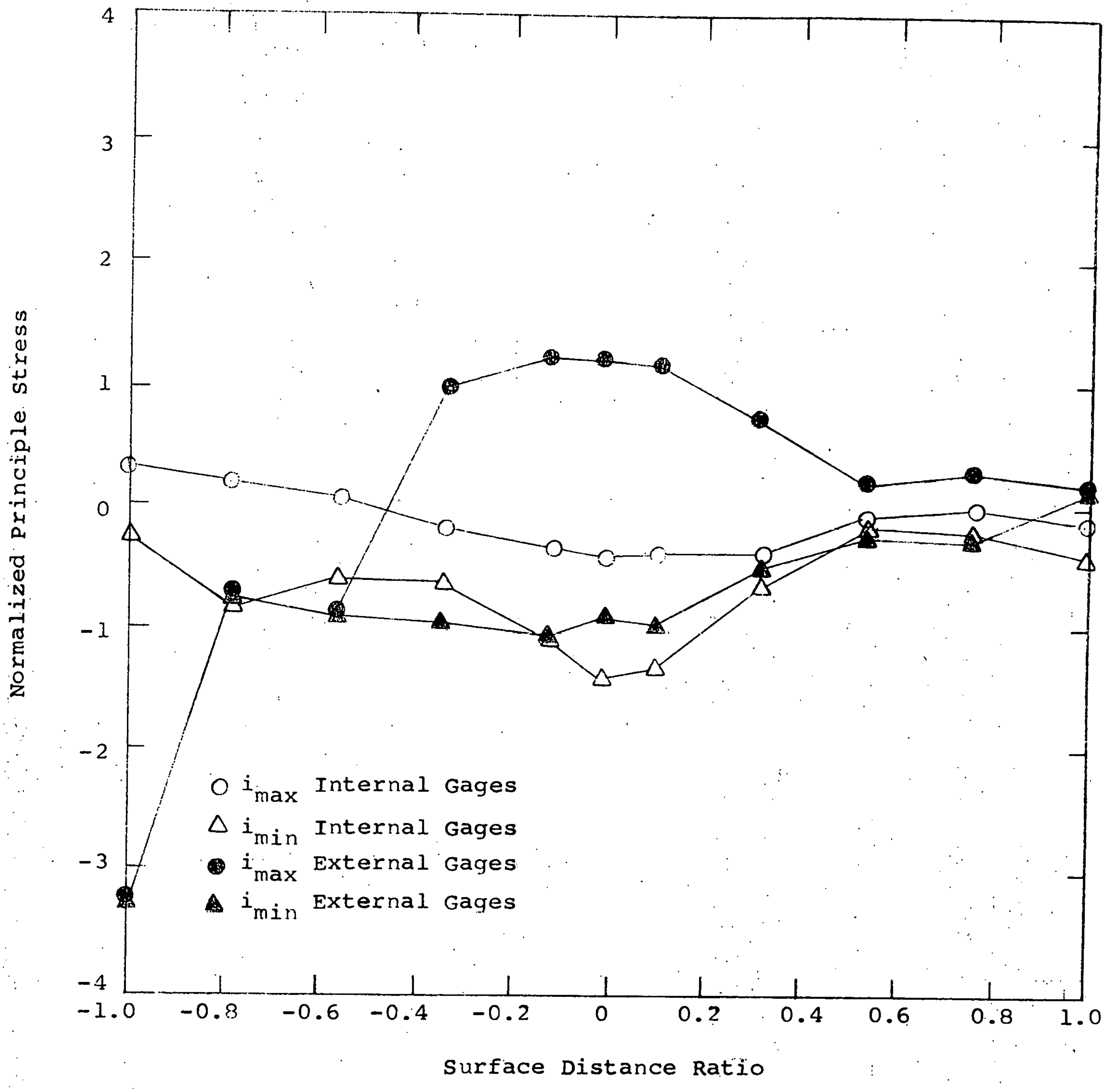


Figure 11 Normalized Principle Stress for row 2, quadrant -X, +Y, -Z for F2Y loading

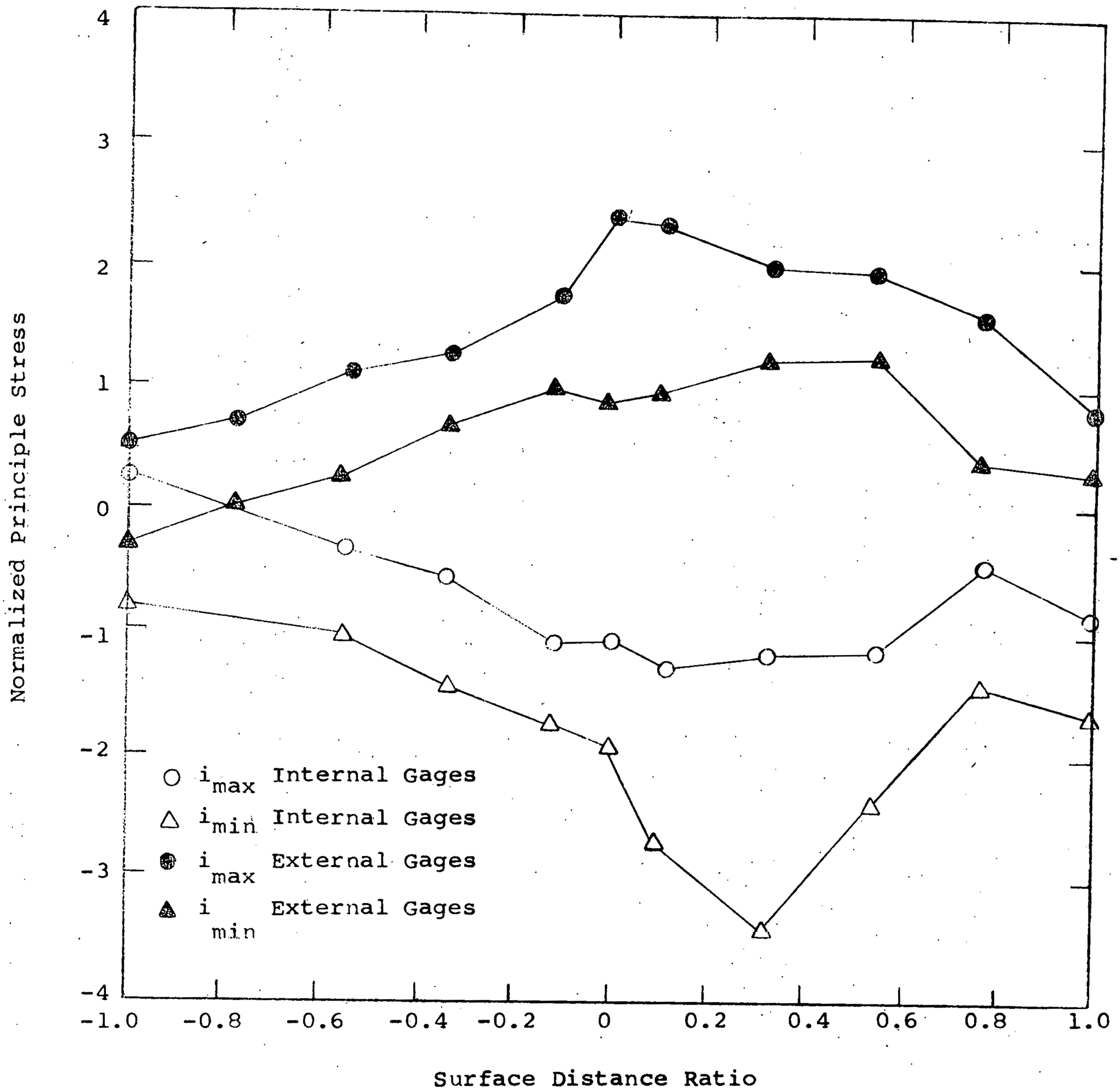


Figure 12 Normalized Principle Stress for row 2, quadrant -X, +Y, -Z for M2X loading

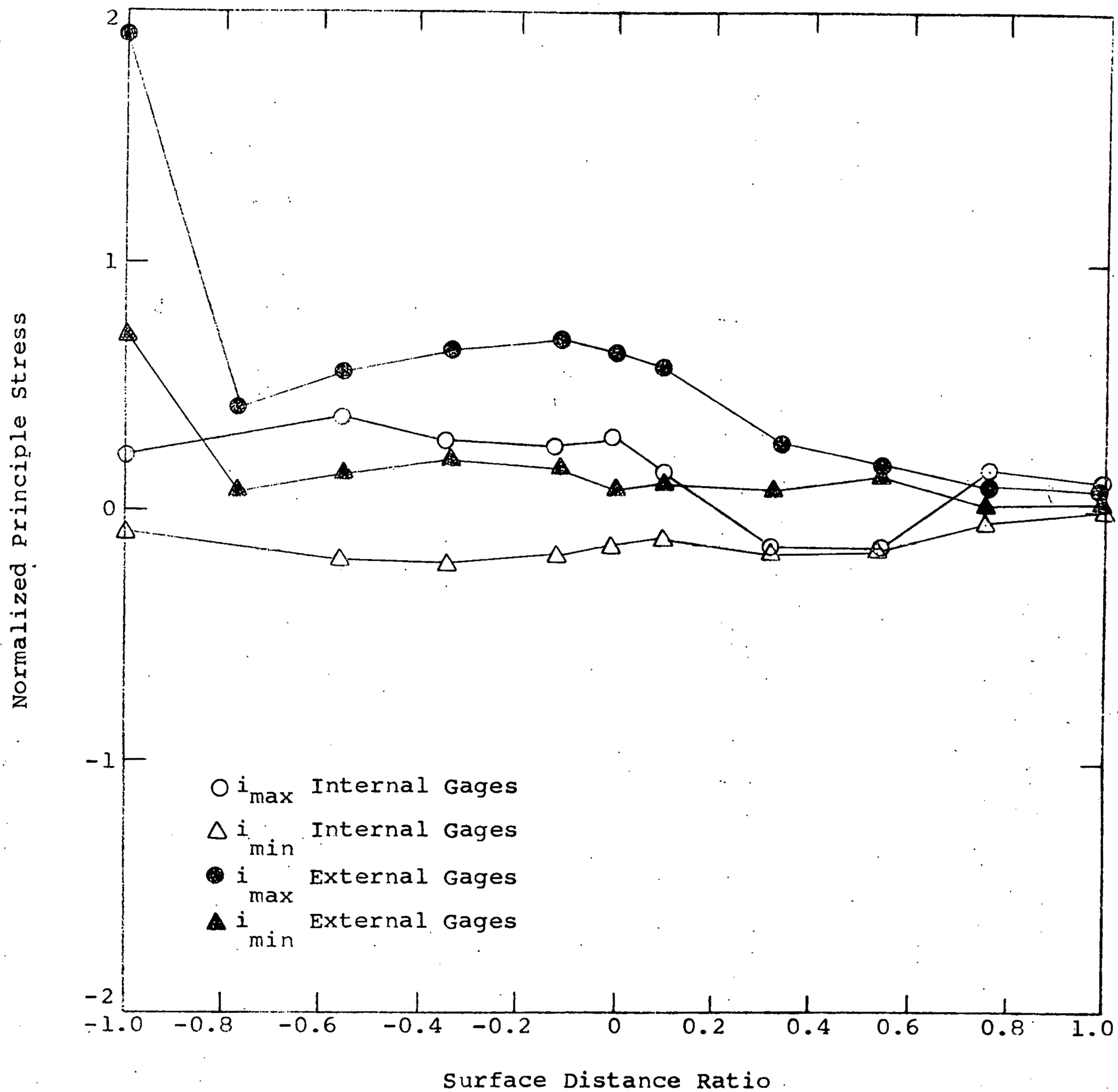


Figure 13 Normalized Principle Stress for row 2, quadrant -X, +Y, -Z for M2Y loading

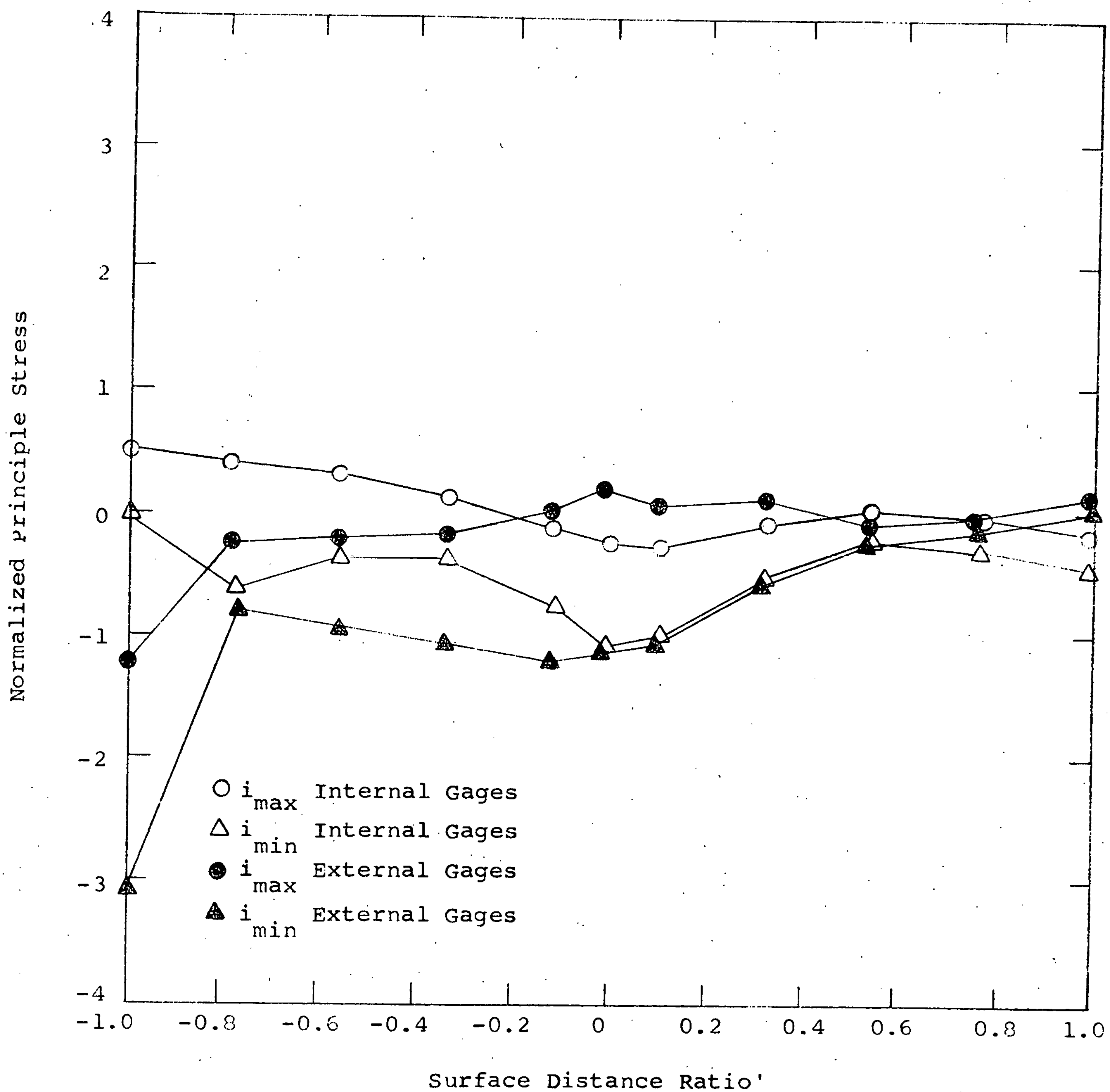


Figure 14 Normalized Principle Stress for row 2, quadrant -X, +Y, -Z for M2Z loading

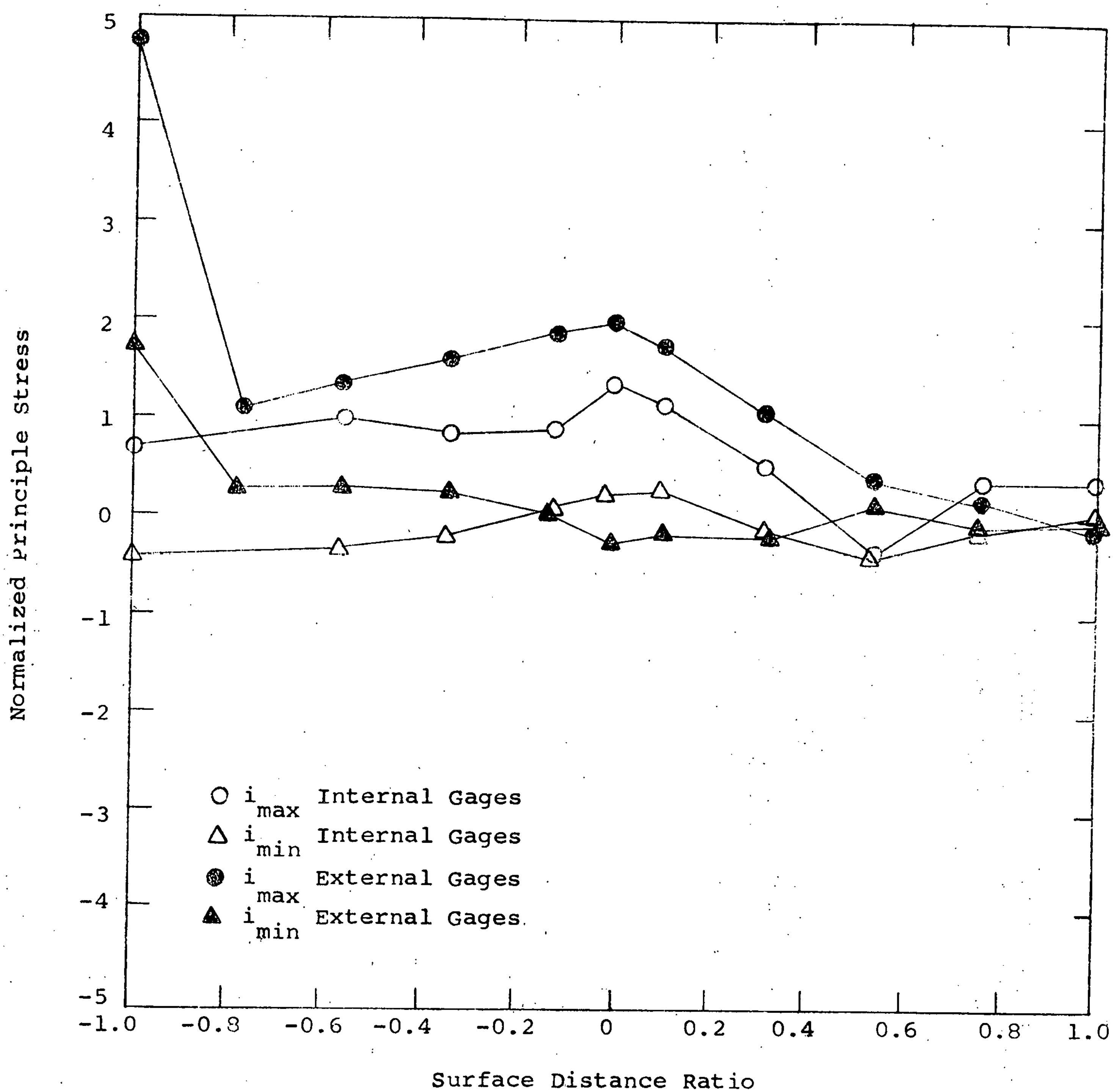


Figure 15 Normalized Principle Stress for row 2, quadrant -X, +Y, -Z for F2X loading

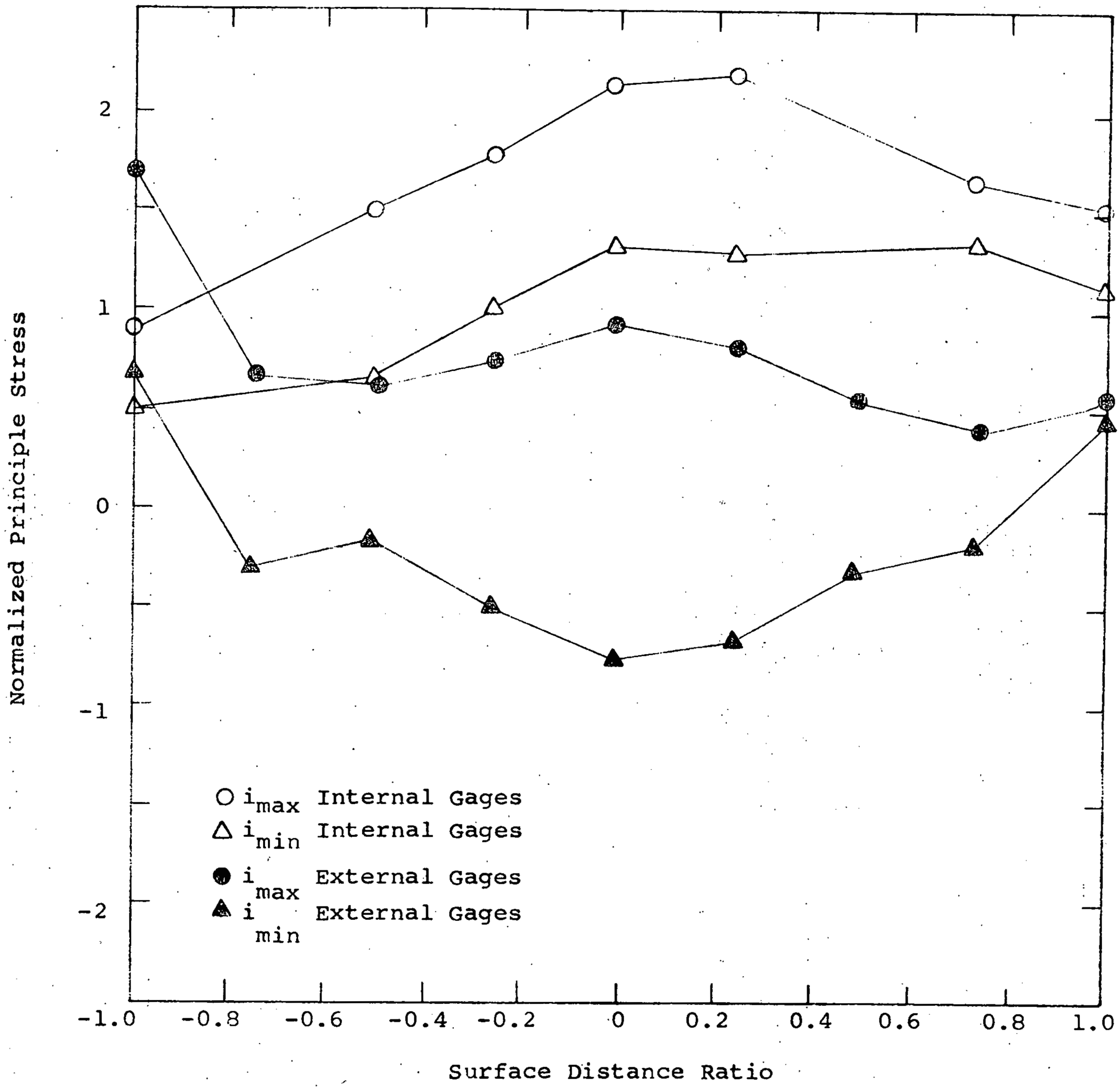


Figure 16 Normalized Principle Stress for row 5, quadrant +X, +Y, +Z for Internal Pressure Loading

strength of materials equations with measured rotations and deflections. A single flexibility factor is normally not sufficient to describe all of the load-displacement relationships for a component. For symmetrical tees 42 non-zero independent flexibility factor have been hypothesized (9).

Flexibility factors can be defined in several different ways. The most obvious definition and the one used in the ASME Code (6) is:

$$K = \theta_{ab}/\theta_{nom}$$

where θ_{ab} = the measured rotation of end, a, of a piping component with respect to end, b.

θ_{nom} = value calculated using nominal pipe dimensions and simple beam theory.

Another definition of flexibility factor given in Ref. 10 is:

$$K = \frac{\theta_{ab} - \theta_{nom}}{\theta_{D}}$$

where θ_{D} = is the relative rotation on a one-diameter length of pipe.

Reference 10 describes each of these flexibility factors in detail and compares numerical values obtained using each of these definitions.

A problem common to both of these definitions is that to experimentally determine K, θ_{ab} must be measured. In most cases both plane a, and plane b, do not remain plane after deformation. Therefore the definition used for flexibility factors in this study was:

$$K = \frac{\theta_{mea} - \theta_{corr}}{\theta_{nom}}$$

where θ_{mea} = the measured rotation between LVDT support hardware attachment points.

θ_{corr} = 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} = the nominal rotation computed by simple beam theory between weld lines on the tee using nominal pipe dimensions. Nominal length for the branch is measured from the branch weld line to the branch-run centerline intersection.

The dimensions used in these calculations are given on C-E Dwg. D-62874-027 in Appendix "B". It should be noted that using this definition negative values of K are possible whereas this is not the case when K is defined as in the ASME Code (6).

The subscript on the flexibility factor identifies the axis about which the rotation is taken and the two planes of relative rotation as shown in Figure 6. 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 which is used as the reference plane.

Table 3 summarizes the flexibility factors for nine loading conditions. It is interesting to note that many of the flexibility factors are larger than one. Previously tested tees with heavier walls did not exhibit this type of behavior.

An overall check of the loading and gage accuracy can be obtained from the reciprocal deflection theorem (7). This theorem, for this application, states that if a moment, M_A, is applied to a linear elastic system at point A and produces a rotation θ_B at some point B, then the same moment (magnitude and direction) applied at point B will produce a rotation at A of $\theta_A = \theta_B$.

TABLE 3 Summary of Flexibility Factors

Load	RUN K Subscript	RUN K Magnitude	BRANCH K Subscript	BRANCH K Magnitude
7. M2X	X21	0.65	X31	0.55
8. M2Y	Y21	0.37	Y31	0.42
9. M2Z	Z21	2.5	Z31	2.5
10. F2X[1]	Z21		Z31	
11. F2Y(M2Z)[3]	Z21	2.5	Z31	2.0
12. F2Z(M2Y)[3]	Y21	0.31	Y31	1.2
1. M3X	X21		X31	1.2
2. M3Y	Y21	0.37	Y31	1.0
3. M3Z	Z21	2.4	Z31	3.3
5. F3Y[2]	Z21		Z31	1.5
6. F3Z(M3X)[3]	X21	1.5	X31	1.2

[1] The flexibility factors for the F2Z loading can not be defined; consequently only the rotation for the maximum load are presented in Table 4.

[2] The magnitudes of the stresses and deflection due to this load are small. Consequently, it is felt the flexibility factor, Z21, for this load is unreliable.

[3] These forces produce moments as indicated in parenthese.

The following tabulation indicates how the test data compare with the reciprocal deflection theorem in two of the instances where cross-checks were possible. Good agreement exist in all of the comparisons.

Load Condition	k subscript	K magnitude
8. M2Y	Y31	0.42
2. M3Y	Y21	0.37
9. M2Z	Z31	2.5
3. M3Z	Z21	2.4

A few comments, relative to rotations that are due to a moment but that are in a direction different from the direction of the moment, seem appropriate. Several of these measurements were made and their magnitudes were found to be negligible. Since no formal definition of a flexibility factor based on these rotations has been agreed upon, most piping flexibility analyses are not able to include these rotations. Table 4 summarizes the measured secondary rotations resulting from these moments. The secondary rotations for the end forces and internal pressure are also presented in Table 4. All secondary rotations are for maximum loads.

TABLE 4 Summary of Secondary Rotations (θ_{mea})[1]

Load Case and Name	Applied Load	RUN Subscript	RUN Magnitude (Radians)	BRANCH Subscript	BRANCH Magnitude (Radians)
7. M2X	$4.45X10^{5}$ in-lb			Z31	$0.4115X10^{-4}$
8. M2Y	$-1.20X10^{6}$ in-lb	Z21	$0.7392X10^{-4}$		
9. M2Z	$5.19X10^{5}$ in-lb	Y21	$0.1341X10^{-4}$	X31	$-.3384X10^{-4}$
10. F2X	$-6.43X10^{4}$ lb	Y21	$-0.9455X10^{-4}$		
10. F2X	$-6.43X10^{4}$ lb	Z21	$0.9918X10^{-3}$	Z31	$0.5265X10^{-3}$
11. F2Y(M2Z)[2]	$3.09X10^{3}$ lb	Y21	$0.4325X10^{-4}$	X31	$0.2610X10^{-3}$
12. F2Z(M2Y)[2]	$1.07X10^{4}$ lb	Z21	$0.3245X10^{-4}$		
1. M3X	$5.19X10^{5}$ in-lb			Z31	$0.82226X10^{-4}$
2. M3Y	$-7.72X10^{5}$ in-lb	Z21	$0.3078X10^{-4}$		
3. M3Z	$7.48X10^{5}$ in-lb	Y21	$0.5241X10^{-4}$	X31	$0.1067X10^{-3}$
5. F3Y	$2.40X10^{4}$ lb	Y21	$0.1205X10^{-4}$	X31	$0.5362X10^{-4}$
6. F3Z(M3X)[2]	$7.72X10^{3}$ lb			Z31	$0.7424X10^{-4}$

1 θ_{corr} can be calculated using nominal pipe dimensions and the appropriate length as given on C-E Dwg. D-62874-027-0 of Appendix "C".

2 These forces produce moments as indicated in parenthesis.

5.0 LOW CYCLE FATIGUE TEST

A low cycle fatigue test of the tee was performed by applying a completely reversing displacement, $\pm\delta$ to the branch of the tee. The tee was pressurized to the design pressure of 300 psi throughout the fatigue test. A special loading assembly bolted to the tee assembly was used for this test as shown in Figure 17. Two actuators located 187 inches apart applied equal and opposite forces to the loading assembly. One actuator was equipped with a load cell to measure the applied force and an LVDT to measure the displacement, δ, of the ram. The displacement of the ram was also checked using a dial indicator.

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 choosen so as produce a failure in approximately 7000 cycles which is the log-mean value between 500 and 100,000 cycles. Using Markl's equation for austenitic stainless steel at room temperature (11) the maximum stress amplitude, C_2K_2S, can be calculated as follows:

$$C_2K_2S = 562{,}000\ N^{-.2}$$

where C_2K_2 are stress indices as used in Section NB-3653.6 of Ref. 6

S is the nominal stress amplitude (not range) occurring in the component

and N is the number of cycles required to produce a through-the-wall failure

Thus using 7000 as the required number of cycles to failure

$$C_2K_2S = 562{,}000\ (7000)^{-.2} = 95{,}700 \text{ psi}$$

Fatigue life calculations were also made using the Simplified Elastic-Plastic Discontinuity Analysis from the ASME Code, Section III (6). In these calculations both the value of C_2K_2 specified in the Code and the experimentally determined value of C_2K_2 were used. The calculations can be found in Appendix "C" and the results are summerized below:

$N_c = 5$

$N_e = 360$

$N_t/N_c = 469$

$N_t/N_e = 6.5$

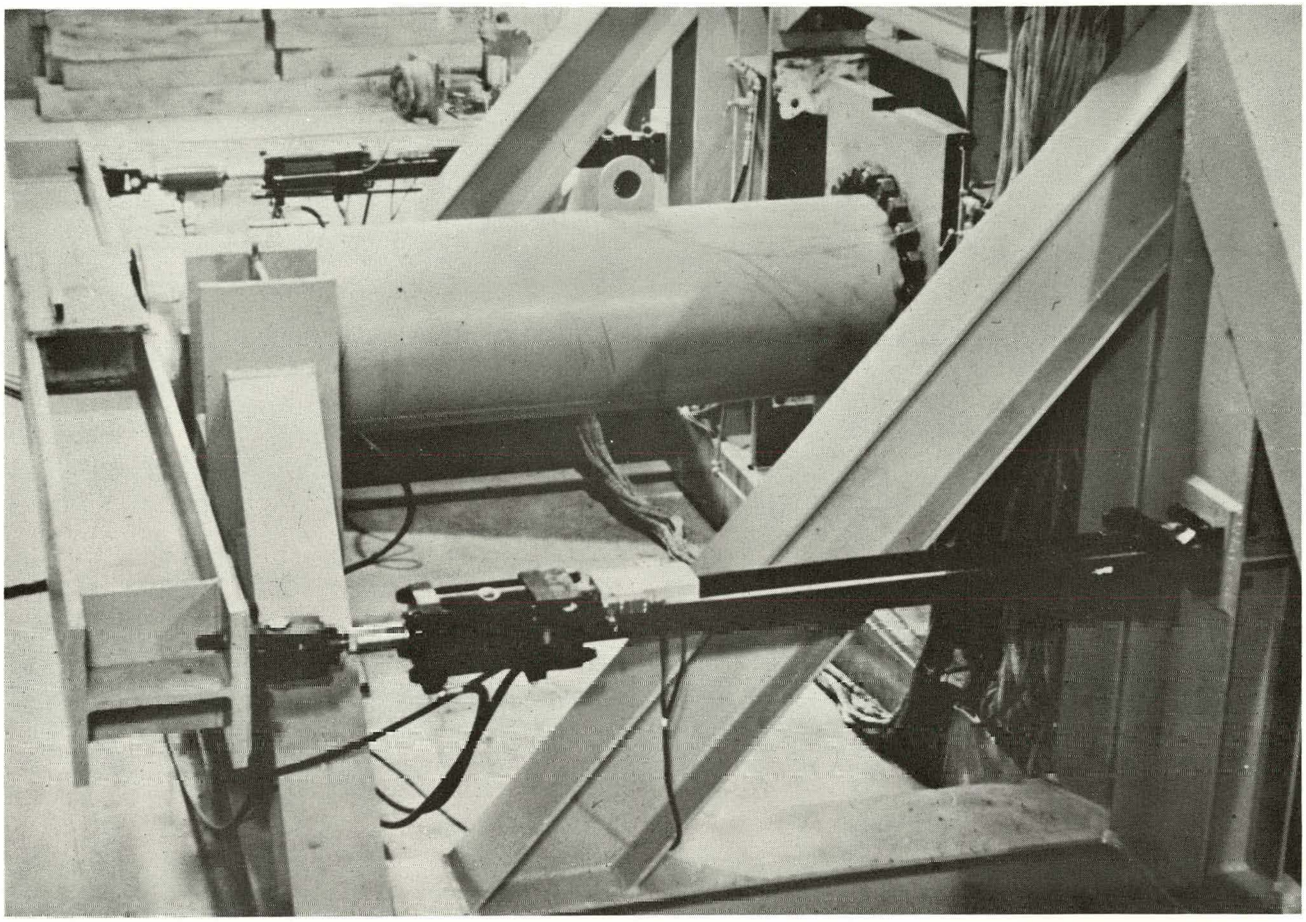


Fig. 17 View of Structural Loading System 5-2

where N_c is the design life calculated using the code value for C_2K_2

N_e is the design life calculated using experimentally determined values for C_2K_2

N_t is the life of the tee as measured in this test

To determine the displacement that would be required to produce this maximum stress amplitude a plot was made of the actuator displacement versus the maximum stress. The value of E used was $28.3X10^6$ psi and Poisson's ratio was assumed to be 0.3. The maximum stress was limited to 20,000 psi to ensure that the tee was not plastically deformed. Once this curve was established it was extrapolated to find the deflection required to produce an apparent maximum stress amplitude of 95,700 psi. By "apparent maximum stress" is meant the stress that would be calculated assuming linear elastic behavior.

The first 22 cycles of the fatigue test were performed with the structural loading system in the manual mode. During these cycles approximately 35 rosettes in the highest strained areas of the tee assembly were monitored. These gages were also monitored for cycles 435, 602, and 1201. The complete computer listings for these cycles have been sent to ORNL.

Figures 18 and 19 summarize the response of the tee assembly during the fatigue test. Figure 18 is a plot of Actuator Displacement versus Applied Load for several cycles. The Applied Load was measured using the load cell. To calculate the magnitude of the moment applied to the branch the applied load can be multipled by 187 inches. Figure 19 is a plot of Actuator Displacement versus the Maximum Apparent Stress. These plots indicate the amount of "shake-down" that occurred during the test.

At 2344 cycles a through-the-wall crack developed. With 300 psi pressure applied to the tee and no moment loading transformer fluid did not leak through the crack. However, as soon as the moment loading was increased slightly leakage was evident. From the outside of the tee the crack appeared to be approximately 2½ inches long. The crack location is shown in Fig. 6. The crack occurred in the branch weld near the top of the tee in the vicinity of strain gage rosette no. 34. This is near the neutral axis of the branch and opposite the fixed end of the tee. At present

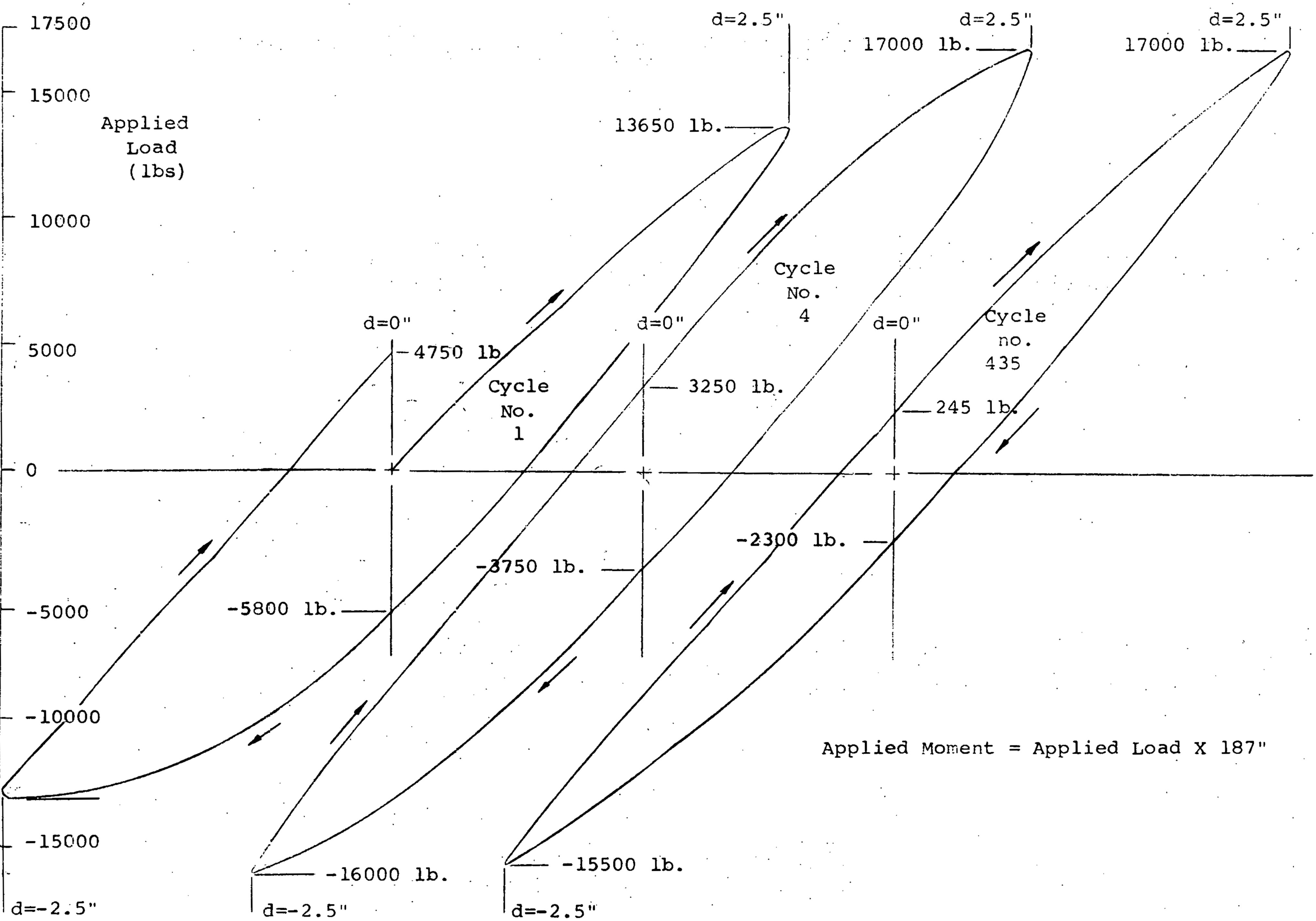


Figure 18 Plot of Actuator Displacement versus Applied Load

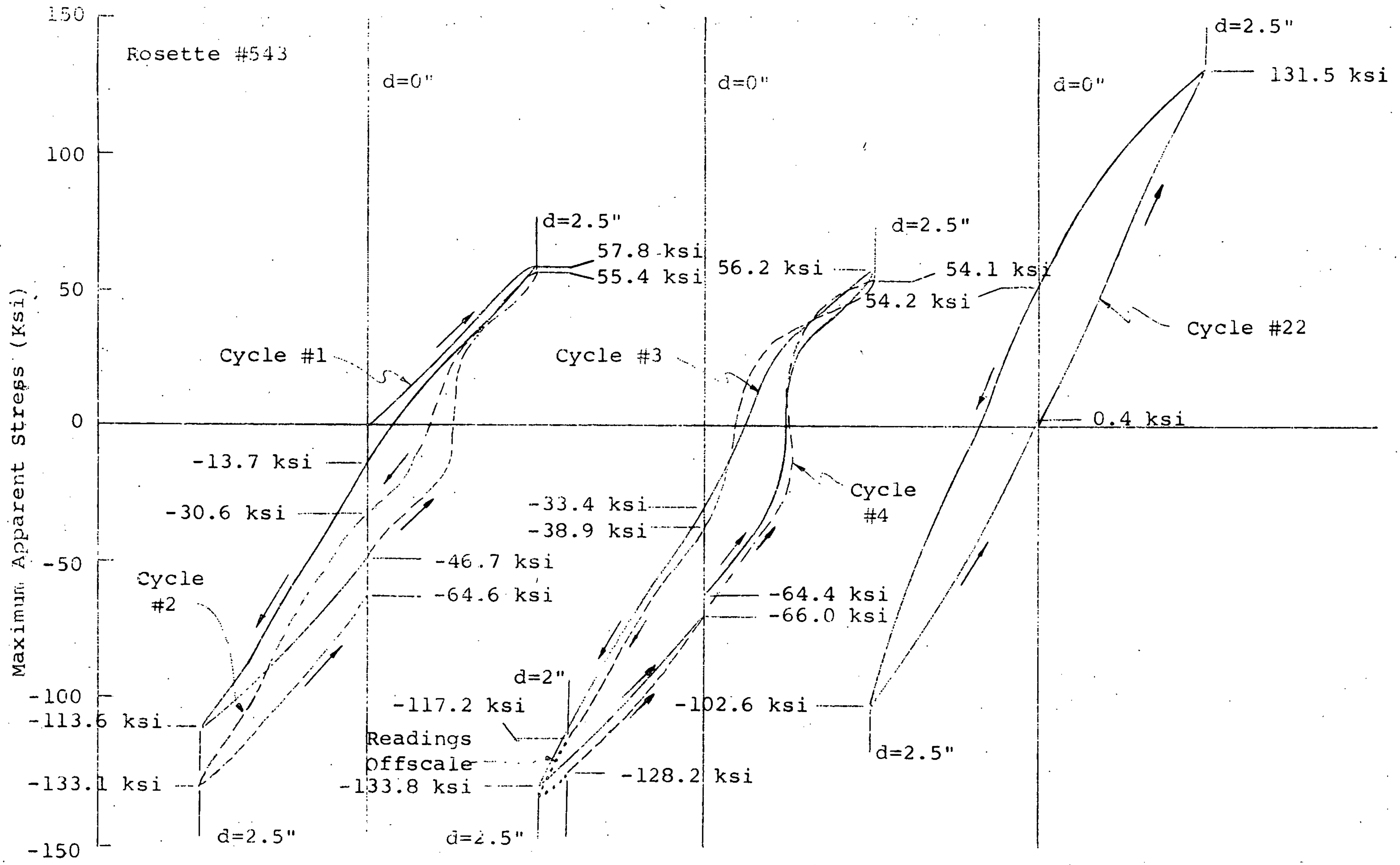


Figure 19 Plot of Actuator Displacement versus Maximum Apparent Stress

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 porousity less than 1/32 in. in diameter in this region. Similar indication were noted in a region approximately 90° away from the point were failure occurred. It should be noted that although this tee was ordered as a Sch 10 tee, the manufacture 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.

6.0 COMPARISON OF RESULTS WITH ASME CODE, SECTION III

The methods used to obtain the normalized stress intensity are in agreement with the definition of stress indices in the ASME Code (6). In the Code the secondary stress indices are represented by "C" and the peak stress indices by "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 seperate 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 index in the Code as shown in Table 2.

Next, the flexibility factors are compared to the ASME Code. The Code states that the load displacement relationship for ANSI B16.9 tees shall be obtained by assuming that the run pipe and branch pipe extend to the intersection of the run pipe centerline with the branch pipe centerline. The imaginary junction is assumed to be rigid. This is equivalent to defining the flexibility factor as 1.0. The flexibility factors can easily be compared to 1.0 by referring to Table 3.

7.0 CONCLUSIONS

1. The normalized stress intensity values for all loadings were determined to be less than those found by using the ASME Code (6). This indicates that the Code values are conservative for the loadings as applied to this tee.

2. Many of the flexibility factors were determined to be greater than 1.0. Flexibility factors ranged from 0.31 to 3.3.

3. A low cycle fatigue test was run by loading the tee assembly with a cyclic in-plane bending moment of ±3,085,500 in-lb and the total number of cycles, N_t, until a through-the-wall crack developed was determined to be 2,344. Indications were not detected by ultra sonic examination. ASME Code (6) calculations yielded a design life, N_c, of 5 cycles. Similar calculations were made using experimental values of C_2K_2 and yielded a design life, N_e, of 360 cycles. The ratios of these design lives to the measured life are:

$$N_t/N_c = 469$$

$$N_t/N_e = 6.5$$

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.

5. The fatigue failure that occurred was in an unexpected location. X-rays of the weld in this are showed indications of less than 1/3 inch diameter. Similar indications were noted in other areas of the weld. It is recommended the metallographic examination be performed to learn more about the failure.

8.0 REFERENCES

1. Greenstreet, W. L., Program Director, Moore, S. E., Program Coordinator - "Program Plan for the ORNL Piping Program; Design Criteria for Piping Pumps and Valves". Revised August 1, 1973.

2. Hayes, J. K., "Test Report on Experimental Stress Analysis of a 24 Inch Diameter Tee (T-10)", Report No. CENC 1169, November, 1973.

3. Wilson, J. E., "Test Report on Experimental Stress Analysis of a 24 Inch Diameter Tee (ORNL T-11)", Report No. CENC 1186, September, 1972.

4. Henley, D. R., "Test Report on Experimental Stress Analysis of a 24 Inch Diameter Tee (ORNL T-13)", Report No. CENC 1189, February, 1975.

5. Henley, D. R., "Test Report on Experimental Stress Analysis of a 24 Inch Diameter Tee (ORNL T-12)", Report No. CENC 1237, April, 1975.

6. ASME Boiler and Pressure Vessel Code, Section III, Nuclear Power Plant Components, New York, 1971.

7. Hayes, J. K., and Roberts, B., "Testing of Large Piping Components Under Mechanical and Pressure Loadings", presented at Society for Experimental Stress Analysis, October, 1969.

8. Dodge, W. G., and Smith, J. E., "A Diagnostic Procedure for the Evaluation of Strain Data From a Linear Elastic Test", ORNL-TM-3415, November, 1972.

9. Mills, Rodabaugh, and Atterbury, "Determination of Stress Indices and Flexibility Factor for Submarine Piping Components", Battelle Memorial Institute to Naval Ship Research and Development Center, June, 1963.

10. Rodabaugh, E. C., and Moore, S. E., "Stress Indices and Flexibility Factors for Concentric Reducers", ORNL-TM-3795, February, 1975.

11. Rodabaugh, E. C., and Moore, S. E., "Phase Report No. 115-10 on Comparisons of Test Data with Code Methods for Fatigue Evaluation" ORNL-TM-3520, November, 1971.

APPENDIX A

X-Y-Z Coordinate Measurements For Strain Gage Rosette Centerlines

SHEET NO. 1

X-Y-Z COORDINATE LOCATIONS

TEE NO. 16

S/G NO.	"X"	"Y"	"Z"
1	0.000	16.969	11.761
4	0.000	13.198	12.031
7	0.000	9.427	12.443
10	0.000	5.656	12.743
13	0.000	1.885	12.961
16	0.000	0.000	13.038
19	1.889	0.000	12.959
22	5.663	0.000	12.755
25	9.437	0.000	12.577
28	13.211	0.000	12.385
31	16.985	0.000	*
34	4.582	16.969	10.909
37	4.668	14.300	11.120
40	4.752	11.628	11.324
43	4.864	8.935	11.594
46	4.985	6.245	11.857
49	5.077	4.932	12.098
52	6.387	4.877	12.958
55	9.005	4.805	12.753
58	11.644	4.735	11.573
61	14.285	4.670	11.428
64	16.985	*	*
67	8.543	16.969	8.424
70	8.640	15.250	8.510
73	8.773	13.525	8.630
76	9.023	11.829	8.861
79	9.400	10.180	9.200
82	9.641	9.373	9.451
85	10.415	9.174	9.248
88	12.017	8.892	8.968

* INDICATES GAGE LOCATION IS ON ¢ OF WELD & CANNOT BE MEASURED. (TYP. ALL SHEETS)

SHEET NO. 2

X-Y-Z COORDINATE LOCATIONS

TEE NO. 16

S/G NO.	"X"	"Y"	"Z"
91	13.655	8.748	8.818
94	15.303	8.643	8.726
97	16.985	*	*
100	11.190	16.969	4.633
103	11.324	15.795	4.695
106	11.569	14.635	4.793
109	11.970	13.520	4.950
112	12.563	13.520	5.208
115	13.557	11.965	4.973
118	14.643	11.575	4.814
121	15.788	11.330	4.725
124	16.985	*	*
127	12.087	16.969	0.000
130	12.279	16.022	0.000
133	12.585	15.125	0.000
136	13.032	14.728 [illegible]	0.000
139	13.641	13.528	0.000
142	14.385	14.415	0.000
145	15.228	13.997 14.997	0.000
148	16.139	13.885 14.885	0.000
151	16.985	*	0.000
154	0.000	-4.891	11.924
157	0.000	-9.040	9.129
160	0.000	-11.794	4.946
163	0.000	-12.700	0.000
166	0.000	+16.969	-11.802
169	0.000	13.198	-12.037
172	0.000	9.427	-12.302
175	0.000	5.636	-12.625
178	0.000	1.885	-12.874

SHEET NO. 3

X-Y-Z COORDINATE LOCATIONS

TEE NO. 16

S/G NO.	"X"	"Y"	"Z"
181	0.000	0.000	-12.927
184	-1.885	0.000	-12.826
187	-5.664	0.000	-12.686
190	-9.425	0.000	-12.525
193	-13.202	0.000	-12.306
196	-16.974	0.000	-12.183
199	-4.573	10.969	-10.909
202	-4.683	14.294	-11.115
205	-4.733	11.595	-11.171
208	-4.845	8.920	-11.374
211	-5.017	6.250	-11.692
214	-5.127	4.925	-11.956
217	-6.438	4.867	-11.842
220	-9.056	4.785	-11.641
223	-11.698	4.724	-11.499
226	-14.335	4.670	-11.361
229	-16.974	*	-11.231
232	-8.515	16.969	-8.414
235	-8.626	15.230	-8.506
238	-8.705	13.490	-8.546
241	-8.917	11.750	-8.724
244	-9.277	10.078	-9.072
247	-9.523	9.273	-9.326
250	-10.335	9.089	-9.133
253	-11.962	8.865	-8.902
256	-13.621	8.753	-8.790
259	-15.285	8.657	-8.702
262	-16.974	*	-8.596
265	-11.125	16.969	-4.579
268	-11.266	15.743	-4.630

SHEET NO. 4

X-Y-Z COORDINATE LOCATIONS

TEE NO. 16

S/G NO.	"X"	"Y"	"Z"
271	-11.474	14.520	-4.711
274	-11.907	13.365	-4.881
277	-12.553	12.345	-5.165
280	-13.522	11.827	-4.948
283	-14.633	11.505	-4.806
286	-15.811	11.333	-4.717
289	-16.974	*	-4.610
292	-12.052	16.969	0.000
295	-12.253	16.030	0.000
298	-12.546	15.126	0.000
301	-12.982	14.255	0.000
304	-13.597	13.522	0.000
307	-14.365	14.415	0.000
310	-15.205	13.991	0.000
313	-16.115	13.763	0.000
316	-16.974	*	0.000
319	0.000	-4.856	-11.807
322	0.000	-8.977	-9.001
325	0.000	-11.850	-4.872
328	0.000	+16.969	+11.359
331	0.000	13.198	11.651
334	0.000	9.427	7.996
337	0.000	5.656	11.990
340	0.000	-1.885	12.202
343	0.000	0.000	12.297
346	1.889	0.000	12.192
349	5.663	0.000	11.974
352	9.437	0.000	11.793
355	13.211	0.000	11.808
358	16.985	0.000	11.824

SHEET NO. 5

X-Y-Z COORDINATE LOCATIONS

TEE NO. 16

S/G NO.	"X"	"Y"	"Z"
361	4.443	16.969	10.523
364	4.485	14.240	10.814
367	4.518	11.490	10.770
370	4.580	8.740	10.936
373	4.685	6.007	11.153
376	4.785	4.650	11.385
379	6.135	4.600	11.233
382	8.837	4.506	10.999
385	11.556	4.441	10.876
388	14.268	4.441	10.874
391	16.985	4.441	10.896
394	8.250	16.969	8.159
397	8.290	15.130	8.189
400	8.324	13.305	8.200
403	8.474	11.490	8.329
406	8.844	9.723	8.694
409	9.076	8.853	8.929
412	9.911	8.644	8.724
415	11.649	8.335	8.418
418	13.416	8.225	8.299
421	15.187	8.225	8.299
424	16.985	8.236	8.311
427	10.860	16.969	4.485
430	10.847	15.615	4.485
433	10.870	14.271	4.460
436	11.317	13.000	4.628
439	11.953	11.850	4.940
442	13.104	11.195	4.687
445	14.335	10.744	4.493
448	15.655	10.744	4.493

SHEET NO. 6

X-Y-Z COORDINATE LOCATIONS

TEE NO. 16

S/G NO.	"X"	"Y"	"Z"
451	16.985	10.760	4.493
454	11.696	16.969	0.000
457	11.668	15.797	0.000
460	11.815	14.784	0.000
463	12.305	13.805	0.000
466	12.974	12.915	0.000
469	13.799	12.209	0.000
472	14.785	11.623	0.000
475	15.883	11.611	0.000
478	16.985	11.640	0.000
481	0.000	-4.590	11.358
484	0.000	-8.475	8.743
487	0.000	-10.550	4.829
490	0.000	-11.440	0.000
493	0.000	+16.969	-11.383
496	0.000	13.198	-11.674
499	0.000	9.427	-11.682
502	0.000	5.656	-11.802
505	0.000	1.885	-12.054
508	0.000	0.000	-12.090
511	-1.886	0.000	-12.025
514	-5.658	0.000	-11.820
517	-9.430	0.000	-11.732
520	-13.202	0.000	-11.735
523	-16.974	0.000	-11.751
526	-4.434	16.969	-10.642
529	-4.499	14.240	-10.759
532	-4.524	11.490	-10.765
535	-4.541	8.722	-10.772
538	-4.656	5.975	-10.990

SHEET NO. 7

X-Y-Z COORDINATE LOCATIONS

TEE NO. 16

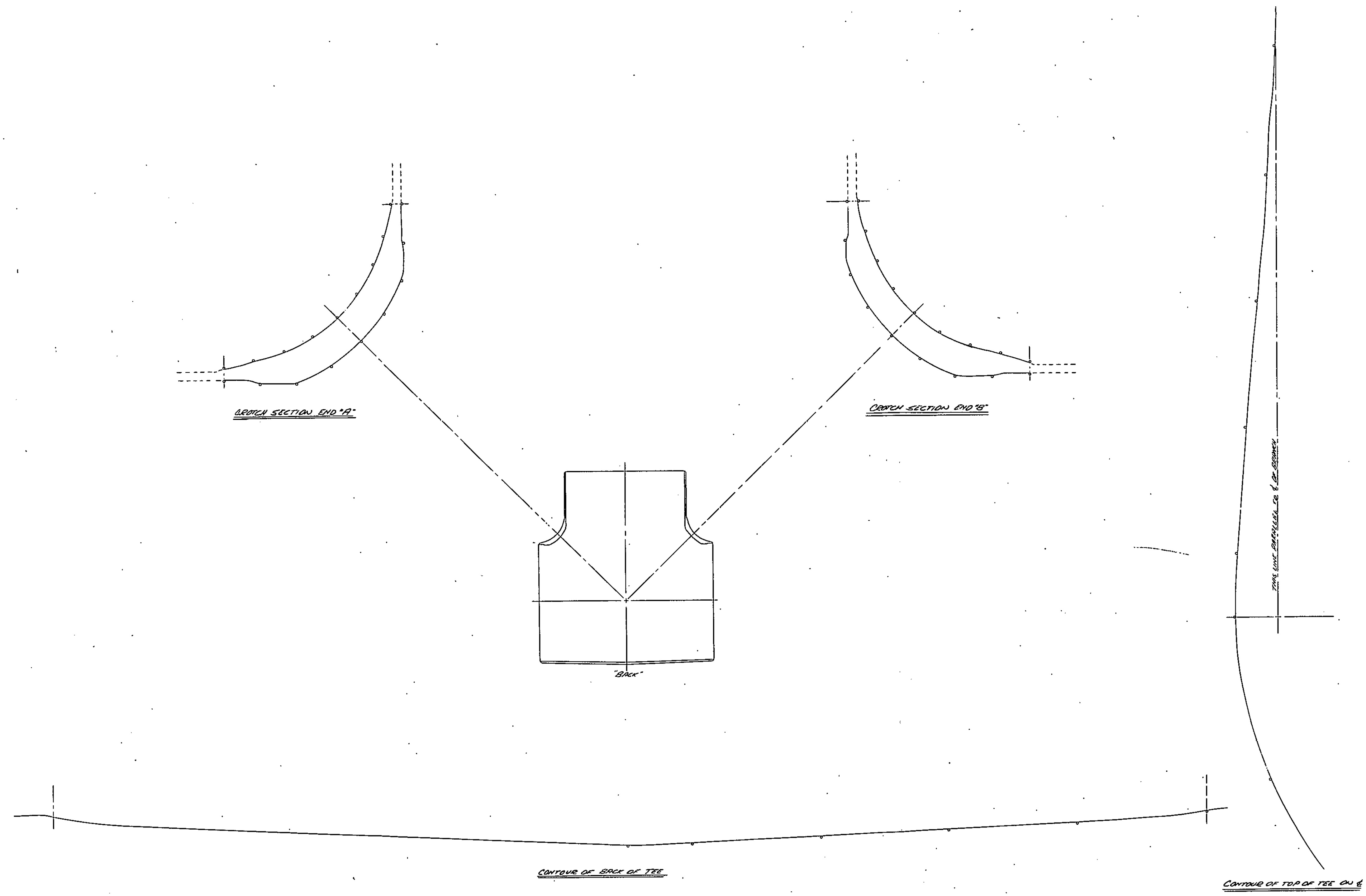
S/G NO.	"X"	"Y"	"Z"
541	-4.774	4.634	-11.259
544	-6.119	4.575	-11.110
547	-8.836	4.492	-10.902
550	-11.548	4.455	-10.827
553	-14.256	4.455	-10.827
556	-16.974	4.462	-10.864
559	-8.274	16.969	-8.226
562	-8.274	15.120	-8.196
565	-8.317	13.256	-8.199
568	-8.350	11.430	-8.239
571	-8.694	9.610	-8.567
574	-8.964	8.755	-8.852
577	-9.834	8.525	-8.636
580	-11.581	8.290	-8.334
583	-13.386	8.238	-8.287
586	-15.184	8.238	-8.287
589	-16.974	8.269	-8.319
592	-10.852	16.969	-4.435
595	-10.769	15.592	-4.427
598	-10.789	14.207	-4.459
601	-11.193	12.895	-4.632
604	-11.881	11.721	-4.912
607	-13.021	11.100	-4.666
610	-14.305	10.750	-4.494
613	-15.639	10.750	-4.494
616	-16.974	10.818	-4.523
619	-11.696	16.969	0.000
622	-11.674	15.862	0.000
625	-11.734	14.769	0.000
628	-12.243	13.783	0.000

SHEET NO. 8

X-Y-Z COORDINATE LOCATIONS

TEE NO. 16

S/G NO.	"X"	"Y"	"Z"
631	-12.940	12.914	0.000
634	-13.774	12.192	0.000
637	-14.752	11.660	0.000
640	-15.863	11.622	0.000
643	-16.974	11.690	0.000
646	0.000	-4.590	11.071
649	0.000	-8.455	8.457
652	0.000	-10.550	4.517
655	2.557	+2.478	12.773
658	7.395	7.235	11.005
661	11.234	11.134	7.563
664	13.394	13.339	2.701
667	-2.592	2.509	-12.689
670	-7.401	7.167	-10.876
673	-11.174	10.966	-7.464
676	-13.323	13.202	-2.697
679	+2.409	2.338	+12.118
682	6.976	5.850	10.479
685	10.643	10.589	7.192
688	12.811	12.709	2.564
691	-2.407	2.300	-11.905
694	-6.916	5.780	-10.247
697	-10.552	10.380	-7.073
700	-12.674	12.582	-2.557



GENERAL NOTES:
CONTOUR SECTIONS TRACED FROM MOLDS MADE OF MOLDING PLASTER
• INDICATES LAYOUT LOCATIONS FOR STRAIN GAGES.

THIS DRAWING MADE BY CHATTANOOGA

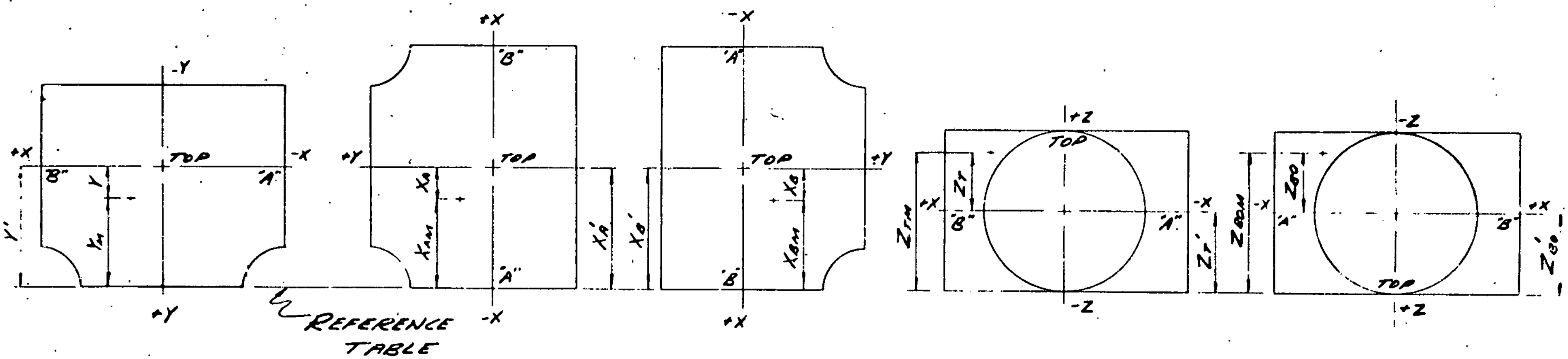
CONTRACT NO.

FOR AS BUILT CONTOURS OF "T-16"

SCALE ~
DRAWN BY L.R.HAYES
TRACED BY
DATE 1-26-73
CHECKED BY
APPROVED

DRAWING NO. E-62873-003-0

REVISIONS



$Y = Y' - Y_M$
(1)

$X = -(X'_A - X_{AM})$
(2)

$X = X'_B - X_{BM}$
(3)

$Z = Z_{TM} - Z'_T$
(4)

$Z = -(Z_{BOM} - Z'_{BO})$
(5)

NOMENCLATURE

M MEASUREMENTS AS RECORDED FROM REFERENCE TABLE
A "A" END
B "B" END
T TOP & DIMS ASSOCIATED WITH THE TOP
BO BOTTOM & DIMS ASSOCIATED WITH THE BOTTOM.
Y DISTANCE FROM PLANE INCLUDING RUN ℄ & ⊥ TO BRANCH ℄
X DISTANCE FROM PLANE INCLUDING BRANCH ℄ & ⊥ TO RUN ℄
Z DISTANCE FROM PLANE INCLUDING RUN ℄ & BRANCH ℄.

RECORDED DIMENSIONS

Y' 27.300" X'_B 16.974" Z'_{BO} 15.329"

X'_A 16.985" Z'_T 15.307"

ORIGINATED BY CHATTANOOGA   CONTRACT NO.

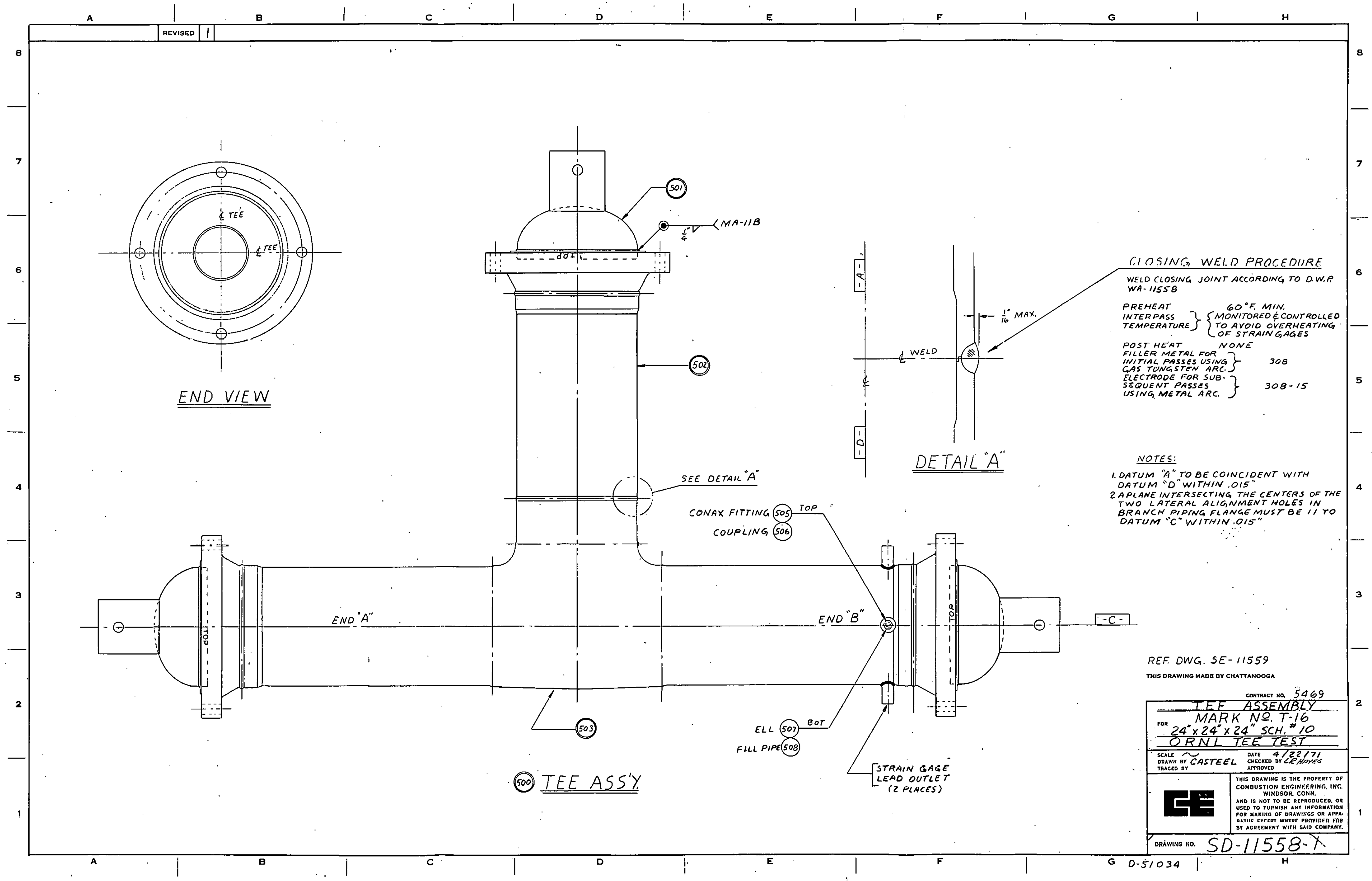
FOR XYZ COORDINATE MEASUREMENTS
ORNL T-15 TEE

SCALE ~
DRAWN BY L R HAYES
TRACED BY
DATE
CHECKED BY
APPROVED

DRAWING NO. B-62675-041-0

APPENDIX B

1. Fabrication Dwgs. for T-16 Tee
2. Instrumentation Dwgs. for T-16 Tee
3. Plots of Stress Intensification versus Surface Distance Ratio for Each Load Case



REVISED 1
END VIEW
℄ TEE
501
1/4 V MA-11B
TOP
502
DETAIL "A"
℄ WELD
1/16 MAX.
-A-
-D-
CLOSING WELD PROCEDURE
WELD CLOSING JOINT ACCORDING TO D.W.P. WA-11558
PREHEAT INTERPASS TEMPERATURE 60°F. MIN. MONITORED & CONTROLLED TO AVOID OVERHEATING OF STRAIN GAGES
POST HEAT NONE
FILLER METAL FOR INITIAL PASSES USING GAS TUNGSTEN ARC. 308
ELECTRODE FOR SUBSEQUENT PASSES USING METAL ARC. 308-15
NOTES:
1. DATUM "A" TO BE COINCIDENT WITH DATUM "D" WITHIN .015"
2. A PLANE INTERSECTING THE CENTERS OF THE TWO LATERAL ALIGNMENT HOLES IN BRANCH PIPING FLANGE MUST BE ⊥ TO DATUM "C" WITHIN .015"
SEE DETAIL "A"
CONAX FITTING 505 TOP
COUPLING 506
END "A"
END "B"
-C-
503
ELL 507 BOT
FILL PIPE 508
STRAIN GAGE LEAD OUTLET (2 PLACES)
500 TEE ASS'Y
REF. DWG. SE-11559
THIS DRAWING MADE BY CHATTANOOGA
CONTRACT NO. 5469
TEE ASSEMBLY
MARK NO. T-16
FOR 24" x 24" x 24" SCH. #10
ORNL TEE TEST
SCALE ~
DRAWN BY CASTEEL
TRACED BY
DATE 4/22/71
CHECKED BY C.R. HAYES
APPROVED
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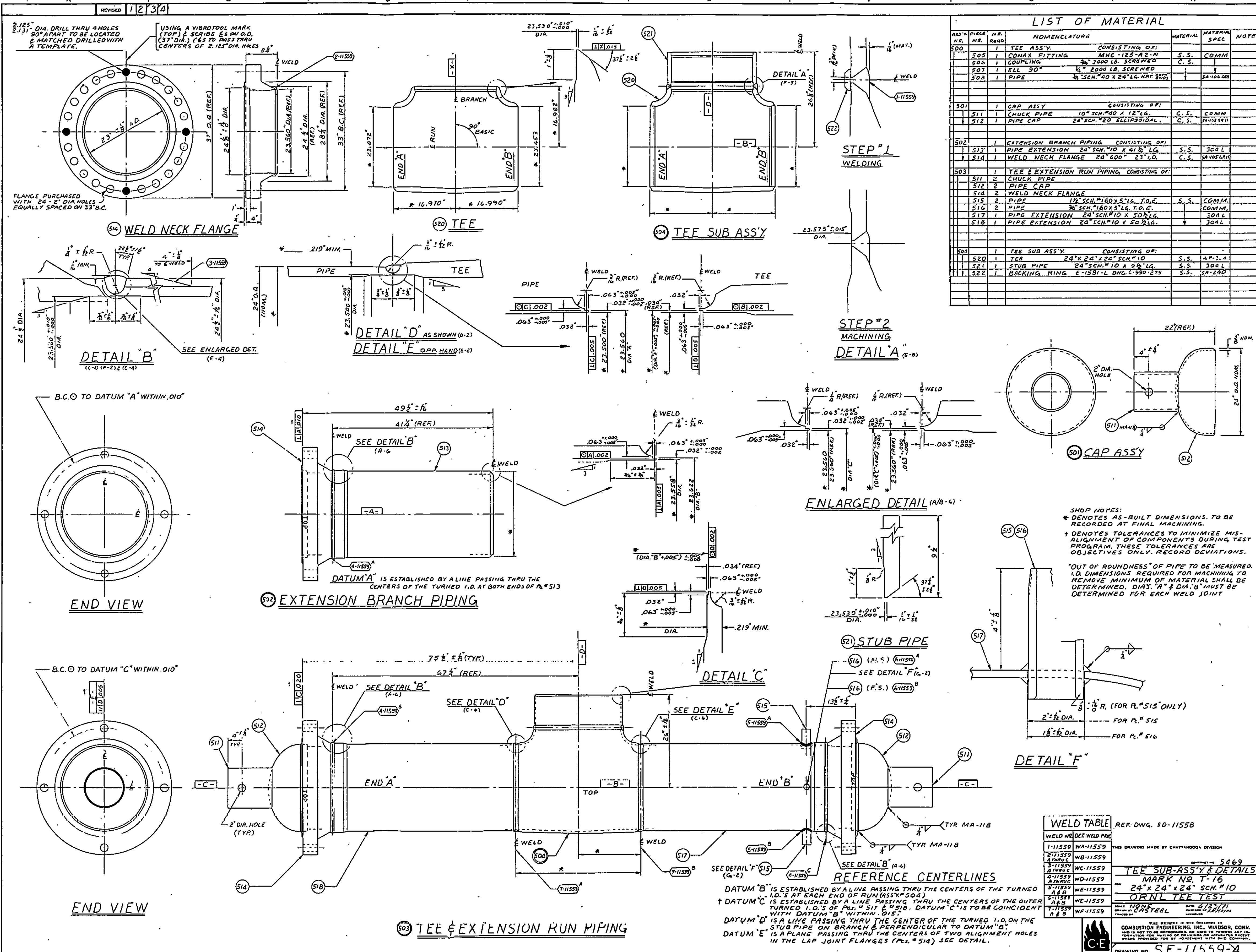
DRAWING NO. SD-11558-1
D-51034



LIST OF MATERIAL

ASS'Y. NO.	PIECE NO.	NO. REQD	NOMENCLATURE	MATERIAL	MATERIAL SPEC	NOTE
500		1	TEE ASS'Y. CONSISTING OF:			
	505	1	CONAX FITTING MHC-125-A2-N	S.S.	COMM	
	506	1	COUPLING 3/4" 3000 LB. SCREWED	C.S.		
	507	1	ELL 90° 1/4" 2000 LB. SCREWED			
	508	1	PIPE 1/4" SCH.#40 X 24" LG. NAT. BOTH ENDS		SA-106 GRB	
501		1	CAP ASSY CONSISTING OF:			
	511	1	CHUCK PIPE 10" SCH.#40 X 12" LG.	C.S.	COMM	
	512	1	PIPE CAP 24" SCH.#20 ELLIPSOIDAL.	C.S.	SA-105 GR II	
502		1	EXTENSION BRANCH PIPING CONSISTING OF:			
	513	1	PIPE EXTENSION 24" SCH.#10 X 41 1/4" LG.	S.S.	304 L	
	514	1	WELD NECK FLANGE 24" 600# 23" I.D.	C.S.	SA-105 GR II	
503		1	TEE & EXTENSION RUN PIPING, CONSISTING OF:			
	511	2	CHUCK PIPE			
	512	2	PIPE CAP			
	514	2	WELD NECK FLANGE			
	515	2	PIPE 1 1/2" SCH.#160 X 5" LG. T.O.E.	S.S.	COMM.	
	516	2	PIPE 3/4" SCH.#160 X 5" LG. T.O.E.		COMM.	
	517	1	PIPE EXTENSION 24" SCH.#10 X 50 1/2" LG.		304 L	
	518	1	PIPE EXTENSION 24" SCH.#10 X 50 1/2" LG.		304 L	
504		1	TEE SUB ASS'Y. CONSISTING OF:			
	520	1	TEE 24" X 24" X 24" SCH.#10	S.S.	NP-3-4	
	521	1	STUB PIPE 24" SCH.#10 X 9 1/2" LG.	S.S.	304 L	
	522	1	BACKING RING E-1581-L DWG. C-990-275	S.S.	SA-240	

SHOP NOTES:

* DENOTES AS-BUILT DIMENSIONS. TO BE RECORDED AT FINAL MACHINING.

† DENOTES TOLERANCES TO MINIMIZE MIS-ALIGNMENT OF COMPONENTS DURING TEST PROGRAM. THESE TOLERANCES ARE OBJECTIVES ONLY. RECORD DEVIATIONS.

"OUT OF ROUNDNESS" OF PIPE TO BE MEASURED. I.D. DIMENSIONS REQUIRED FOR MACHINING TO REMOVE MINIMUM OF MATERIAL SHALL BE DETERMINED. DIA'S. "A" & DIA. "B" MUST BE DETERMINED FOR EACH WELD JOINT

REFERENCE CENTERLINES

DATUM "B" IS ESTABLISHED BY A LINE PASSING THRU THE CENTERS OF THE TURNED I.D.'S AT EACH END OF RUN (ASS'Y.# 504)

† DATUM "C" IS ESTABLISHED BY A LINE PASSING THRU THE CENTERS OF THE OUTER TURNED I.D.'S OF Pcs.# 517 & #518. DATUM "C" IS TO BE COINCIDENT WITH DATUM "B" WITHIN .015".

DATUM "D" IS A LINE PASSING THRU THE CENTER OF THE TURNED I.D. ON THE STUB PIPE ON BRANCH & PERPENDICULAR TO DATUM "B".

DATUM "E" IS A PLANE PASSING THRU THE CENTERS OF TWO ALIGNMENT HOLES IN THE LAP JOINT FLANGES (Pcs.# 514) SEE DETAIL.

WELD TABLE	
WELD NO.	DET. WELD PROC.
1-11559	WA-11559
2-11559 A THRU C	WB-11559
3-11559 A THRU C	WC-11559
4-11559 A THRU C	WD-11559
5-11559 A & B	WE-11559
6-11559 A & B	WE-11559
7-11559 A & B	WF-11559

REF. DWG. SD-11558

THIS DRAWING MADE BY CHATTANOOGA DIVISION

CONTRACT NO. 5469

TEE SUB-ASS'Y. & DETAILS
MARK NO. T-16
FOR 24" x 24" x 24" SCH. #10
ORNL TEE TEST

SCALE NONE DATE 4/23/71
DRAWN BY CASTEEL CHECKED BY [illegible]
TRACED BY APPROVED

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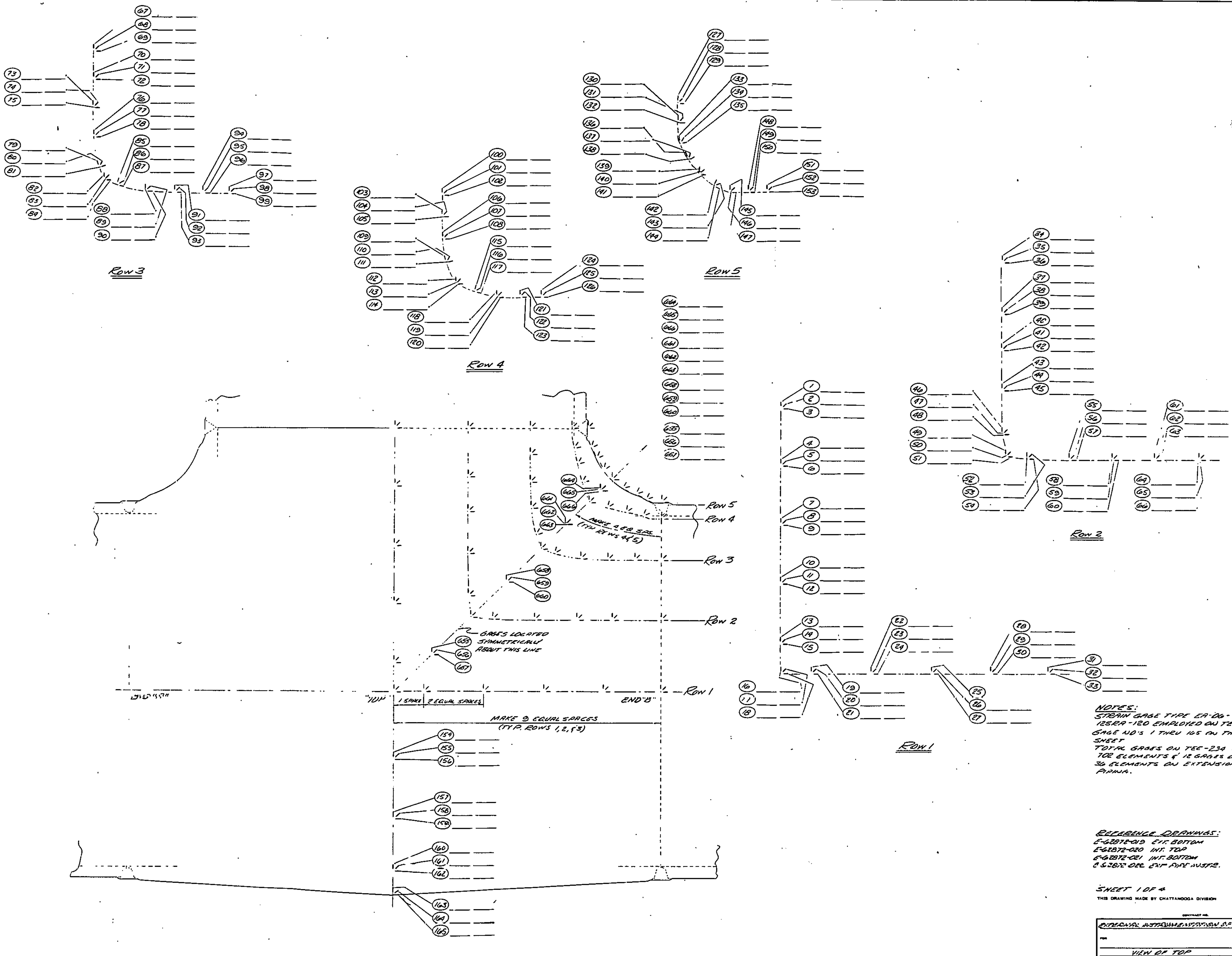
DRAWING NO. SE-11559-4

D-51034

REVISED 1 REV: ROW 5 -139 THRU 141. 9-28-74 L.S.R.



NOTES:
STRAIN GAGE TYPE EA-06-125RA-120 EMPLOYED ON TEE.
GAGE NO'S 1 THRU 165 ON THIS SHEET
TOTAL GAGES ON TEE-234 OR 702 ELEMENTS & 12 GAGES OR 36 ELEMENTS ON EXTENSION PIPING.

REFERENCE DRAWINGS:
E-62872-019 EXT. BOTTOM
E-62872-020 INT. TOP
E-62872-021 INT. BOTTOM
C 62872-022 EXT PIPE INSTR.

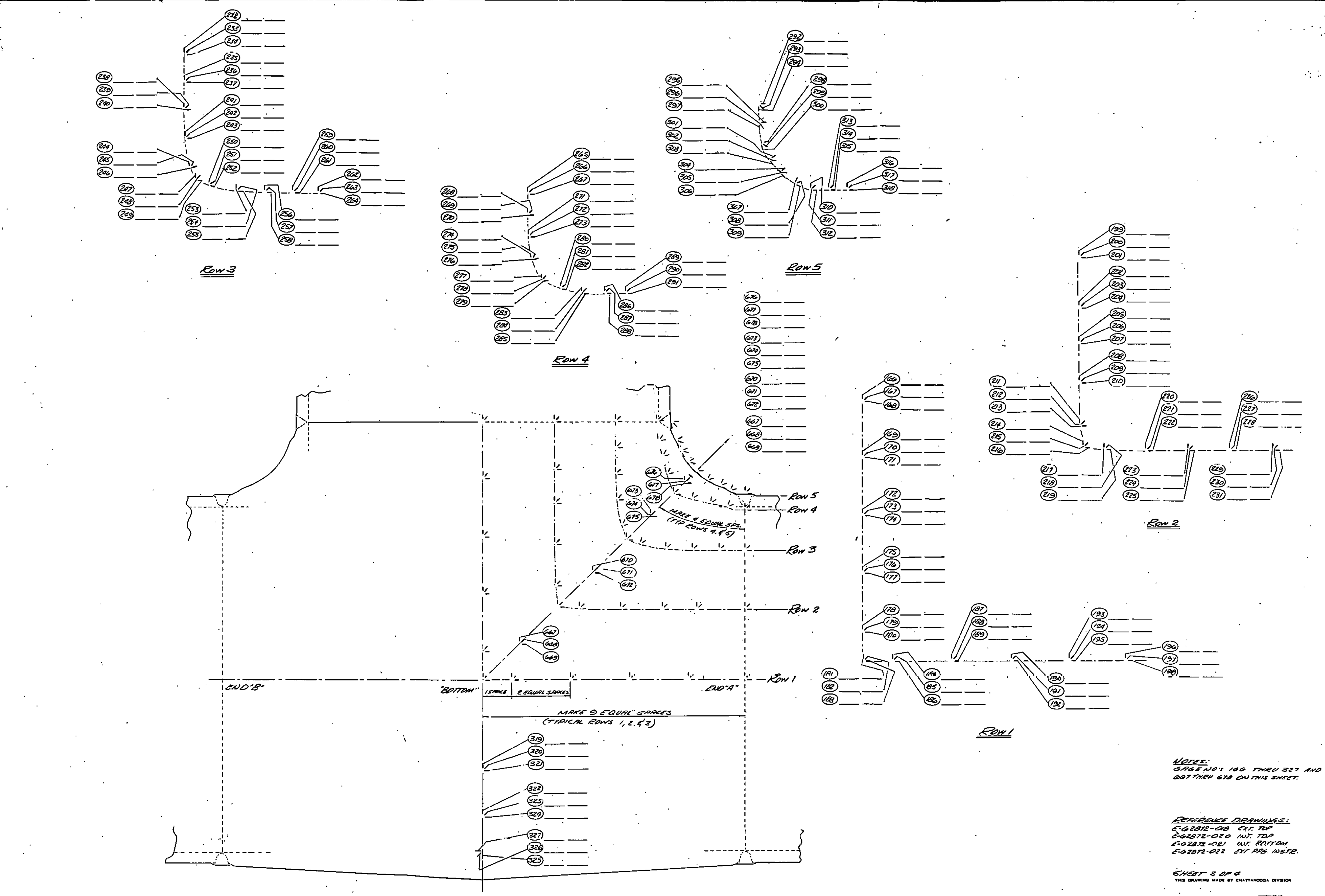
SHEET 1 OF 4

THIS DRAWING MADE BY CHATTANOOGA DIVISION

CONTRACT NO.
EXTERNAL INSTRUMENTATION 9.0" T-16"
FOR
VIEW OF TOP
SCALE ~ DATE 6/12/72
DRAWN BY L.R.NAILES CHECKED BY
TRACED BY APPROVED

DRAWING NO. E-62872-018-1

REVISED 1 ROW 5 - REV. 292 THRU 306. 3-28-74. CSR



NOTES:
GAGE NO'S 166 THRU 327 AND 667 THRU 678 ON THIS SHEET.

REFERENCE DRAWINGS:
E-62872-018 EXT. TOP
E-62872-020 INT. TOP
E-62872-021 INT. BOTTOM
E-62872-022 EXT PPG. INSTR.

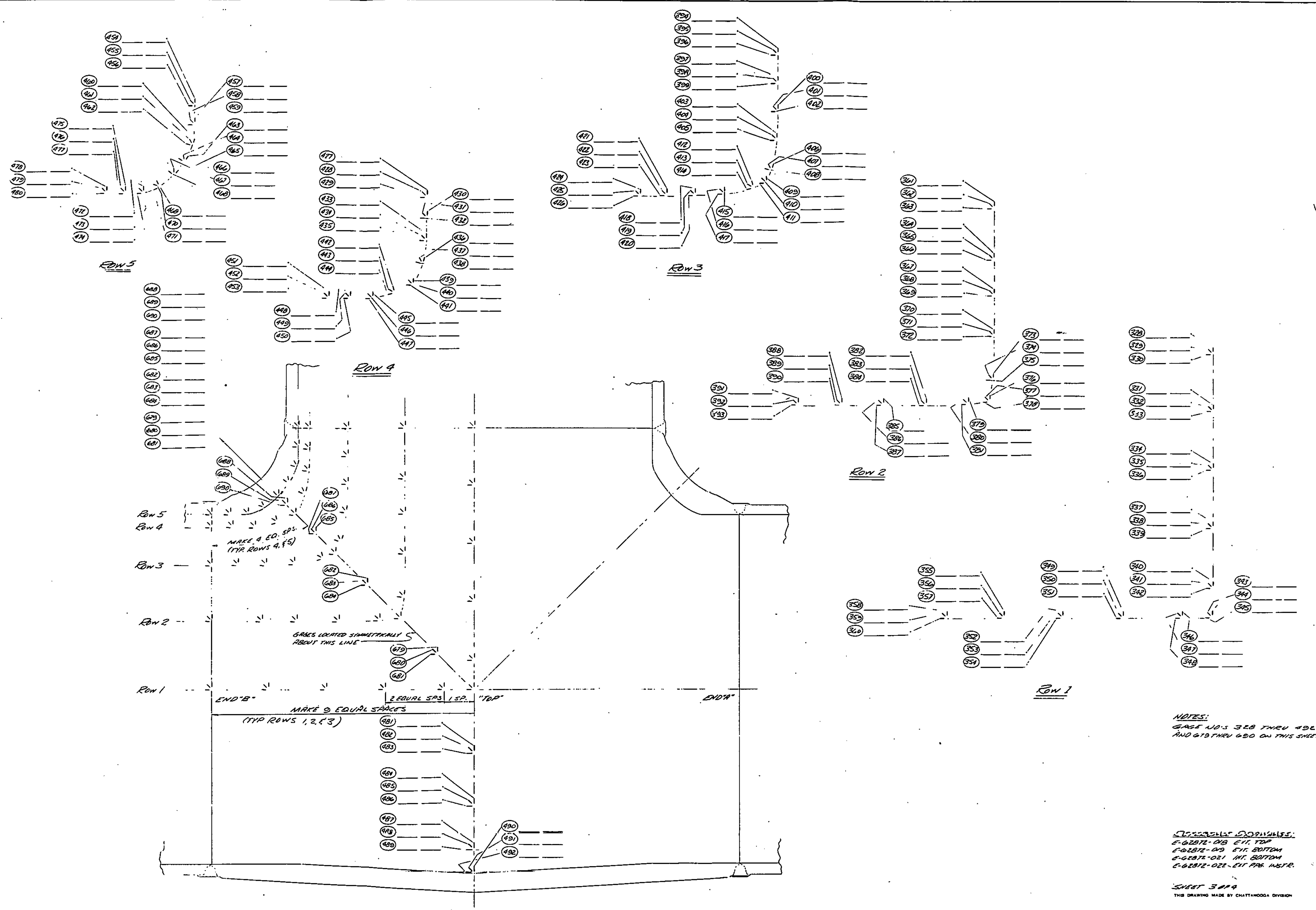
SHEET 2 OF 4
THIS DRAWING MADE BY CHATTANOOGA DIVISION

EXTERNAL INSTRUMENTATION OF "T-16"

VIEW OF BOTTOM

SCALE ~ DRAWN BY L.R. HAYES DATE 6/12/72

DRAWING NO. E-62872-019-1



NOTES:
GAGE NO'S 328 THRU 492 AND 679 THRU 690 ON THIS SHEET

E-62872-018 EXT. TOP
E-62872-019 EXT. BOTTOM
E-62872-021 INT. BOTTOM
E-62872-022 EXT PPG. INSTR.

SHEET 3 OF 4

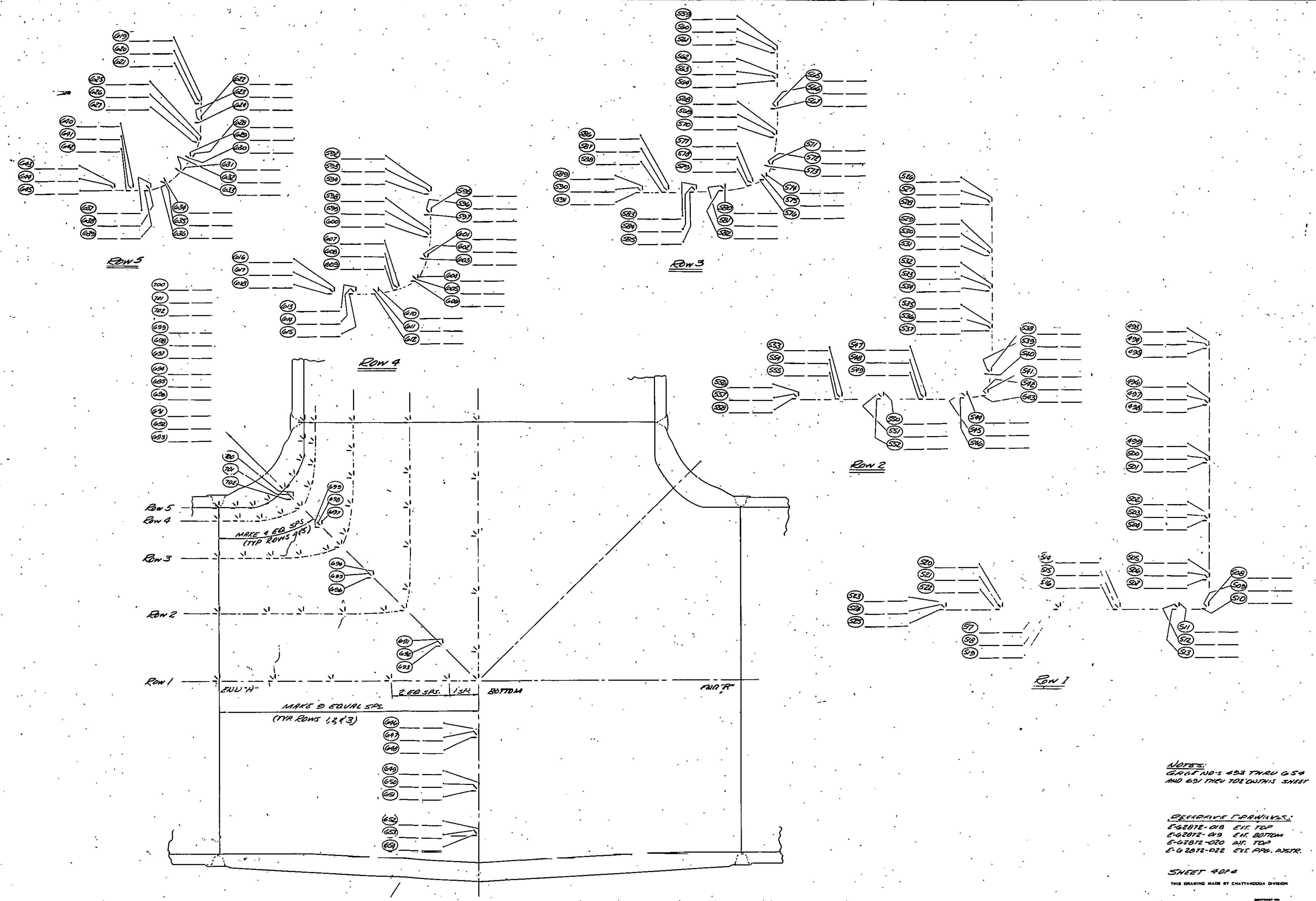
THIS DRAWING MADE BY CHATTANOOGA DIVISION

INTERNAL INSTRUMENTATION OF "T-16"

VIEW OF TOP

DRAWN BY L.R. HAYES — DATE 6/12/72

DRAWING NO. E-62872-020-0



NOTES:
GAGE NO'S 493 THRU 654 AND 691 THRU 702 ON THIS SHEET

REFERENCE DRAWINGS:
E-62872-018 EXT. TOP
E-62872-019 EXT. BOTTOM
E-62872-020 INT. TOP
E-62872-022 EXT. PPG. INSTR.

SHEET 4 OF 4

THIS DRAWING MADE BY CHATTANOOGA DIVISION

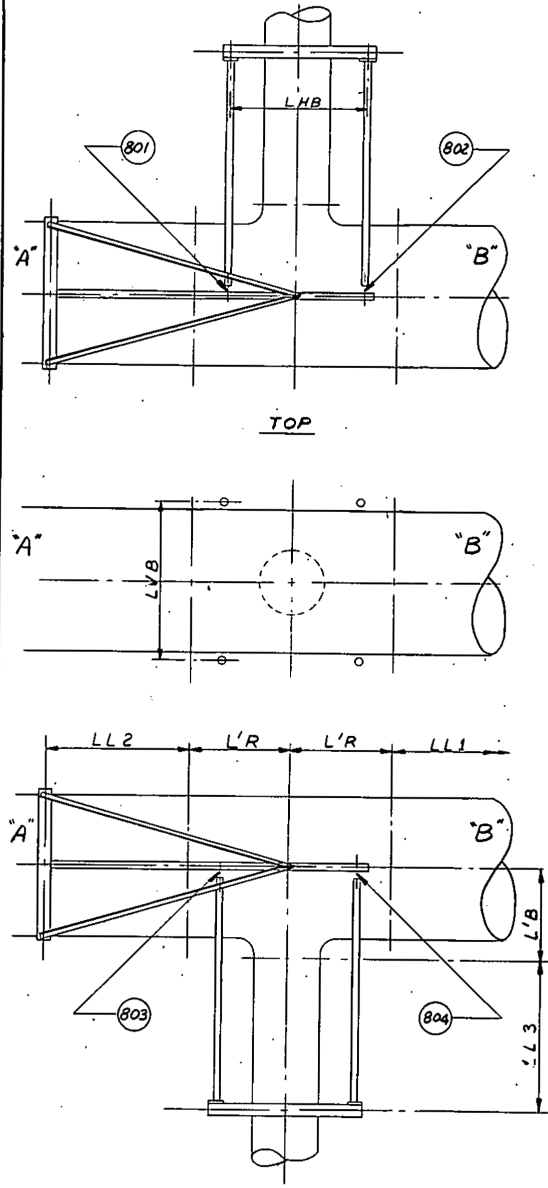
INTERNAL INSTRUMENTATION OF "T-16"

VIEW OF BOTTOM

SCALE: N
DRAWN BY: L.R. HAYES
TRACED BY:
DATE: 6/12/72
CHECKED BY:
APPROVED:

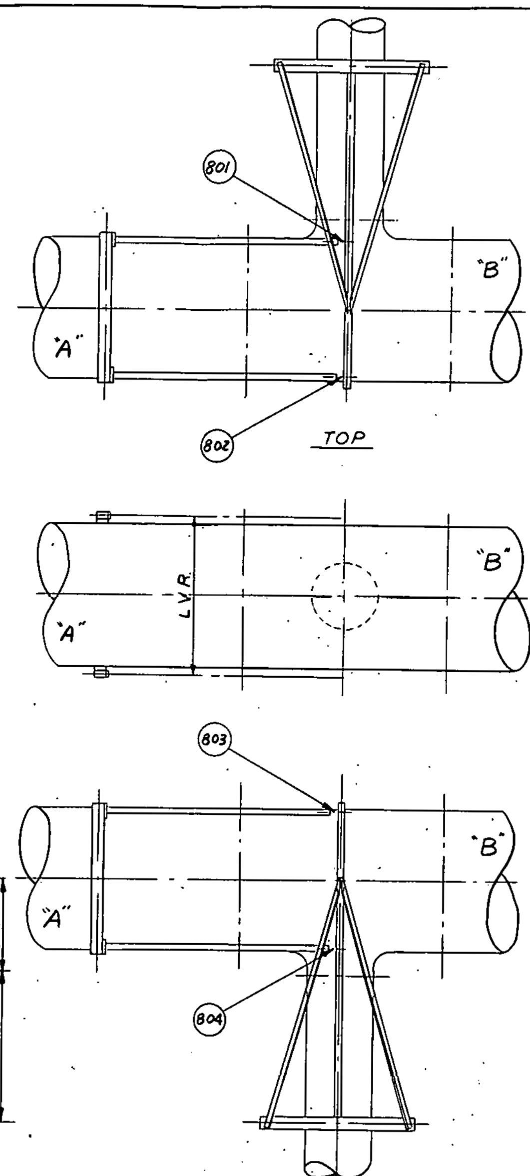
DRAWING NO. E-62872-021-0

REVISED



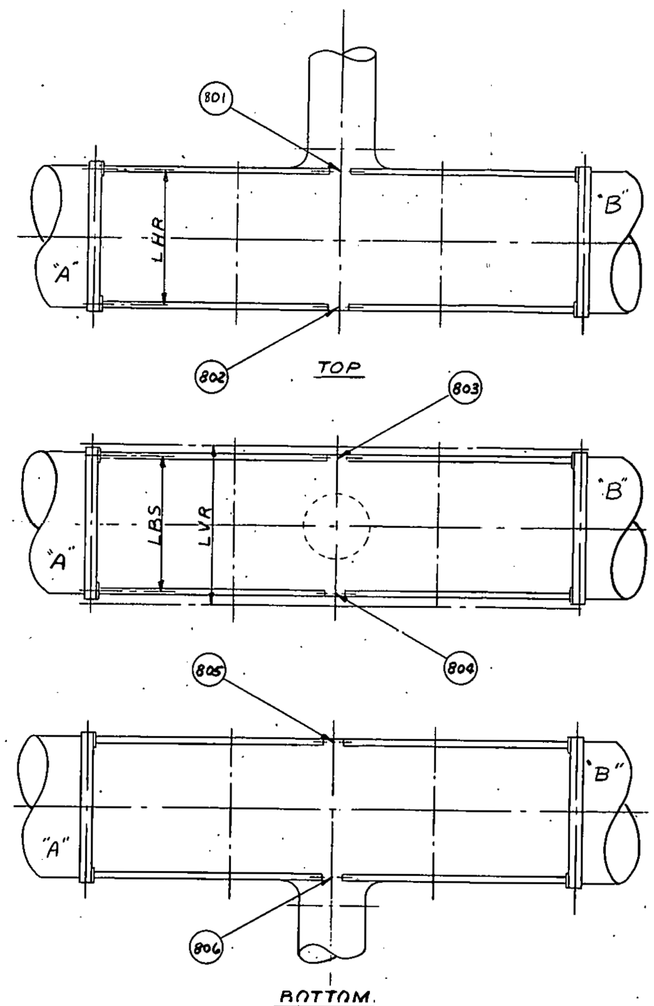
MEASUREMENT OF θZ31 & θX31

FIGURE #2



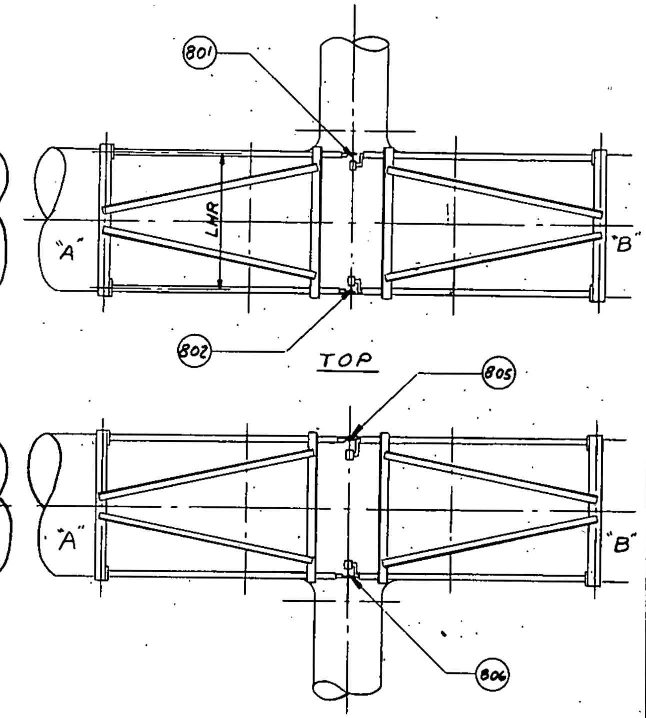
MEASUREMENT OF θY31

FIGURE #3



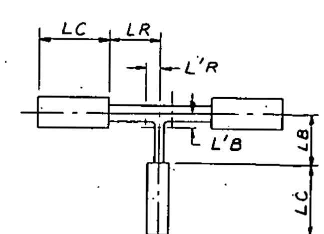
MEASUREMENT OF θZ21 & θY21

FIGURE #4



MEASUREMENT OF θX21

FIGURE #5



○ DENOTES L.V.D.T. NO.

TABLE

LOC.	DIMENSION	
	NOM.	T-16
LB	77"	77"
LC	96"	96"
LR	77"	77"
L'B	15"	15"
L'R	17"	17"
LBS	23"	23"
LHB	23"	23"
LHR	23"	23"
LL1	25.5"	25.5"
LL2	25.5"	25.5"
LL3	27.5"	27.5"
LVB	27.5"	27.5"
LVR	27.5"	27.5"

THIS DRAWING MADE BY CHATTANOOGA

CONTRACT NO. 5469

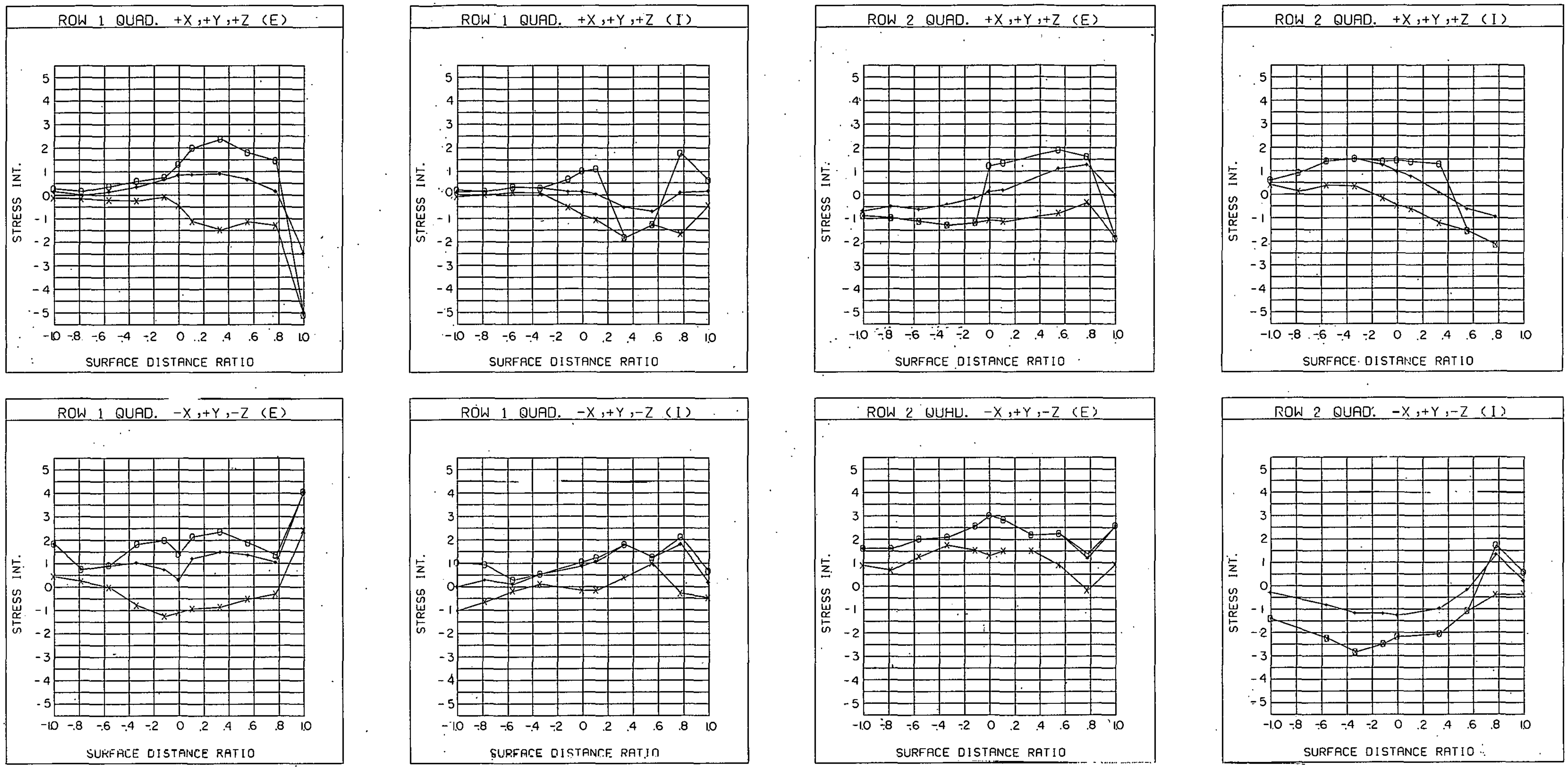
L.V.D.T. SUPPORT CONDITION

FOR FOR T-16

ORNL TEE TEST

SCALE ~ DATE 4-17-74
DRAWN BY CASTEEL CHECKED BY
TRACED BY APPROVED

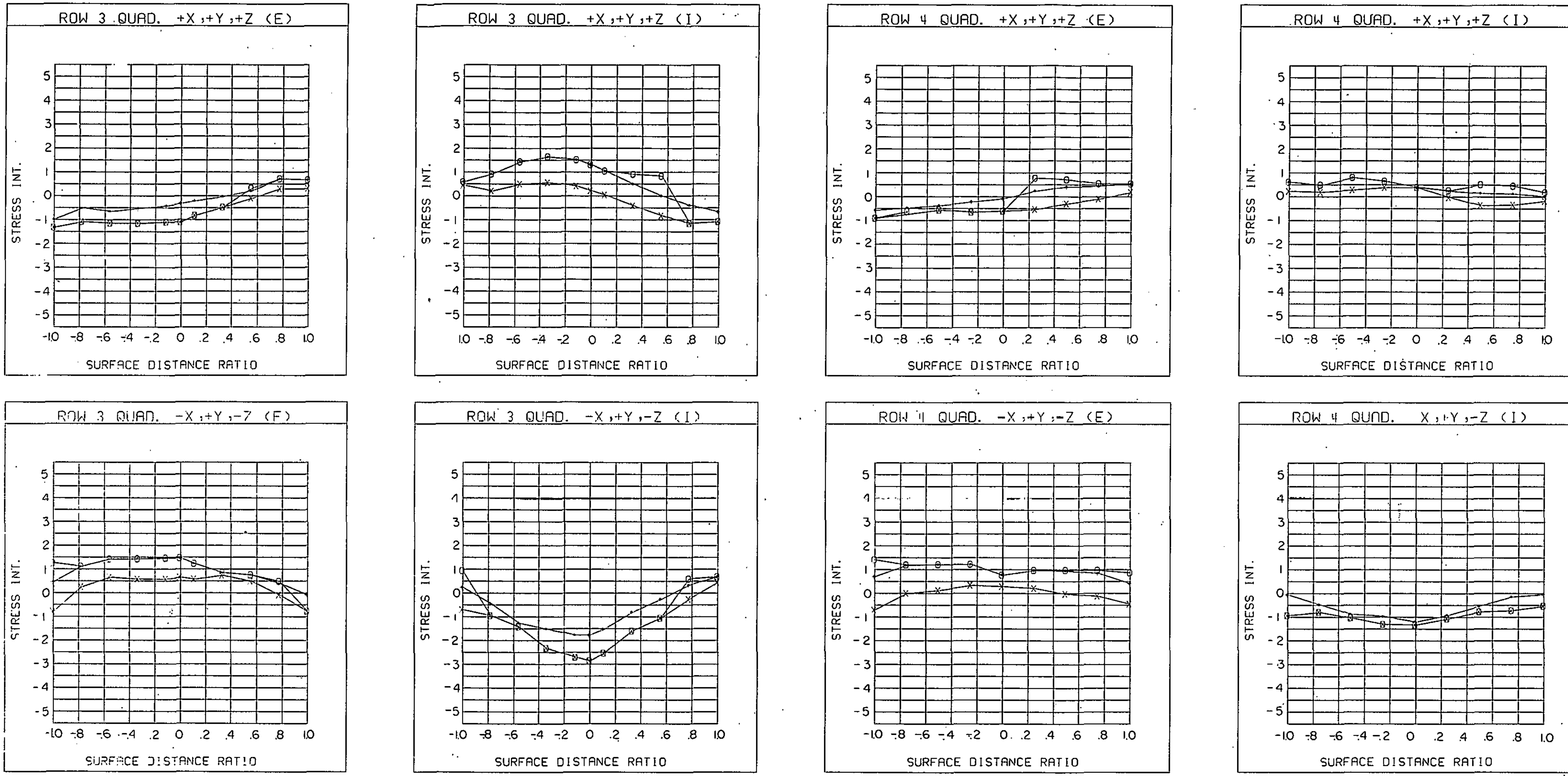
DRAWING NO. D-62874-027-0



M3X-ROWS 1 and 2

ORNL TEE TEST PROGRAM
T-16 TEE (M3X)
LOAD CASE 1
INTERVAL 2

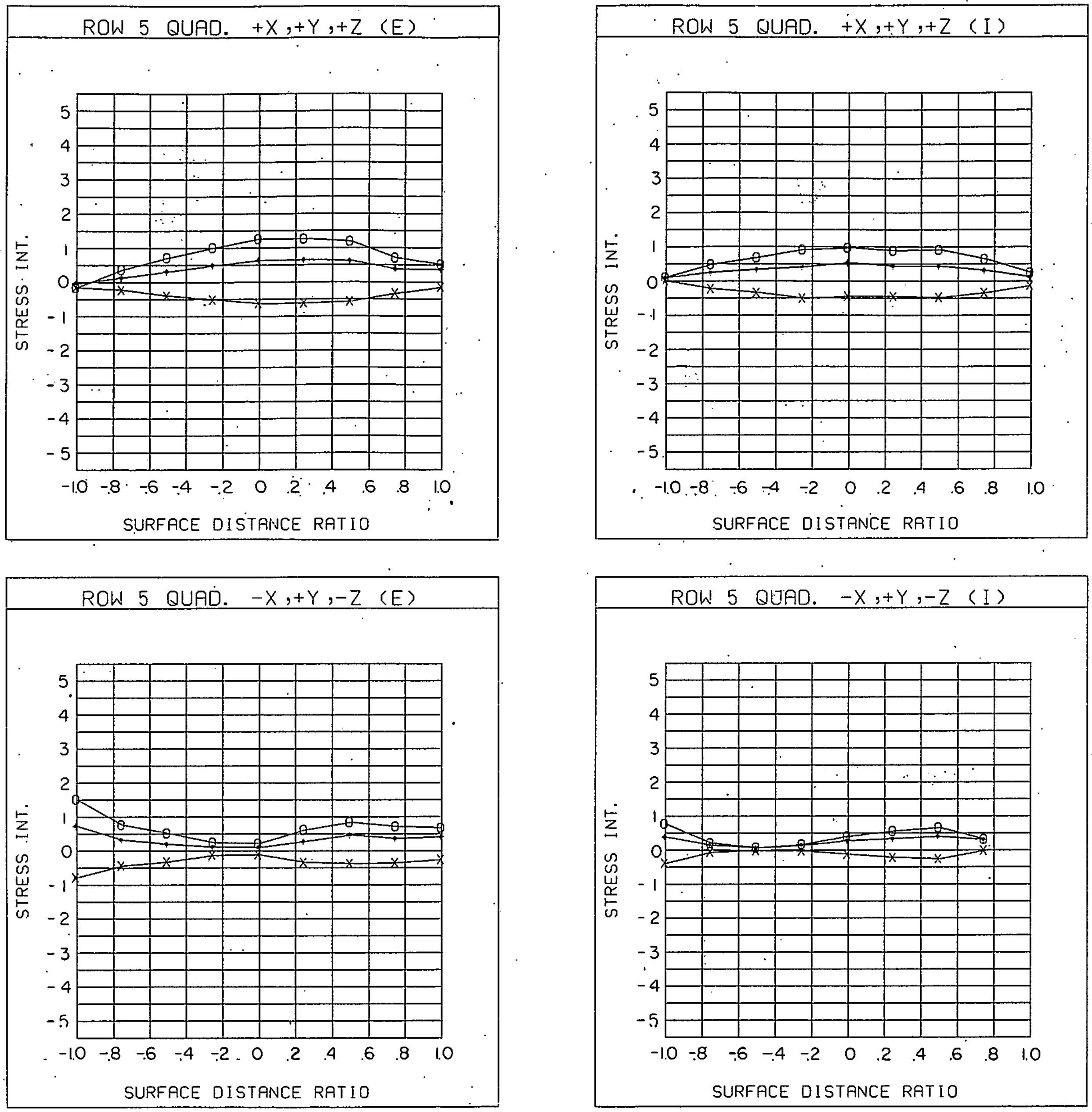
LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



M3X-ROWS 3 and 4

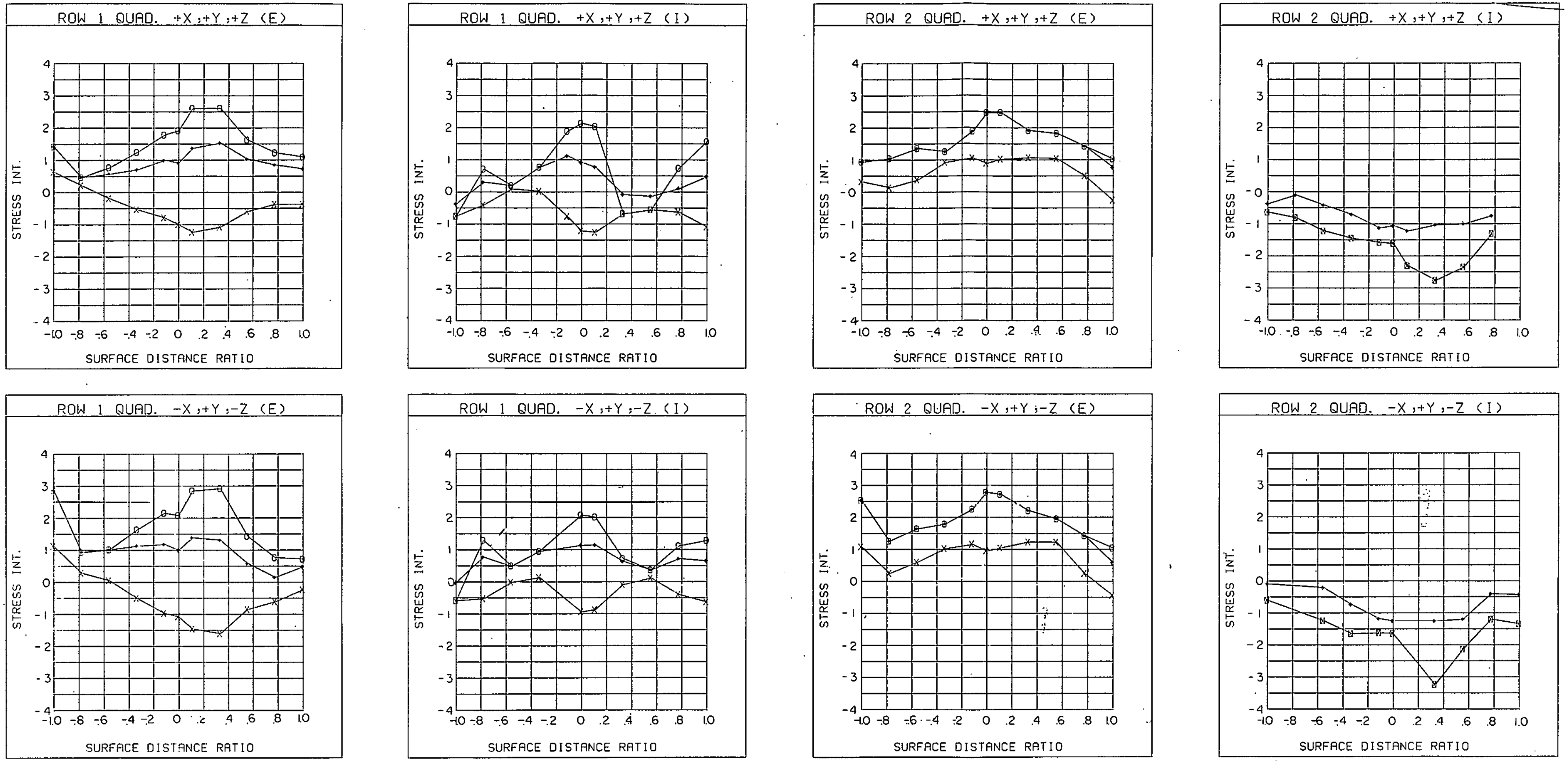
ORNL TEE TEST PROGRAM
T-16 TEE (M3X)
LOAD CASE 1
INTERVAL 2

LEGEND
+ - SIGMA MAX
X = SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



ORNL TEE TEST PROGRAM
T-16 TEE (M3X)
LOAD CASE 1
INTERVAL 2

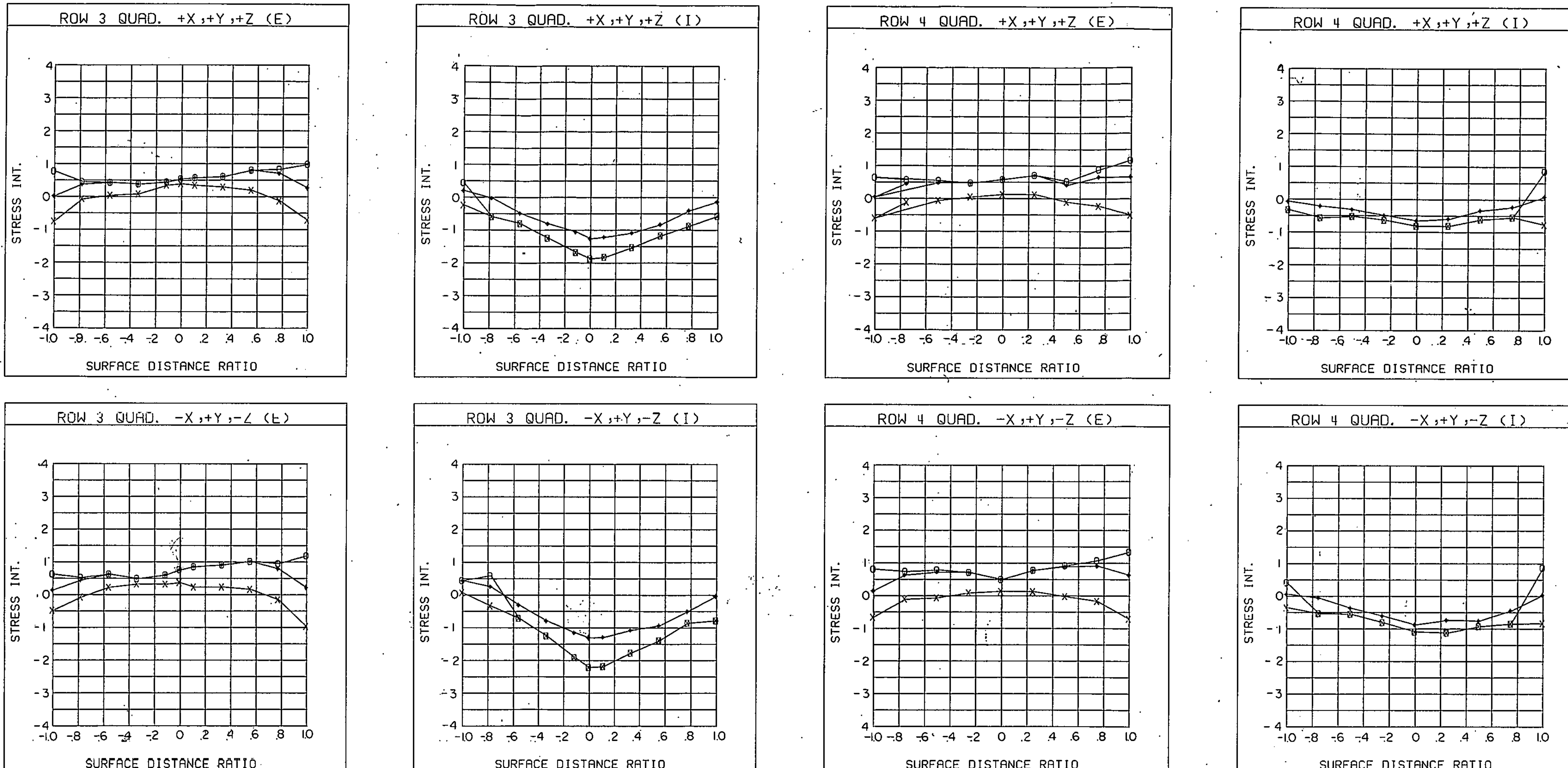
LEGEND
+ - SIGMA MAX
X - SIGMA MIN
0 - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



M3Y-ROWS 1 and 2

ORNL TEE TEST PROGRAM
T-16 TEE (M3Y)
LOAD CASE 2
INTERVAL 2

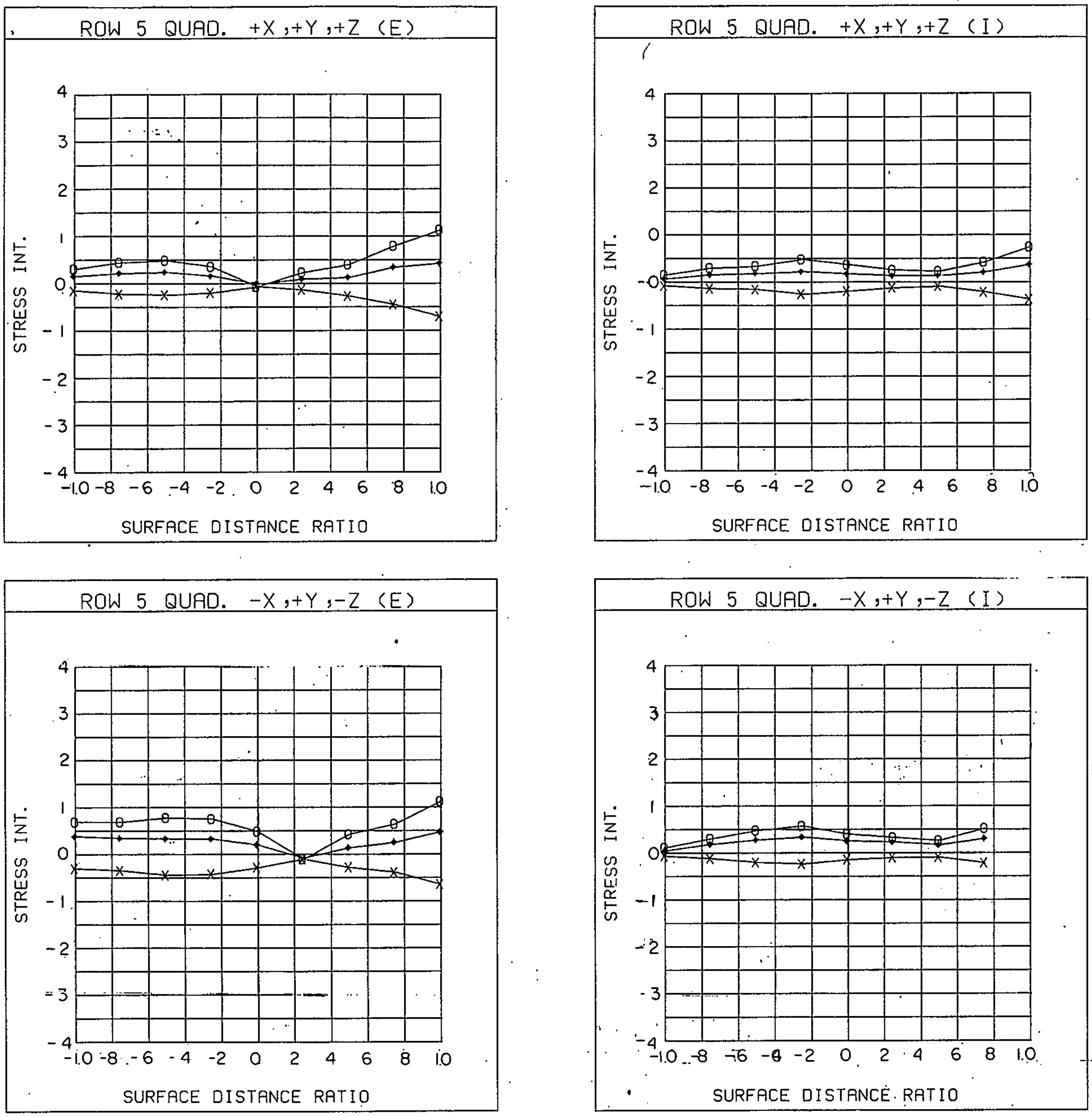
LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



M3Y-ROWS 3 and 4

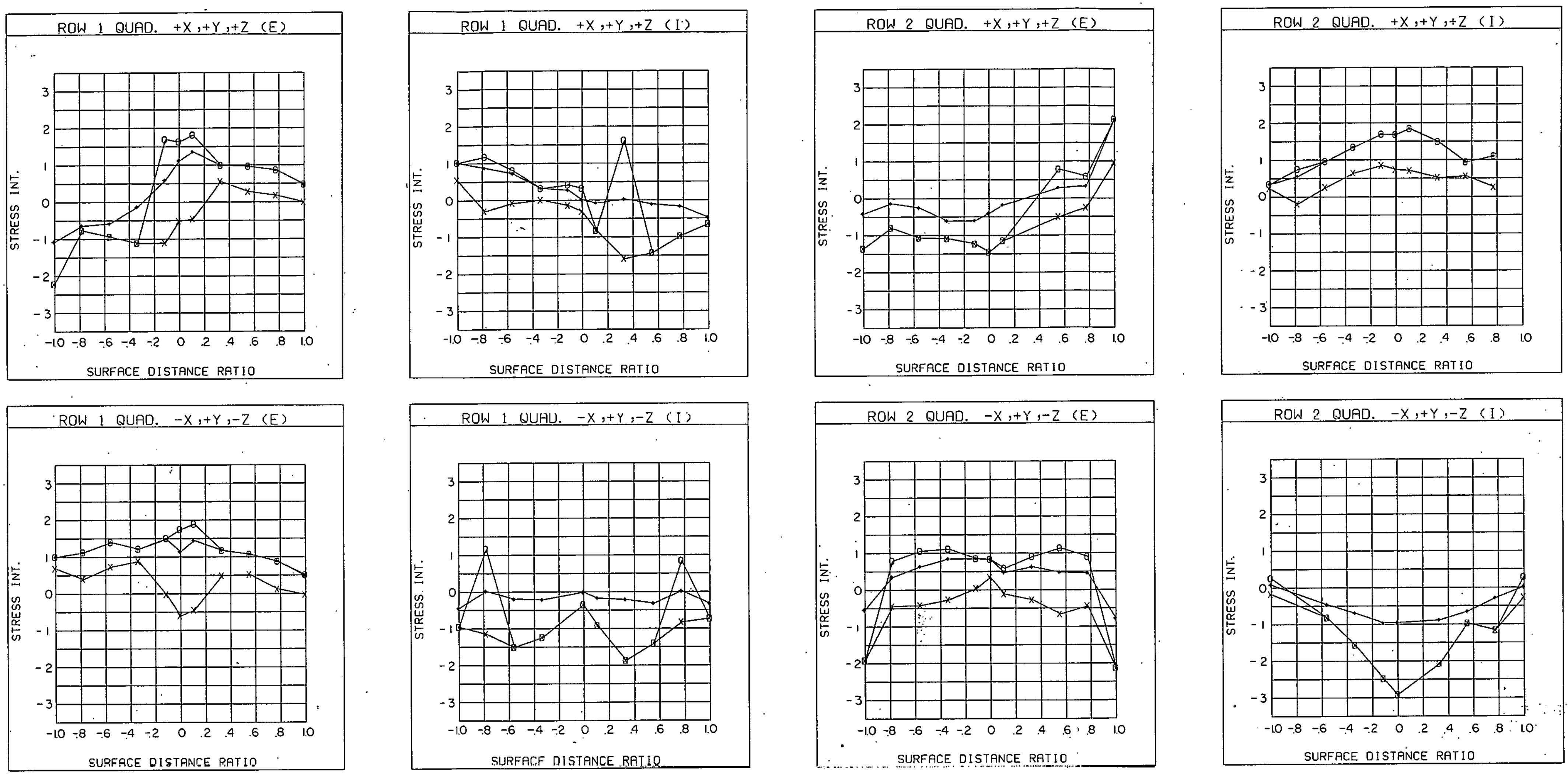
ORNL TEE TEST PROGRAM
T-16 TEE (M3Y)
LOAD CASE 2
INTERVAL 2

LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



URNL TEE TEST PROGRAM
T-16 TEE (M3Y)
LOAD CASE 2
INTERVAL 2

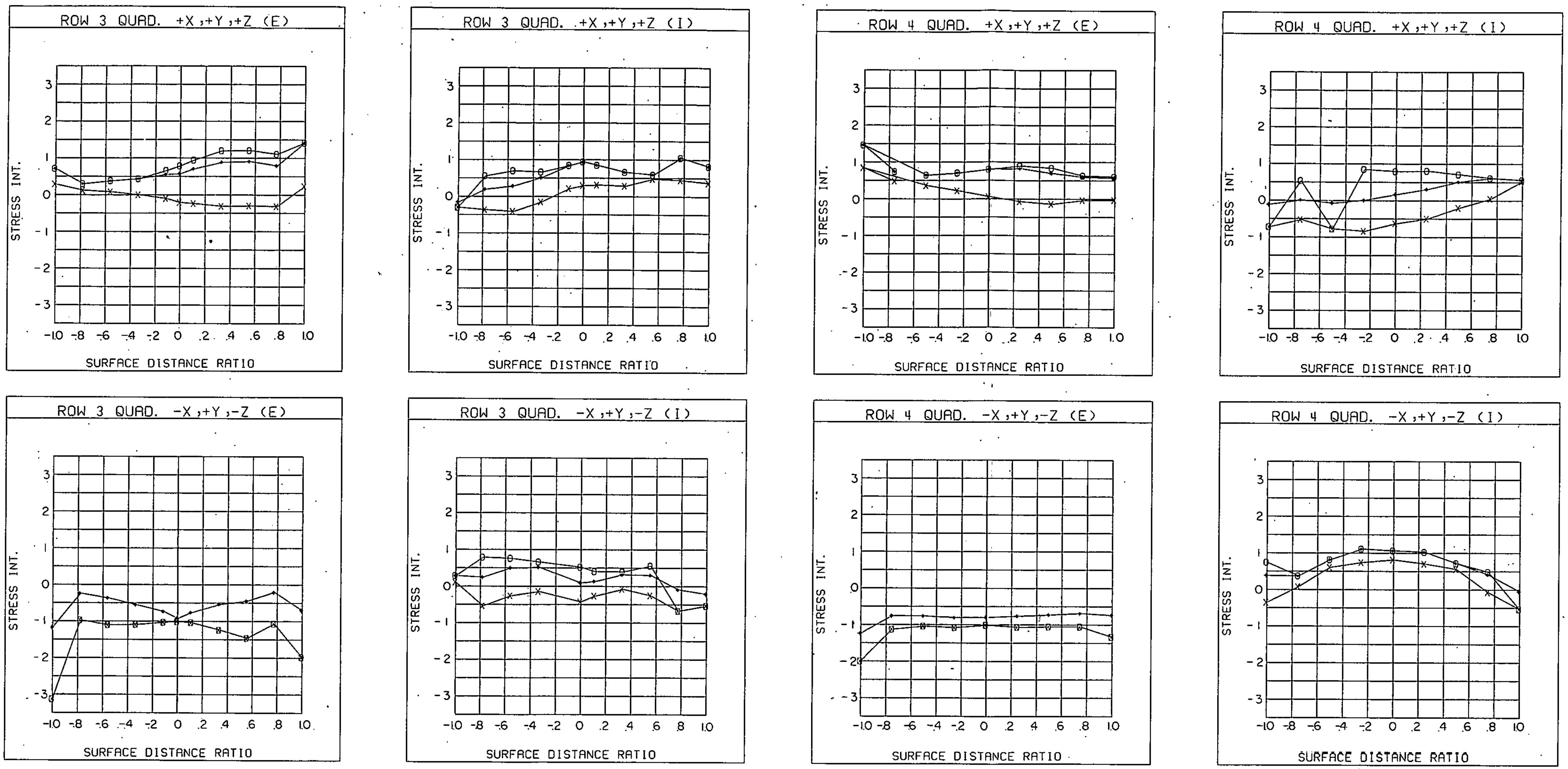
LEGEND
* - SIGMA MAX
X SIGMA MIN
0 - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



M3Z-ROWS 1 and 2

ORNL TEE TEST PROGRAM
T-16 TEE (M3Z)
LOAD CASE 3
INTERVAL 3

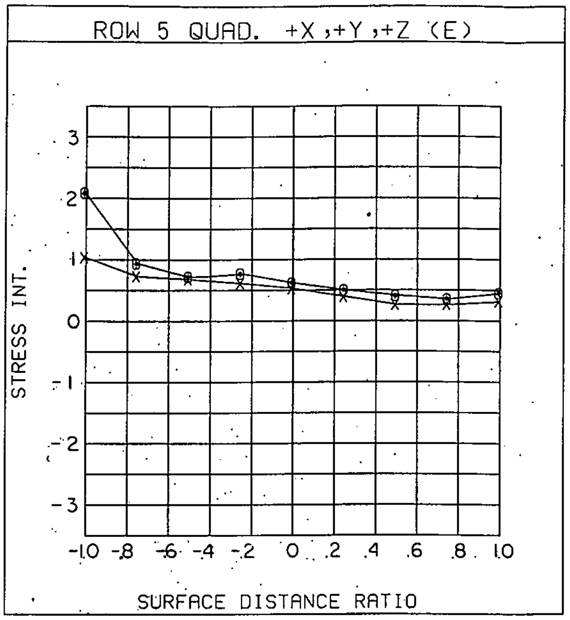
LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL

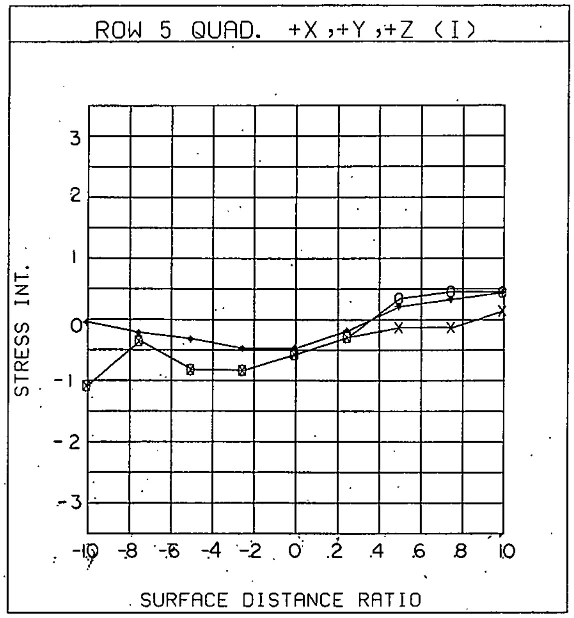


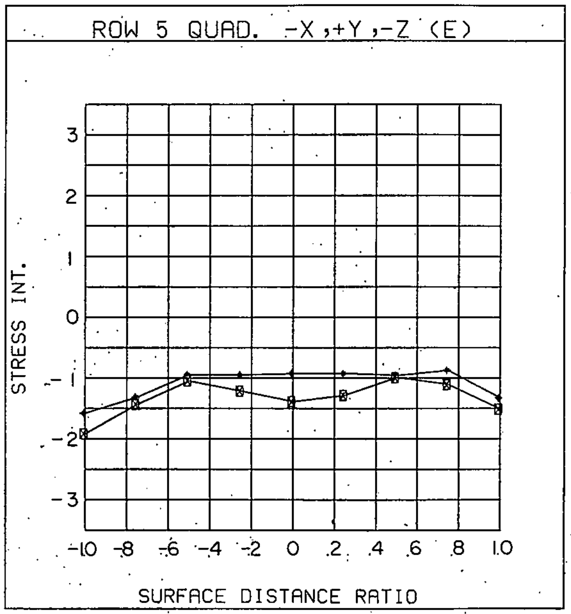
M3Z-ROWS 3 and 4

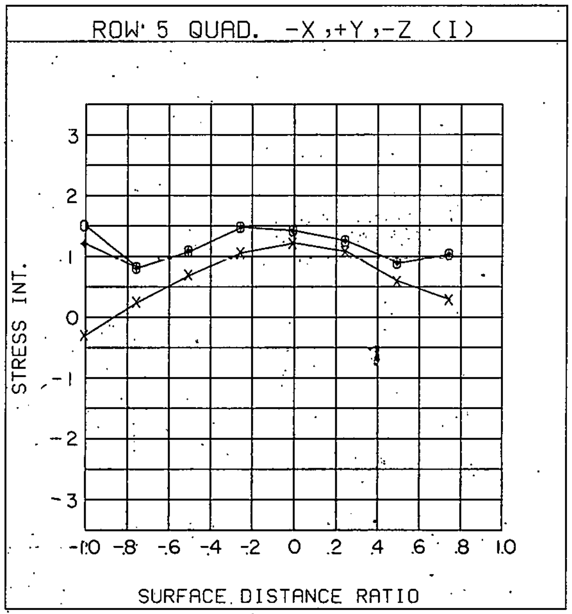
ORNL TEE TEST PROGRAM
T-16 TEE (M3Z)
LOAD CASE 3
INTERVAL 3

LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



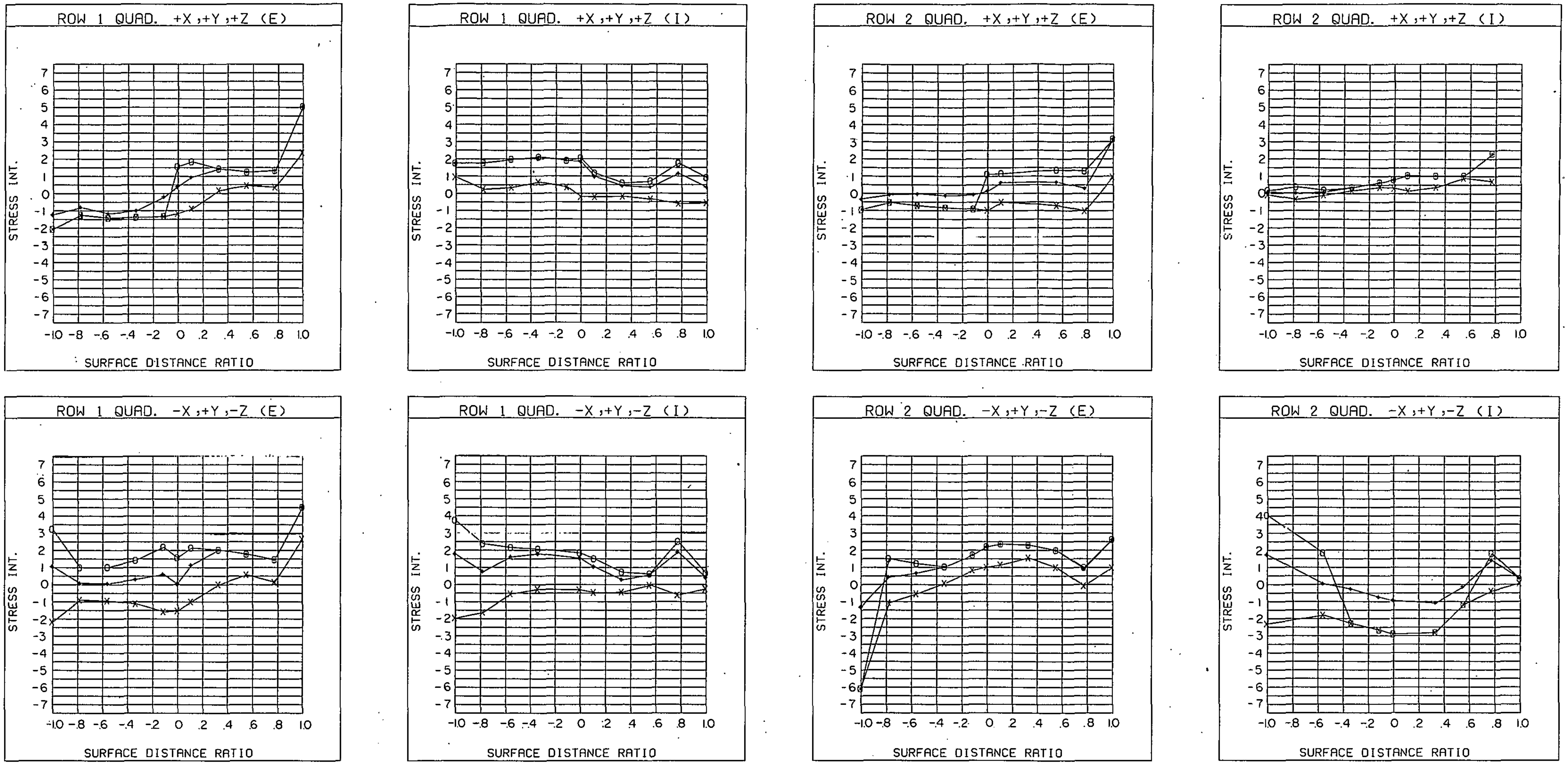






ORNL TEE TEST PROGRAM
T-16 TEE (M3Z)
LOAD CASE 3
INTERVAL 3

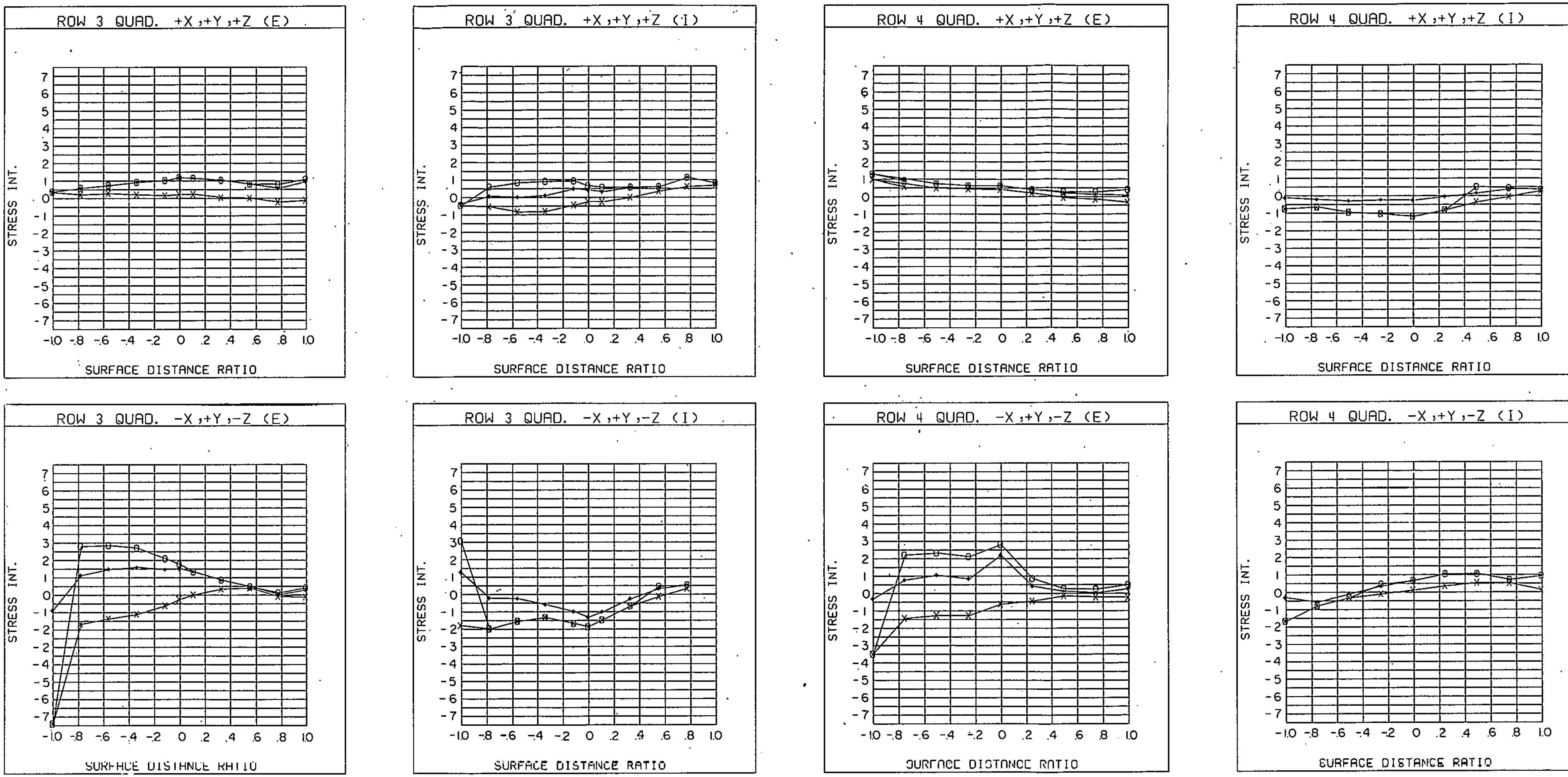
LEGEND
* - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



F3Y-ROWS 1 2

ORNL TEE TEST PROGRAM
T-16 TEE (F3Y)
LOAD CASE 5
INTERVAL 1

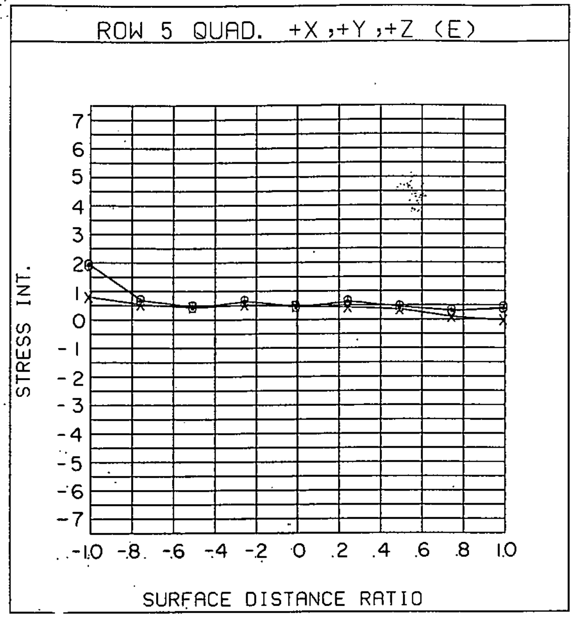
LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL

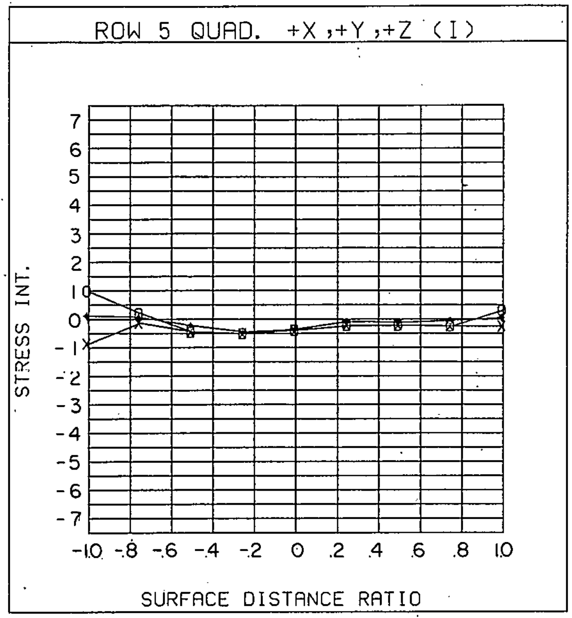


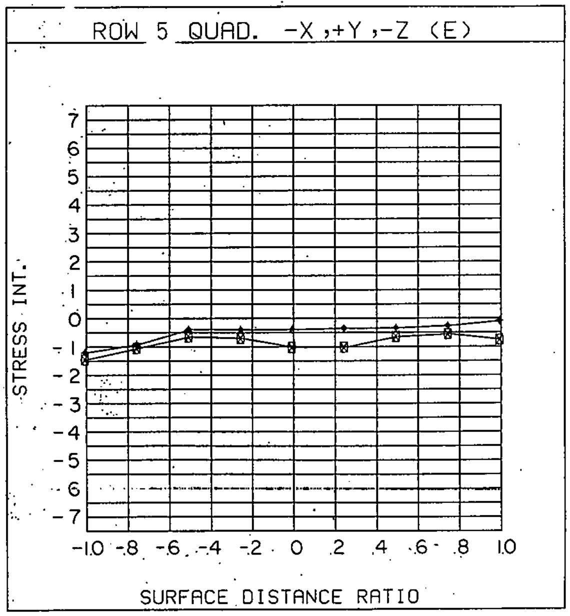
F3Y-ROWS 3 and 4

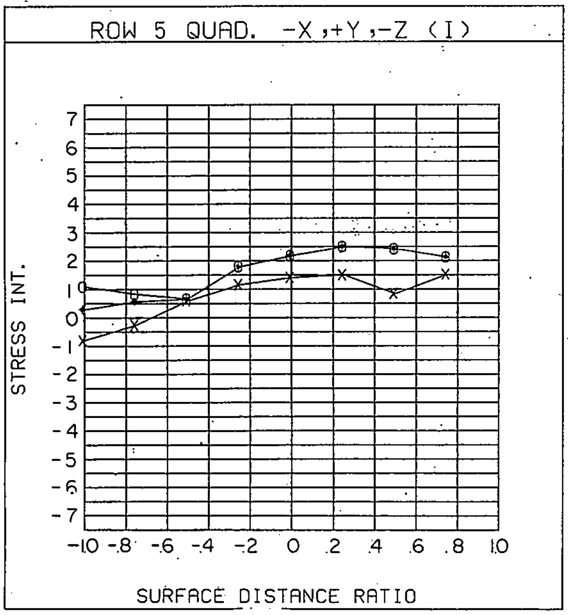
ORNL TEE TEST PROGRAM
T-16 TEE (F3Y)
LOAD CASE 5
INTERVAL 1

LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



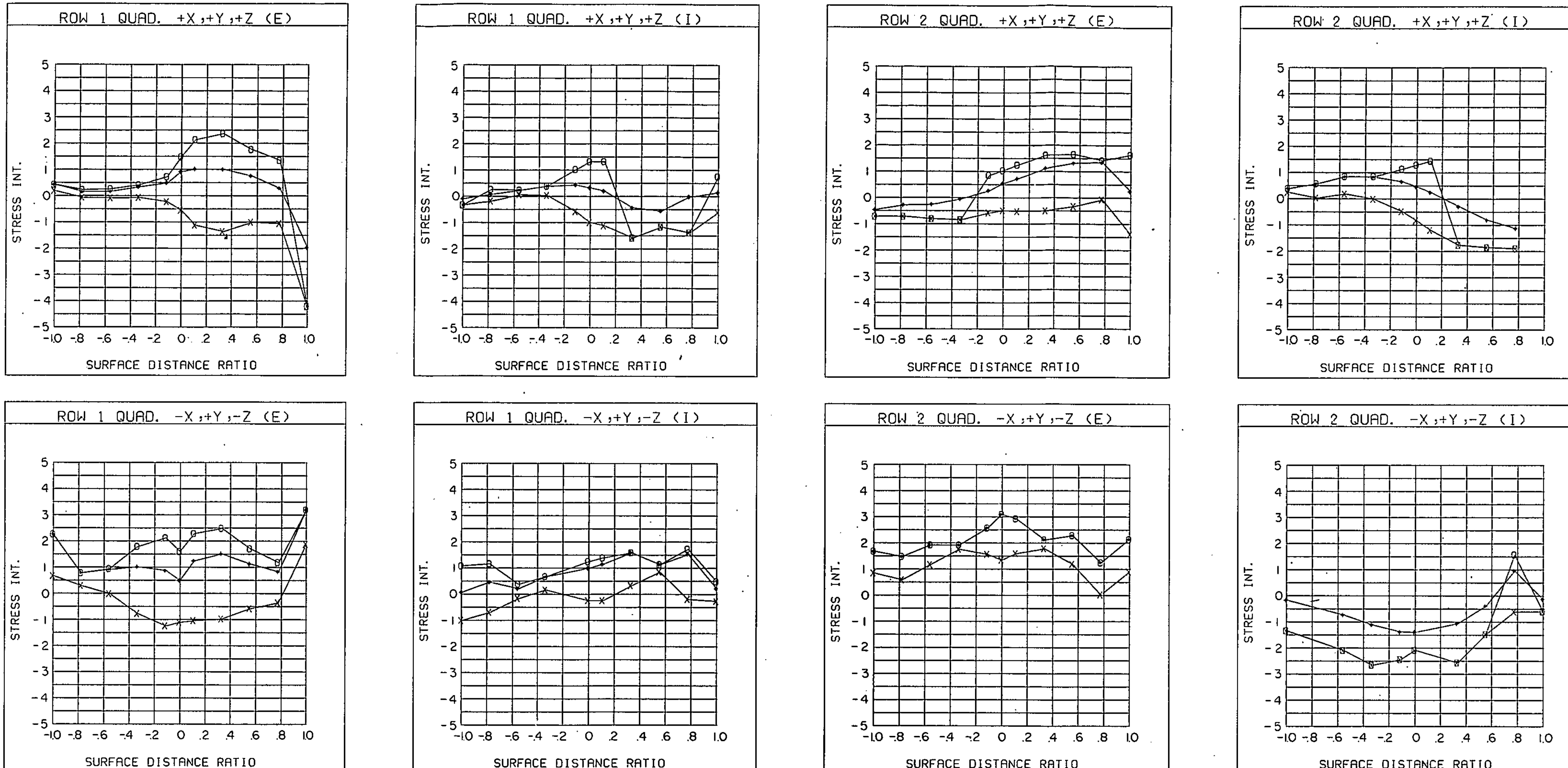






ORNL TEE TEST PROGRAM
T-16 TEE (F3Y)
LOAD CASE 5
INTERVAL 1

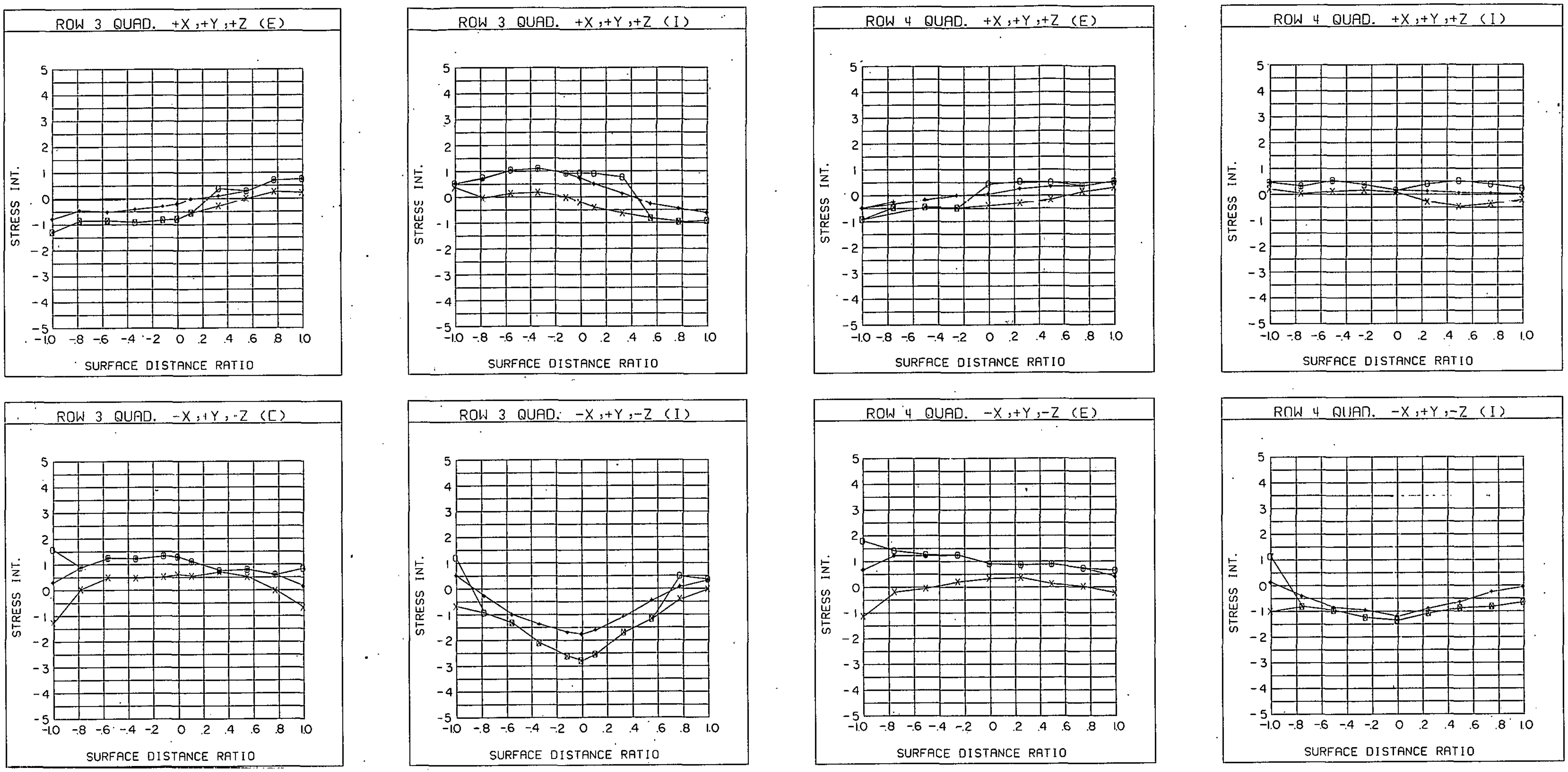
LEGEND
* - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



F3Z-ROWS 1 and 2

ORNL TEE TEST PROGRAM
T-16 TEE (F3Z)
LOAD CASE 6
INTERVAL 2

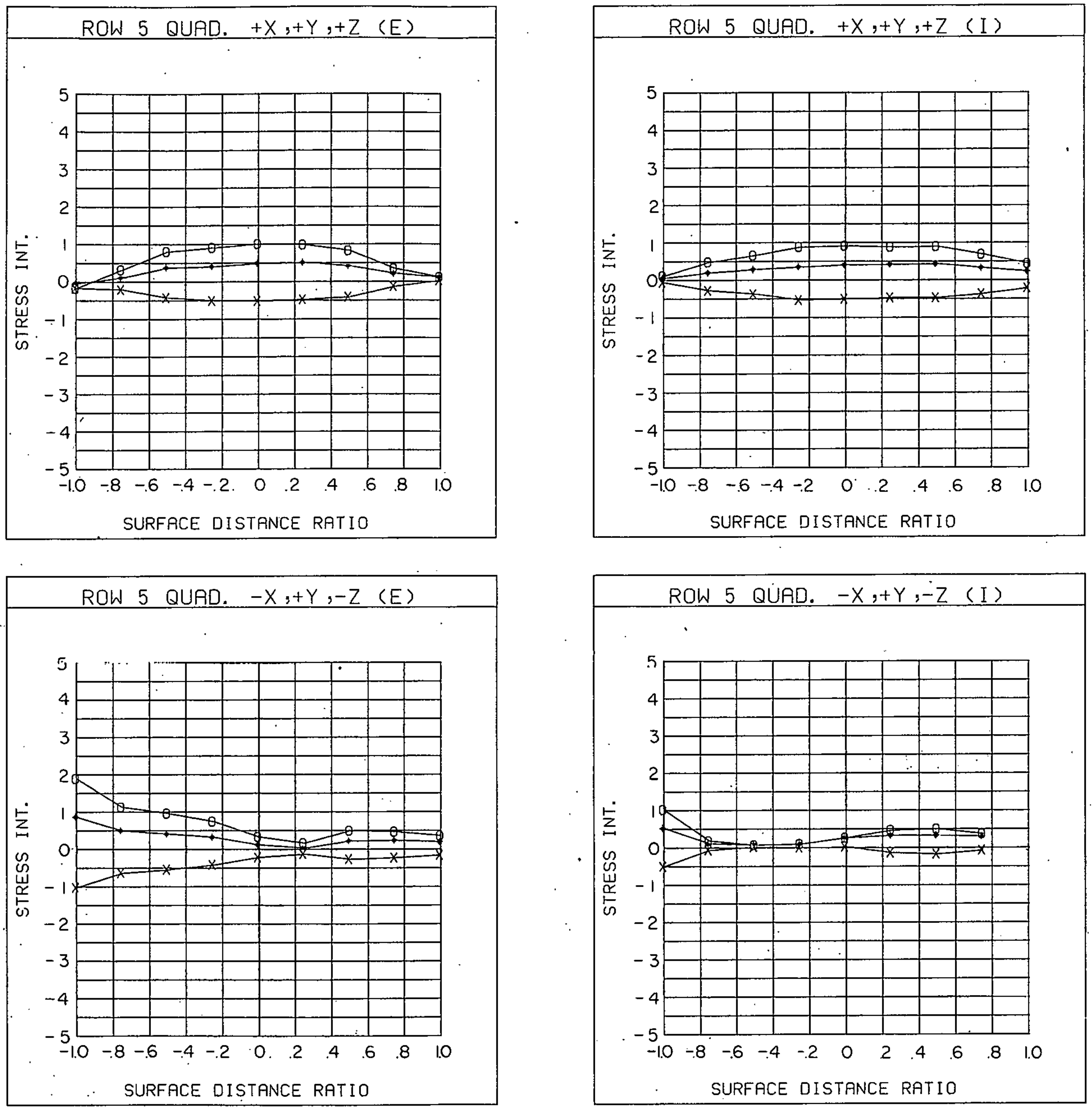
LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



F3Z-ROWS 3 and 4

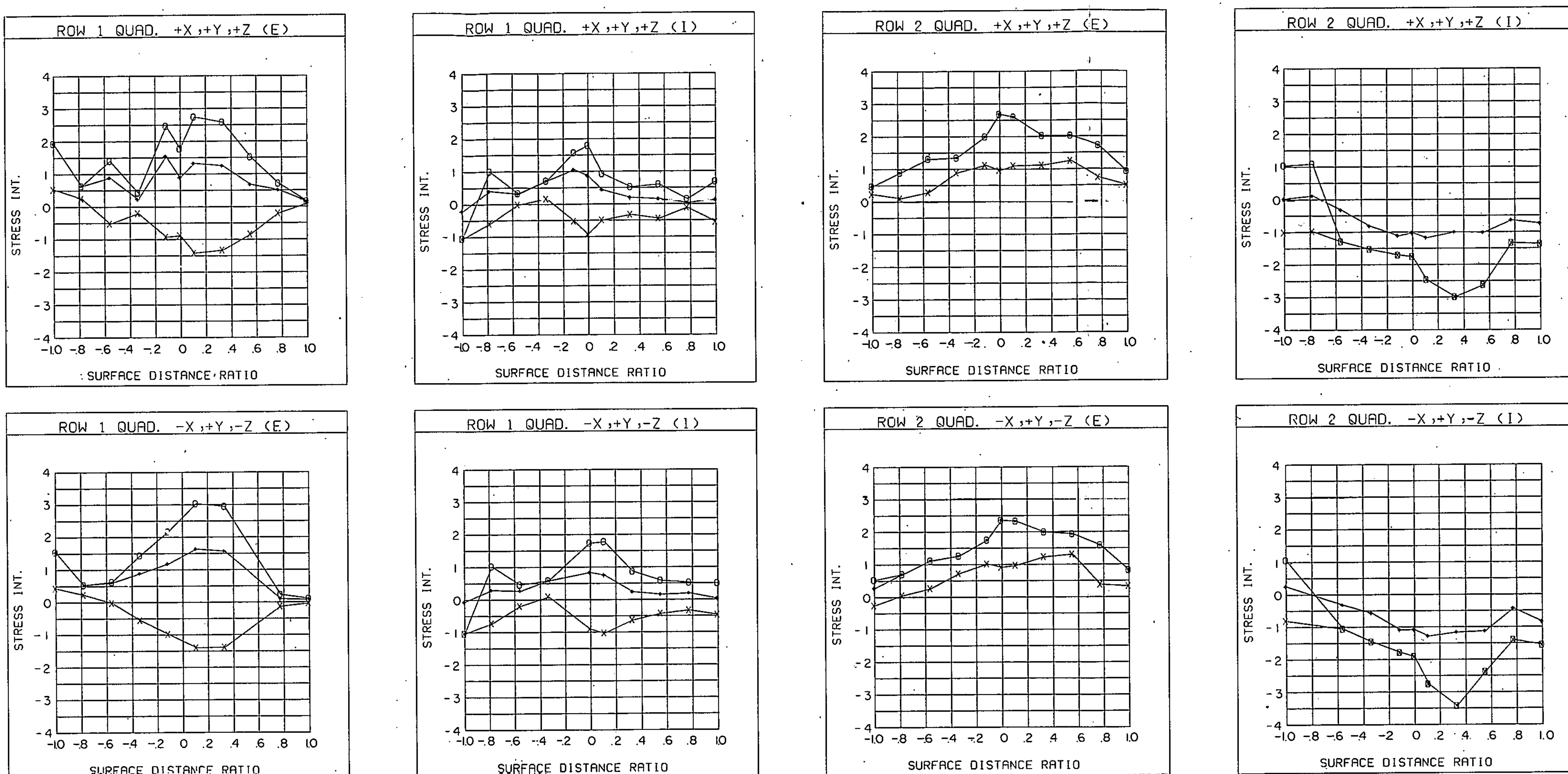
ORNL TEE TEST PROGRAM
T-16 TEE (F3Z)
LOAD CASE 6
INTERVAL 2

LEGEND
+ - SIGMA MAX
X = SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



ORNL TEE TEST PROGRAM
T-16 TEE (F3Z)
LOAD CASE 6
INTERVAL 2

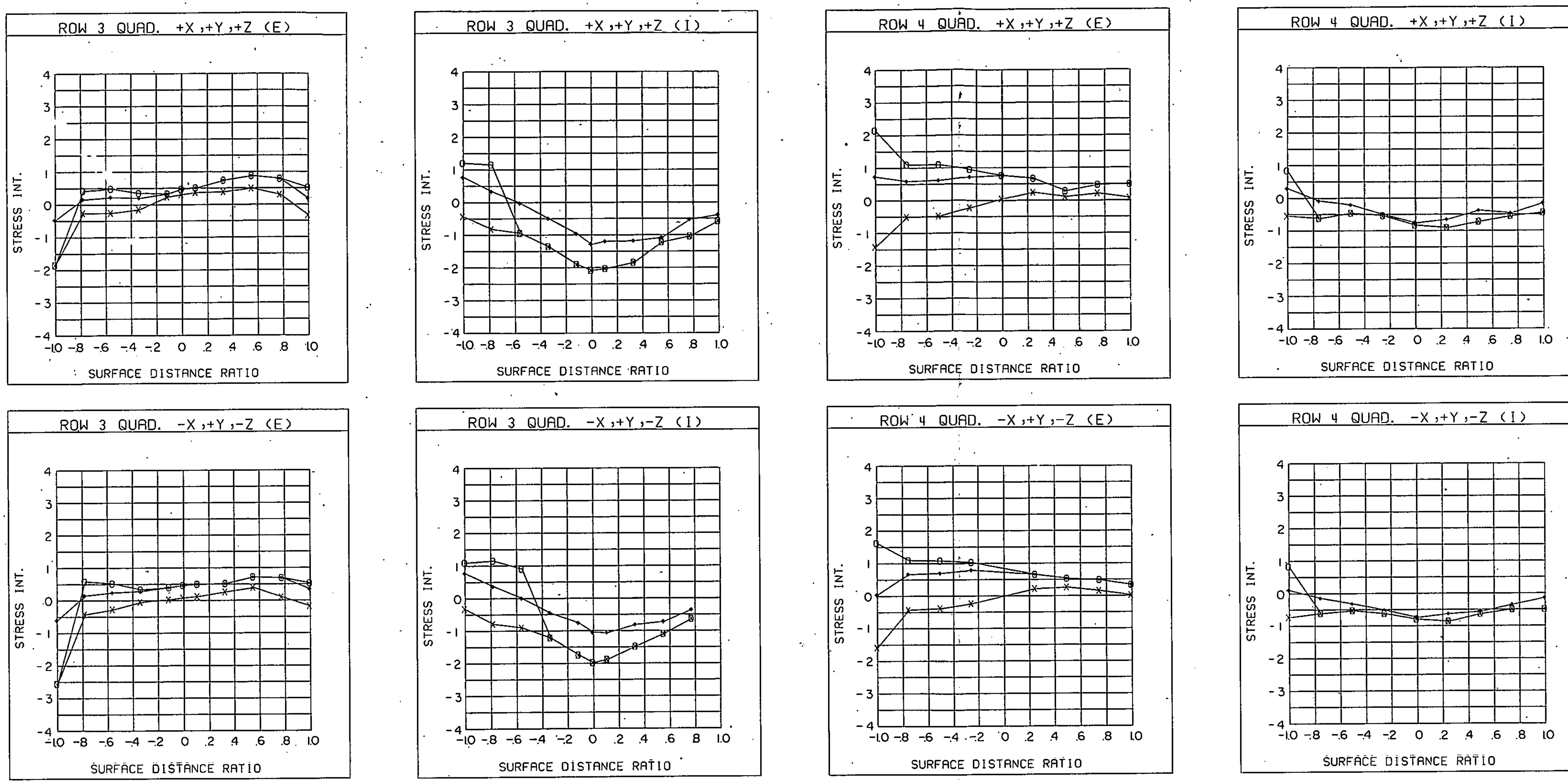
LEGEND
* - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



M2X-ROWS 1 and 2

ORNL TEE TEST PROGRAM
T-16 TEE (M2X)
LOAD CASE 7
INTERVAL 3

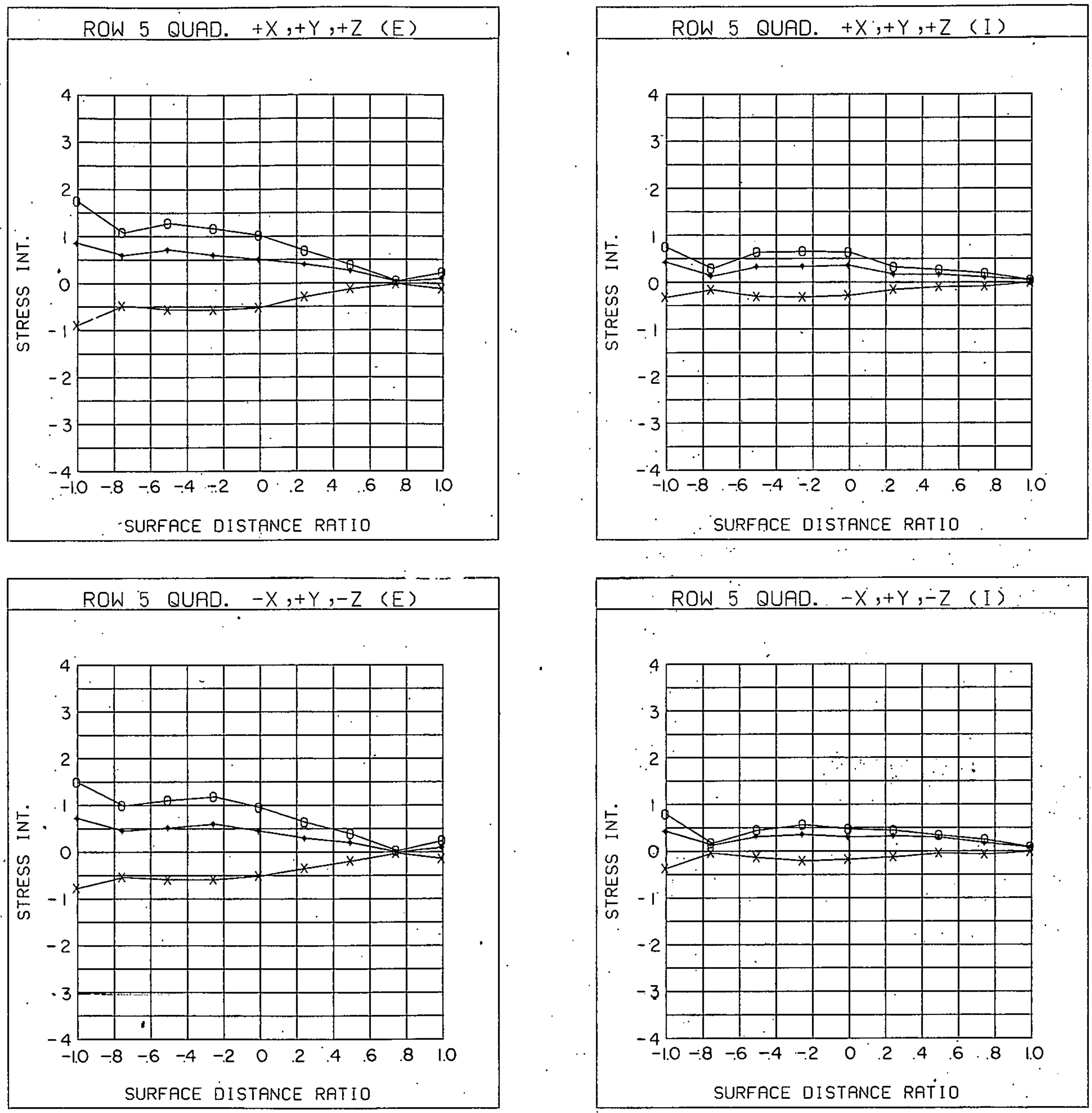
LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



M2X-ROWS 3 and 4

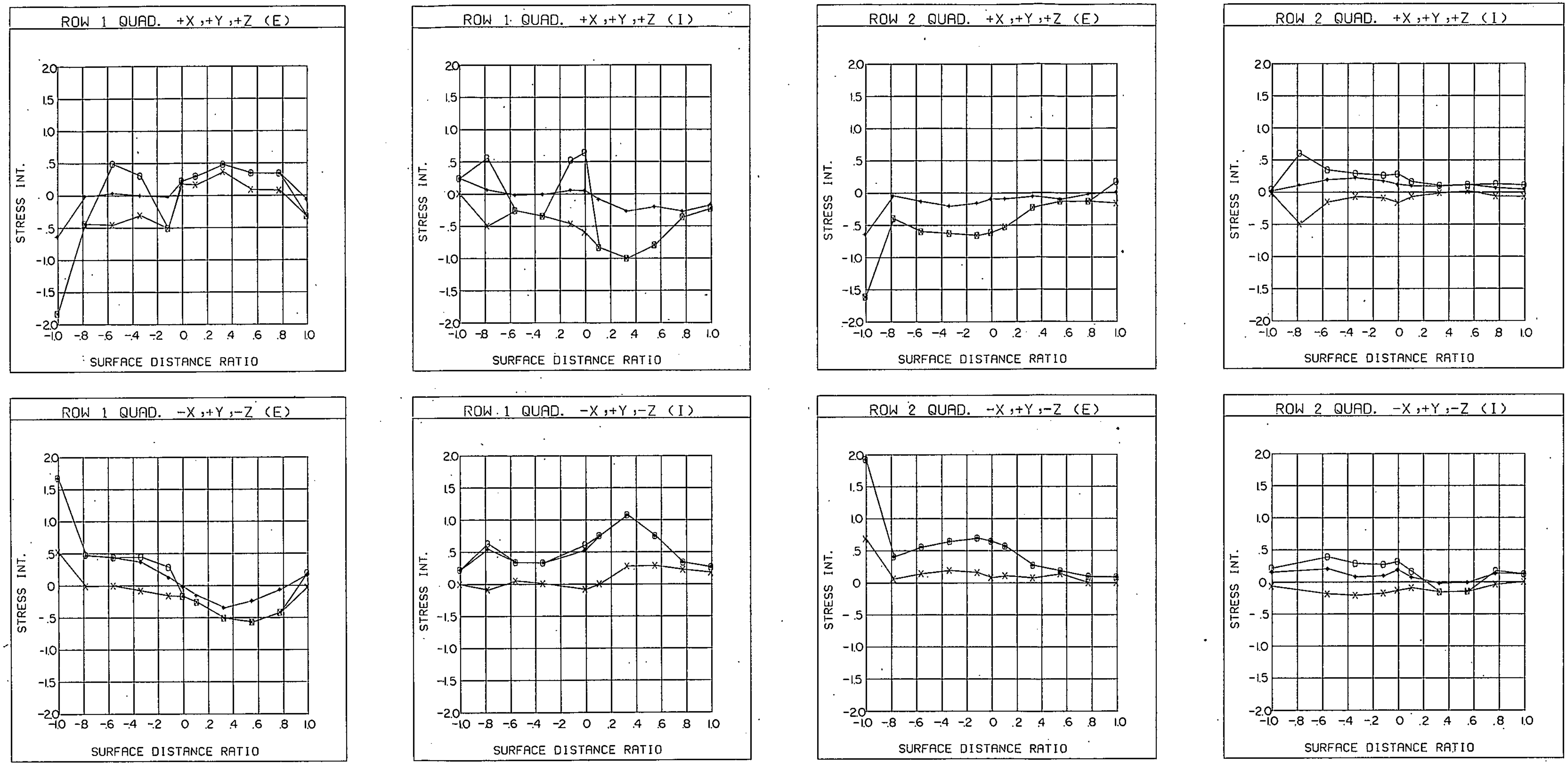
ORNL TEE TEST PROGRAM
T-16 TEE (M2X)
LOAD CASE 7
INTERVAL 3

LEGEND
- ♦ SIGMA MAX
- X - SIGMA MIN
- O - 2 TAU MAX
- (I)-INTERNAL
- (E)-EXTERNAL



ORNL TEE TEST PROGRAM
T-16 TEE (M2X)
LOAD CASE 7
INTERVAL 3

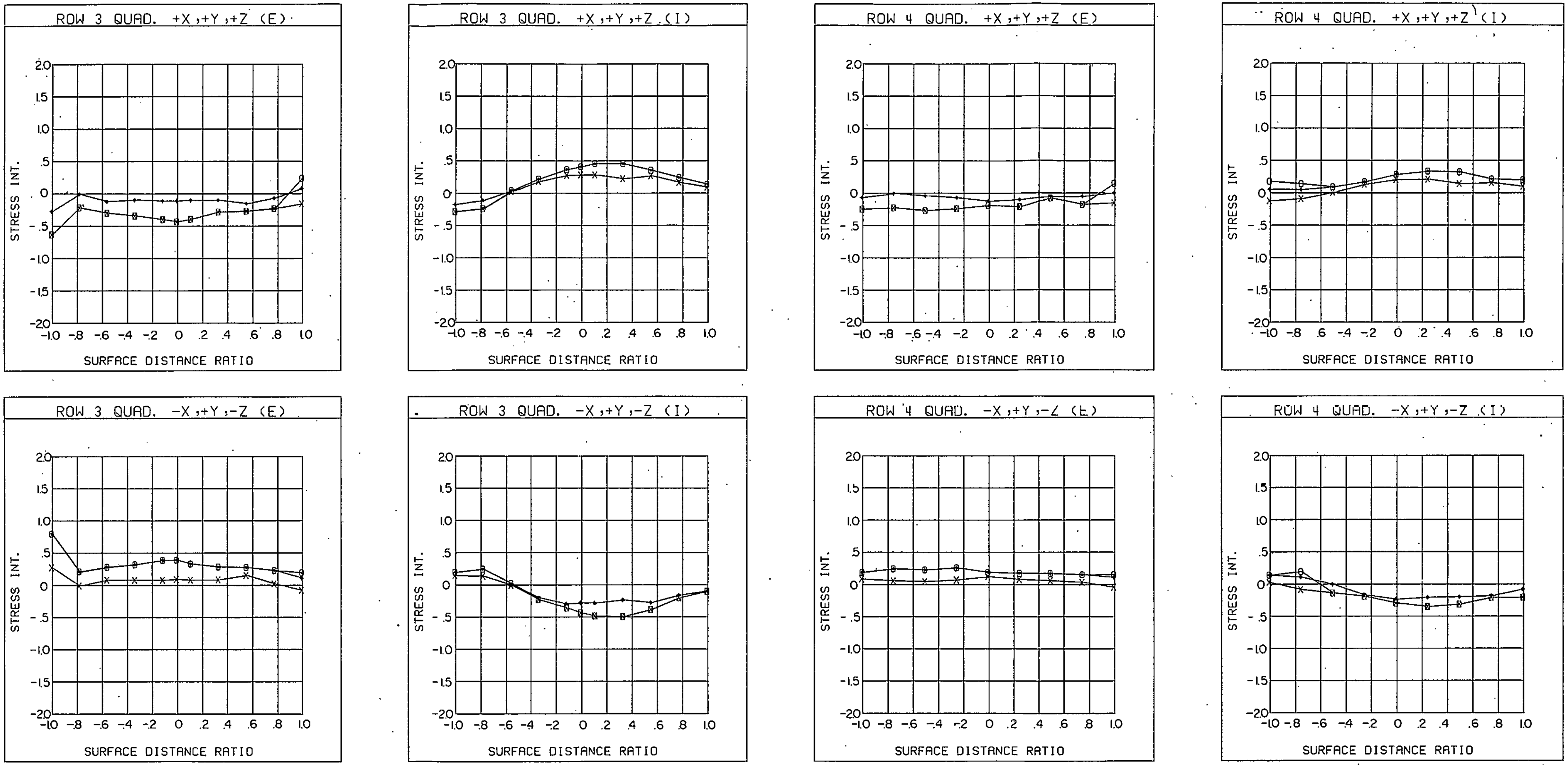
LEGEND
* - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



M2Y-ROWS 1 and 2

ORNL TEE TEST PROGRAM
T-16 TEE (M2Y)
LOAD CASE 8
INTERVAL 3

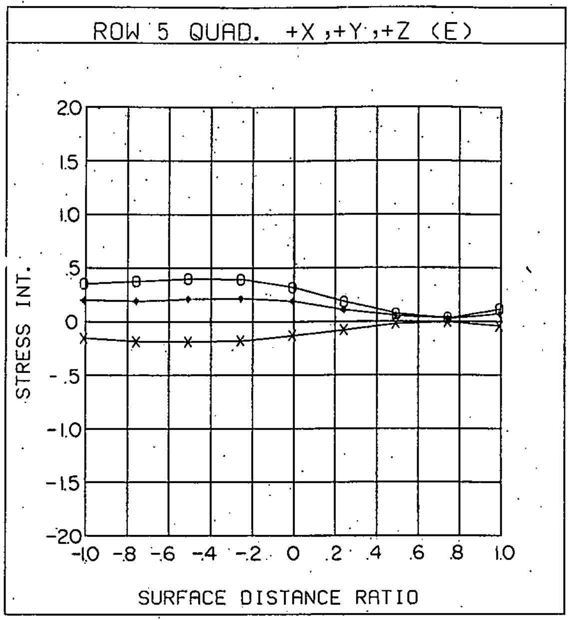
LEGEND
+ - SIGMA MAX
X SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL

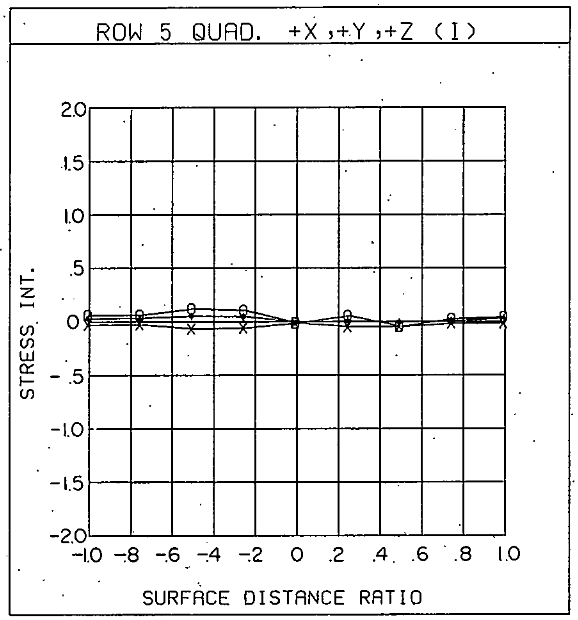


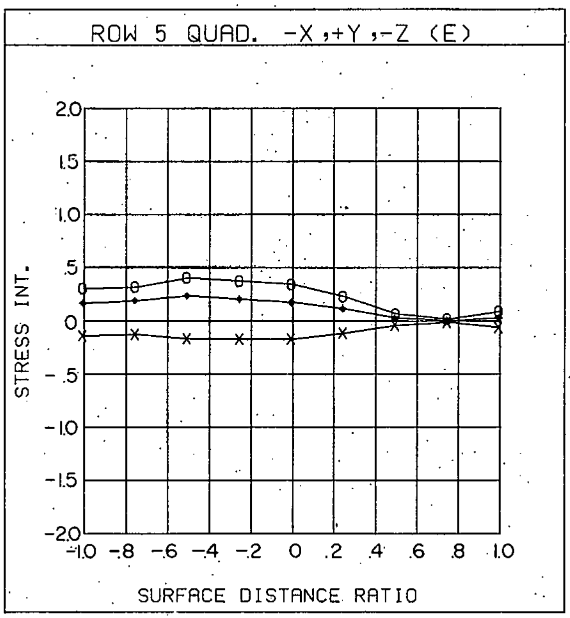
M2Y-ROWS 3 and 4

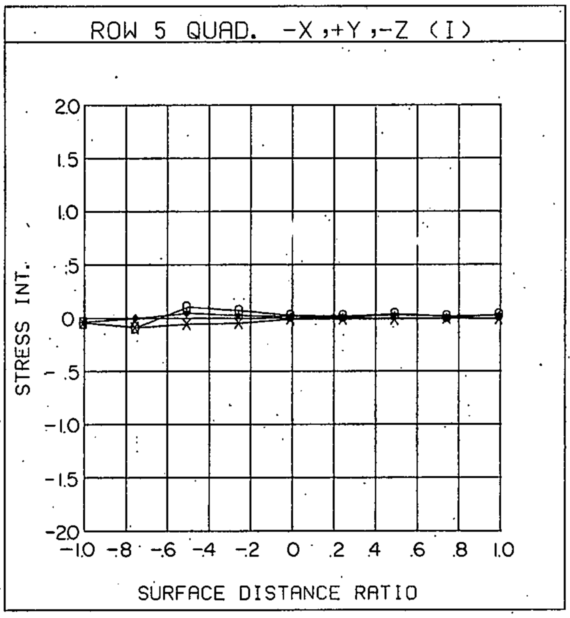
ORNL TEE TEST PROGRAM
T-16 TEE (M2Y)
LOAD CASE 8
INTERVAL 3

LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



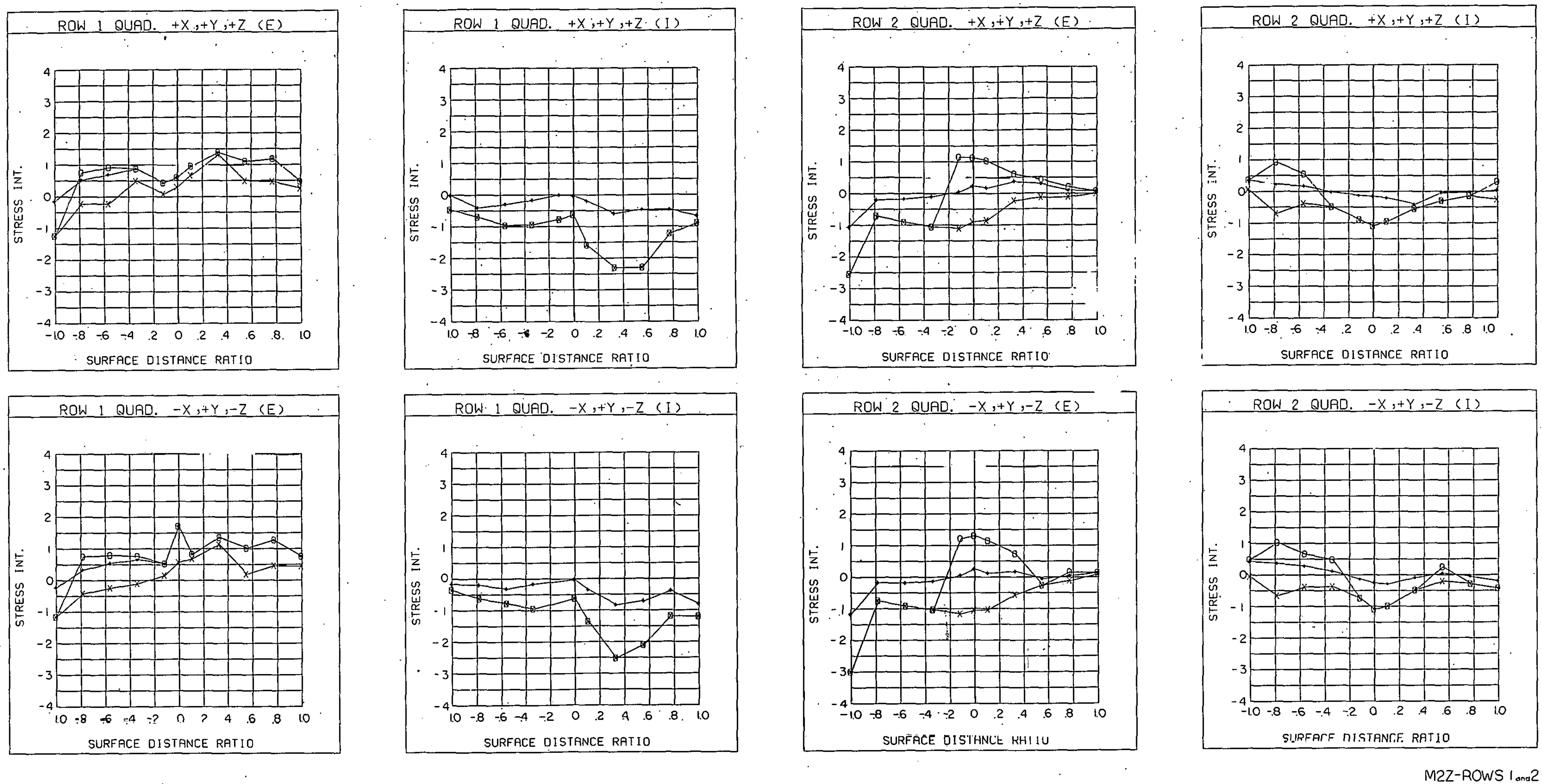






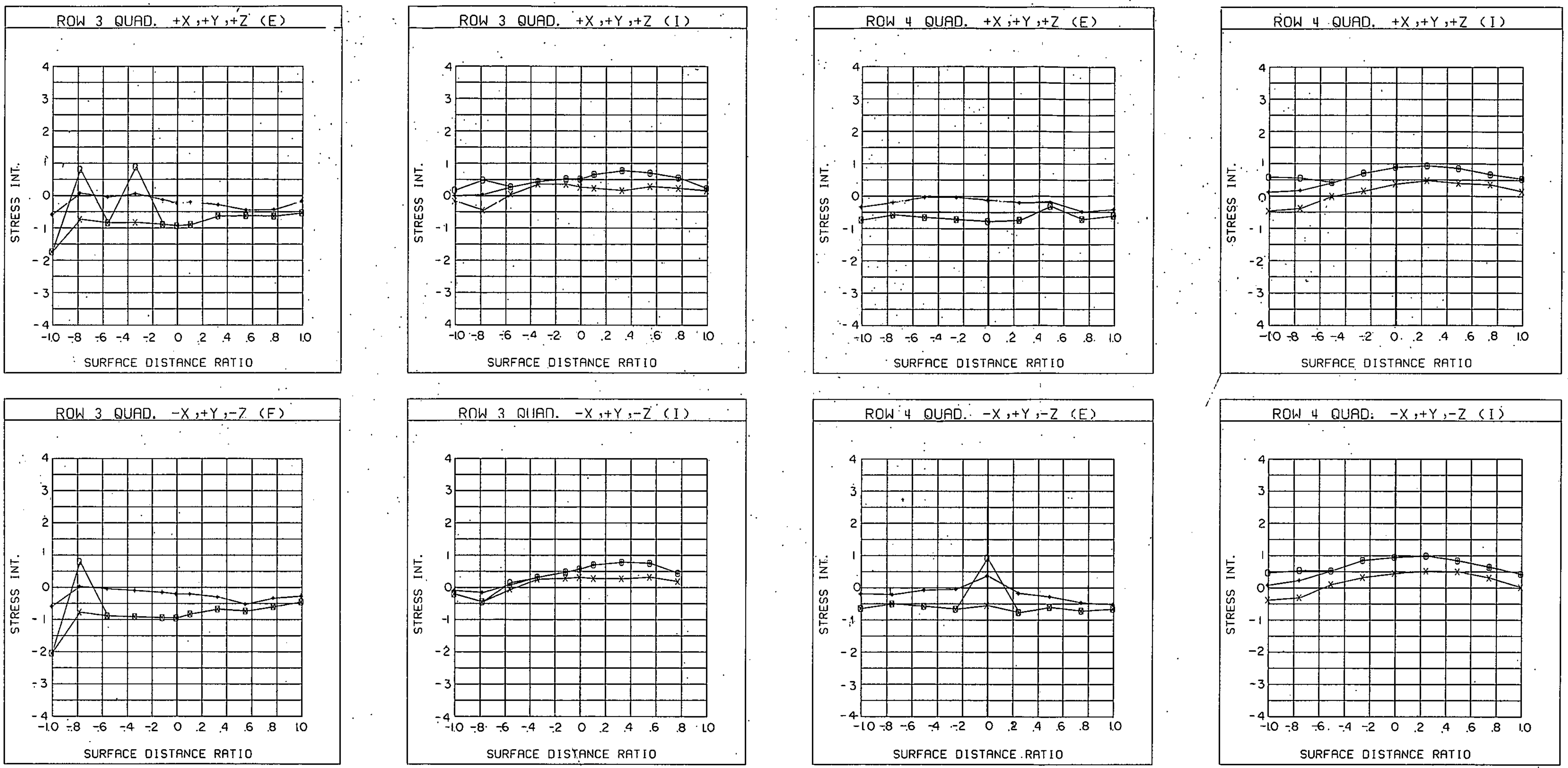
ORNL TEE TEST PROGRAM
T-16 TEE (M2Y)
LOAD CASE 8
INTERVAL 3

LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



ORNL TEE TEST PROGRAM
T-16 TEE (M2Z)
LOAD CASE 9
INTERVAL 1

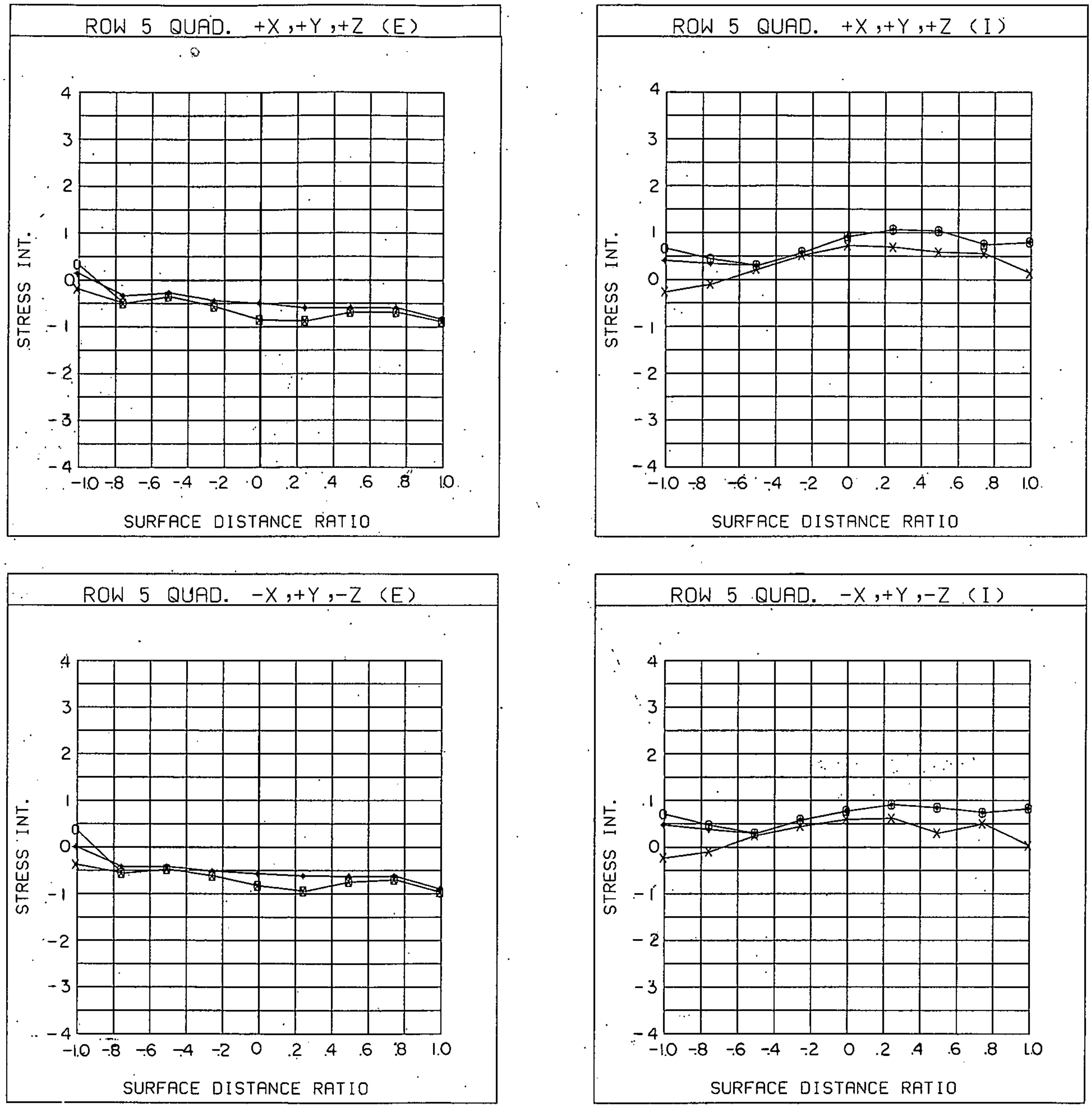
LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



M2Z-ROWS 3 and 4

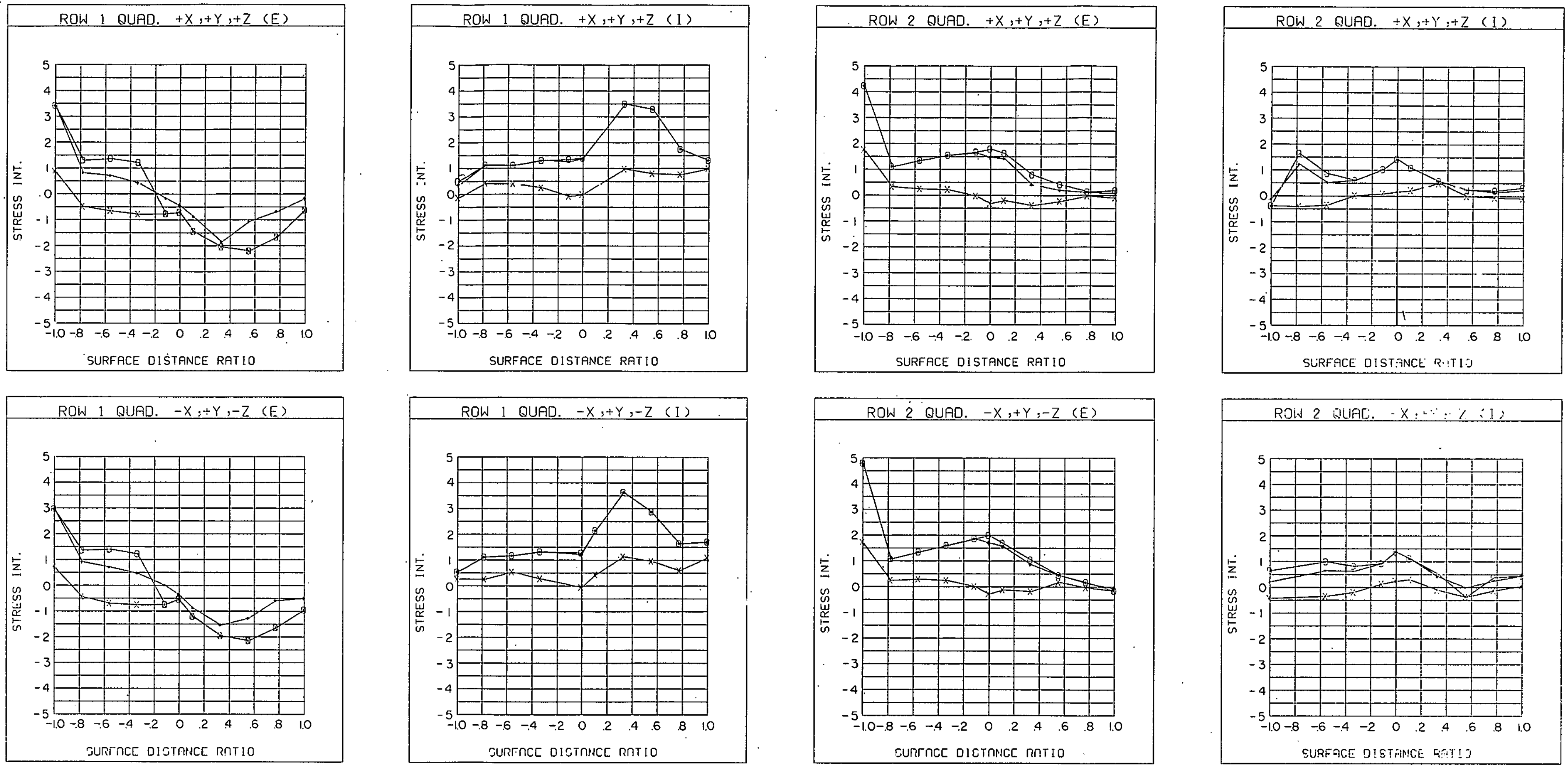
ORNL TEE TEST PROGRAM
T-16 TEE (M2Z)
LOAD CASE 9
INTERVAL 1

LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



ORNL TEE TEST PROGRAM
T-16 TEE (M2Z)
LOAD CASE 9
INTERVAL 1

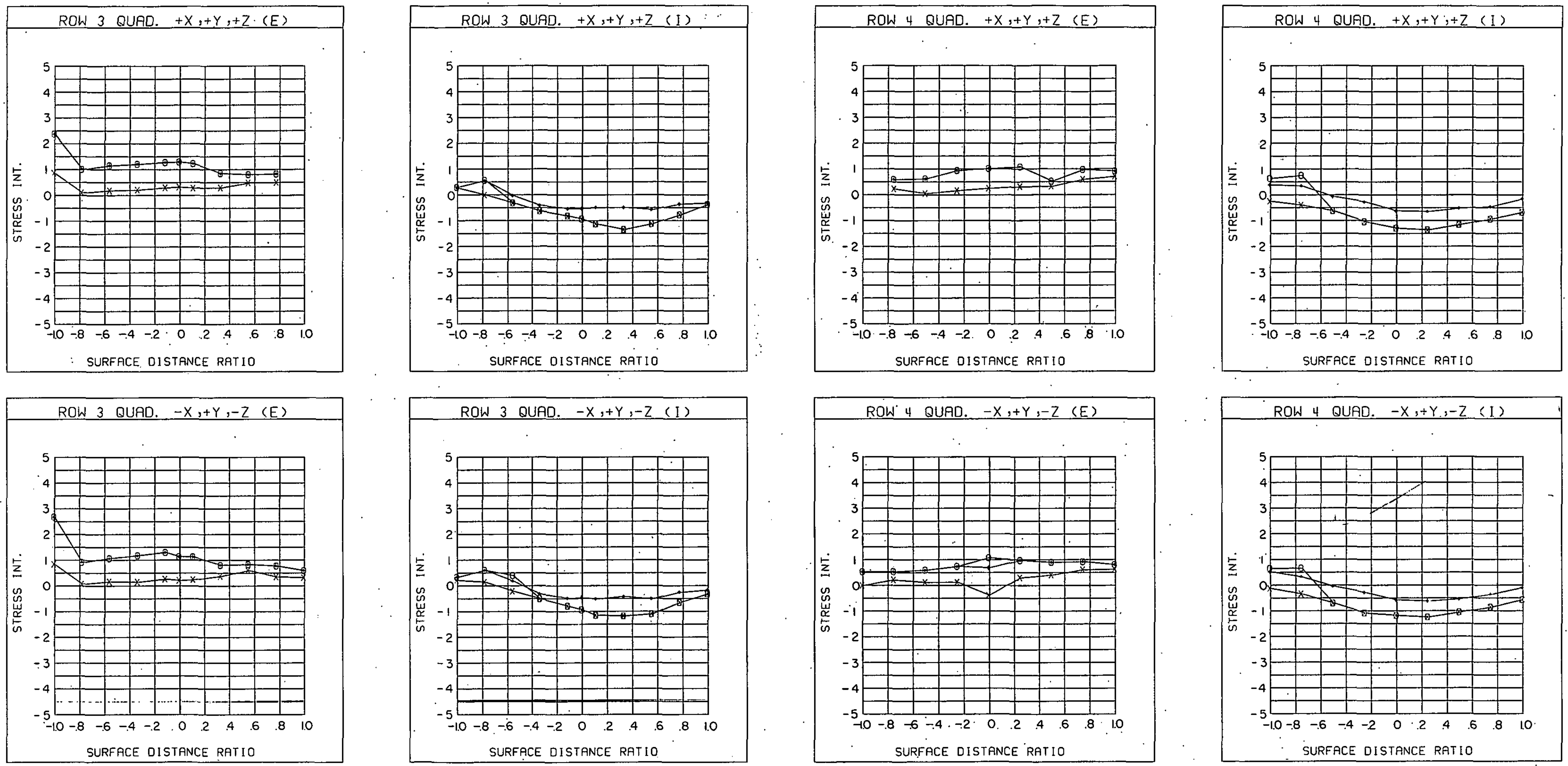
LEGEND
* - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



F2X-ROWS 1 and 2

ORNL TEE TEST PROGRAM
T-16 TEE (F2X)
LOAD CASE 10
INTERVAL 2

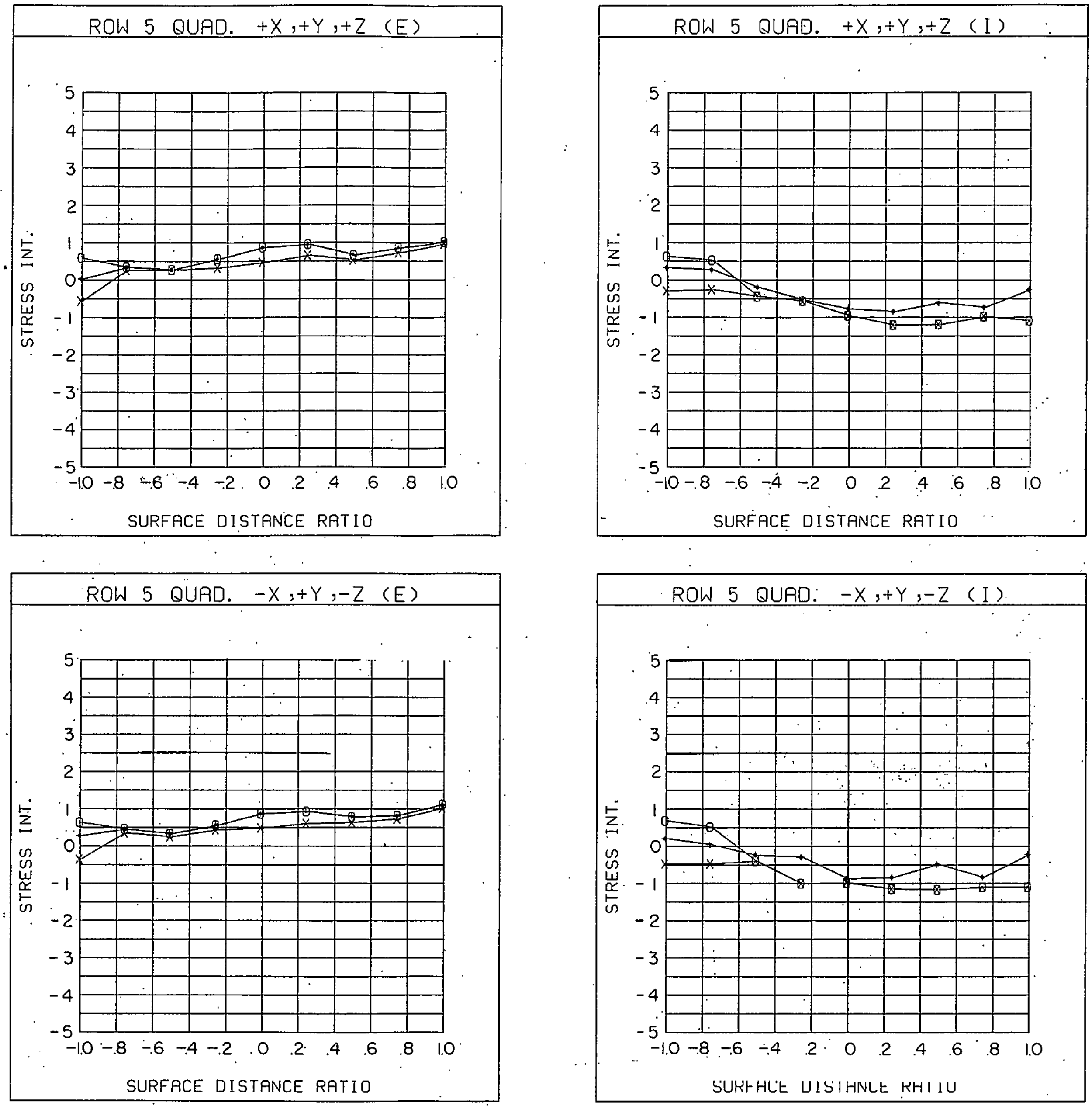
LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



F2X-ROWS 3 and 4

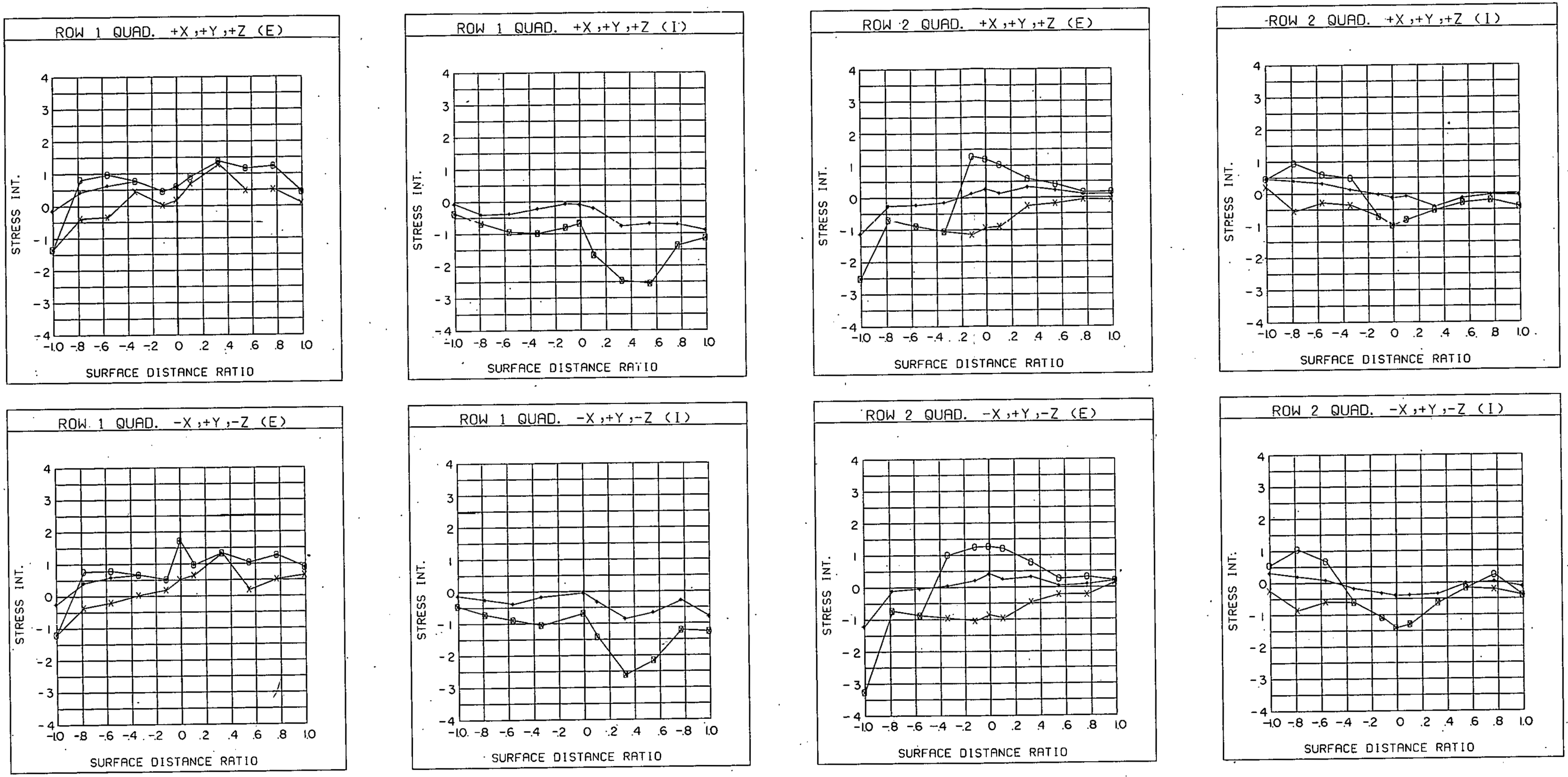
ORNL TEE TEST PROGRAM
T-16 TEE (F2X)
LOAD CASE 10
INTERVAL 2

LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



ORNL TEE TEST PROGRAM
T-16 TEE (F2X)
LOAD CASE 10
INTERVAL 2

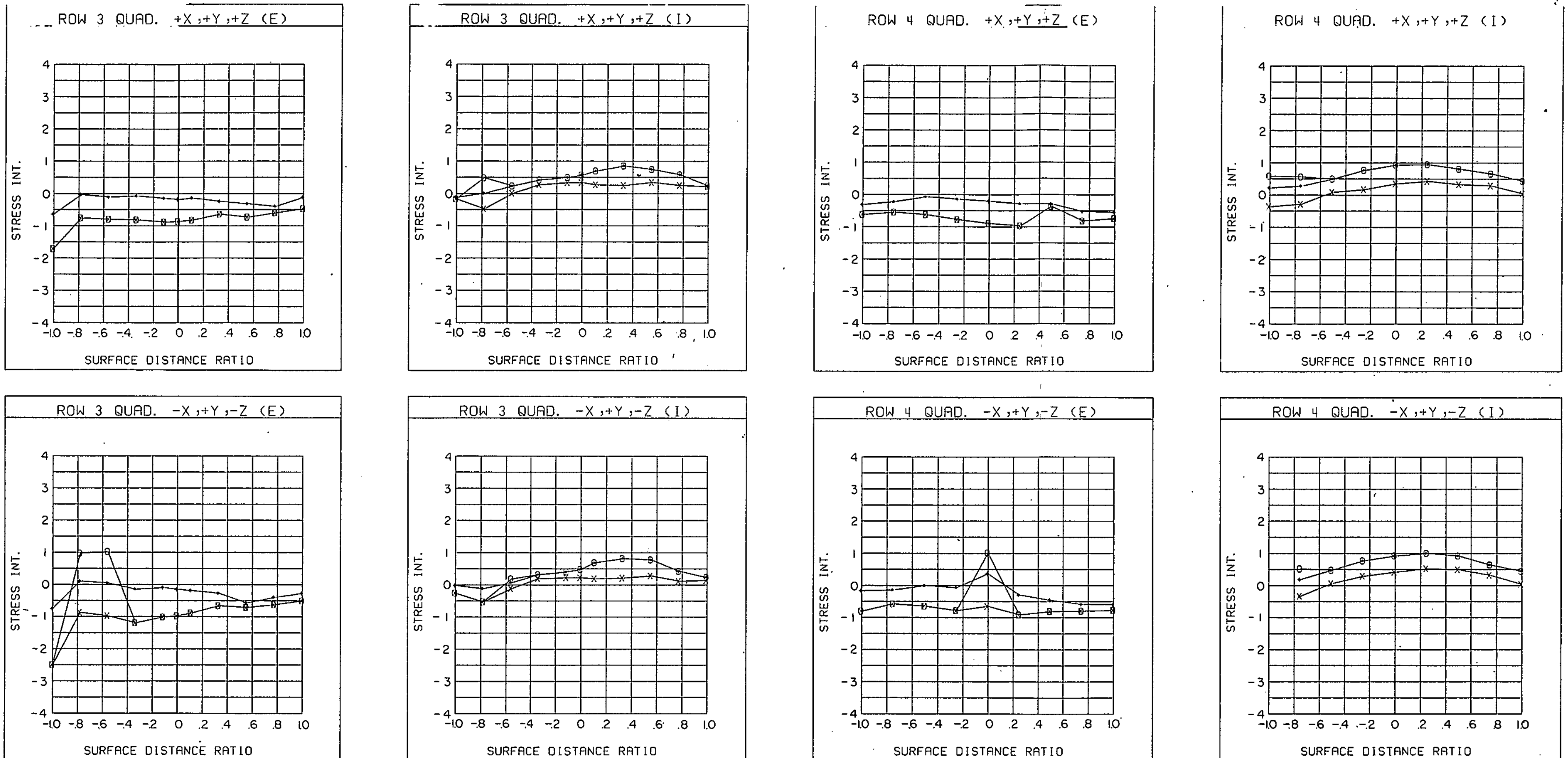
LEGEND
* - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



F2Y-ROWS 1 & 2

ORNL TEE TEST PROGRAM
T-16 TEE (F2Y)
LOAD CASE 11
INTERVAL 2

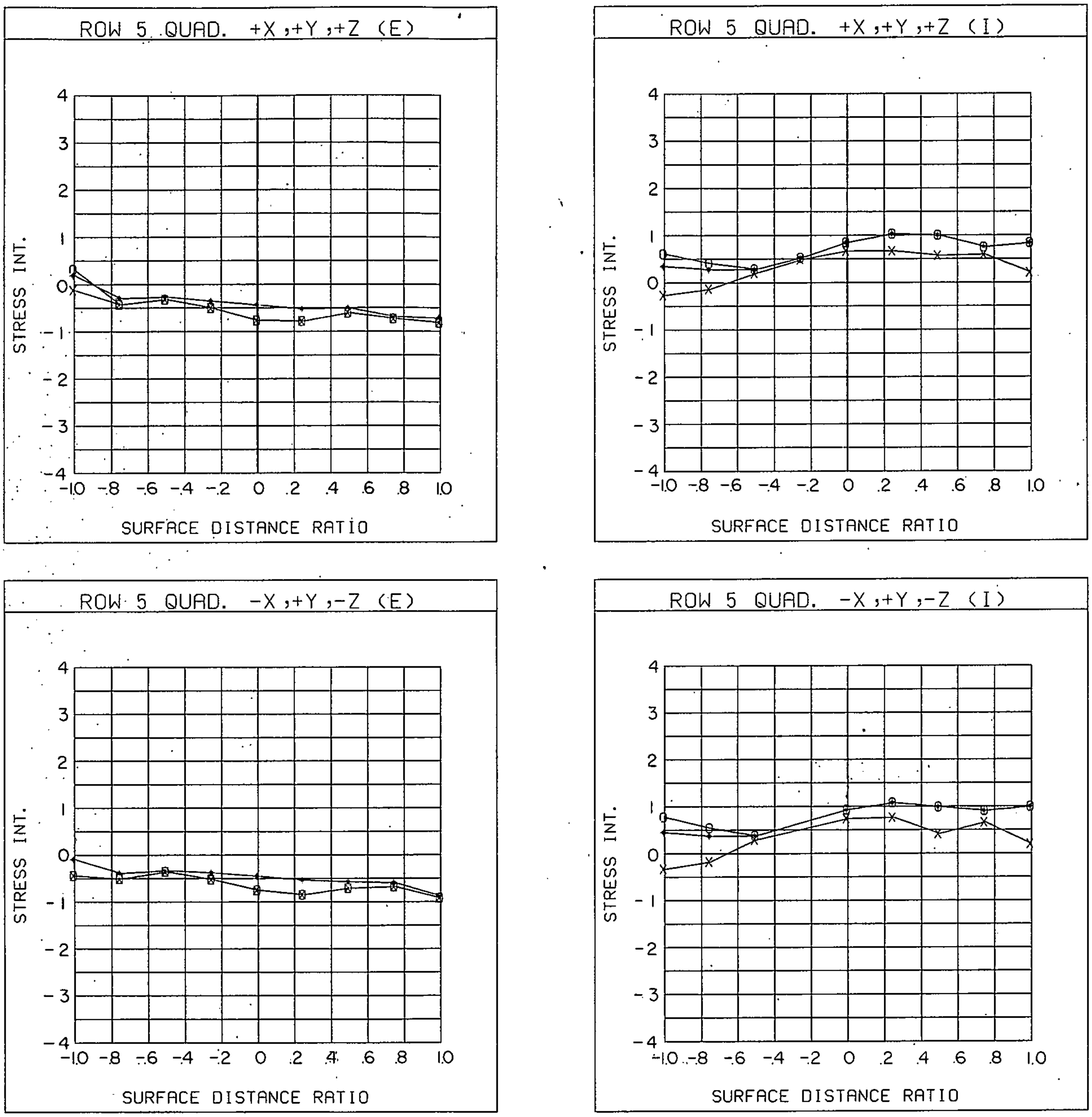
LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



F2Y-ROWS 3 and 4

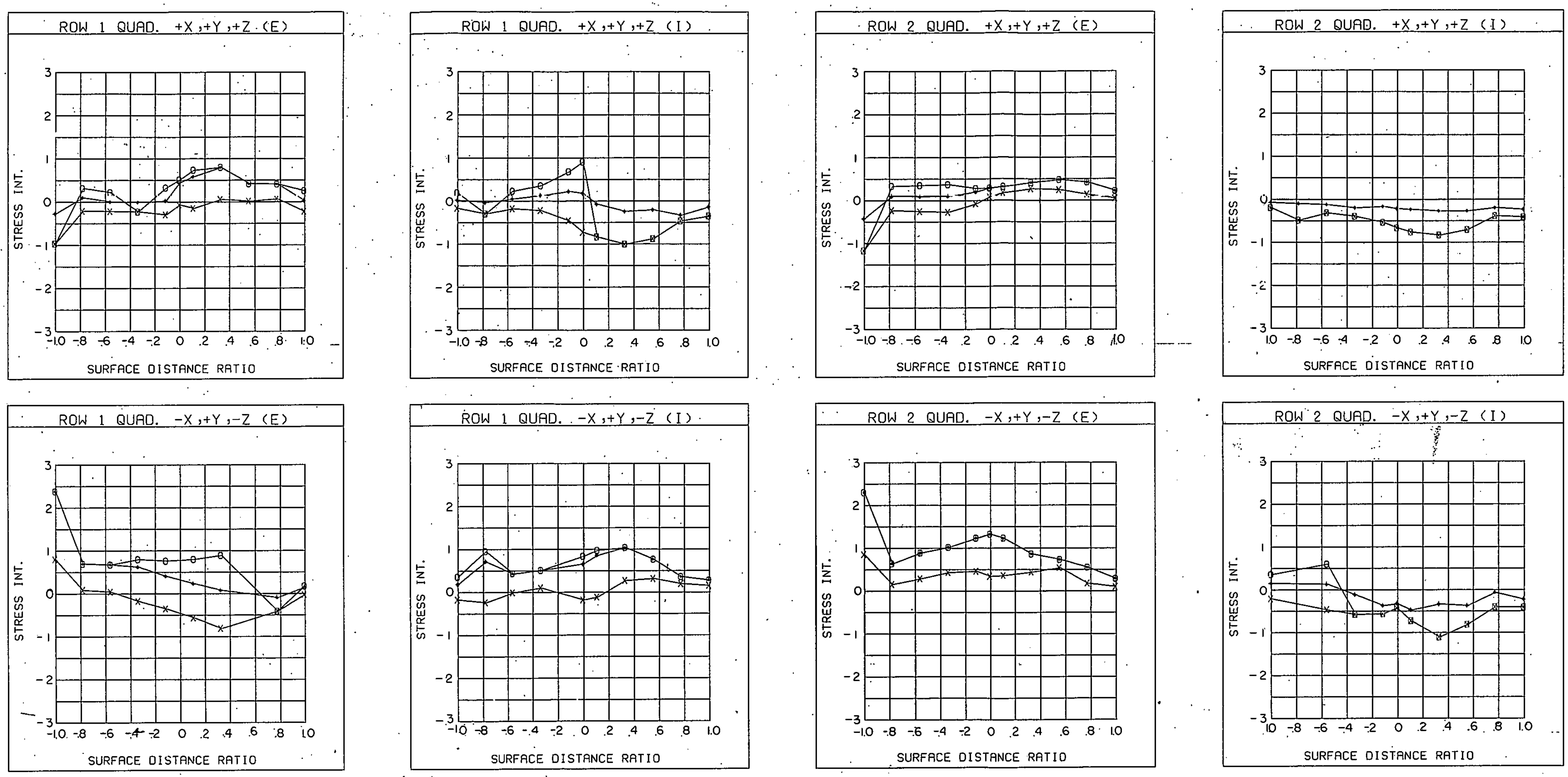
ORNL TEE TEST PROGRAM
T-16 TEE (F2Y)
LOAD CASE 11
INTERVAL 2

LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



ORNL TEE TEST PROGRAM
T-16 TEE (F2Y)
LOAD CASE 11
INTERVAL 2

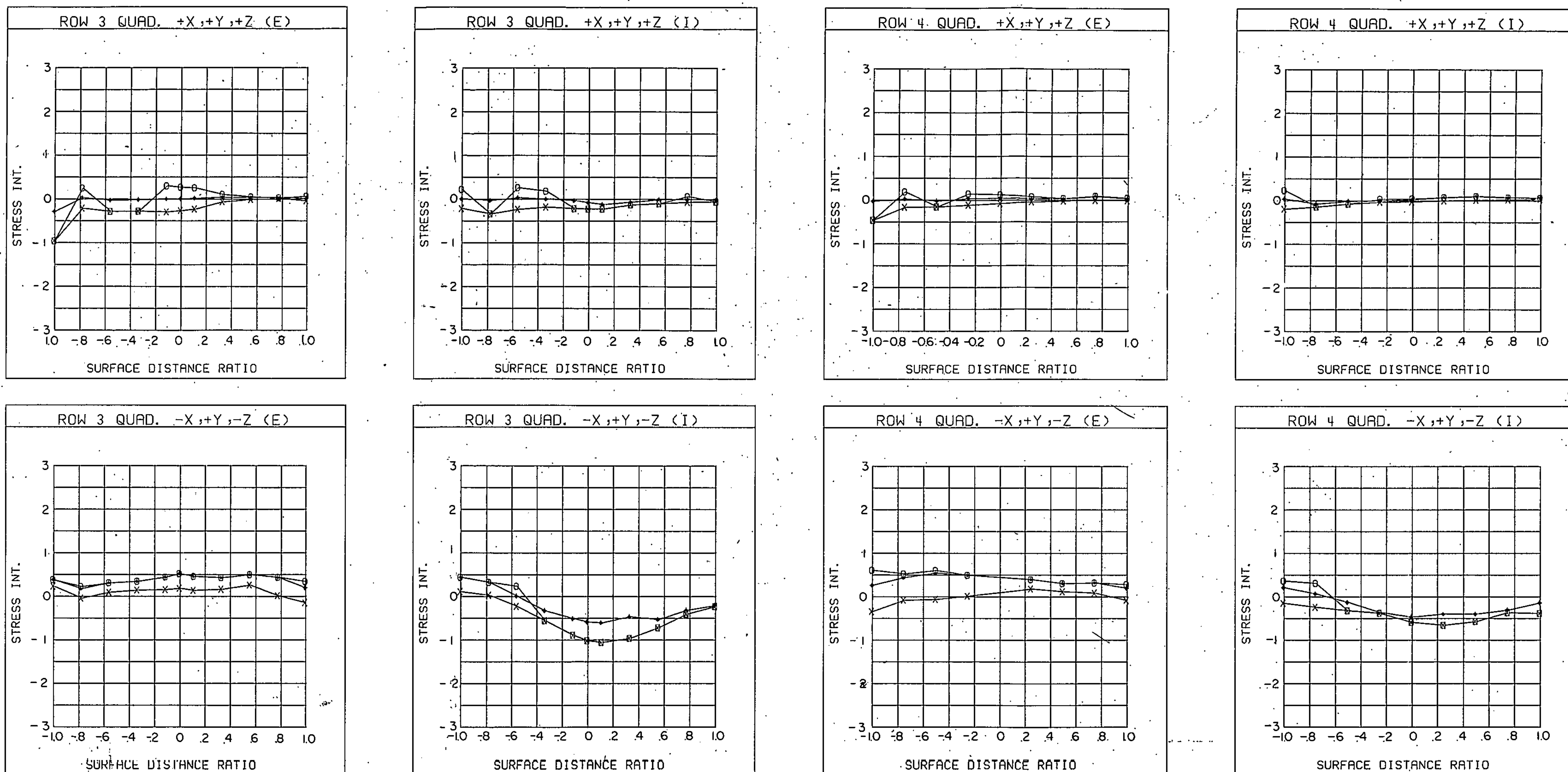
LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



F2Z-ROWS 1 and 2

ORNL TEE TEST PROGRAM
T-16 TEE (F2Z)
LOAD CASE 12
INTERVAL 3

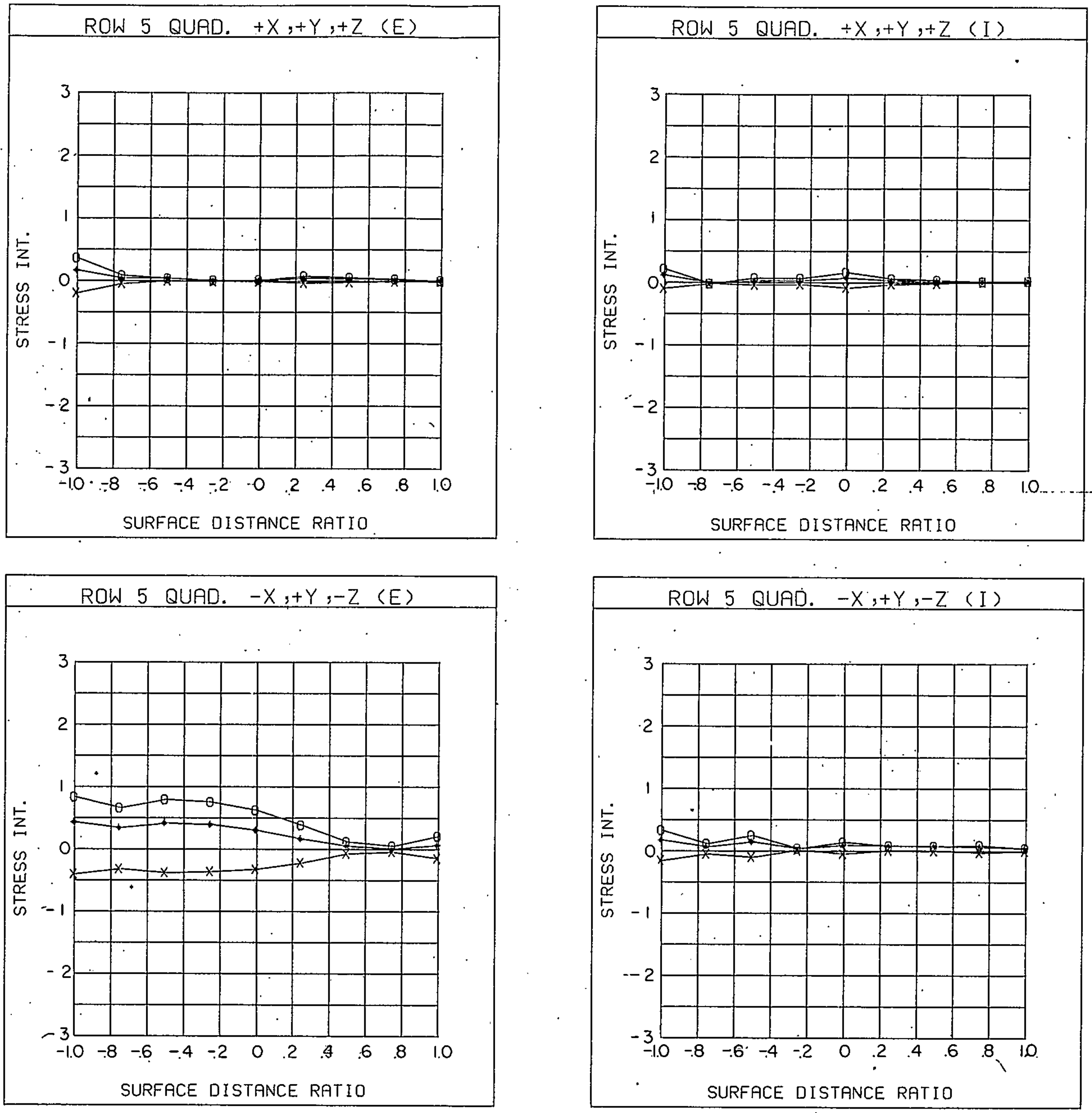
LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



F2Z-ROWS 3 and 4

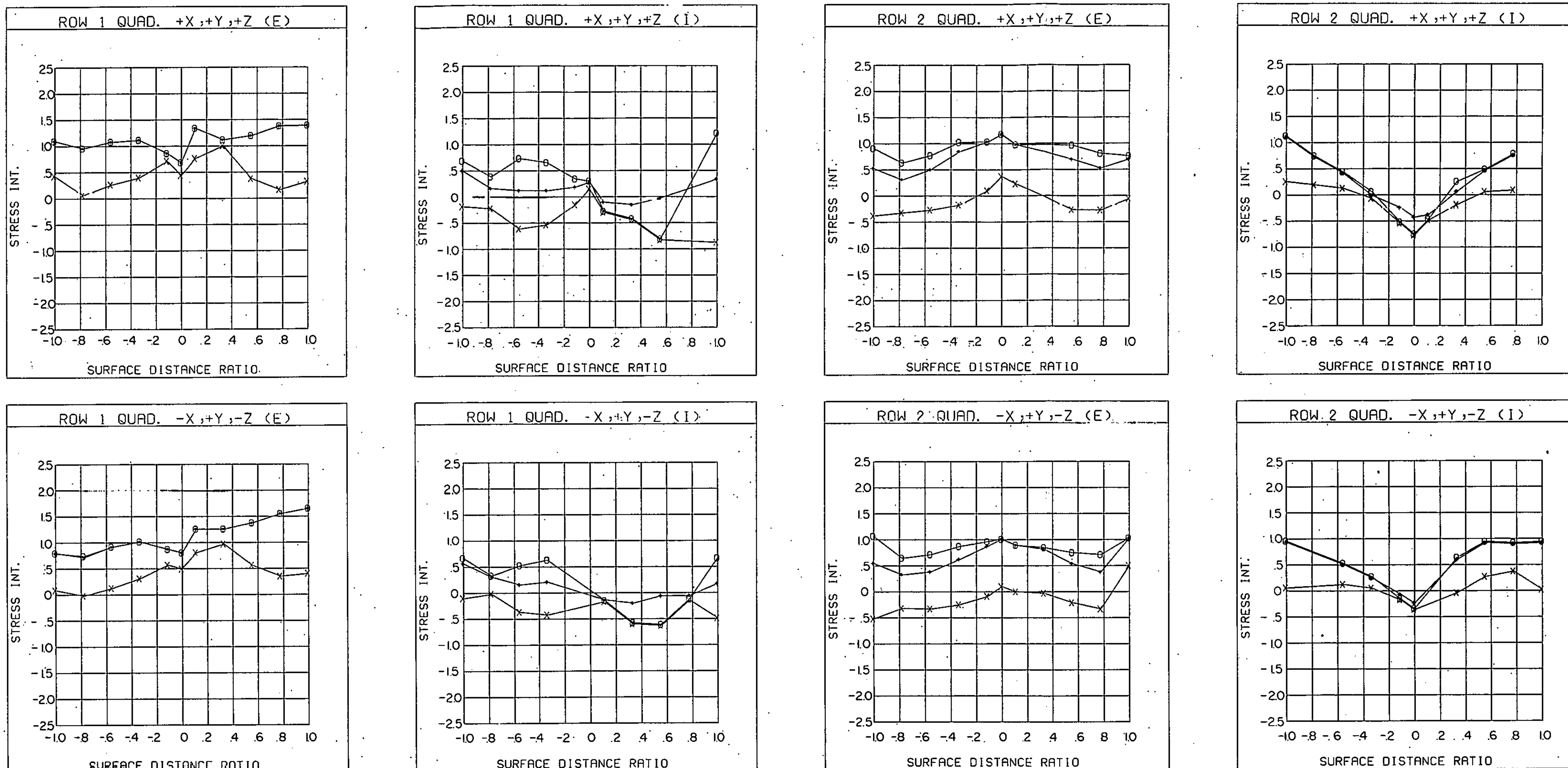
ORNL TEE TEST PROGRAM
T-16 TEE (F2Z)
LOAD CASE 12
INTERVAL 3

LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



ORNL TEE TEST PROGRAM
T-16 TEE (F2Z)
LOAD CASE 12
INTERVAL 3

LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL



P - ROWS 1 and 2

ORNL TEE TEST PROGRAM

T-16 TEE (P)

LOAD CASE 13

INTERVAL 1

LEGEND

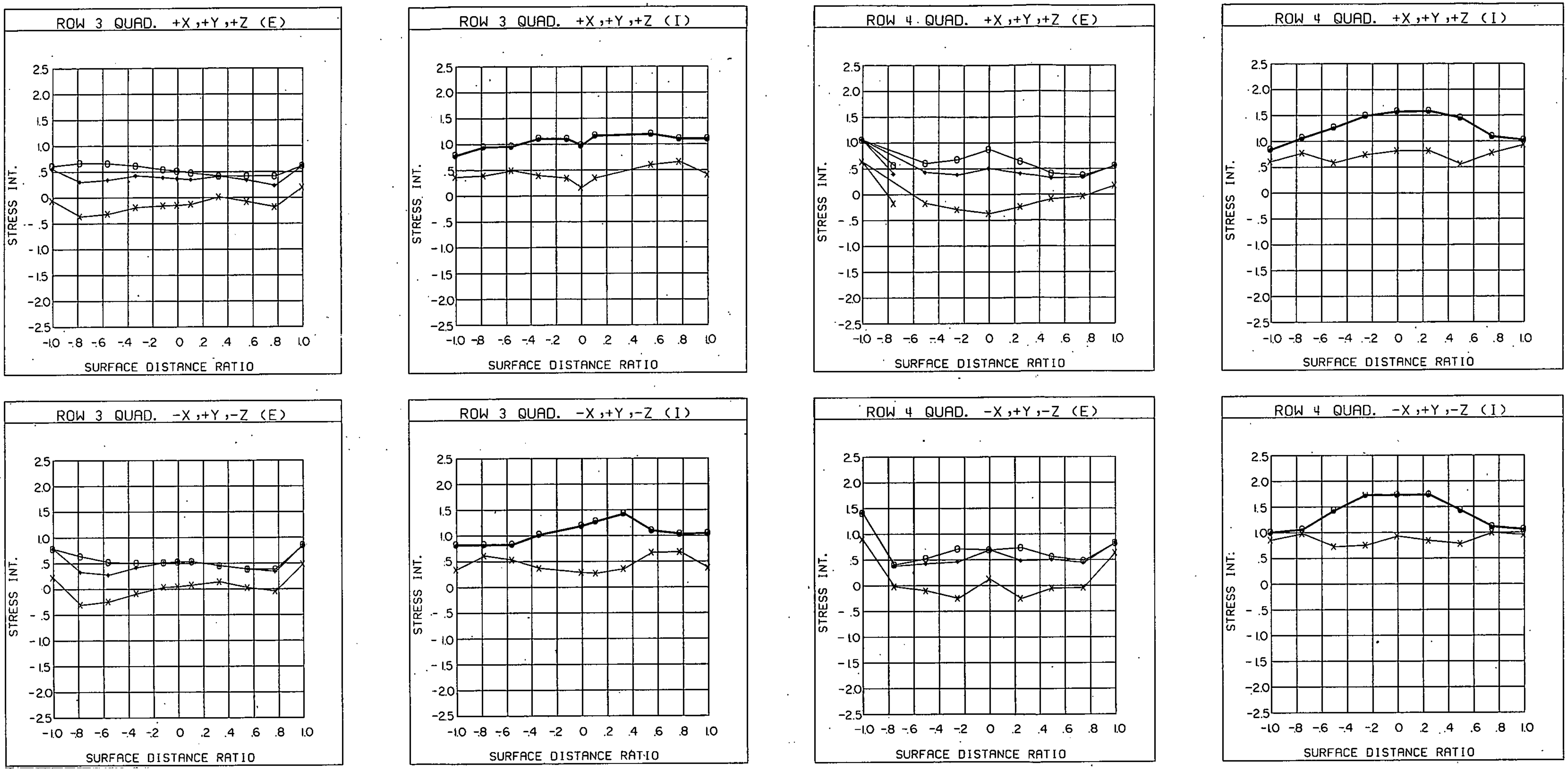
+ - SIGMA MAX

X - SIGMA MIN

O - 2 TAU MAX

(I)-INTERNAL

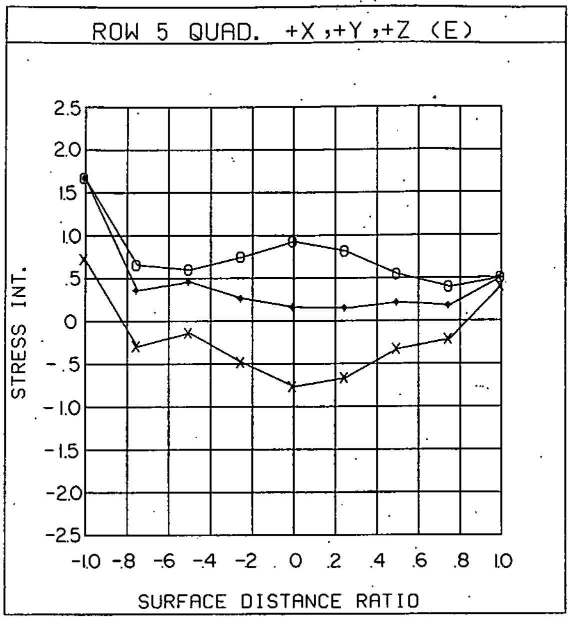
(E)-EXTERNAL

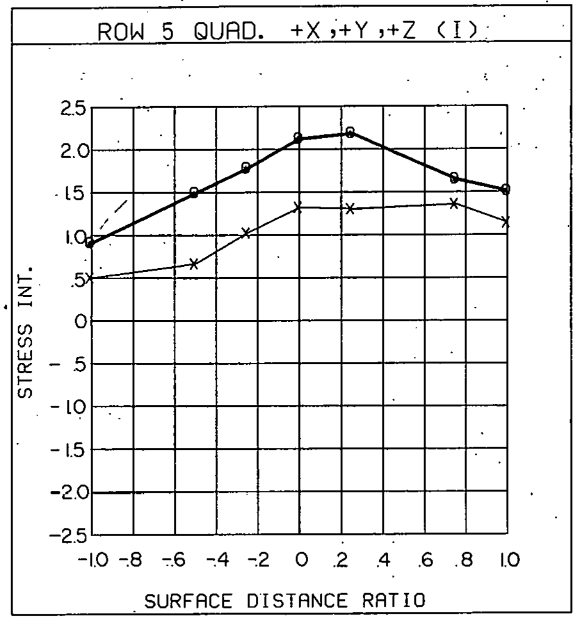


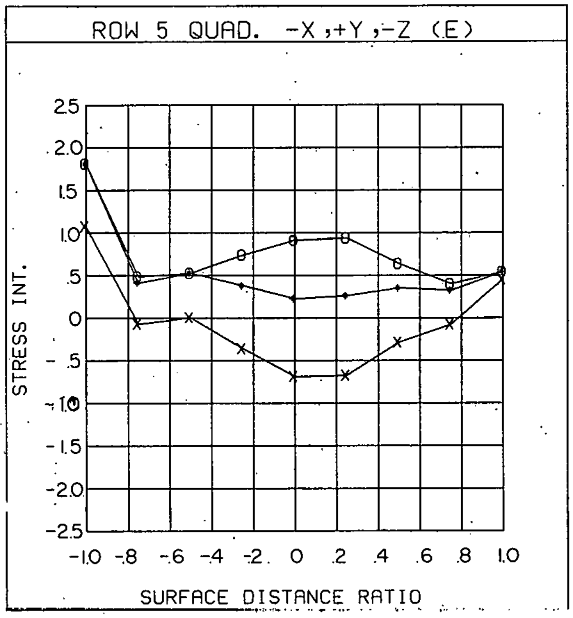
P-ROWS 3 and 4

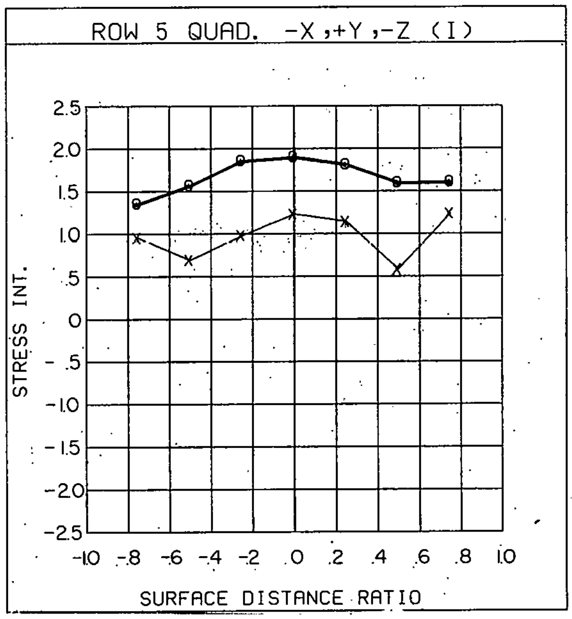
ORNL TEE TEST PROGRAM
T-16 TEE (P)
LOAD CASE 13
INTERVAL 1

LEGEND
+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL









ORNL TEE TEST PROGRAM
T-16 TEE (P)
LOAD CASE 13
INTERVAL 1

LEGEND
\+ - SIGMA MAX
X - SIGMA MIN
O - 2 TAU MAX
(I)-INTERNAL
(E)-EXTERNAL

APPENDIX C

Calculation of Fatigue Design Life

Simplified Elastic-Plastic Discontinuity Analysis for T-16 Tee Low Cycle Fatigue Test

Description: 24" X 24" X 24" Sch. 10[1] t=0.250"
Material: SA 403 W 304 L S_m = 16.7 ksi S_{ult} = 75 ksi
Loading: In-plane bending moment[2] of ±3,085,500 in-lb

Calculations Using Code Stress Indices

$C_2 = 0.67\ (R_m/t_r)^{2/3} = 8.79$ $K_2 = 1.0$

$S_n = S_p = C_2 D_o M/2I = 495{,}000$ psi

Eq. 10 of NB-3653.1 is not satisfied

$m = 1.7$ $n = 0.3$

$Ke = \frac{1}{n} = 3.33$ for $S_n \geq 3_m S_m$

$Salt = Ke\ (S_p/2) = 824{,}175$ psi

Extrapolating from the Design Fatigue Curve[3] I-9-1

$N_c = 5$

$N_t/N_c = 2344/5 = 469$

[1] This tee was ordered as a Sch 10 tee, however, the manufacture indicated that standard practice is to manufacture these tees as Sch 20 tees and then bore out the straights.

[2] Applied load after shake-down.

[3] No adjustment was made to $\overline{\sigma_{alt}}$ to account for the difference in the Modulus of Elasticity. Paragraph NB-3653.4 does not suggest any adjustment be made, however, paragraph NB-3222.4 (e-4) of the ASME Code, Section III does.

Calculations Using Experimental Values for Stress Indices

$C_2K_2 = 2.9$ (see Fig. 4) $K_2 = 1$

$S_n = S_p = C_2 D_o M/2I = 81{,}592$ psi

Eq. 10 of NB-3653.1 is not satisfied

$m = 1.7 \quad n = 0.3$

$$K = 1.0 + \frac{1-n}{n(m-1)} \quad \frac{S_n}{3S_m} \quad -1 = 3.10 \text{ for } 3S_m \angle S_n \angle 3_m S_m$$

$S_{alt} = Ke\ (S_p/2) = 126{,}500$ psi

From The Design Fatigue Curve[1] I-9-1

$N_e = 360$

$N_t/N_e = 2344/360 = 6.5$

1 No adjustment was made to σ_{alt} to account for the difference in the Modulus of Elasticity. Paragraph NB-3653.4 does not suggest any adjustment be made, however, paragraph NB-3222.4 (e-4) of the ASME Code, Section III does.