NUREG/CR-3893

Laboratory Studies: Dynamic Response of Prototypical Piping Systems

Final Report

ANCO Engineers, Inc.

Prepared for
U.S. Nuclear Regulatory Commission
and
The Electric Power Research Institute

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NUREG/CR-3893
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Manuscript Completed: June 1984
Date Published: August 1984

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NRC FIN B8907

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PREFACE

This research program was guided by and benefited from the support of: Dr. John O'Brien, U.S. Nuclear Regulatory Commission; and Drs. H.T. Tang and Y.K. Tang, Nuclear Power Division, Electric Power Research Institute. The project team at ANCC Engineers, Inc., and authors of this report were Dr. George E. Howard (Project Manager), Mr. William B. Walton and Mr. Blake A. Johnson. Very substantial support during execution of the testing reported herein was received from the following ANCO staff: Mr. Thomas J. Solimeo, Mr. R. Steve Keowen, Mr. Phil Martinez, Mr. G. Bruce Taylor, and Mr. James Avery.

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1.0 SUMMARY

The U.S. Nuclear Regulatory Commission and the Electric Power Research Institute have jointly sponsored a piping research program involving the design, analysis, fabrication, erection, and dynamic testing of prototypical piping systems. Objectives of the research included the following:

1. to expand the limited data base on damping in piping systems at response levels at the Operating Basis Earthquake (OBE) stress limit and up to the Safe Shutdown Earthquake (SSE) stress limit;
2. to stimulate recognition of safety margins implicit in ASME Boiler and Pressure Vessel Code rules for Class 2 and 3 piping by demonstrating the existence of large design margins in piping and support systems when subject to seismic loads much greater than those acceptable according to ASME Code; and
3. to obtain a data base for benchmarking computer methods for analysis of pressurized piping systems for varying support conditions and at response levels both below and above pipe yielding.

Two test configurations were used to achieve the project objectives. One was a three-dimensional layout of six-inch and eight-inch diameter pipe without branch lines. The second was a similar but shorter pipe run with two branch lines of three-inch diameter. All lines were water filled and pressurized to 1,150 psig at room temperature and subjected to simultaneous dynamic inputs through the supports. Very limited tests were conducted on the second configuration with one branch removed after the completion of all other tests. A total of 101 tests were conducted and included variations in support conditions, load magnitude, load direction, and load wave form.

This report presents details of the test methods, test specimens, and a preliminary assessment of results. Detailed data analysis will be conducted and reported separately. Important preliminary observations include the following:

1. at response levels below the Level D (e.g., Safe Shutdown Earthquake) peak stress condition, log decrement piping damping (based on the first two or three cycles of oscillation) appeared to vary from 2% to 4% of critical;

2. at about the Level D pipe stress condition, the damping for the configuration with mechanical snubbers was about 5%—further evaluation is needed, however, to validate this value since it is derived from difficult-to-evaluate data;

3. for the all-strut support configuration at about the Level D pipe stress condition, damping was approximately 3%;

4. the piping systems sustained no apparent damage from earthquake load testing, despite the imposition of seismic inputs which were approximately four times the input required to just achieve the Level D stress limit in the Class 2 piping system; and

5. One of the two test piping systems successfully withstood the equivalent of 5 OBEs (Operating Basis Earthquakes), 9 SSEs (Safe Shutdown Earthquakes) as well as nearly 30 severe shock tests.

2.0 TEST APPROACH AND CONFIGURATIONS

As a continuation of an earlier EPRI-sponsored, laboratory-based piping dynamic test program conducted at ANCO Engineers, Inc., (ANCO), a joint NRC/EPRI program was initiated in December, 1982, to conduct dynamic tests of prototypical nuclear piping systems with response levels above their design limits. In contrast to the earlier EPRI program [1] which was performed on a simple two-elbow, 4-in. diameter piping run (generally referred [2] to as "Z-bend pipe"), the NRC/EPRI joint effort focused on testing of more complex three-dimensional, multi-bend, multi-supported configurations. The objectives of this research effort were threefold:

1. to expand the limited controlled data base on damping in piping systems at response levels at and well above Operating Basis Earthquake (OBE) stress conditions;
2. to stimulate recognition of safety margins implicit in ASME code rules for Class 2 or 3 piping by demonstrating the existence of large design margins in piping and support systems when subjected to seismic loads producing response well above the Safe Shutdown Earthquake (SSE) stress limit; and
3. to obtain a data base for benchmarking computer methods for analysis of pressurized piping systems with representative supports and for response levels below and above pipe yielding.

The test scope included design, analysis, fabrication, erection, and dynamic testing of two moderate-size nuclear piping systems, one without branch lines, and the second with two branch lines.

The ultimate goal of this test program was to provide a controlled data base to support more realistic design and licensing evaluation of nuclear power piping systems. Test results will be disseminated to organizations such as the Pressure Vessel Research Committee (PVRC) as supporting material for possible Code revision considerations.

The tests described herein were conducted at ANCO's test facility in Culver City, California. The test setup consisted of a reinforced concrete foundation with U-shaped, 2-ft thick strong walls and concrete pedestals rising 5 ft to 9 ft above the foundation mat. The tested piping systems were attached to the walls and foundation mat at selected support locations through support hardware mounted on specially designed bases (support sleds). Dynamic forces were applied to the piping supports through the motion of the bases driven by hydraulic actuators.

The hydraulic actuation system was upgraded to a total load capacity exceeding 50,000 lb, capable of driving a multi-supported piping system to an upper bound load level three or four times higher than its design limits (Level D, $2.4S_h$ or 36 ksi in this case), depending on the number of supports. The high-flow servo valves of each hydraulic actuator allowed a maximum displacement of ± 3 in. and a maximum velocity of 90 in./sec. The maximum acceleration achievable at each support depended on the number of supports in the system and the mass of the assembly.

The support sleds were designed in such a way that they could be rotated 90° horizontally between tests so that the support excitation could be applied in two directions.

The piping systems tested were three-dimensional--that is, the straight pipe sections ran in three orthogonal directions. The piping supports consisted of struts, mechanical shock arresters, and hydraulic shock arresters. The pipelines were supported at several locations by the support sleds. The snubber (shock arrester) and strut supports were distributed along the length of the pipelines.

The piping systems were extensively instrumented to measure acceleration, displacement, strain, force, and internal pressure. The recording of the data was accomplished using a computer-based data acquisition system.

The methods of testing consisted of: (1) impulse--a sudden, uniform change in the position of the support sleds from one constant value to another; (2) sine dwell with a concentrated force--steady-state forced harmonic response; (3) earthquake--input of uniform base motion that was representative of an earthquake. The excitation levels ranged from those inducing stresses below Level B to well above Level D. (i.e., below OBE to above SSE conditions).

2.1 Piping Systems Tested

Two different piping systems were designed, fabricated, and tested. For a given pipeline, the system to be described consisted of the pipeline, end and mid-point supports, bases used to mount and move the pipeline, and the hydraulic actuator system used to move (drive) the bases. Both systems, and a variation in one of them, will be described herein.

2.1.1 Main Pipeline Without Branch Lines

The first piping system to be tested was a single run of A106B carbon steel (no branch lines) about 70 ft. long. It is shown in Figure 2.1. Six-inch Schedule 40 and eight-inch Schedule 40 piping was employed, with the larger diameter pipe located at the ends of the pipe run. This was done in an attempt to keep the ends of the pipeline from being the highest stressed points in the system. There was more interest in having the largest stresses occur in the pipe elbows rather than at the ends of the pipeline. The 6-in. and 8-in. pipe were joined together using standard 6 x 8 reducers. The pipe elbows were 90° long radius elbows. The pipe ends were terminated using welding neck flanges. A description of the pipe sizes and pipe components is given in Table 2.1.

The materials used for the pipeline were ASTM* materials. The material properties for the pipe and pipe components are given in Table 2.2. While it was originally the intent of this program to use Class 2 nuclear grade piping systems, delivery and cost problems with ASME materials were too limiting. With sponsor approval, ASTM materials were used to fabricate the

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* ASTM refers to American Society of Testing Materials

TABLE 2.1: SIZE OF PIPE AND COMPONENTS

Item	Description
6-in. Schedule 40 Pipe	6.625 in. OD* 0.280 in. WT**
8-in. Schedule 40 pipe	8.625 in. OD 0.322 in. WT
6-in. Schedule 40 90° long radius elbow	9-in. radius of curvature ANSI B 16.9
8-in. Schedule 40 90° long radius elbow	12-in. radius of curvature ANSI B 16.9
8-x-6 concentric reducer	Transition for 8-in./6-in. Schedule 40 pipe, ANSI B 16.9
Welding neck flange for pipeline ends	Class 600 flange ANSI B 16.5

* OD refers to the outside diameter.

** WT refers to the wall thickness.

TABLE 2.2: MATERIAL PROPERTIES FOR PIPE AND COMPONENTS

Item	Heat Number	Yield Point (psi)	Ultimate Strength (psi)	Percent Elongation	Material
6-in. Sch. 40 pipe	67270	52,260	78,097	32	SA-106 Grade B
8-in. Sch. 40 pipe	93232	49,700	77,300	40	ASTM A-106-B-80
6-in. 90° elbow	W9255	53,290	84,380	37.5	SA-234 WPB
8-in. 90° elbow	W9487	37,900	79,500	36	SA-234 WPB
8-x-6 reducer	L21400	51,300	74,400	37	ASTM A-234 WPB
Class 600 flange	ETCT	54,230	79,605	28	ASTM A-105

pipeline. However, the pipeline parts (pipe and components) were aligned and welded according to the specifications in the ASME code; the welding material used was ASTM material. All welds were radiographed and inspected by the fabricator and certified by the fabricator to be acceptable according to the ASME code.*

A simulated valve was installed in the pipeline. The main body of the valve was made of hot finished steel tubing and was welded to the test pipe according to the ASME Code.

The ends of the pipeline were closed by welding 1-in. thick circular steel plates into the inside of the welding neck flanges. A threaded hole was made in both plates. The holes were closed with bolts to contain the water in the pipeline (all tests were performed with water in the pipeline). To be able to fill the pipeline with water and remove all air in the pipe, two drain holes were inserted in the pipeline using Thread-o-Lets.**

The pipeline was supported at its two ends (Locations S1 and S4) and at two other points (Locations S2 and S3). These locations are shown in Figure 2.1. At Locations S1 and S4, the pipe was clamped to the base. "Clamped,"

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* The assembly welding was performed according to the specifications in Sections III and IX of the "ASME Boiler and Pressure Vessel Code." The 1974 edition of the Code, together with all addenda through the Summer of 1975, was used. The pipeline was fabricated by Pullman Power Products Corporation (Piping Fabrication), 14807 South Paramount Blvd., Paramount, CA 90723.

** This is the trade mark name for a device used to very securely close a hole (for draining) in a pipeline. It is secured in the pipe hole using extensive welding. The wall thickness of the Thread-O-Let, at its base, is about twice that of the pipe.

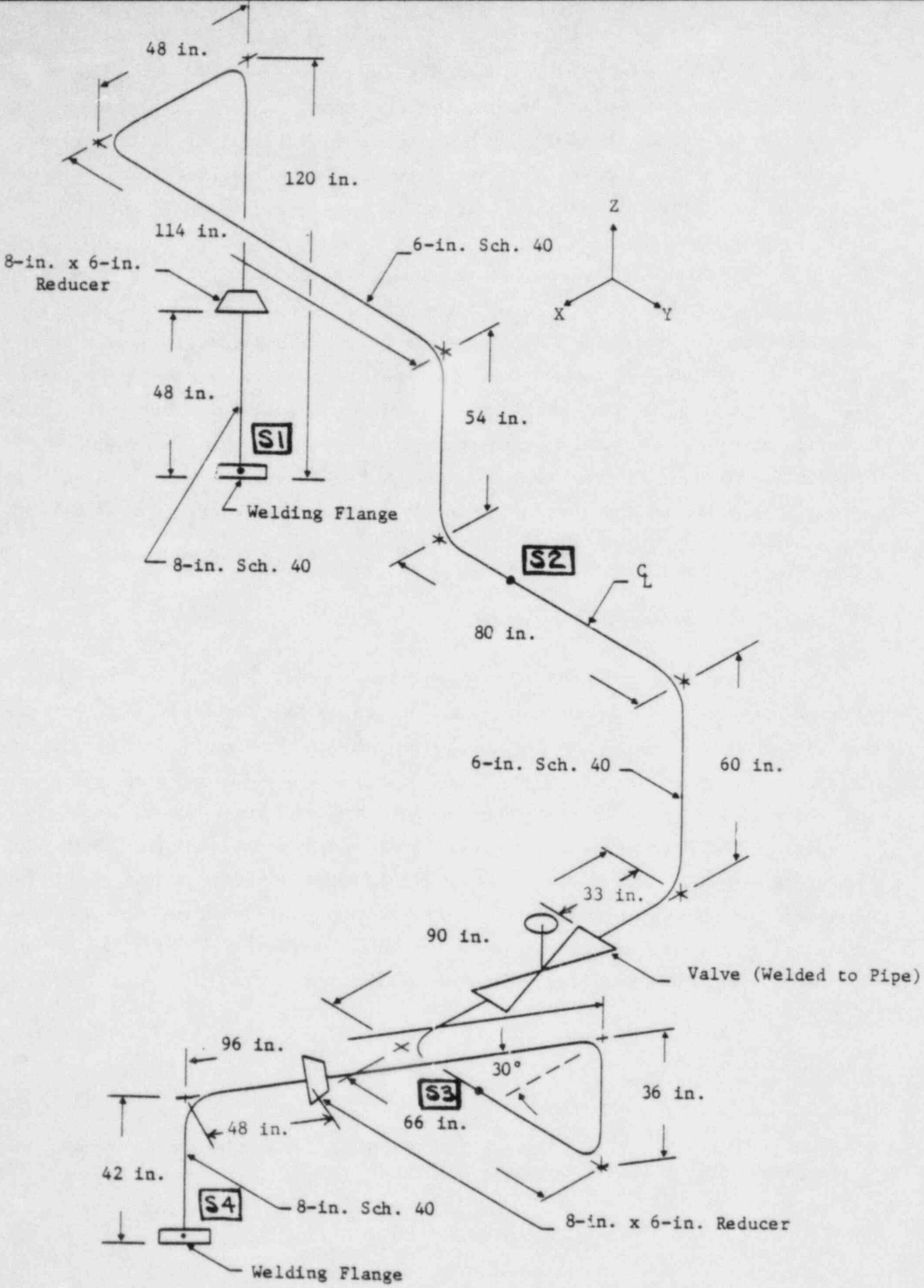

Figure 2.1: As-built Dimensions for Pipeline Without Branch Lines

as used here, refers to all six degrees-of-freedom of the pipe being restrained relative to the base. The attachment of the pipe ends to the bases (sleds) was accomplished by bolting the pipe flanges to mating flanges on the bases using twelve 1.125 in. diameter Grade 8 bolts.* Each bolt was given an initial torque (during tightening) of about 200 ft-lbf.

The pipeline was supported at Locations S2 and S3 using strut- or snubber-type supports. At both these locations, the pipe was always supported by a vertical strut. There was always a horizontal support in the global X-direction at these two support points. All supports were attached to the pipeline at one end, and to the bases at the other end. The horizontal supports varied from being struts to mechanical snubbers to hydraulic snubbers. Gaps associated with the horizontal struts were also used. The bases at the two "mid-points" are described later in this section.

2.1.1.1 Bases for Pipeline Ends

With the ends of the pipeline clamped to the bases, large forces/moments could be exerted on the bases by the pipeline. This was an essential consideration in designing the bases. It was also important to minimize the mass of the bases. Thus, a plate and rib design approach was selected. Figure 2.2 illustrates one of the end bases (both bases were identical). The essential features of a base consist of: (1) a carriage structure made of plates and containing two hardened steel raceways for the bearings to ride upon; (2) four bearing structures, each containing three bearings riding on the raceways attached to the carriage; (3) a steel plate, to which the four bearing-containing structures are attached, and (4) a

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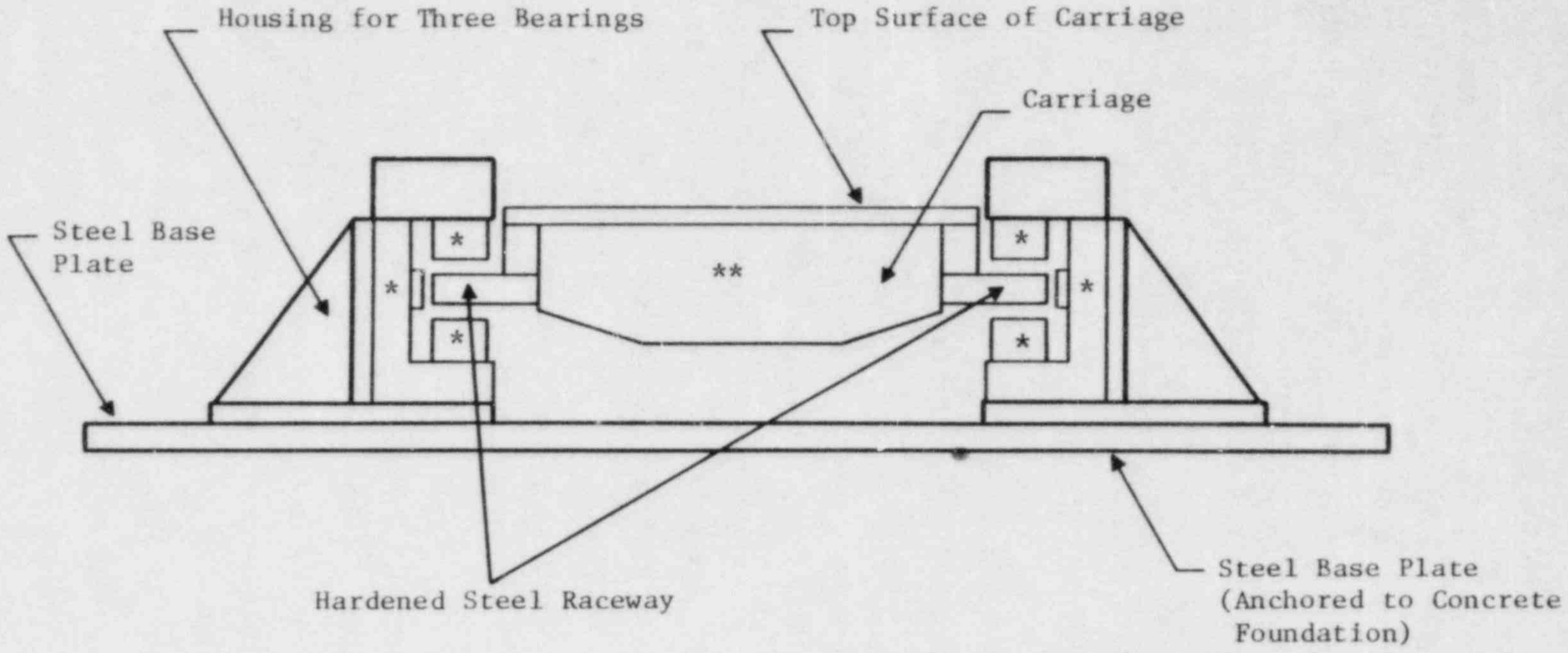
* The cross-sectional area moment for the 12 bolts was about 3.9 times the area moment for the 8-in. Schedule 40 pipe.



* Linear bearing housing.

** Motion is out of the page.

Figure 2.2: Conceptual Picture of Pipeline End Base

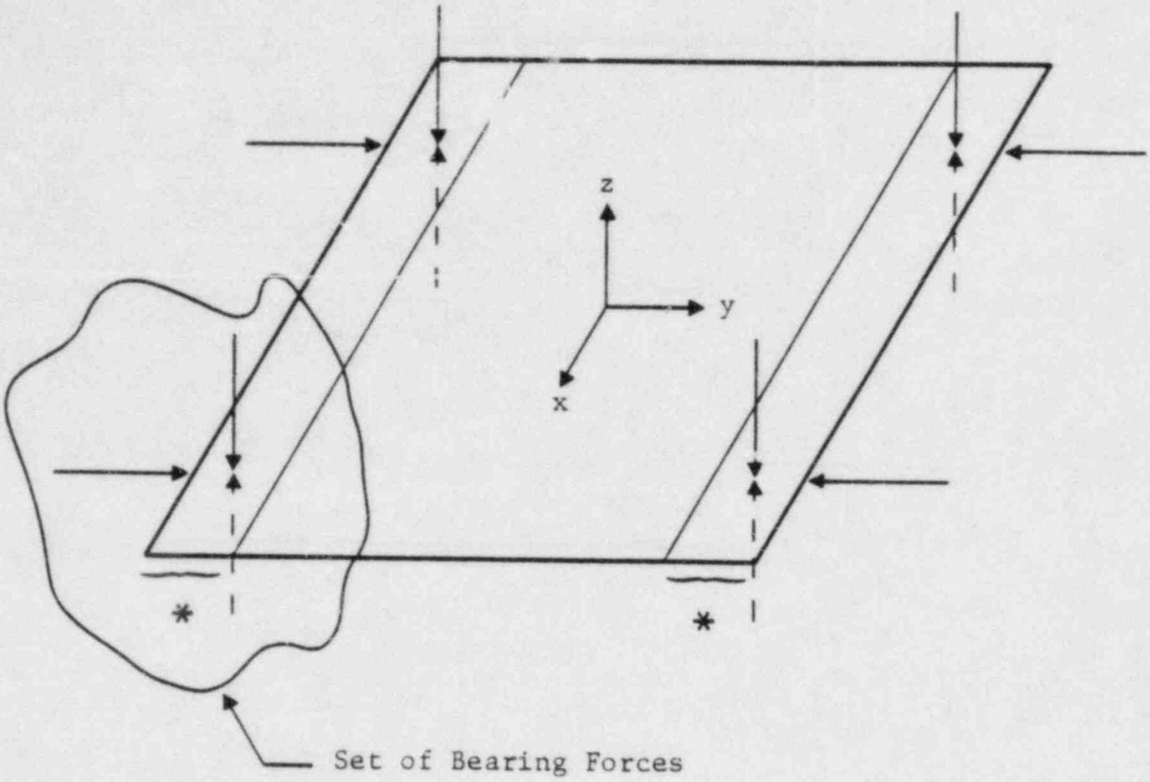
thick-walled tube which extends through the base and has a mating flange (for the pipe end flange) attached to it at one end.

Each set of bearings (the three bearings in one of the four structures) has one of the bearings on the top of a raceway, one bearing on the bottom of the raceway, and the other to the side of the raceway. This is shown conceptually in Figure 2.3, where an arrow represents the force the corresponding bearing can exert on the raceway. The force can be exerted in only the direction of the arrow.

2.1.1.2 Bases for Pipeline at Its Mid-Points

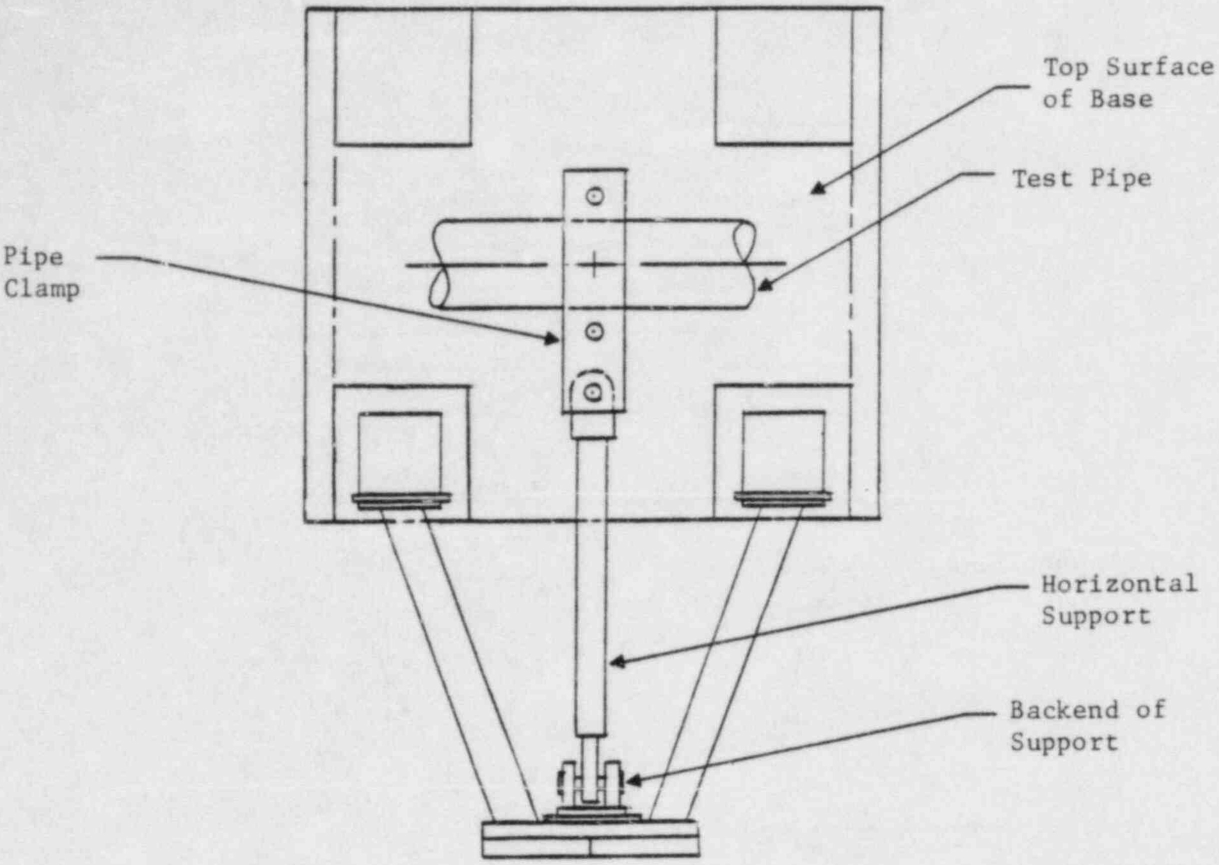
There were two pipe support points between the ends of the pipe--they were at Locations S2 and S3, shown in Figure 2.1. At each of these locations, a mid-point support base was used as illustrated in Figure 2.4. The basic features of such a base were: (1) a carriage, to which four linear bearings were attached on its underside and to which a frame was attached on its top surface; (2) two hardened circular steel shafts on which the linear bearings rode; (3) a steel plate to which the steel shafts were attached; and (4) a steel framework system attached to the carriage. The frame work served as the anchor points for the back end of the two supports (one vertical and one horizontal at each location).

The bases were designed so the pipeline could be driven in either the X or Y directions. The framework for the supports could be detached from the carriage, keeping the vertical and horizontal supports in exactly the same position. The frame could then be reattached to the carriage, keeping the vertical and horizontal supports in exactly the same position. Of course, when these bases were rotated 90 degrees, the bases at the pipe ends were also rotated 90 degrees in the same direction.

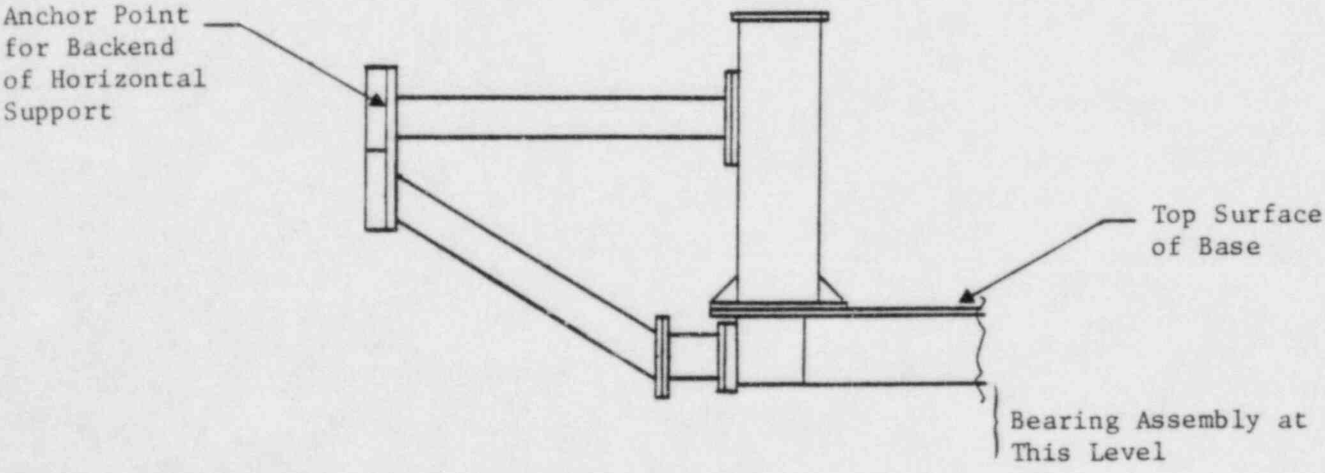


* Represents a bearing raceway.

Figure 2.3: Conceptual Representation of Base Carriage Together with Bearing Forces

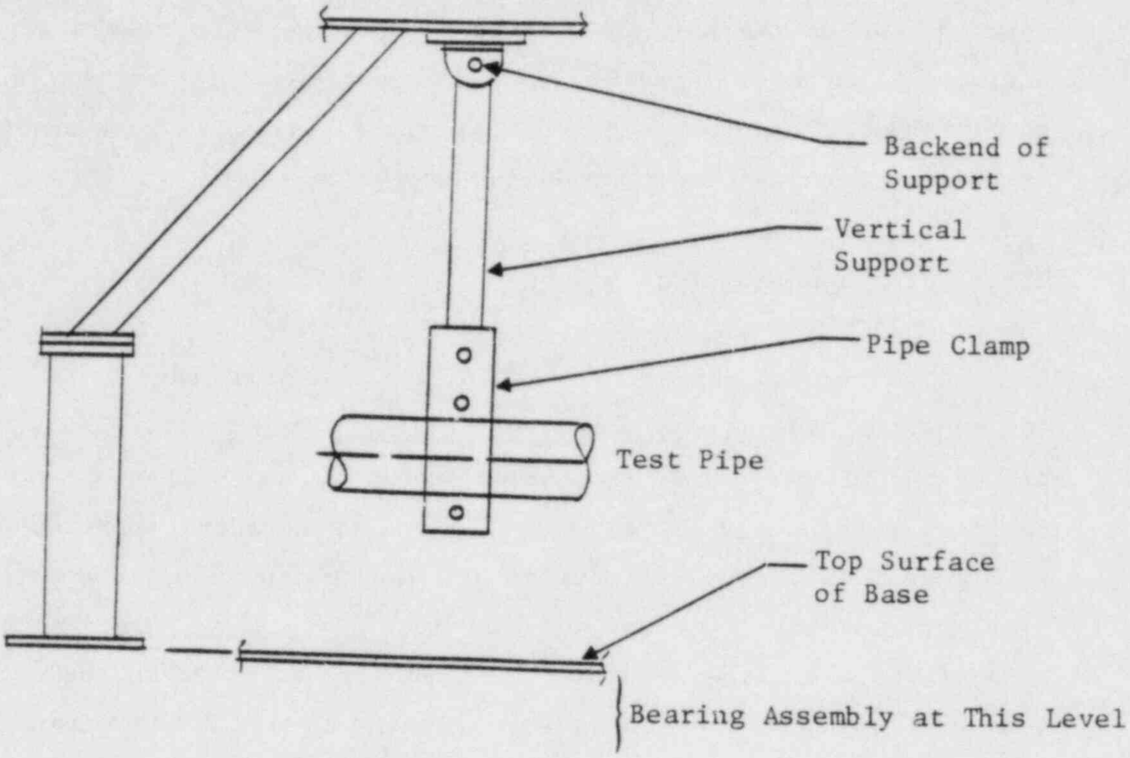


(a) Top View of Base, Including Horizontal Support Frame, Horizontal Support, and Top Surface of Base



(b) Side View of Horizontal Support Frame

Figure 2.4: Picture of a Midpoint Base



(c) Side View Showing Vertical Support

Figure 2.4 (Concluded)

2.1.1.3 Supports Used at Pipeline Mid-Points

The pipeline was supported at Locations S2 and S3 with the use of struts* and snubbers. The vertical supports were always struts, and the horizonal supports were various combinations of struts and snubbers, as described in Tables 2.3 and 2.4, and Figure 2.5. The snubbers were set at their mid-stroke position during assembly.

2.1.2 Pipeline With Branch Lines

The second pipeline tested consisted of two 3-in. Schedule 40 branch lines tied into a mainline similar to but shorter than the first line tested. In designing the second system, the first design system was modified between Locations S2 and S4 and two branch lines added as shown in in Figure 2.6. Standard reducers and long radius 90 degree pipe elbows were used for the main line and welding neck flanges were used to terminate the ends of the main line. The branch lines were attached to the main line using standard tees and the elbows used for the branch lines were 90 degree long radius elbows. Welding neck flanges were also used to terminate the branch lines. A description of the branch line pipe and components is given in Table 2.5.

The materials used for this second pipeline were also ASTM materials, as shown in Table 2.6. The same fabrication procedures were used for the second pipeline as were used for the first pipline.

The simulated valve described previously was reused for the second pipeline. The valve end was remilled before it was welded into the second pipeline. Drain/vent holes were installed as before.

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* A strut consisted of a steel tube with pin connections at each end. The pin connections prevented any moments from being transmitted to the pipe, as long as the relative displacement of the pipe, at the support point, remained small enough. The pin connections were made using Pacific Scientific snubber ends for PSA3 snubbers.

TABLE 2.3: HORIZONTAL SUPPORT CONFIGURATIONS TESTED

Configuration	Support at S2	Support at S3
1	Strut	Strut
2	PSA3*	Strut
3	PSA3	PSA3
4	BP2525-10**	Strut
5	BP2525-10	BP2525-10
6	Strut/Gap 1#	Strut/Gap 1
7	Strut/Gap 2#	Strut/Gap 2

* PSA3 refers to Pacific Scientific mechanical snubber; the model number is PSA3.

** BP2525-10 refers to a Bergen-Paterson hydraulic snubber; the model number is 2525-10.

\# Gap 1 and Gap 2 refer to gaps that were milled into the clevis pins used for the horizontal struts. One clevis pin, with a milled-in-gap, was used for each strut.

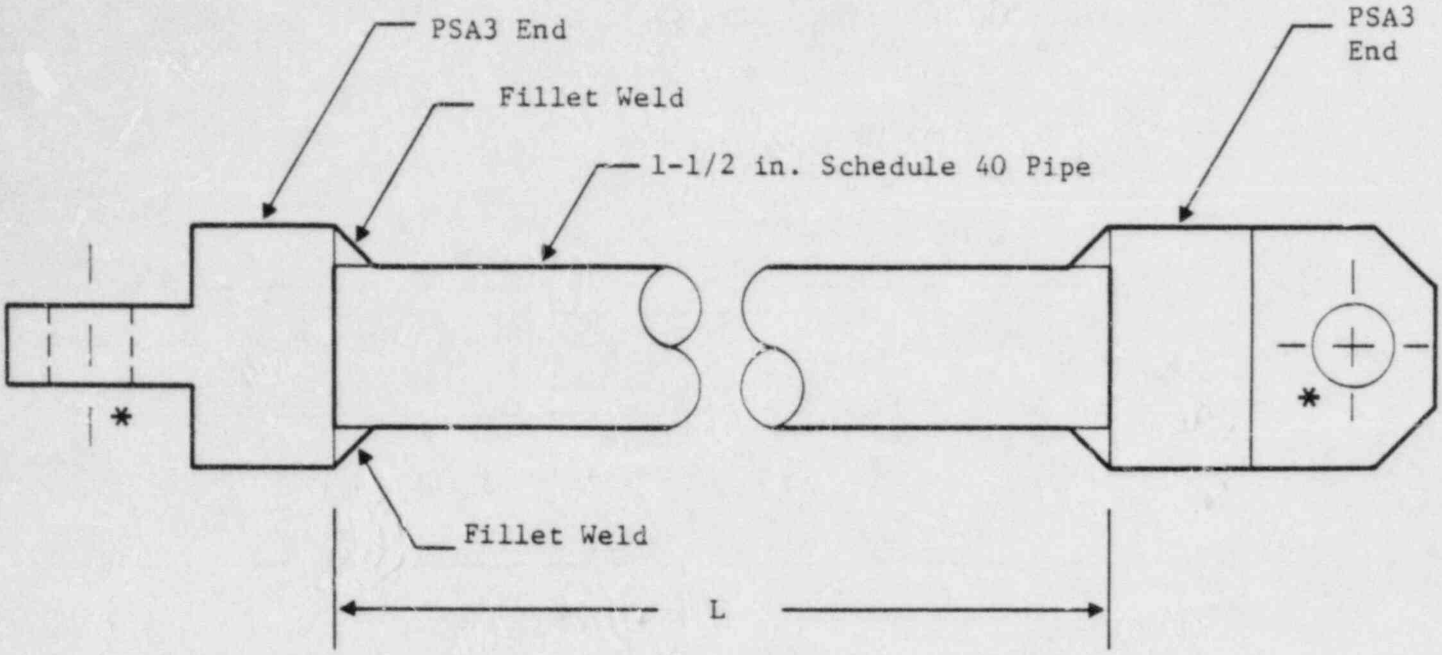
TABLE 2.4: DESCRIPTION OF MECHANICAL AND HYDRAULIC SNUBBERS--BASIC PROPERTIES

Mechanical Snubber

Make: Pacific Scientific Shock Arrester
Model: PSA3
Stroke: 5.0 in.
A/B Load: 6,000 lbf
C/D Load: 10,380 lbf

Hydraulic Snubber

Make: Bergen-Paterson
Model: 2525-10
Stroke: 6 in.
Bore: 2.5 in.
A/B Load: 10,000 lbf
D Load: 15,000 lbf



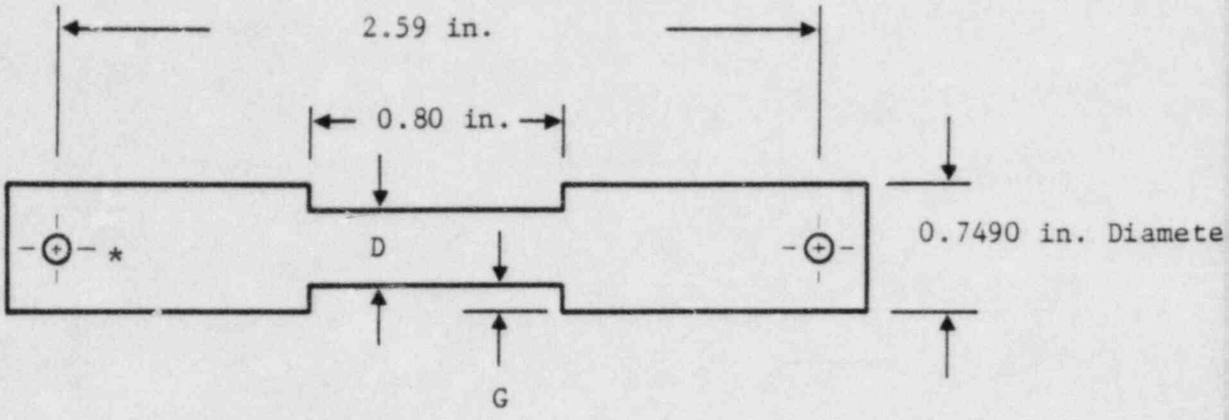
* Hole for clevis pin. The centerlines of the two holes are 90° apart.

Strut Support	Length of Tube, L (in.) X Forcing**	Y Forcing
S2, horizontal	21.1	21.1
S2, vertical	14.8	14.8
S3, horizontal	21.3	21.3
S3, vertical	13.0	13.5

** The direction of the base motion was either X or Y.

(a) Strut

Figure 2.5: Struts and Gaps Used for Tests Without Branch Lines



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* Modified PSA3 pin for backend of strut.

Gap 1: D = 0.717 in.
G = 0.016 in.

Gap 2: D = 0.621 in.
G = 0.064 in.

(b) Gaps in Clevis Pins

Figure 2.5 (Concluded)

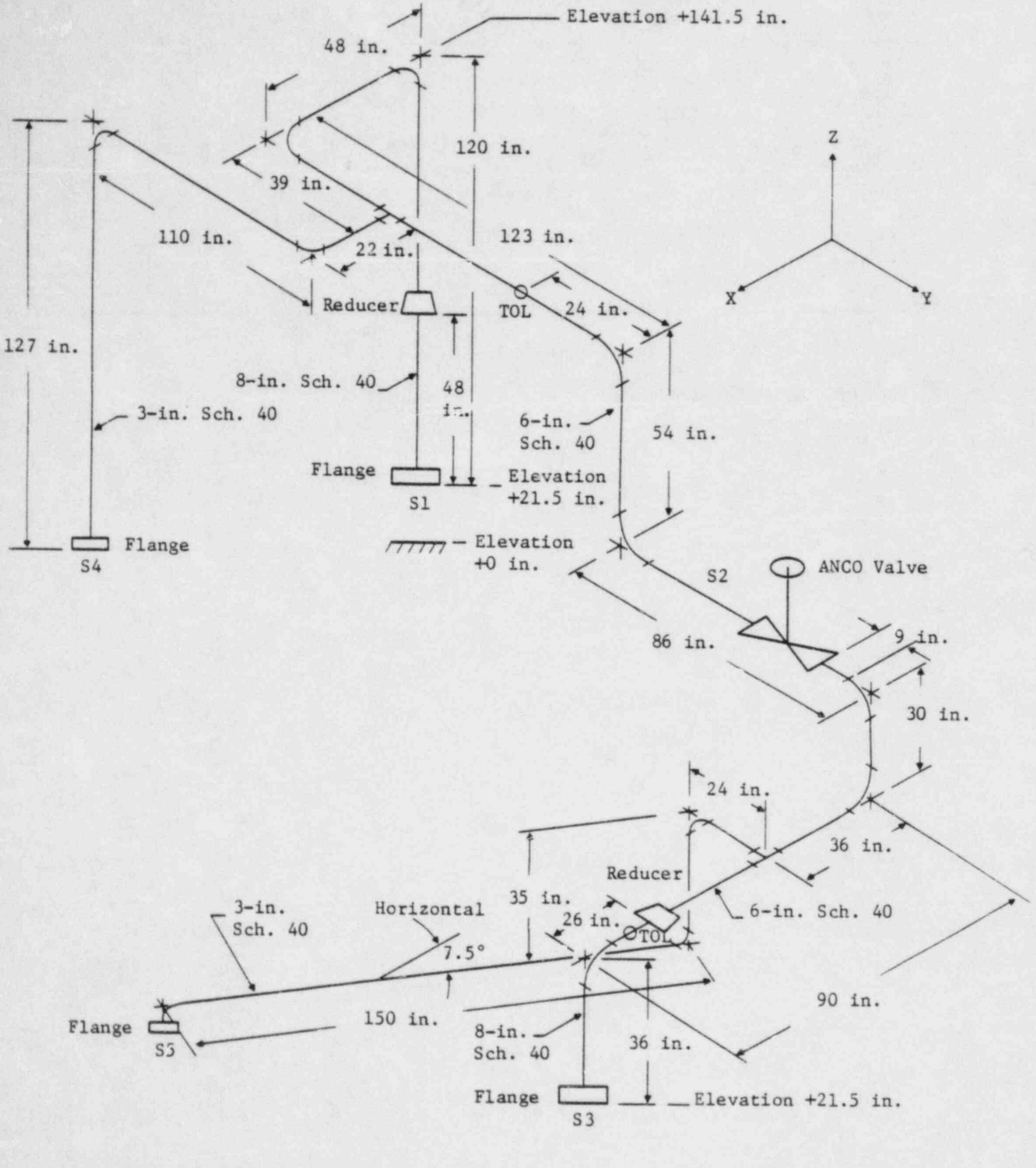


Figure 2.6: As-built Dimensions for Pipeline With Branch Lines

TABLE 2.5: SIZE OF BRANCH LINE PIPE AND COMPONENTS

Item	Description
3-in. Schedule 40 pipe	3.500 in. OD * 0.216 in. WT **
3-in. Schedule 40 90° long radius elbow	4.5-in. radius of curvature ANSI B 16.9
Welding neck flange for branch line ends	Class 600 flange ANSI B 16.5

* OD refers to the outside diameter.

** WT refers to the wall thickness.

TABLE 2.6: MATERIAL PROPERTIES FOR PIPELINE WITH BRANCH LINES

Item	Heat Number	Yield Point (psi)	Ultimate Strength (psi)	Percent Elongation	Material
6-in. Sch. 40 pipe (1)	L61034	52,000	78,700	38.0	ASTM A-106 Grade B
6-in. Sch. 40 pipe (2)	429965	47,572	70,488	38.0	ASTM A-106 Grade B
6-in. Sch. 40 pipe (3)	421803	43,200	67,200	43.6	ASME SA-106 Grade B
8-in. Sch. 40 pipe (4)	27215	50,280	74,310	36.0	ASTM A-106 Grade B
8-in. Sch. 40 pipe (5)	L41158	45,400	71,800	35.5	ASTM A-106 Grade B
3-in. Sch. 40 pipe	412121	48,200	71,800	35.0	ASTM A-106 Grade B
6-in. 90° elbow	1018*	47,650	71,410	40.0	ASTM A-254 WPB
8-in. 90° elbow	4306*	51,770	76,090	50.0	ASTM A-234 WPB
3-in. 90° elbow	5389*	52,630	74,680	45.0	ASTM A-234 WPB
8-x-6 reducer	413014	47,700	71,500	41.5	ASTM A-234 WPB
6/3 tee	NN27**	47,900	72,500	40.8	ASTM A-234 WPB
8-in. Class 600 flange	ETRI	51,217	79,510	30.0	ASTM A-105
3-in. Class 600 flange	GDCD	55,820	81,380	33.5	ASTM A-105

(1) Pipe between reducer and Elbow 1.

(2) Pipe between Elbows 1 and 2, Elbows 3 and 4, and Elbows 6 and 7.

(3) Pipe between Elbows 2 and 3, Elbows 4 and 5, and Elbows 5 and 6.

(4) Pipe connected to flanges at S1 and S3.

(5) Pipe between reducer and elbow 7.

* This number is the mill work number.

** This number is the heat code.

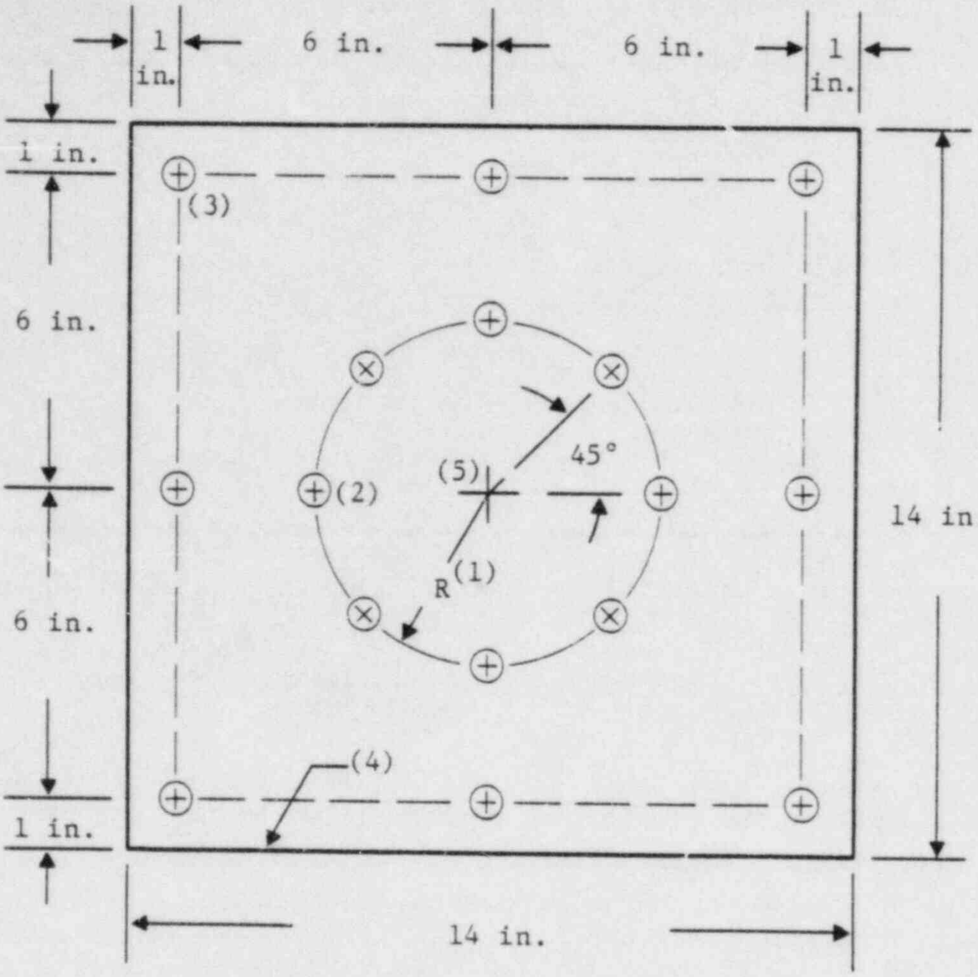
The pipeline with branch lines was supported at its four ends (Locations S1, S3, S4, and S5) and at one other point (Location S2), shown in Figure 2.6 above. The ends of the 8-in./6-in. pipeline were clamped to the previously used pipe-end bases and the ends of the branch lines were attached to bases by bolting the pipe-end flanges to a 1-in. thick steel plate which in turn was then bolted to the base. Figure 2.7 describes this. The bases used for the branch line ends were the same type of base as was used for the mid-point supports for the first piping system (Figure 2.4), and the mid-point support arrangement and base at Location S2 was the same as for the first pipeline tested.

The same type of supports were used at Location S2 as were used before (Figure 2.5 and Table 2.4). The horizontal support configurations tested are described in Table 2.7. The struts used at S2 are described in Figure 2.8. The same snubbers and gaps were used for these tests as were used for the first test series.

2.2 Base Motion Input

Each of the bases was driven by its own hydraulic actuator. The 11,000-lbf capacity actuators were servo-controlled, extending or contracting in proportion to a supplied displacement signal and were driven by a 90-gpm, 3,000-psi hydraulic power supply. Eight 10-gallon accumulators provided smooth rates of hydraulic fluid flow and ensured adequate supply pressure during dynamic events. A flow chart of the base excitation system is shown in Figure 2.9.

The input time histories were generated on a Data General NOVA-3 minicomputer. The time history used was then transferred through a digital-to-analog ([D/A] converter) and stored on FM tape. During a test, the analog time history was reproduced by the FM recorder, and the signal conditioned and filtered prior to insertion into the actuator controllers. A strip chart recorder, with built-in, medium-gain amplifiers, was used for monitoring purposes.



Notes: (1) Bolt circle radius for flange on end of branch line; R = 3.31 in.

(2) Drilled and tapped for 3/4-in. bolts.

(3) Through drill for 1/2-in. bolts.

(4) Steel plate 1-in. thick.

(5) Fixture plate to be placed at the center of the base.

Figure 2.7: Plate Used to Bolt Branch Line End Flanges to Bases

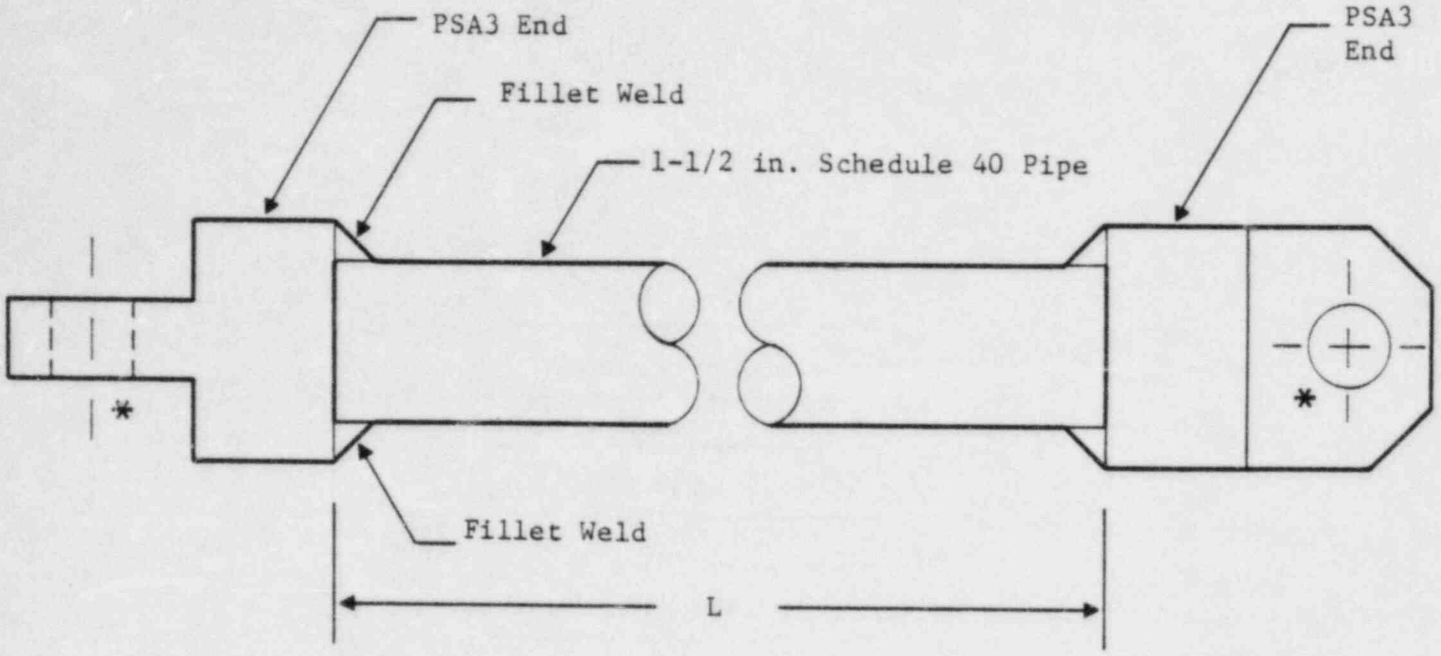
TABLE 2.7: HORIZONTAL SUPPORT CONFIGURATIONS TESTED

Configuration	Support at S2
1	Strut
2	PSA3*
3	BP2525-10**
4	Strut/Gap 1#
5	Strut/Gap 2#

* PSA3 refers to a Pacific Scientific mechanical snubber; the model number is PSA3.

** BP2525-10 refers to a Bergen-Paterson hydraulic snubber; the model number is 2525-10

\# Gap 1 And Gap 2 refer to gaps that were milled into the clevis pins used for the horizontal struts. One clevis pin, with a milled-in gap, was used for each strut.



* Hole for clevis pin. The centerlines of the two holes are 90° apart.

Strut Support	Length of Tube, L (in.)
S2, horizontal	20.7
S2, vertical	14.1

Figure 2.8: Struts Used for Tests With Branch Lines

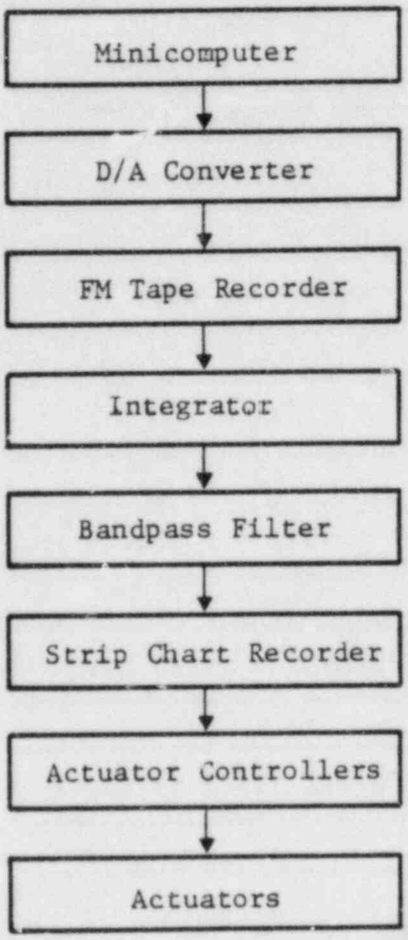


Figure 2.9: Base Excitation System Flowchart

2.3 Instrumentation for Piping Systems

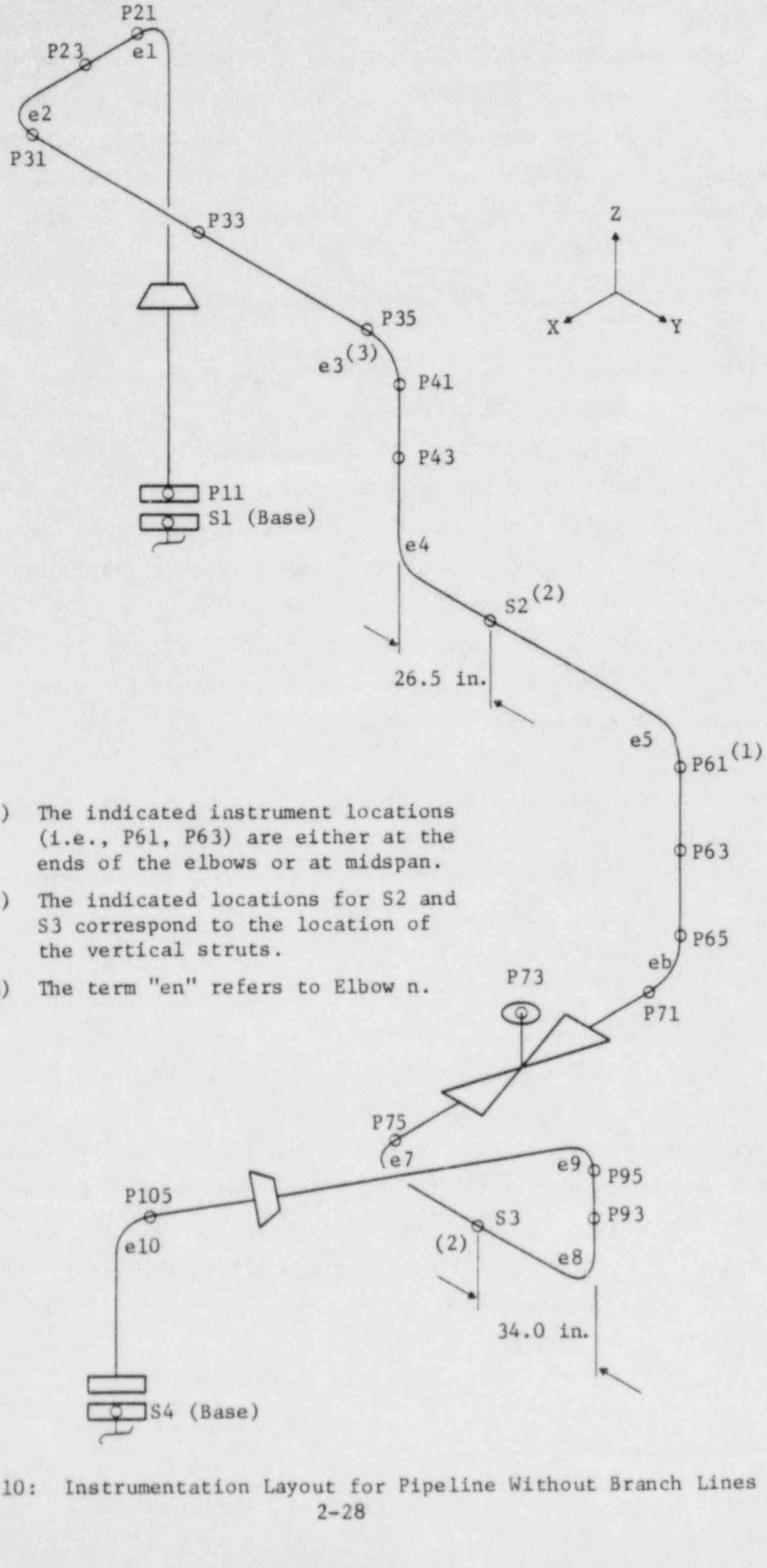
The test specimens were instrumented with accelerometers, displacement transducers, strain gauges, load cells, and a pipe-internal pressure transducer. There are some similarities between the instrumentation layout for the two piping systems because of the similarities between the systems. The instrumentation used for the pipe lines is described herein.

2.3.1 Instrumentation for Pipeline Without Branch Lines

The base motion input was recorded using both accelerometers and displacement transducers. A triaxial accelerometer array was placed on both pipe-end sleds (at S1 and S4), and displacement transducers were used to measure the displacement of the pipe-end bases in the base-forcing direction (X or Y). The motion of the two mid-point bases was measured using accelerometers placed at the back end of the supports. Accelerometers were oriented in the base forcing direction--one per support. An accelerometer was also oriented in the direction of the centerline of each support. (Sometimes, the forcing and centerline directions were the same and only one accelerometer was needed for the support).

Instrumentation placement was guided by the results of linear elastic finite element analyses of the system. The accelerometers and displacement transducers were placed to capture both the largest net responses (multiple modes) and some modal responses (single mode). The strain gauges were placed at the highest stressed locations.

Figures 2.10 and 2.11 and Tables 2.8 and 2.9 describe the instrumentation layout used for X or Y direction base in motion. All instruments were located relative to the locations indicated in Figures 2.10 and 2.11. The instrumentation was slightly different for X and Y forcing because different modes were excited to different levels for different forcing directions. It should be noted that during testing, all the instrumentation was continually checked for (1) overloading, (2) underloading, and (3) loose transducers, i.e., accelerometers which had come loose. Care was taken to



Notes:
(1) The indicated instrument locations (i.e., P61, P63) are either at the ends of the elbows or at midspan.
(2) The indicated locations for S2 and S3 correspond to the location of the vertical struts.
(3) The term "en" refers to Elbow n.

Figure 2.10: Instrumentation Layout for Pipeline Without Branch Lines

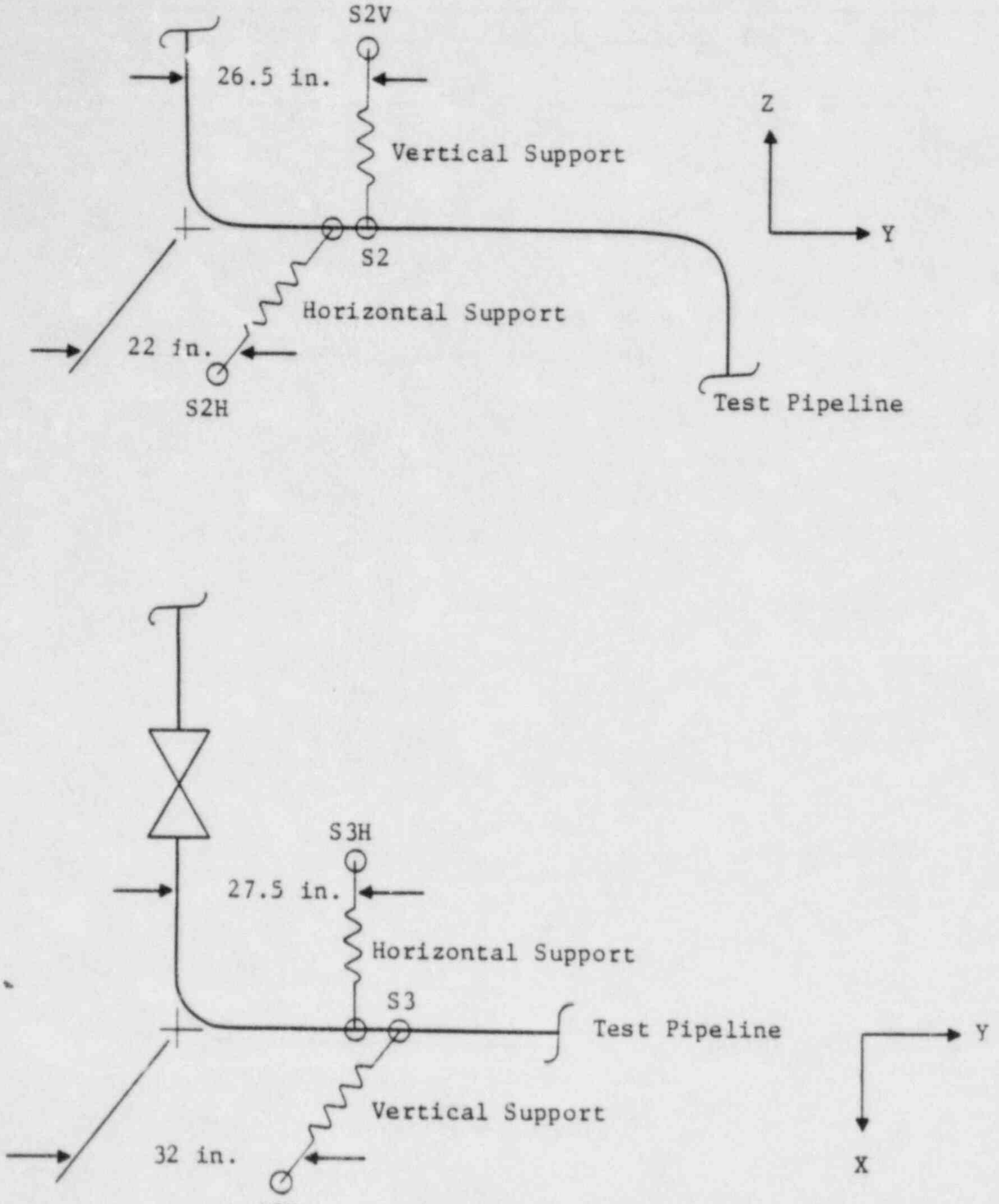


Figure 2.11: Midpoint Support Instrumentation Locations

TABLE 2.8: INSTRUMENTATION FOR PIPELINE WITHOUT BRANCH LINES (X-DIRECTION BASE MOTION)

Global Location	Local Location (in.) and Direction of Instrument Acceleration	Displacement	Strain	Load
S1	X,Y,Z(1)	X		
P21	+6;Y(2)		+2;Y,Z,-Y(3)	
P31	+6;X	+9;X		
P33		+9;X		
P35	-6;X,Z(4)	0;X		
P41	+5;Y			
S2H	X	X(5)		X
S2V	X			Z
P61	+5;X			
P63		0;X		
P65	-5;X	-1;X		
P71	+5;Z			
P73	+5;X			
P75	-6;Y,Z		-3;Y,Z,-Y	
S3H	X	X		X
S3V	X			Z
P93		+9;X		
P95	-5;X			
P105			-3;Y,Z,-Y	
S4	X,Y,Z(1)	X		

TABLE 2.8 (Concluded)

NOTES: (1) The X and Y direction accelerometers were located on the base flange that was bolted to the test pipe flange. The Z direction accelerometer was located on the top surface of the base. The direction X, Y, or Z refers to the direction a given transducer is oriented in--motion will be measured in the direction of orientation.

(2) The accelerometer was located 6 in. from point P21. The plus sign, +, was attached to the 6 in. because the accelerometer was on the S4 side of P21.

(3) The directions refer to the circumferential location of the strain rosettes at the specified pipe-axial location. A circumferential location is specified by indicating the direction of the outward normal vector to the pipe at the circumferential location.

(4) The accelerometers are 6 in. from P35. They are on the S1 base side of P35.

(5) These displacements were measured across the horizontal supports--the displacement of one end relative to the other end.

TABLE 2.9: INSTRUMENTATION FOR PIPELINE WITHOUT BRANCH LINES (Y-DIRECTION BASE MOTION)

Global Location	Local Location (in.) and Direction of Instrument			
	Acceleration	Displacement	Strain	Load
S1	X,Y,Z(1)	Y		
P21	+6;Y(2)		+2;Y,Z,-Y(3)	
P23		0;Y		
P31	+6;X			
P35	-6;X,Z(4)			
P41	+5;Y			
P43		0;Y		
S2H	Y	X(5)		X
S2V	Y			Z
P61	+5;X			
P63		0;Y		
P71	+5;Y,Z	+14;Y		
P73	Y			
P75	-6;Y,Z	-1;Y	-3;Y,Z,-Y	
S3H	Y	X(5)		X
S3V	Y			Z
P93		0;Y		
P95	-5;X			
P105			-3;Y,Z,-Y	
S4	X,Y,Z(1)	Y		

TABLE 2.9 (Concluded)

NOTES:

(1) The X and Y direction accelerometers were located on the base flange that was bolted to the test pipe flange. The Z direction accelerometer was located on the tope surface of the base. The direction X,Y, or Z refers to the direction a given transducer is oriented in--motion will be measured in the direction of orientation.

(2) The accelerometer was located 6 in. from point P21. The plus sign, +, was attached to the 6 in. because the accelerometer was on the S4 side of P21.

(3) The directions refer to the circumferential location of the strain rosettes at the specified pipe-axial location. A circumferential location is specified by indicating the direction of the outward normal vector to the pipe at the circumferential location.

(4) The accelerometers are 6 in. from P35. They are on the S1 base side of P35

(5) These displacements were measured across the horizontal supports--the displacement of one end relative to the other end.

ensure that quality data was obtained. The types of transducers are described in Table 2.10.

2.3.2 Instrumentation for Pipeline With Branch Lines

The procedure for selecting types of instrumentation, and their locations, for the pipeline with branch lines was the same as for the first pipeline. The locations for the instrumentation are described in Figures 2.12 and 2.13 and Table 2.11.

2.4 Testing Methods Used

Several items are discussed herein; they are (1) types of tests performed, (2) the acquisition of data, and (3) data analysis methods used to produce a preliminary assessment of results.

2.4.1 Types of Tests Conducted

The types of tests performed for the piping systems, described above, are listed in Table 2.12.

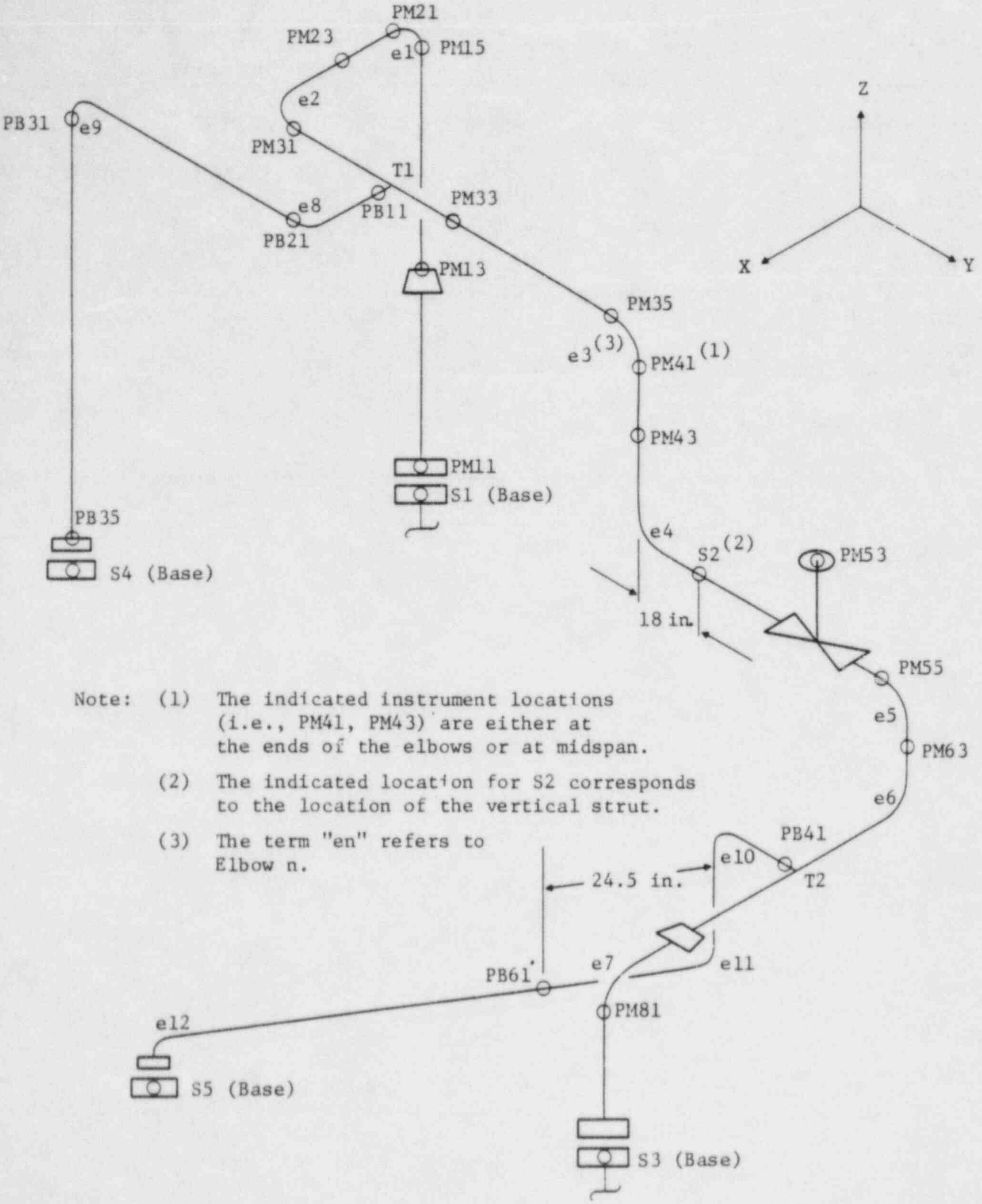
2.4.2 Data Acquisition

Data acquisition was provided by ANCO's computerized vibration test and analysis system. The system, based on a Data General NOVA-3 minicomputer, consisted of the following:

1. 12-slot NOVA-3/12 chassis;
2. 256-kbyte memory and CPU;
3. 10-Mbyte disk drive with adapter;
4. 9-track digital tape system;
5. CRT interactive terminal;
6. DEC Writer II printing terminal;
7. Houston Instruments DP-11 incremental plotter;
8. Computer Products Real Time Peripheral (RTP) System with 96 channels of A/D converters and 4 channels of D/A converters;

TABLE 2.10: TRANSDUCER TYPES USED FOR TESTS

Transducer Type	Manufacturer	Model Number	Response Characteristics	
			Full-Scale Output	Resolution
Accelerometer	Columbia	321-H-HT-I	±5g to ±1,000g	0.0002g to 0.04g
Accelerometer	Dytran	3100	±25g to ±100g	0.004g to 0.001g
Displacement	Celesco	PT101	±10 in.	0.01 in.
Strain gauge	Micro Measurement	CEA-06-1250R-350	±5,000 με	2 με
Strain gauge	Micro Measurement	CEA-06-1250W-350	±5,000 με	2 με
Load cell	Strainsert	1933-2-B	±15,000 lbf	6 lbf



Note: (1) The indicated instrument locations (i.e., PM41, PM43) are either at the ends of the elbows or at midspan.

(2) The indicated location for S2 corresponds to the location of the vertical strut.

(3) The term "en" refers to Elbow n.

Figure 2.12: Instrumentation Layout for Pipeline With Branch Lines

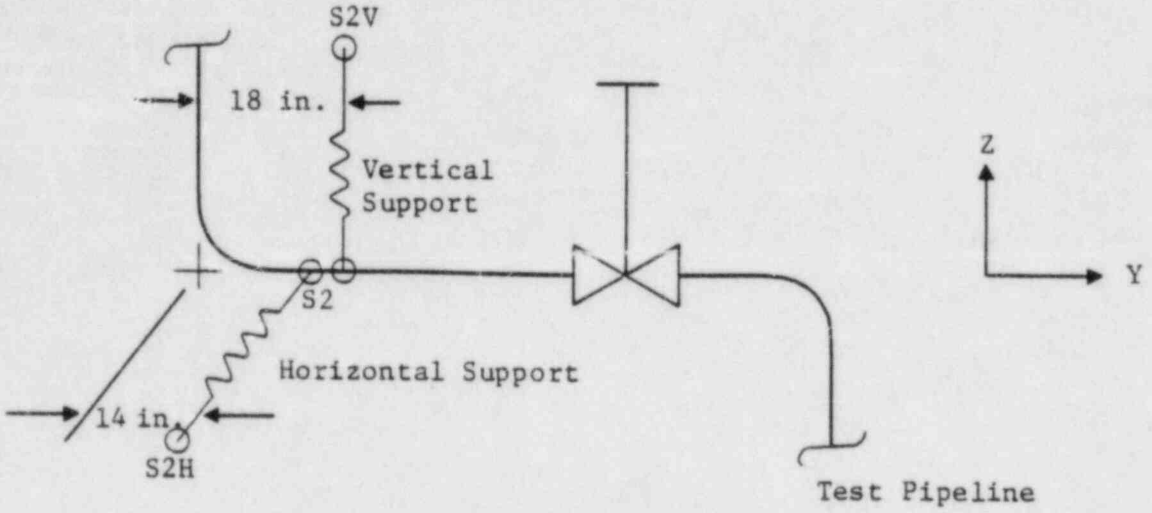


Figure 2.13: Instrumentation Locations for Midpoint Supports

TABLE 2.11: INSTRUMENTATION FOR PIPELINE WITH BRANCH LINES

Global Location	Local Location (in.) and Direction of Instrument			
	Acceleration	Displacement	Strain	Load
S1	X,Y,Z(1)	X		
PM13			+6;X,-Y,-X(2)	
PM15			-6;X,-Y,-X	
PM21	+6;X(3)			
PM23		-5;Y(4)		
PM31	+11;Y	+16;X		
PM33	+32;X,Y	+18;X		
PM43		+2;Y		
S2UP	X,Z			Z
S2LOW	X	X		X
PM53	X,Y	X		
PM55			-4;Z,X,-Z	
PM63	0;Y,Z	-1;X		
PM81			+6;X,-Y,-X	
S3	X,Y,Z(1)	X		
PB11			+6;Y,Z,-Y	
PB21	+13;Z(5)			
PB31	+8;X,Y			
PB35			-4;X,-Y,-X	

TABLE 2.11 (Concluded)

Global Location	Local Location (in.) and Direction of Instrument			
	Acceleration	Displacement	Strain	Load
S4	X,Y,Z			
PB41			+6;X,Z,-X	
FB61	0;X',Y' (6)			
S5	X,Y,Z			

NOTES: (1) The X and Y direction accelerometers were located on the base flange that was bolted to the test pipe flange. The Z direction accelerometer was located on the top surface of the base. The direction X, Y, or Z refers to the direction a given transducer is oriented in--motion will be measured in the direction of orientation.

(2) The directions refer to the circumferential location of the strain gauges at the specified pipe-axial location. A circumferential location is specified by indicating the direction of the outward normal vector to the pipe at the circumferential location.

(3) The accelerometer was located 6 in. from Point PM21. The plus sign, +, indicates that the accelerometer was on the S3 side of the point (PM21).

(4) The displacement transducer was attached to the pipe 5 in. from Point PM23. The minus sign, -, indicates that the transducer was on the S1 side of the point.

(5) The accelerometer was located 13 in. from point PB21. The plus sign, +, indicates that the accelerometer was on the S4 side of the point.

(6) The coordinate directions X', Y', are local directions defined at Point PB61. X' is parallel to the pipe centerline at PB61. Y' is perpendicular to X', and lies in a horizontal plane.

TABLE 2.12: DESCRIPTION OF TYPES OF TESTS

Type of Test	Description
Static pressure only	The bases were locked and the pipeline was pressurized to 1,150 psi. Strain gauge measurements were made.
Impulse	The bases were all given a simultaneous, sudden, step in displacement. That is, the displacement of the bases was changed from the initial value to a different constant value.
Sine Dwell	The bases were held fixed. A single harmonic force was applied to the pipeline. The forcing frequency was varied between two extreme values. At preselected values of forcing frequency (between the extreme values), the forcing frequency was held constant long enough to allow the transient response to become zero. The steady-state response was then recorded.
Earthquake	The bases were given in-phase earthquake-like motions.
Static Displacement of one base	One of the bases was moved quasi-statically to a final position. The remaining bases were held fixed.
Initial static displacement of one base plus earthquake	An earthquake is super-imposed on the previously defined static case. This procedure simulates a static preload followed by earthquake loading.

9. 64 channels of STI differential amplifier/anti-aliasing filters; and
10. 24 channels of Frequency Devices filters.

Analog output from the transducers was low pass filtered using the STI and Frequency Devices amplifier-filter system and then digitized using the RTP system and the program XFAST. In addition to creating a file containing the digitized test data, XFAST sets up all title, test and run information and the digitizing time step and time duration of data acquisition as part of the data file.

For both piping systems, the following digitization/filter parameters were use:

- sample rate per channel = 200 points/s
- low pass cutoff frequency = 42.6 Hz

2.4.3 Data Analysis

Following execution of a test, the data was corrected for time interval shifts and, subsequently, processed to generate some of the categories of information illustrated in Table 2.13.

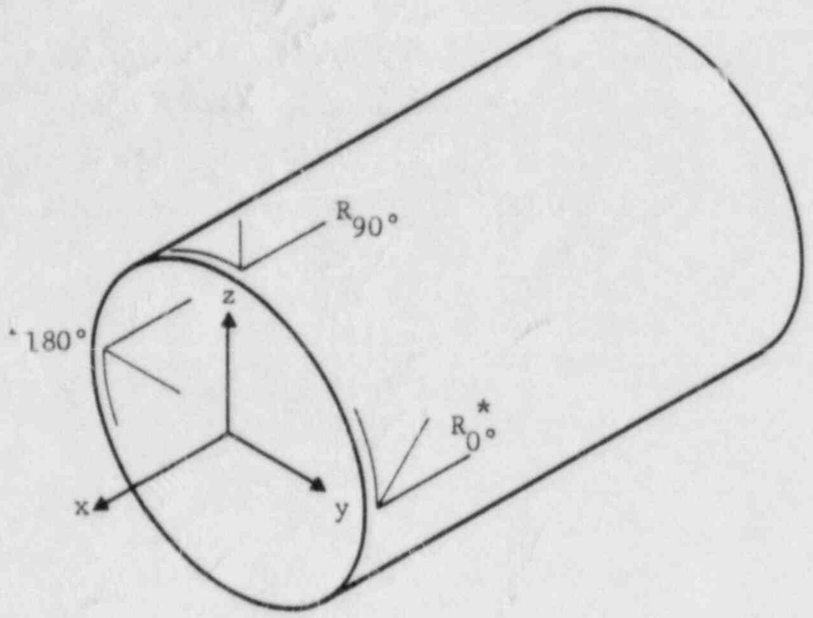
A few comments are appropriate regarding the calculation of the pipe cross-sectional loads and the ASME stress ratio. Various pipe cross-sections were instrumented with strain gauges, an example of which is shown in Figure 2.14. For the strain gauge arrangement in Figure 2.14 (and assuming linear material behavior), it is possible to determine all six cross-sectional loads. For other arrangements, less than six loads can be calculated. The computer code LOADS is used to calculate stresses from strains. The stresses are then used to calculate cross-sectional loads.

Of key importance is the calculation of the two bending moments, M_y and M_z, and the torsion, M_x, at a given pipe cross-section. LOADS does

TABLE 2.13: TYPICAL POST PROCESSING OF DATA

	Information That Can Be Obtained	Method Used
1.	Extreme values of response for each data channel.	Computer Code TIMEPEAK* searches channel by channel for maximum and minimum.
2.	Time history plots of data.	TIMEPLOT plots transducer amplitude as a function of time.
3.	Pipe cross-sectional loads and ASME stress ratio as a function of time.	For pipe cross sections with appropriate strain gage instrumentation, LOADS is used.
4.	Principal strains and von Mises ratios for locations on pipe outer surface.	For points on pipe surface with strain gage rosettes, STRESS is used.
5.	Fourier transform of transient data.	XFILT is used to obtain transform and, also, to filter data and obtain inverse transform.
6.	Plot Fourier transform of data.	FOURPLOT plots real and imaginary components or modulus and phase.
7.	Response spectrum.	XBETL5 and XCETLDP calculates and plots response spectra for accelerometer channels of interest, respectively.
8.	Determine time history which is a linear combination of various data time histories; this can be used to determine the relative motion (to the base motion) of the pipe.	LINCOM and TIMEDGEN calculates the new time history and adds header information to the new file, respectively.

* Words with all letters capitalized (i.e., LOADS) refer to computer codes.



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* R_θ refers to a strain gauge rosette configuration of gauges located at θ degrees from the y-axis. The adjacent gauges in a rosette are 45° from each other.

Figure 2.14: An Arrangement of Strain Gauges

this for each time point of a transient event. It then calculates the resultant sectional moment, $M_i(t)$, from the following:

$$M_i(t) = [M_x^2(t) + M_y^2(t) + M_z^2(t)]^{1/2} \tag{1}$$

The resultant moment calculated by Equation 1, includes the effects of the dynamic response. If the strain gauge settings are not nulled (zeroed) out after pressurization of the pipe, the calculated resultant moment will also include the effect of the pipe internal pressure (a sustained load).

3.0 PRELIMINARY TEST RESULTS

For each test conducted, all the data was plotted, peak response values were determined for all data channels, and peak ASME stress ratios were calculated for particular strain-gauged locations. This report presents only preliminary observations regarding system behavior. Detailed data analysis will be performed at a later time and under a different NRC contract.

3.1 Tests Conducted and Peak Response Values

For all of the tests for both piping systems, the following test and run designators were used:

Test = (Direction)(Type)n
Run = (Configuration)m

where Direction = direction of base motion (X or Y)

Type = PO (pressure only loading)
IM (base impulse motion)
SD (sine dwell)
EQ (base earthquake motion)

n = sequence number
Configuration = support configuration
m = configuration number

An example of this is Test = XEQ3 and Run = C2. This test and run refer to the following:

- X direction base motion
- earthquake input
- for XEQ tests of Configuration 2, the sequence number is 3
- Configuration 2

The resultant moment is calculated per Equation 1 in the prior section of this report. LOADS then calculates the ASME Code stress ratio using the following equation:

$$SR(t) = S_{OL}(t)/CSL = [B_1(PD_o/2t) + B_2(M_i(t)/Z)]/CSL \qquad (2)$$

where $SR(t)$ = ASME stress ratio (t=time)

$S_{OL}(t)$ = stress due to primary loads (i.e., earthquake), as calculated by the method described in the "ASME Boiler and Pressure Vessel Code."

CSL = ASME Code stress limit

$P(t)$ = pipe internal pressure

D_o = outside pipe diameter

t = pipe wall thickness

$M_i(t)$ = resultant cross-sectional moment

Z = section modulus

B_1 = stress index for pipe pressure term

B_2 = stress index for moment term

The 1980 edition of the ASME Code for Class 2 piping was used in the response evaluations.* An important point should be made concerning the resultant moment for Class 2 piping. The computer code LOADS calculates the resultant moment due to any effects included in the recorded strain data. Thus, if the strain gauge settings are not nulled out before a dynamic test, as was the case for these tests, the calculated resultant moment reflects both the pipe pressure and dynamic effects. However, the stress equation

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* The term ASME Code will refer to the "ASME Boiler and Pressure Vessel Code," Section III, Division 1. In the Winter Addenda, 1981, the stress equations and limits changed from those used herein.

for primary loads for Class 2 piping has its moments in the form $M_A + M_B(t)$, where M_A and M_B are the resultant moments due to sustained and occasional loads, respectively. For the tests performed, the difference between the resultant moment calculated by both approaches was negligible, i.e., M_i was very similar to $M_A + M_B$. The values of the constant terms in Equation 2, used for calculating the stress ratio, are given in Table 3.1.

The tests conducted for the first piping system (without branch lines) are listed in Table 3.2. The peak base input is given together with select peak response quantities. It should be noted that ASME stress ratios greater than one (1) do not necessarily have any meaning because the moments used to calculate the ASME stress were calculated from strains. When the strains are in the inelastic range, it is not valid to so calculate moments. The tests conducted for the second pipeline (with branch lines) are listed in Table 3.3. Also, some select peak results are presented.

3.2 Calculated Damping for Piping Systems

Limited damping calculations were performed for the piping system without branch lines to obtain a preliminary assessment of behavior. The results of the limited calculations (using log decrement) are presented in Figures 3.1 through 3.3. For a given figure, the time histories used for the calculations are presented.

It may be seen that the selected time histories consist almost entirely of single mode response, making it possible to apply the log decrement method to calculate the damping. The results can be seen on the nomograph, which is equivalent to using the following formula:

$$\beta^{(i)} = \ln(z_o/z_i)/2\pi i$$

where z_o and z_i are the amplitude of the peaks of the o<u>th</u> and i<u>th</u> cycles, respectively.

TABLE 3.1: CONSTANT VALUES FOR CALCULATING ASME STRESS RATIO

Constant	8x6 Reducer	6-in. Straight Pipe**	6-in. Pipe Elbow**	8-in. Pipe Elbow**
D_o(in.3)	6.625	6.625	6.625	8.625
t (in.3)	0.280	0.280	0.280	0.322
Z (in.3)	8.50	8.50	8.50	16.81
B_1	0.50	0.50	0.50	0.50
B_2	1.00	1.00	1.70	1.83
CSL(psi)#	36,000	36,000	36,000	36,000

* Narrow end of reducer (6-in. end).

** Schedule 40 pipe.

The code stress limit is $2.4S_h$. All ASME stress calculations were done using the 1980 edition of the code.

TABLE 3.2: PEAK BASE MOTION AND PEAK PIPE RESPONSE FOR PIPELINE WITHOUT BRANCH LINES

	Measured Base Motion		Measured Pipe Response			Support Condition	
Test/Run	Displacement(in.)	Acceleration(g)	Absolute Displacement (in.)	Acceleration (g)	ASME Stress Ratio*	Support Load (kip)	Percent of A/B**
YP01/C1	NA	NA	0.19(P75Y)	NA	0.23(e10)	-0.84(S2V)	NA
YIM2/C1R1	1.23	-10.73	2.64(P71Y)#	-16.89(P35Z)	0.76(e10)	-4.21(S2H)	NA
YIM5/C1R1	3.02	-14.94	5.92(P71Y)	-29.07(P73Y)	1.18(e10)	-5.56(S2H)	NA
YIM1/C2R1	1.24	-10.19	2.62(P71Y)	-15.86(P35Z)	0.75(e10)	-3.85(S2H)	64
YIM2/C2R1	2.13	-13.23	4.52(P71Y)	-17.02(P35Z)	1.08(e10)	-5.33(S2V)	NA
YIM3/C2	1.06	- 9.45	2.31(P71Y)	-14.57(P35Z)	0.72(e10)	-3.66(S2H)	61
YIM2/C3R2	1.94	-13.23	4.00(P71Y)	-17.38(P35Z)	1.04(e10)	-4.85(S2V)	NA
YIM1/C3R1	0.59	- 7.95	1.26(P71Y)	-11.17(P61X)	0.57(e10)	-3.07(S2V)	NA
YEQ3/C3R1	1.18	- 3.43	-3.46(P63Y)	- 7.87(P71Y)	1.37(e10)	-5.77(S3H)	96
YIM1/C2R2	0.50	- 6.58	1.08(P71Y)	- 9.34(P61X)	0.51(e10)	-2.81(S3V)	NA
YIM2/C1R2	0.51	- 6.93	1.12(P71Y)	10.00(P61X)	0.53(e10)	-2.84(S3V)	NA
YEQ3/C3R2	1.05	- 3.36	3.21(P63Y)	8.72(P71Y)	1.29(e10)	-5.31(S3H)	89
YEQ3/C3R3	0.53	- 1.45	1.79(P63Y)	5.42(P71Y)	0.91(e10)	-2.83(S3H)	47
XIM1/C1	0.43	- 3.66	0.77(P35X)	- 7.94(P73X)	0.54(e10)	-1.66(S2H)	NA
XIM2/C1	0.30	- 3.03	0.55(P35X)	- 5.62(P73X)	0.40(e7)	2.29(S3H)	NA
XIM3/C1	0.90	4.44	1.55(P35X)	-11.53(P73X)	0.60(e7)	5.77(S3H)	NA
XEQ1/C1	-0.14	0.44	0.32(P35X)	- 1.75(P35Z)	0.38(e10)	0.82(S3H)	NA
XIM4/C1	1.50	4.89	2.38(P35X)	-11.38(P61X)	0.76(e7)	6.88(S3H)	NA
XIM1/C3	0.83	4.28	1.42(P31X)	- 8.44(P73X)	0.59(e10)	-5.43(S3H)	91
XIM2/C3	-0.07	5.40	3.29(P31X)	10.54(P35Z)	0.80(e7)	-7.05(S3H)	118
XEQ1/C3	0.27	- 0.72	0.49(P35X)	- 2.87(P35Z)	0.45(e10)	-1.40(S2H)	23
XIM5/C1	2.52	5.36	3.89(P31X)	-12.37(P61X)	0.86(e7)	-7.24(S3H)	NA
XEQ2/C1	0.27	0.80	0.60(P35X)	3.43(P35Z)	0.45(e7)	-1.48(S3H)	NA

TABLE 3.2 (Concluded)

Test/Run	Measured Base Motion Displacement(in.)	 Acceleration(g)	Measured Pipe Response Absolute Displacement (in.)	 Acceleration (g)	 ASME Stress Ratio*	Support Condition Support Load (kip)	 Percent of A/B**
XEQ3/C1	-1.22	-2.24	2.47(P35X)	13.14(P35Z)	0.90(e7)	-5.80(S3H)	NA
XIM3/C3	2.57	5.59	4.15(P35X)	11.60(P35Z)	0.86(e7)	-7.20(S3H)	120
XIM3/C3R1	2.56	5.61	4.17(P35X)	11.93(P35Z)	0.89(e7)	-7.51(S3H)	125
XEQ2/C3	1.31	-2.72	2.52(P35X)	13.89(P35Z)	0.93(e7)	-6.10(S2H)	102
XEQ3/C3	-1.55	-3.45	3.31(P35X)	20.84(P35Z)	0.71(e10)	-5.59(S3H)	93
XEQ4/C3	2.17	-5.11	4.10(P35X)	21.41(P35Z)	0.79(e7)	-6.67(S3H)	111
XIM1/C5	0.78	3.93	1.25(P35X)	-10.08(P73X)	0.60(e10)	-5.55(S3H)	56
XIM2/C5	2.74	5.56	4.21(P35X)	-13.35(P35Z)	0.88(e1)	-7.99(S3H)	80
XIM1/C6	0.79	4.28	1.25(P35X)	-10.89(P73X)	0.59(e10)	-5.65(S3H)	NA
XIM1/C7	0.78	4.31	1.25(P35X)	-11.02(P73X)	0.58(e7)	-5.77(S3H)	NA
XIM2/C7	2.74	5.57	4.24(P35X)	-13.14(P61X)	0.87(e7)	-7.87(S3H)	NA
XEQ1/C5	-2.41	-4.32	3.93(P35X)	17.28(P35Z)	1.17(e1)	6.84(S3H)	68
XEQ2/C5	2.92	-4.86	-4.86(P35X)	-17.87(P35Z)	1.31(e1)	6.83(S2H)	68
XEQ3/C5	3.29	5.38	-5.06(P35X)	-21.87(P35Z)	1.32(e1)	7.22(S2H)	72
YEQ1/C5	2.11	-4.33	6.14(P63Y)	10.57(P71Y)	1.83(e10)	5.56(S3H)	56
YEQ2/C5	2.96	-5.55	7.77(P63Y)	13.71(P71Y)	2.07(e10)	6.75(S3H)	67
YEQ3/C5	0.57	1.75	4.01(P63Y)	9.83(P71Y)	1.81(e10)	4.18(S3H)	42
YEQ4/C5	1.76	8.38	6.93(P63Y)	>50.00(P31X)##	2.32(e10)	7.65(S3H)	76
XSS1/C1	NA	NA					NA

* The ASME stress ratio is based on the Level D stress limit; it was calculated using the 1980 edition of the ASME Code.

** A/B refers to the A/B load for the snubber.

The term in parenthesis, (), designates the location of the measured quantity.

Accelerometer saturated at 50 g.

TABLE 3.3: PEAK BASE MOTION AND PEAK PIPE RESPONSE FOR PIPELINE WITH BRANCH LINES

	Measured Base Motion		Measured Pipe Response			Support Condition	
Test/Run	Displacement(in.)	Acceleration(g)	Absolute Displacement (in.)	Acceleration (g)	ASME Stress Ratio*	Support Load (kip)	Percent of A/B**
XPO1/C1	NA	NA	0.03(PM53X)#	NA		-0.09(S2UP)	NA
XIM1/C1	0.32	-6.00	0.56(PM31X)	-4.85(PM53X)	0.44(PM55)	-1.60(S2UP)	NA
XIM2/C1	0.36	-5.95	0.61(PM31X)	-6.13(PM53Y)	0.53(PM55)	-2.02(S2UP)	NA
XIM3/C1	0.56	-6.16	0.92(PM31X)	8.12(PM53Y)	0.57(PM55)	2.28(S2UP)	NA
XIM4/C1	1.04	-4.80	1.86(PM53X)	-10.04(PM33X)	0.72(PM55)	4.08(S2LOW)	NA
XIM5/C1	1.62	-5.32	2.68(PM33X)	-38.19(PM53Y)	1.08(PM55)	5.12(S2LOW)	NA
XIM1/C2	0.18	-2.98	0.46(PM53X)	4.98(PM33X)	0.49(PM55)	-1.91(S2UP)	NA
XIM2/C2	0.28	-3.55	0.65(PM53X)	- 6.62(PM53X)	0.53(PM55)	-2.16(S2UP)	NA
XPO1/C2	NA	NA	0.04(PM31X)	NA	0.25(PM55)	-0.03(S2UP)	NA
XIM3/C2	1.20	5.00	1.92(PM31X)	11.89(PM33X)	0.75(PM13)	4.13(S2LOW)	69
XIM4/C2	1.61	-5.69	2.68(PM53X)	-14.92(PM53X)	0.93(PM13)	4.98(S2LOW)	83
XIM5/C2	1.04	-9.79	1.80(PM31X)	13.47(PM33X)	0.78(PM55)	4.18(S2LOW)	70
XIM6/C2	1.53	-10.83	2.56(PM31X)	-14.69(PM53X)	0.92(PM55)	5.37(S2LOW)	90
XSTD/C2	0.50(S3X)	NA	0.52(PM63X)	NA	0.49(PM55)	-0.22(S2UP)	4
XIM7/C2	0.44	-7.49	1.18(PM53X)	7.75(PM53X)	0.57(PM55)	-2.4 (S2UP)	40
XEQ1/C2	0.30	0.74	0.64(PM31X)	-3.16(PM33X)	0.68(PM55)	-1.08(S2LOW)	18
XEQ2/C2	0.50	1.40	-1.42(PM33X)	6.05(PM33X)	0.94(PM55)	3.09(S2LOW)	52
XIM1/C3	0.36	-6.68	0.58(PM31X)	8.17(PM53X)	0.45(PM55)	-1.95(S2LOW)	19
XIM2/C3	1.08	-9.21	1.81(PM31X)	13.01(PM53X)	0.70(PM13)	3.88(S2UP)	NA
XIM3/C3	0.85	-10.62	2.28(PM53X)	13.54(PM53X)	0.80(PM55)	4.32(S2UP)	NA
XEQ3/C2	-1.01	-0.59	-1.06(PM31X)	2.29(PM33X)	0.74(PM55)	-1.97(S2LOW)	33
XIM8/C2	1.10	-9.39	1.91(PM53X)	13.34(PM53X)	0.74(PM55)	4.21(S2LOW)	70
XEQ4/C2	-0.47	0.73	-0.50(PM53X)	-2.39(PM33X)	0.46(PM55)	-1.76(S2LOW)	29
XEQ5/C2	-1.72	-1.48	-2.23(PM31X)	-5.02(PM21X)		-1.13(S2LOW)	19
XEQ6/C2	-2.18	2.13	-2.80(PM31X)	-6.38(PM21X)	0.91(PM81)	1.37(S2LOW)	23
XEQ7/C2	2.54	4.75	3.43(PM31X)	-8.48(PM21X)	1.01(PM81)	-1.88(S2LOW)	31
XIM9/C2##	-0.94	-7.25	-0.84(PM31X)	-9.16(PM33X)	0.75(PM15)	-1.69(S2UP)	NA

TABLE 3.3 (Concluded)

	Measured Base Motion		Measured Pipe Response			Support Condition	
Test/Run	Displacement(in.)	Acceleration(g)	Absolute Displacement (in.)	Acceleration (g)	ASME Stress Ratio*	Support Load (kip)	Percent of A/B**
XEQ8/C2	0.61	0.84	0.82(PM33X)	3.27(PM33X)	0.61(PM81)	-0.71(S2LOW)	12
XEQ9/C2	2.43	4.11	3.34(PM33X)	-11.26(PM33X)	1.12(PM15)	-2.35(S2LOW)	39

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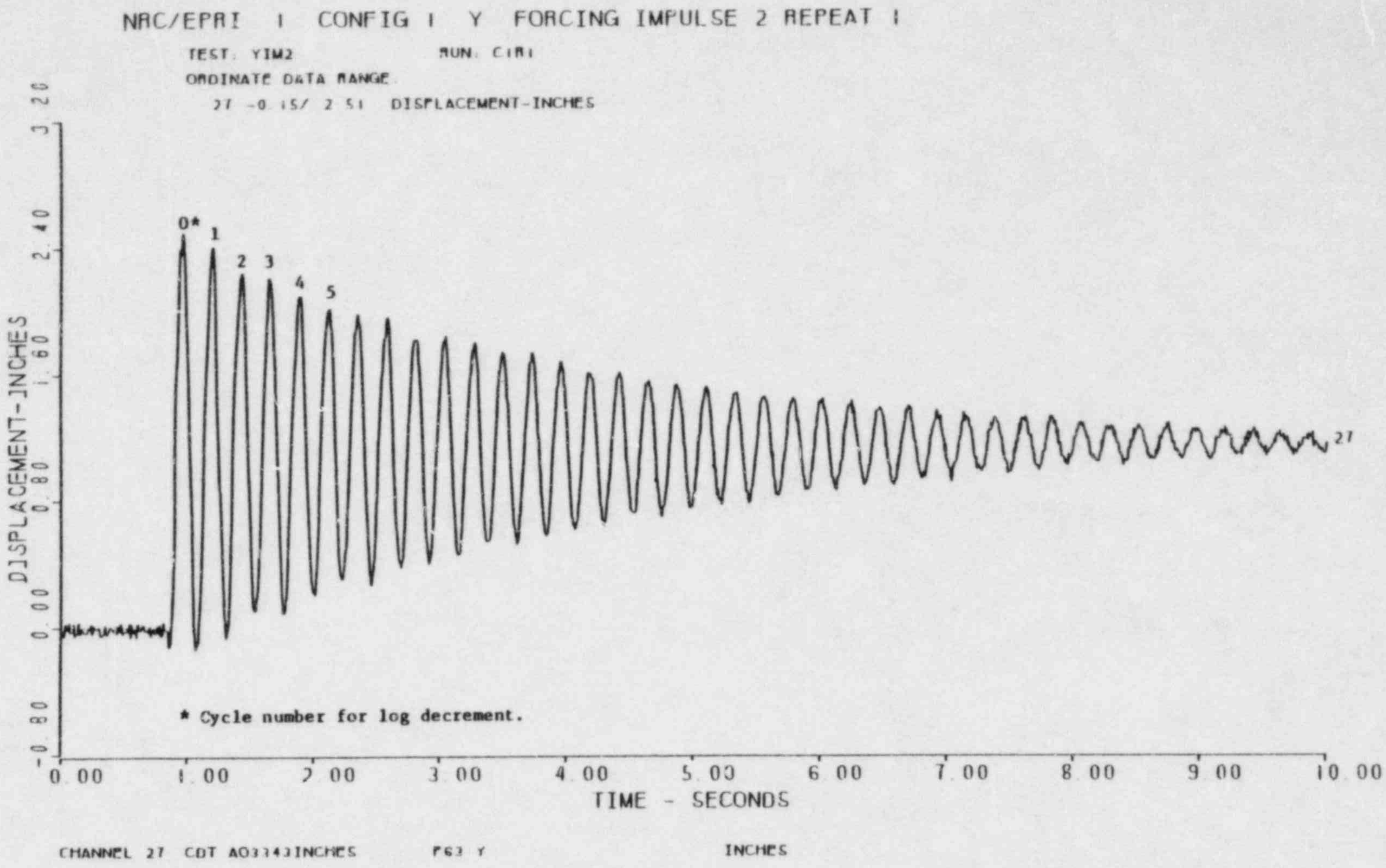
* The ASME stress ratio is based on the Level D stress limit; it was calculated using the 1980 edition of the ASME Code.

** A/B refers to the A/B load for the snubber.

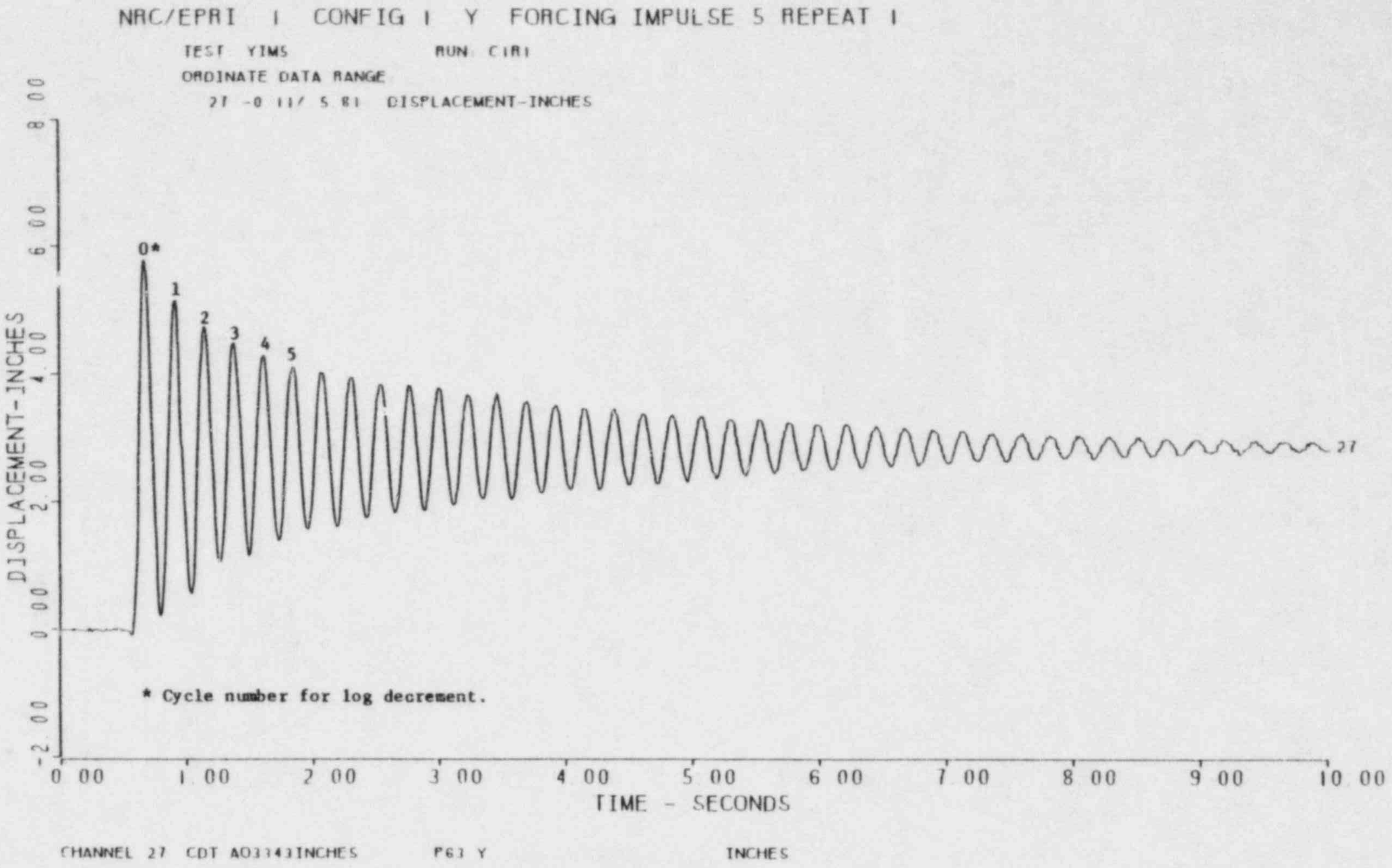
The term in parenthesis, (), designates the location of the measured quantity.

The last three tests were conducted with the branch line, connected to the base at S4, removed.



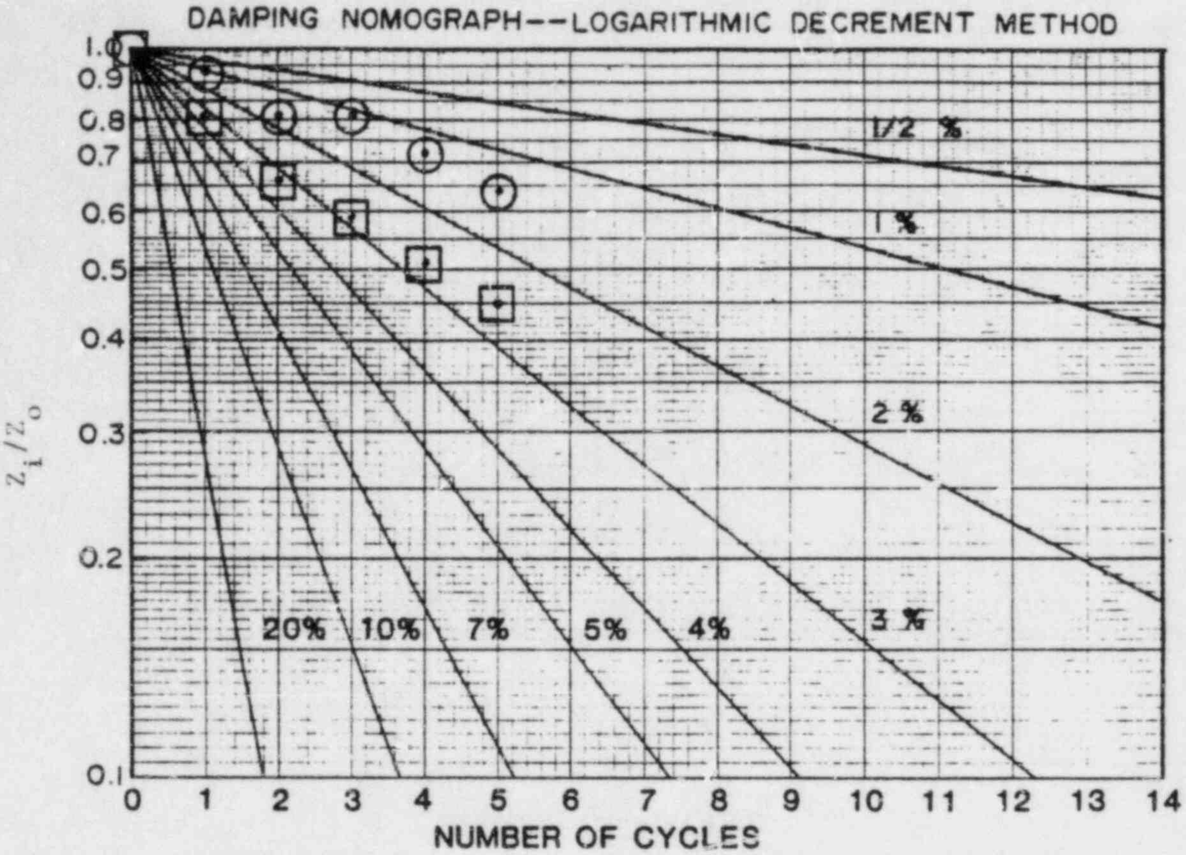
(a) Transient Response for Lower Level Test

Figure 3.1: Log Decrement Damping for Configuration 1--First Mode



(b) Transient Response for Higher Level Test

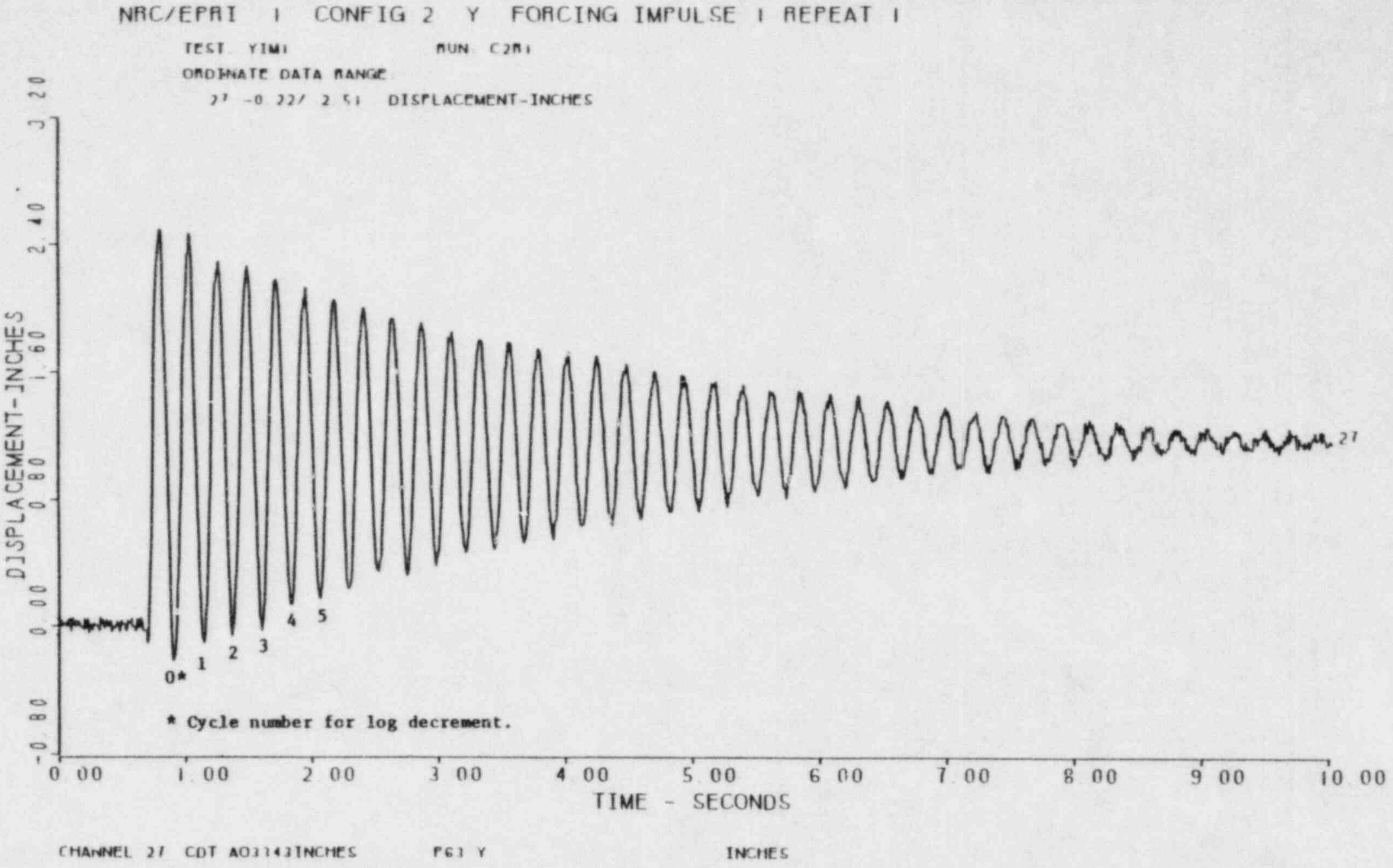
Figure 3.1 (Continued)



Test/Run	Symbol	Peak ASME Stress Ratio (Level D)
YIM2/C1R1	○	0.76
YIM5/C1R1	□	1.18

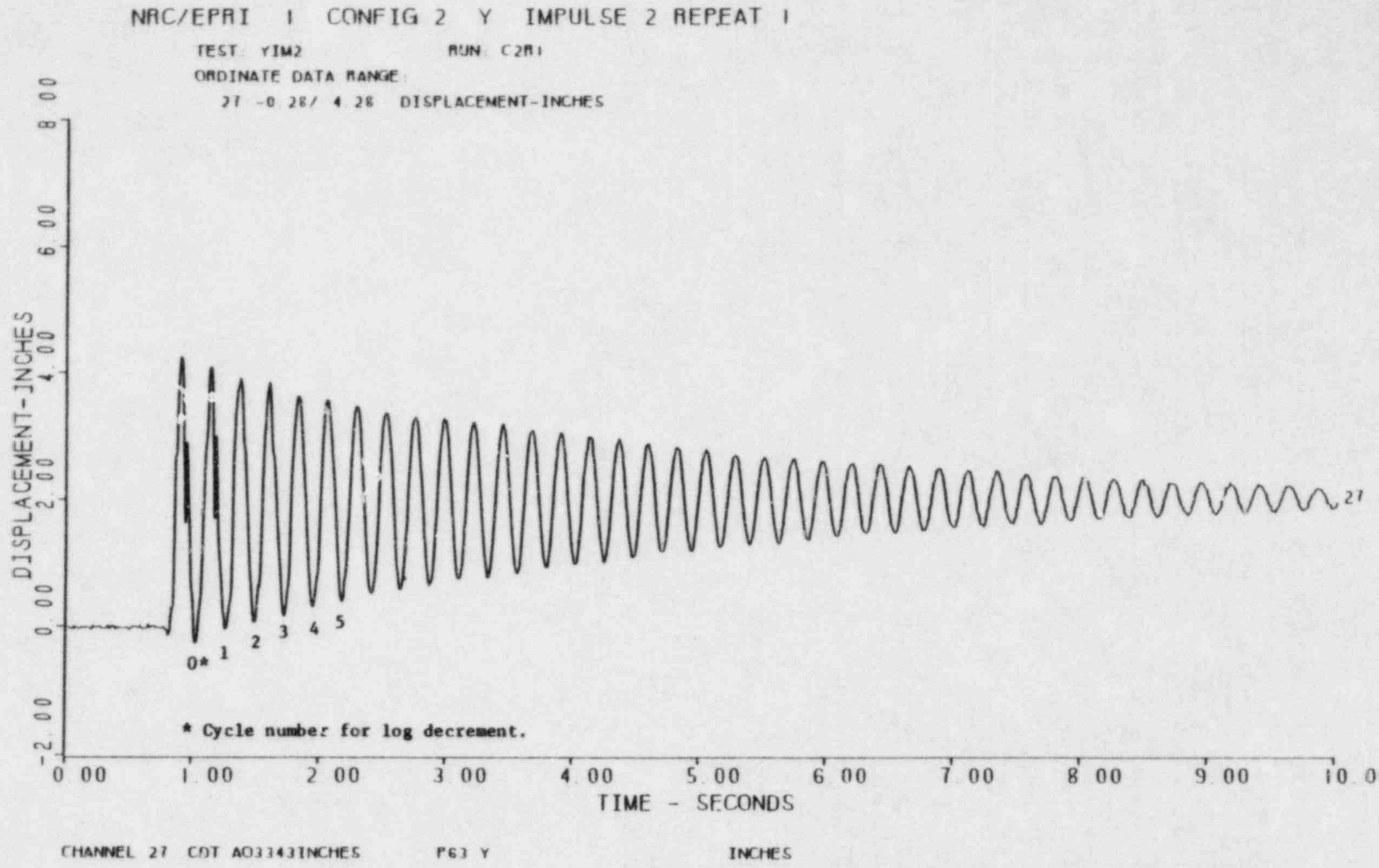
(c) Damping Nomograph

Figure 3.1 (Concluded)



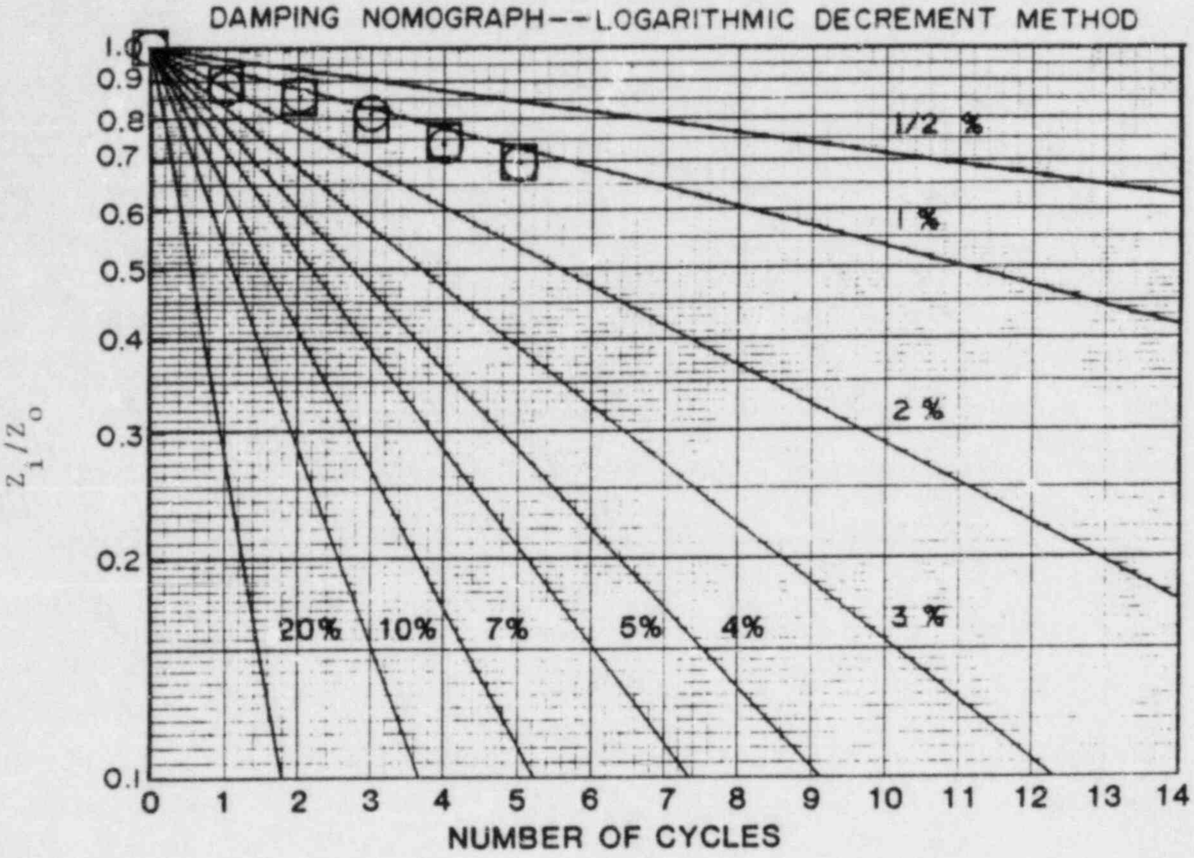
(a) Transient Response for Lower Level Test

Figure 3.2: Log Decrement Damping for Configuration 2--First Mode



(b) Transient Response for Higher Level Test

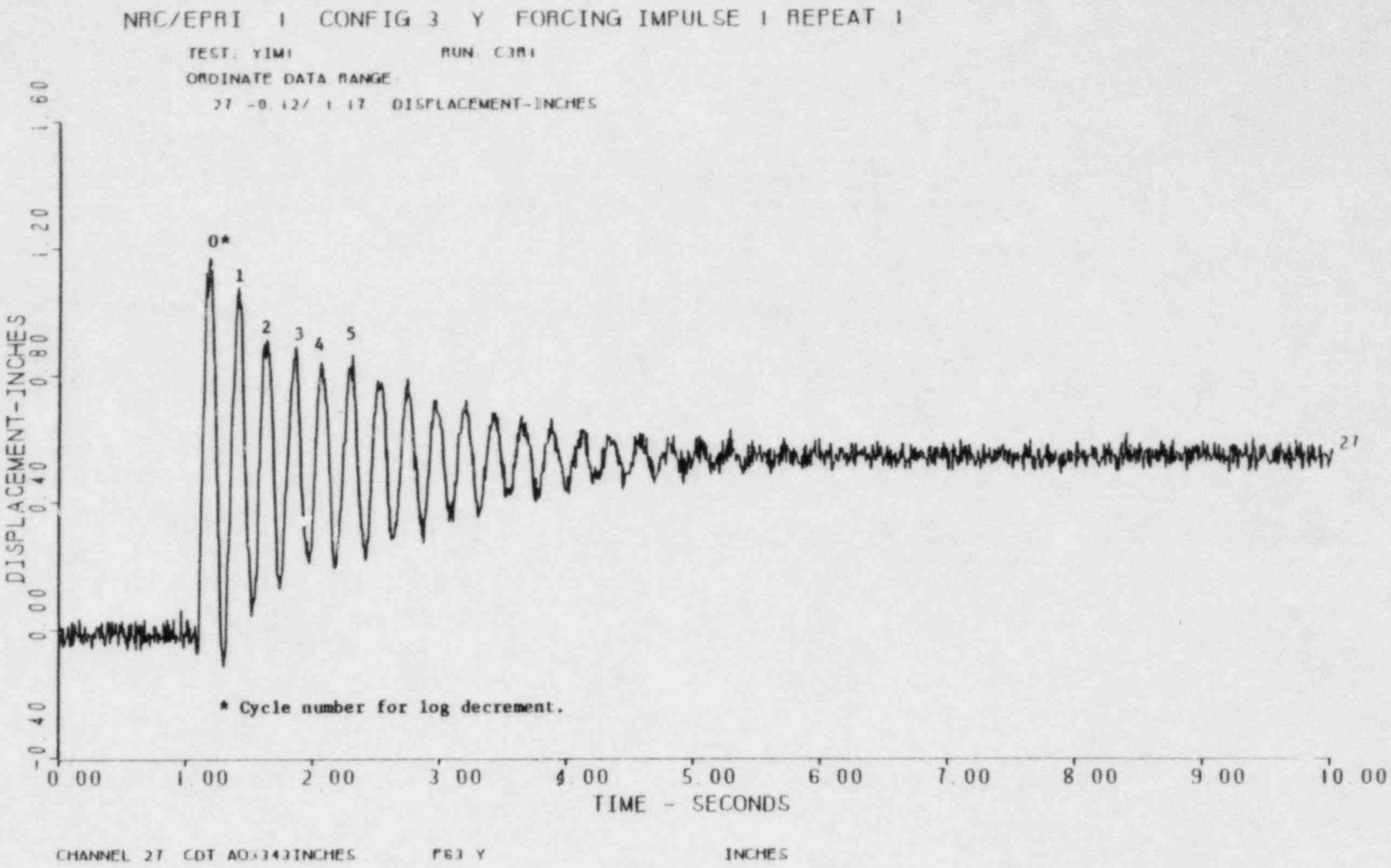
Figure 3.2 (Continued)



Test/Run	Symbol	Peak ASME Stress Ratio (Level D)
YIM1/C2R1	○	0.75
YIM2/C2R1	□	1.08

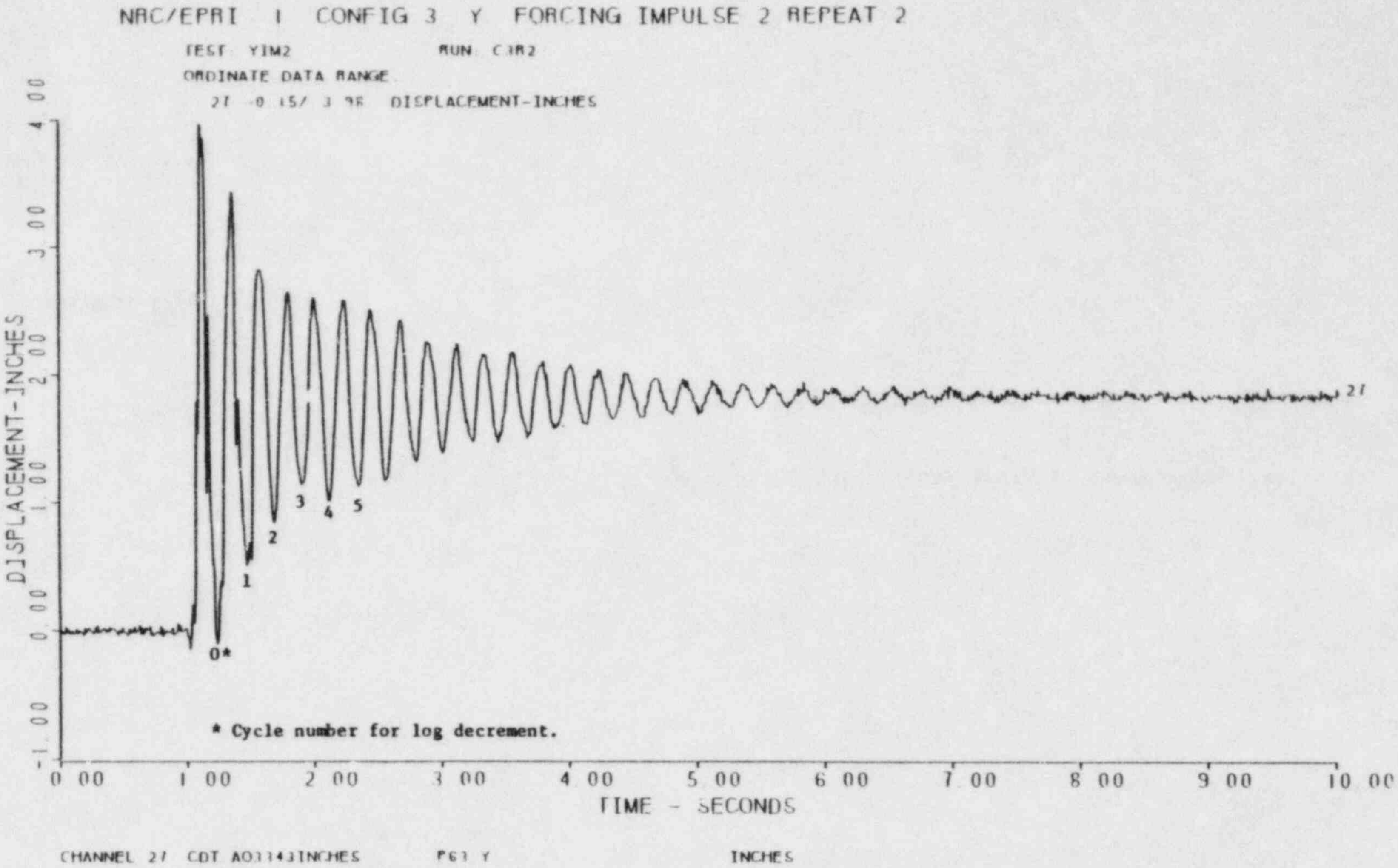
(c) Damping Nomograph

Figure 3.2 (Concluded)



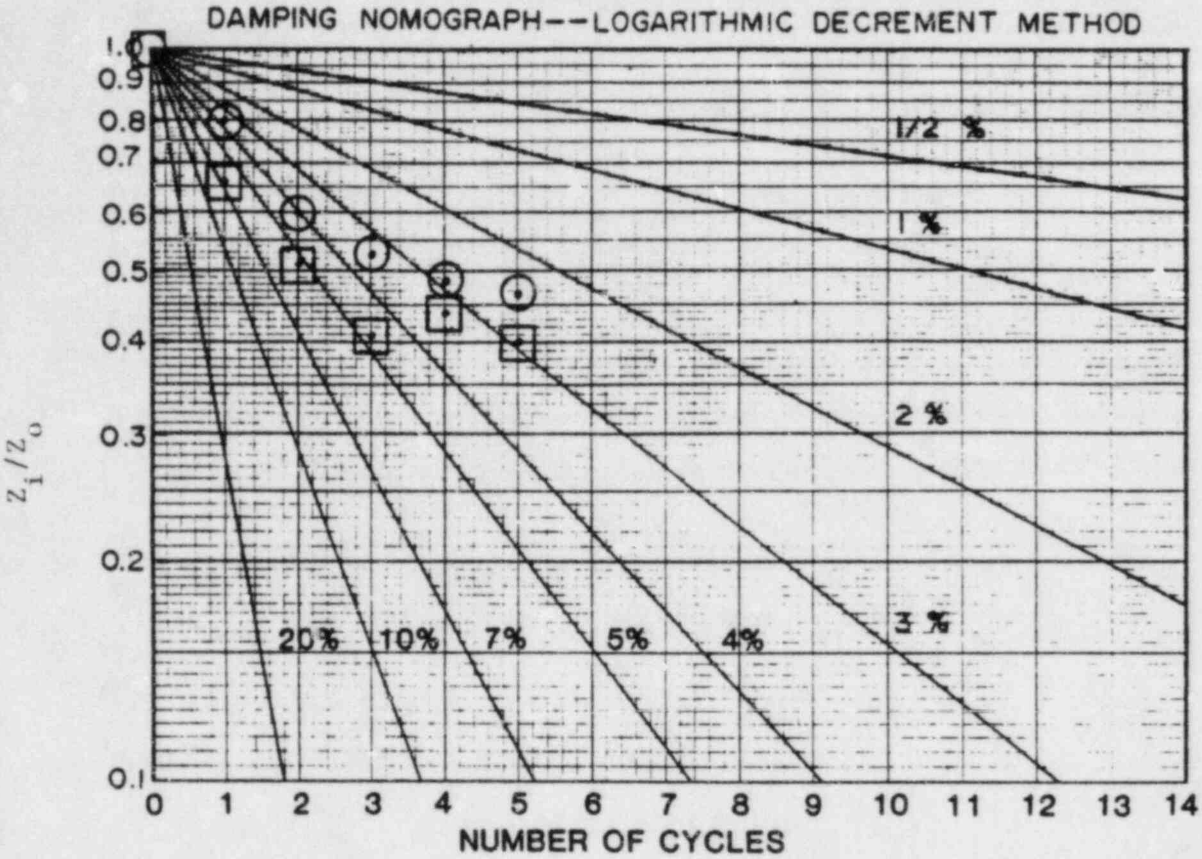
(a) Transient Response for Lower Level Test

Figure 3.3: Log Decrement Damping for Configuration 3--First Mode



(b) Transient Response for Higher Level Test

Figure 3.3 (Continued)



Test/Run	Symbol	Peak ASME Stress Ratio (Level D)
YIM1/C3R1	○	0.57
YIM2/C3R2	□	1.04

(c) Damping Nomograph

Figure 3.3 (Concluded)

The preliminary results for Configuration 1 (all-struts) indicate damping of about 2% and 3% for the tests with a peak stress ratio of 0.76 and 1.18, respectively. The damping remained fairly constant, for a given test, over the five cycles of data shown.

The results for Configuration 2 (struts plus one mechanical snubber) show a damping of about 2% for both tests. The damping was the same for both tests for the five cycles of data shown. The damping was essentially the same for Configurations 1 and 2 for the lower amplitude test.

The results for Configuration 3 indicate a damping of about 4% and 5% for the tests with a peak stress ratio of 0.57 and 1.04, respectively. The damping remained fairly constant for the first two or three cycles.

It was not possible to calculate log decrement damping using the test data in its present form (unfiltered) for the pipeline with branch lines.* This was due to the fact that all the test data showed the influence of two or more modes, as shown in Figure 3.4. Before it will be possible to use this method for obtaining the damping, the data will need to be filtered.

3.3 General Observations

Several things were observed and/or learned during this test series. They deal with: (1) problems that developed from the loosening of bolts in the system; (2) the fact that separate bases can be used as an excellent method for driving a piping system with earthquake like motions; (3) a need for user-friendly, sophisticated, and effective software for calculating damping from time histories which are affected by two or more modes, and slight nonlinearities; and (4) the fatiguing of Elbow 8 to failure in the pipeline with branch lines during long duration sine dwell tests.

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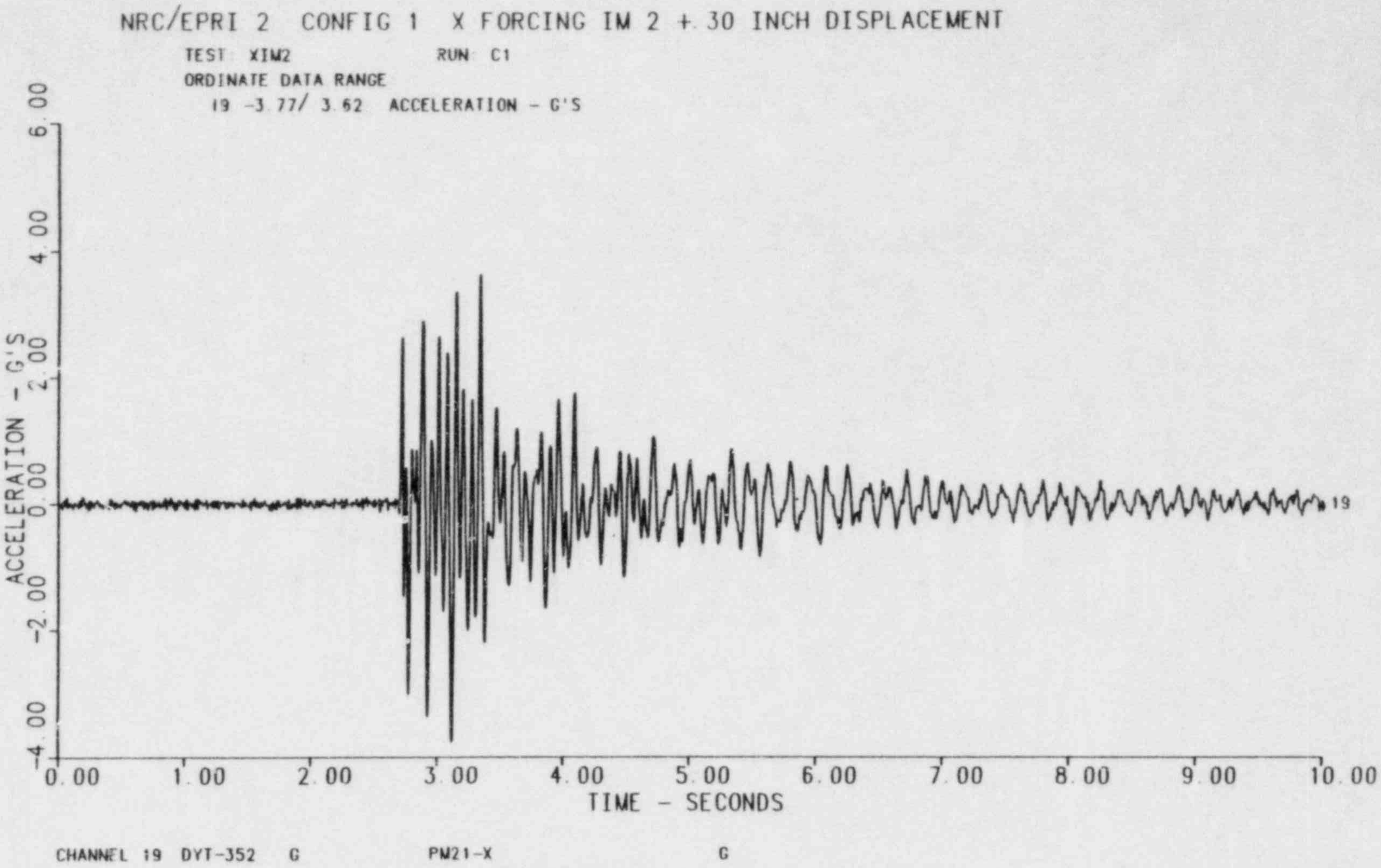
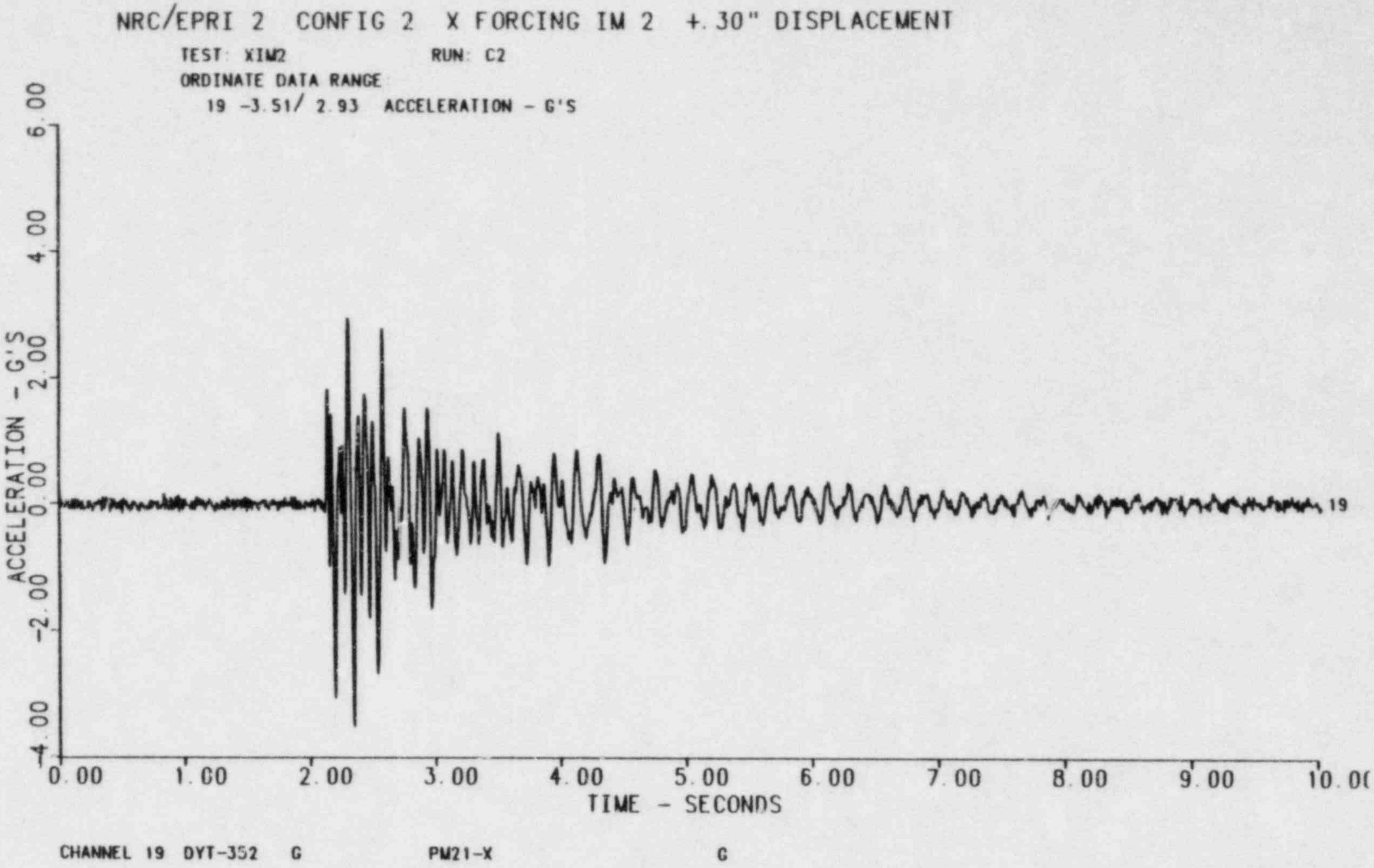
* Prior work has suggested that the log decrement method gives the most consistent assessment of damping in piping systems with slight stiffness nonlinearities [3].



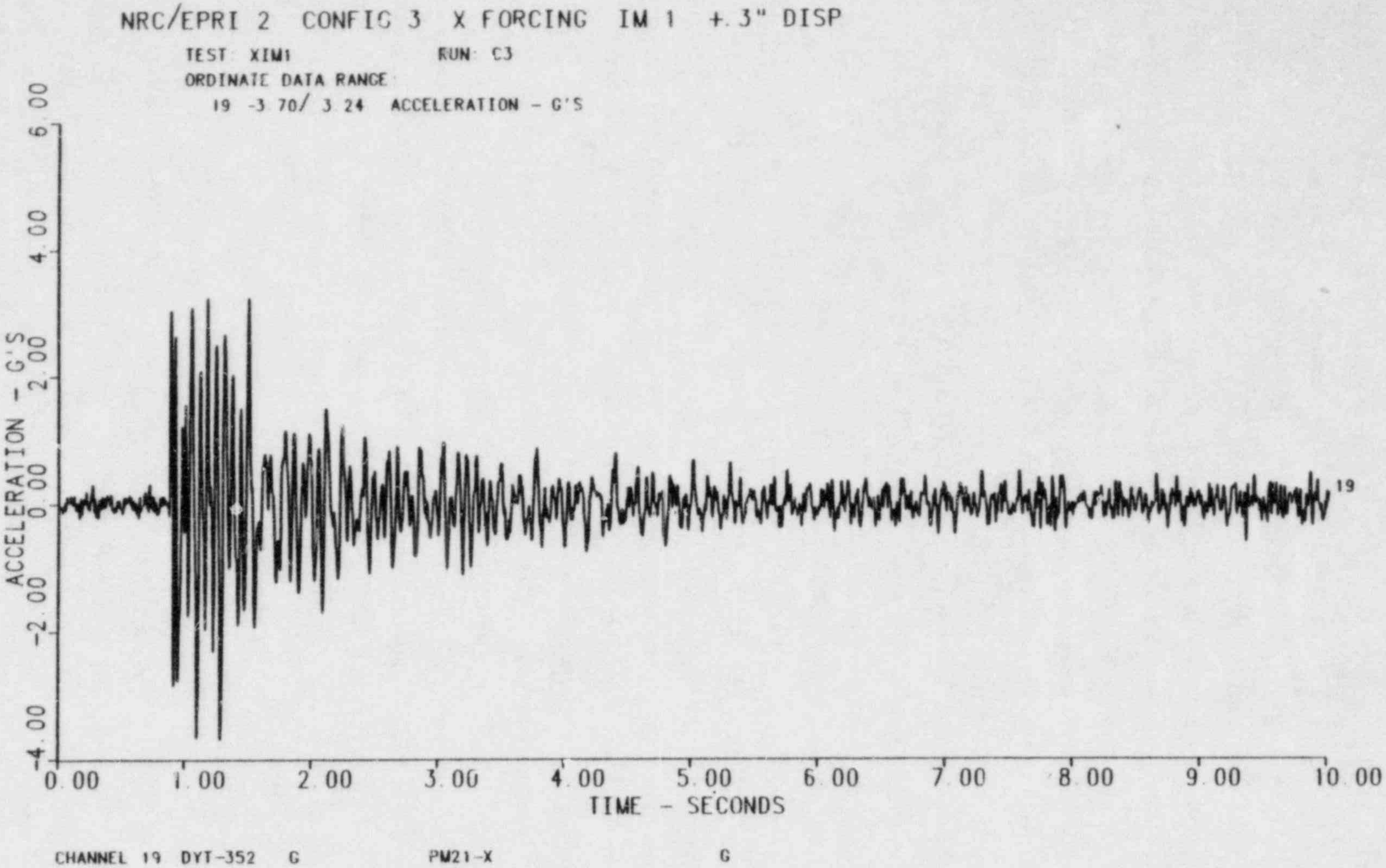
(a) Configuration 1

Figure 3.4: Typical Acceleration Time Histories



(b) Configuration 2

Figure 3.4 (Continued)



(c) Configuration 3

Figure 3.4 (Concluded)

During the earliest stages of testing with the first pipeline some irregularities began to show up in the test data. Before an early earthquake test, the first natural frequency of the system was 4.3 Hz. After the test, it was 3.8 Hz. Also, the calculated damping for the first mode was unusually high. The source of these problems were bolts in the bases which were gradually working loose. The damping increased as the bolts became looser because of the increasing Coulomb friction. The bolts were tightened and the first natural frequency and corresponding damping checked. The frequency was 4.4 Hz, and the damping was lower. At this point, a procedure was implemented dealing with the regular tightening of the bolts. Selected bolts (about one-third of the total number) were tightened after each test. All the bolts were tightened at least once each day. This procedure was adhered to strictly throughout the remainder of the program, and the tests repeated after this problem was detected and corrected.

The bases used for these tests had to be designed to withstand the loads generated during the testing. The pipe-end bases for the mainline (8 in. pipeline) had to be especially strong, because they had to provide clamped points for the pipeline and thus, they had substantial moments exerted on them. From the design and testing process, it was demonstrated that it is possible to build a reasonably light base that will not deform substantially during testing. The peak accelerations of these bases, in the nonforcing directions, was generally about one-twentieth that of the peak acceleration in the forcing direction. It is believed that those smaller accelerations were due to noise, and reflect only very small displacements. Both the pipe-end bases and the mid-point bases withstood the loading due to the testing very well. No failures of any of the base components were experienced.

The second pipeline was tested, in part, using both single-point random and single-point sine dwell methods.* The bases were held fixed by replacing the hydraulic actuators with steel beams. During one of the sine dwell

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* Conducted in conjunction with EG&G Idaho, at request of the Nuclear Regulatory Commission.

tests, Elbow 8 developed a series of small through-wall cracks on its underside and the pipe pressure dropped to zero (0 psig). Apparently, the fatigue usage factor, for that component, became equal to or greater than one. At this point, the pipeline was drained and the elbow was radiographed. The x-rays revealed four small cracks, one of which was barely visible on the pipe. The flaws in the elbow were then ground out, and the elbow was then x-rayed again. This indicated that the elbow was ready for welding. After the elbow was welded, the welds were checked using a dye penetrant. After this, the sine dwell testing was resumed, but at a reduced stress level--at about Level B stress for Elbow 8. There were no noticeable problems with the elbow for the duration of the testing--the pipe internal pressure never dropped from about 1,150 psig.

3.4 Apparent Safety Margin Results

Multiple tests were conducted of the various piping runs with dynamic inputs that exceeded those necessary to just achieve a peak stress equal to the Level D stress limit in the Class 2 systems. To obtain a preliminary assessment of the seismic safety margin apparent in the test program, the most severe earthquake test of the first pipeline (no branch lines) was examined. The pipeline was pressurized to 1,150 psig and driven with a 20-sec input time history that included a peak input acceleration of 8.4 g. To show the severity of that input, the input response spectrum is compared in Figure 3.5 to the input required to just achieve the Level D stress condition in the piping system. The Level D input was determined from previous tests employing the identical time history, but at amplitudes inducing stresses less than the Level D condition*. It may be seen that this severe test was about a factor of four greater than the input necessary to match the Level D stress limits in the frequency region of interest for

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* The Level D spectra was based upon test results for the unbranched system with mechanical snubbers, while the upper curve in Figure 3.5 is for the configuration with hydraulic snubbers. This was necessary because no data existed for the hydraulic configuration at less than the Level D stress condition. Because of the similarity in stress results between configurations, the comparison in Figure 3.5 is satisfactory.

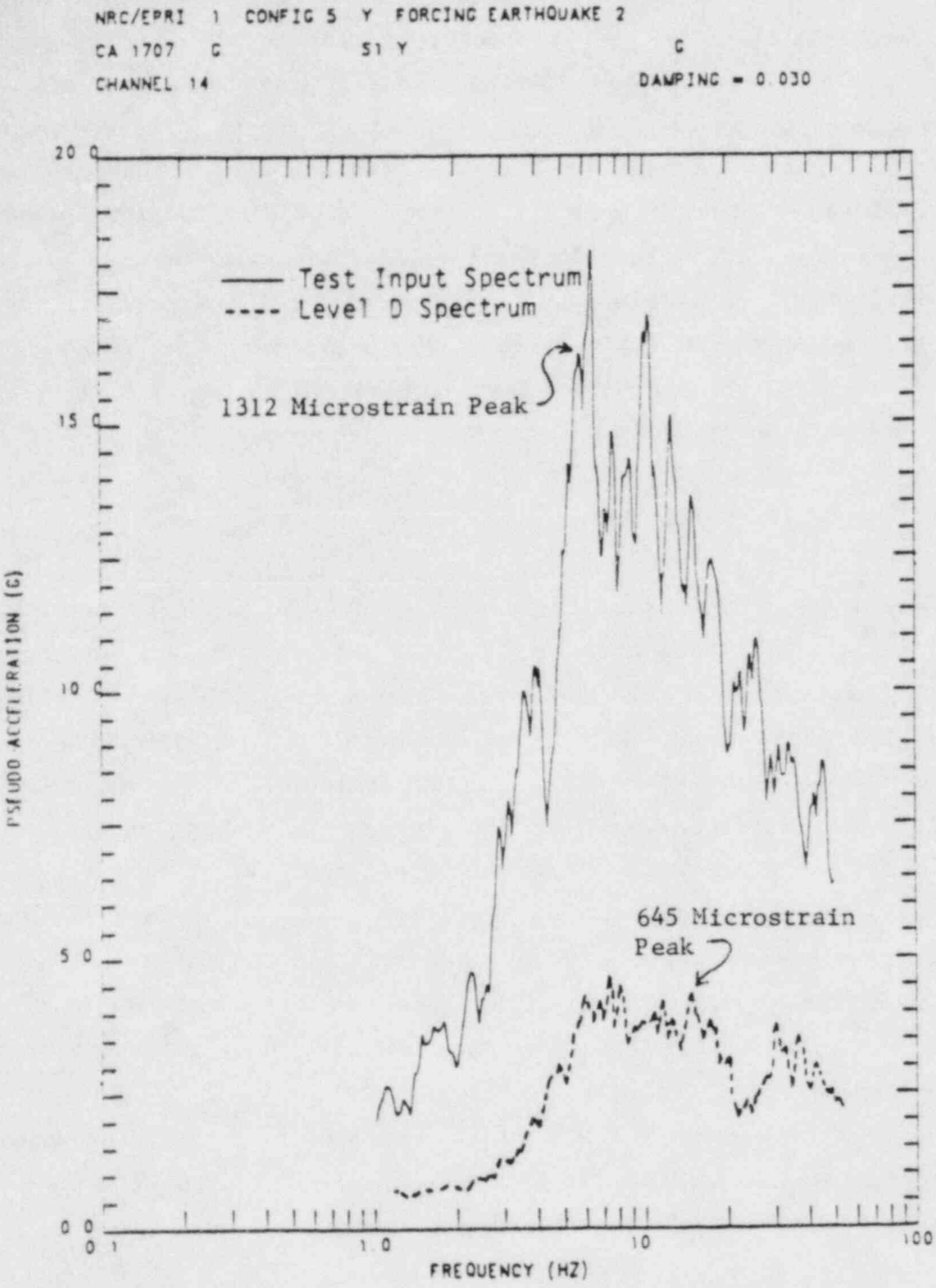

Figure 3.5: Input Response Spectra Comparison

the first piping system. That is, the piping system successfully withstood an earthquake input about four times greater than the Code design rules would indicate to be acceptable. The piping system, in fact, withstood several severe dynamic tests with no gross distortion or loss of pressure retaining capacity.

Also shown in Figure 3.5 are the peak pipe strain values sensed by a single strain gauge during the earthquakes which resulted in the indicated response spectra. The listing of peak strains for the pipeline without branch lines for all gauges recorded during the two earthquake events are shown in Appendices D and E. It should be noted that the Level D spectra and strain are derived by linearly scaling up an earthquake run which resulted in a stress ratio less than 1.0 (i.e., less than Level D condition). Appendix F contains the peak strain listing for the most severe of the seismic tests for the pipeline <u>with</u> two branch lines. It should also be noted that the maximum strain recorded is most probably <u>not</u> the maximum strain that occurred in the piping system. The strain histories can be used to establish the maximum strains at a given cross-section as long as the response remains linear. Load redistribution occurs when the piping undergoes yield.

3.5 Fatigue Considerations

Any assessment of the fatigue suffered by the piping systems must await detailed data interpretation to be conducted at a later date. Such an assessment should count stress cycles and amplitudes, considering that the different input directions, load types, and amplitudes will change the location of the maximum pipe stress. However, it is possible herein to assess pipe capacity to withstand dynamic events in terms of the number of loading events.

For example, the main pipeline (no branch lines) was subjected to the number of tests shown in Table 3.4 without apparent damage. As may be seen, the pipeline suffered 9 earthquakes which produced stresses exceeding the Level D stress limits and a total of 14 earthquakes exceeding the Level B

TABLE 3.4: LOADING EVENT SUMMARY FOR MAIN PIPELINE (NO BRANCH LINES)

Event Description	Number of Events
Impulse Tests Above Level B, Below Level D Stress Limit	24
Impulse Test Equal to or Greater Than Level D Stress Limit	3
Earthquakes Below Level B (OBE) Stress Limit	5
Earthquakes Above Level B (OBE), Below Level D (SSE) Stress Limit	5
Earthquakes Above Level D (SSE) Stress Limit	9

limit. Stated another way, the tested pipeline successfully withstood 14 earthquakes larger than that which can be interpreted as the piping system's Operating Basis Earthquake, including 9 earthquakes equal to or greater than the system's Safe Shutdown Earthquake. Additionally, the pipeline successfully withstood 27 impulse tests at stress levels above the Level B stress limit including three above the Level D stress limit. One interpretation of the system behavior is that it successfully withstood 5 OBEs, 9 SSEs and nearly 30 other strong system transients.

3.6 Data Tapes Generated

Several complete sets of data tapes have been generated. Two of them (one for the NRC and one for EPRI) have the following format and characteristics:

- 800 BPI
- ASCII
- 80 characters/record
- 40 records/block
- no label

4.0 COMMENTS AND CONCLUSIONS

Following are some preliminary comments/conclusions for the test program:

- The piping system withstood, with no apparent damage, seismic inputs which were aproximately four times greater than that which would produce the maximum pipe stresses considered acceptable for design.
- The piping demonstrated a capacity to withstand, without gross deformation or collapse, more severe loading than 5 Operating Basis Earthquakes, 9 Safe Shutdown Earthquakes, and nearly 30 severe shock loads*.
- The observed damping values at response levels from one-half to three-quarters of yield ranged from 2 % to 4% for the strut and mechanical snubber supports. The damping values for the response at about yield were from 3% to 5% for the same support configurations. The all-mechanical-snubber supports piping system were more damped than the system with all strut supports.
- When a piping system is excited to high enough levels to cause plastic deformation in various components, the load/stress distribution throughout the pipeline will change over time. This should be taken into account when strain gauging a test pipeline.
- In testing laboratory piping systems with bolts at highly stressed or vibrating locations, the bolts must be tightened repeatedly. Not doing so can result in erroneous determined values for the natural frequencies and modal damping.
- Separate bases (one-dimensional shake tables) can be used very effectively for supporting and exciting piping systems with earthquake-like motions. Bases can be designed which will provide a variety of support conditions, ranging from clamped to snubber-type connections.
- There is a present need to develop software which will correctly calculate effective damping for multiple mode systems with slight nonlinearities.

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* "More severe than" refers to the fact that many of the dynamic events generated pipe loads exceeding rather than equaling the OBE and SSE stress limits.

5.0 REFERENCES

1. G. E. Howard, et al., "Piping Extreme Dynamic Response Studies," Paper F4/5, Seventh International Conference on Structural Mechanics in Reactor Technology (SMIRT), Chicago, August 22-26, 1983; also, Nuclear Engineering and Design, 77 (1984), 405-417.

2. P. Bezler, et al., "In-Situ and Laboratory Benchmarking of Computer Codes Used for Dynamic Response Predictions of Nuclear Reactor Piping," NUREG/CR-3340, May 1983.

3. D. E. Chitty, G. E. Howard, W. B. Walton, "Damping in Nonlinear Piping Systems," Paper 82-WA/PVP-10, American Society of Mechanical Engineers, Winter Annual Meeting, Phoenix, November 1982.

APPENDIX D

PEAK RESPONSE FOR ALL DATA CHANNELS--HIGH LEVEL EARTHQUAKE FOR PIPELINE WITHOUT BRANCH LINES (TEST YEQ2, RUN C5)

The peak (maximum) values of response, for each data channel, are given in this appendix for Test YEQ2, Run C5 for the first pipeline tested. A description of the transducer locations can be found in Figure 2.10 and Tables 2.8 and 2.9. The strain gauge locations/orientations, given herein, are indicated by (1) elbow number, (2) direction of outward normal vector (to the pipe) at strain gauge location, and (3) the specification of the local orientation of a gauge as being either axial (A), "vector" (V), or circumferential (C). The direction of the normal vector (to the pipe) is either X, Y, or Z. The local orientations A, V, and C refer to the strain gauge being parallel to the pipe centerline, 45° from the A-direction, or in a circumferential direction (90° from the A-direction), respectively.

06-27-83, 09:00
SAG

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                    DATA CHANNEL PEAK VALUES

   C/EPRI  1  CONFIG 5  Y  FORCING EARTHQUAKE 2
 TEST- YEQ2 RUN- C5   DATE-  6/23/83 TIME- 14:17:34

MAXIMUM AT      TIME
 CHANNEL         SEC         VALUE

   + 1           6.12      8.316E 00      G              P21 Y
   - 1           6.62     -9.231E 00      G

   + 2           6.75      1.177E 01      G              P31 X
   - 2           6.80     -8.561E 00      G

   + 3          16.87      7.560E 00      G              P35 X
   - 3           7.85     -7.534E 00      G

   + 4           7.87      1.015E 01      G              P35 Z
   - 4          12.95     -1.023E 01      G

   + 5           4.13      6.738E 00      G              P41 Y
   - 5           6.38     -1.023E 01      G

   + 6           6.94      6.889E 00      G              P61 X
   - 6           6.68     -7.368E 00      G

   + 7          10.77      1.271E 01      G              P71 Y
   - 7           6.38     -1.181E 01      G

   + 8          13.10      7.969E 00      G              P71 Z
   - 8           8.01     -9.425E 00      G

   + 9           6.52      1.018E 01      G              P73 Y
   - 9           8.03     -1.142E 01      G

   +10           6.49      1.017E 01      G              P75 Y
   -10           6.63     -9.107E 00      G

   +11          13.89      6.248E 00      G              P75 Z
   -11           8.02     -6.541E 00      G

   +12           8.14      5.204E 00      G              P95 X
   -12           8.03     -6.572E 00      G

   +13           7.46      3.650E-01      G              S1 X
   -13           8.23     -5.100E-01      G

   +14          14.65      5.145E 00      G              S1 Y
   -14          12.40     -5.555E 00      G

   +15           4.12      2.700E-01      G              S1 Z
   -15          10.90     -3.600E-01      G

   +16           4.05      1.404E 01      G              S2H Y
   -16          17.54     -8.955E 00      G
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06-27-83, 09:00
SAG

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                         DATA CHANNEL PEAK VALUES

      C/EPRI  1  CONFIG 5  Y  FORCING EARTHQUAKE 2
     TEST- YEQ2 RUN- C5   DATE-  6/23/83 TIME- 14:17:34

    MAXIMUM AT      TIME
     CHANNEL         SEC          VALUE

       +17          4.05       1.521E 01      G             S2V Y
       -17          4.07      -1.938E 01      G

       +18         16.80       6.360E 00      G             S3H Y
       -18         17.55      -8.595E 00      G

       +19         16.80       7.335E 00      G             S3V Y
       -19         17.55      -9.870E 00      G

       +20          8.12       2.450E-01      G             S4 X
       -20          8.26      -1.200E-01      G

       +21         16.34       4.675E 00      G             S4 Y
       -21         12.39      -6.025E 00      G

       +22         23.84       8.600E-01      G             S4 Z
       -22          6.76       7.100E-01      G

       +23          4.48       2.960E 00      INCHES        S1 Y
       -23          4.09      -2.897E 00      INCHES

       +24          6.38       5.030E 00      INCHES        P23 Y
       -24          7.67      -4.290E 00      INCHES

       +25          6.38       6.155E 00      INCHES        P43 Y
       -25          7.68      -5.300E 00      INCHES

       +26          2.39       9.500E-02      INCHES        S2H X
       -26         12.47      -3.125E-01      INCHES

       +27          6.37       7.770E 00      INCHES        P63 Y
       -27          7.67      -7.230E 00      INCHES

       +28          6.38       7.530E 00      INCHES        P71 Y
       -28          7.67      -7.205E 00      INCHES

       +29          6.38       5.520E 00      INCHES        P75 Y
       -29          7.67      -5.415E 00      INCHES

       +30         17.75       6.475E-01      INCHES        S3H X
       -30          3.67      -2.625E-01      INCHES

       +31          6.38       4.485E 00      INCHES        P93 Y
       -31          7.67      -4.645E 00      INCHES

       +32          4.48       2.848E 00      INCHES        S4 Y
       -32          4.08      -2.915E 00      INCHES
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06-27-83, 09:00
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                          DATA CHANNEL PEAK VALUES

  C/EPRI  1  CONFIG 5  Y  FORCING EARTHQUAKE 2
TEST- YEQ2 RUN- C5   DATE-  6/23/83 TIME- 14:17:34

MAXIMUM AT       TIME
 CHANNEL          SEC          VALUE

    +33          7. 69       4. 425E 02       MICROSTRAIN  ELBOW 1 Y A
    -33          7. 81      -2. 550E 02       MICROSTRAIN

    +34          4. 57       5. 325E 02       MICROSTRAIN  ELBOW 1 Y V
    -34          6. 62      -4. 175E 02       MICROSTRAIN

    +35          4. 72       6. 925E 02       MICROSTRAIN  ELBOW 1 Y C
    -35          2. 84      -1. 775E 02       MICROSTRAIN

    +36         17. 68       3. 925E 02       MICROSTRAIN  ELBOW 1 Z A
    -36          7. 94      -3. 025E 02       MICROSTRAIN

    +37          6. 50       5. 425E 02       MICROSTRAIN  ELBOW 1 Z V
    -37          6. 37      -1. 750E 02       MICROSTRAIN

    +38          7. 95       8. 900E 02       MICROSTRAIN  ELBOW 1 Z C
    -38          8. 02      -4. 000E 01       MICROSTRAIN

    +39          7. 79       4. 775E 02       MICROSTRAIN  ELBOW 1 -Y A
    -39          4. 57      -1. 325E 02       MICROSTRAIN

    +40          4. 12       4. 350E 02       MICROSTRAIN  ELBOW 1 -Y V
    -40          6. 38      -1. 450E 02       MICROSTRAIN

    +41          7. 85       7. 575E 02       MICROSTRAIN  ELBOW 1 -Y C
    -41          7. 94      -1. 075E 02       MICROSTRAIN

    +42          6. 87       2. 800E 02       MICROSTRAIN  ELBOW 7 Y A
    -42          6. 91      -1. 400E 02       MICROSTRAIN

    +43          4. 26       4. 975E 02       MICROSTRAIN  ELBOW 7 Y V
    -43          6. 60      -1. 150E 02       MICROSTRAIN

    +44          6. 26       5. 675E 02       MICROSTRAIN  ELBOW 7 Y C
    -44          6. 83       7. 000E 01       MICROSTRAIN

    +45          2. 84       7. 250E 02       MICROSTRAIN  ELBOW 7 Z A
    -45         17. 65      -4. 525E 02       MICROSTRAIN

    +46          8. 17       4. 300E 02       MICROSTRAIN  ELBOW 7 Z V
    -46         14. 07       5. 500E 01       MICROSTRAIN

    +47          6. 83       8. 200E 02       MICROSTRAIN  ELBOW 7 Z C
    -47          6. 26      -1. 275E 02       MICROSTRAIN

    +48          6. 91       3. 250E 02       MICROSTRAIN  ELBOW 7 -Y A
    -48          6. 87      -2. 000E 02       MICROSTRAIN
```

06-27-83, 09:00
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                              DATA CHANNEL PEAK VALUES

  C/EPRI  1  CONFIG 5  Y  FORCING EARTHQUAKE 2
TEST- YEQ2 RUN- C5   DATE-  6/23/83 TIME- 14: 17: 34

MAXIMUM AT       TIME
 CHANNEL          SEC         VALUE

   +49            4. 12      4. 750E 02     MICROSTRAIN  ELBOW 7 -Y V
   -49           12. 95      3. 250E 01     MICROSTRAIN

   +50           14. 16      7. 600E 02     MICROSTRAIN  ELBOW 7 -Y C
   -50            6. 59     -4. 250E 01     MICROSTRAIN

   +51            6. 50      1. 105E 03     MICROSTRAIN  ELBOW 10 Y A
   -51            6. 63     -1. 020E 03     MICROSTRAIN

   +52            7. 67      3. 600E 02     MICROSTRAIN  ELBOW 10 Y V
   -52            6. 39     -6. 000E 01     MICROSTRAIN

   +53           13. 84      5. 625E 02     MICROSTRAIN  ELBOW 10 Y C
   -53            3. 56     -8. 750E 01     MICROSTRAIN

   +54            6. 49      2. 825E 02     MICROSTRAIN  ELBOW 10 Z A
   -54            6. 63     -7. 750E 01     MICROSTRAIN

   +55            6. 62      5. 025E 02     MICROSTRAIN  ELBOW 10 Z V
   -55            6. 49     -1. 500E 01     MICROSTRAIN

   +56            6. 62      5. 850E 02     MICROSTRAIN  ELBOW 10 Z C
   -56           12. 97      1. 375E 02     MICROSTRAIN

   +57            6. 63      1. 312E 03     MICROSTRAIN  ELBOW 10 -Y A
   -57            6. 49     -1. 005E 03     MICROSTRAIN

   +58            3. 67      7. 600E 02     MICROSTRAIN  ELBOW 10 -Y V
   -58            6. 50     -4. 025E 02     MICROSTRAIN

   +59            6. 49      8. 000E 02     MICROSTRAIN  ELBOW 10 -Y C
   -59            6. 62     -2. 700E 02     MICROSTRAIN

   +60           12. 66      1. 245E 03     PSIG         S4
   -60           12. 56      1. 083E 03     PSIG

   +61            6. 40      2. 363E 03     LBS          S2 V
   -61           17. 02     -2. 265E 03     LBS

   +62           13. 03      3. 623E 03     LBS          S2 H
   -62            3. 92     -3. 967E 03     LBS

   +63            8. 00      2. 753E 03     LBS          S3 V
   -63            6. 46     -2. 633E 03     LBS

   +64            7. 99      6. 750E 03     LBS          S3 H
   -64            2. 85     -4. 725E 03     LBS
```

APPENDIX E

PEAK RESPONSE FOR ALL DATA CHANNELS-- MODERATE LEVEL EARTHQUAKE FOR PIPELINE WITHOUT BRANCH LINES (TEST YEQ3, RUN C3R3)

The peak (maximum) values of response, for each data channel, are given in this appendix for Test YEQ3, Run C3R3 for the first pipeline tested. A description of the transducer locations can be found in Figure 2.10 and Tables 2.8 and 2.9. The strain gauge locations/orientations, given herein, are indicated by (1) elbow number, (2) direction of outward normal vector (to the pipe) at strain gauge location, and (3) the specification of the local orientation of a gauge as being either axial (A), "vector" (V), or circumferential (C). The direction of the normal vector (to the pipe) is either X, Y, or Z. The local orientations A, V, and C refer to the strain gauge being parallel to the pipe centerline, 45° from the A-direction, or in a circumferential direction (90° from the A-direction), respectively.

06-13-83 09:15
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                    DATA CHANNEL PEAK VALUES

NRC/EPRI  1  CONFIG 3  Y  FORCING EARTHQUAKE 3 REPEAT 3
TEST- YEQ3 RUN- C3R3 DATE-  6/13/83 TIME-  7: 7: 2

MAXIMUM AT       TIME
 CHANNEL          SEC        VALUE

   + 1           6.52     2.197E 00      G          P21 Y
   - 1          14.09    -2.876E 00      G

   + 2          15.38     2.610E 00      G          P31 X
   - 2          15.42    -2.819E 00      G

   + 3          12.74     1.811E 00      G          P35 X
   - 3          12.42    -1.759E 00      G

   + 4          15.33     3.073E 00      G          P35 Z
   - 4          14.82    -2.944E 00      G

   + 5          14.46     3.092E 00      G          P41 Y
   - 5          14.55    -3.435E 00      G

   + 6          14.23     2.687E 00      G          P61 X
   - 6          15.46    -3.697E 00      G

   + 7          14.65     5.417E 00      G          P71 Y
   - 7          14.36    -4.439E 00      G

   + 8          14.64     2.197E 00      G          P71 Z
   - 8          14.34    -2.409E 00      G

   + 9          19.43     4.536E 00      G          P73 Y
   - 9          14.36    -4.062E 00      G

   +10          14.43     3.865E 00      G          P75 Y
   -10          14.38    -2.859E 00      G

   +11          14.80     2.750E 00      G          P75 Z
   -11           5.36    -2.456E 00      G

   +12          14.42     3.192E 00      G          P95 X
   -12          14.31    -2.146E 00      G

   +13          10.37     5.500E-02      G          S1  X
   -13          11.78    -1.250E-01      G

   +14          10.73     7.500E-01      G          S1  Y
   -14          14.09    -1.455E 00      G

   +15           6.19    -5.500E-02      G          S1  Z
     5           6.17    -1.700E-01      G

   +16          16.37     1.065E 00      G          S2H Y
   -16           6.18    -1.200E 00      G
```

06-13-83, 09:15
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                    DATA CHANNEL PEAK VALUES

NRC/EPRI  1  CONFIG 3  Y  FORCING EARTHQUAKE 3 REPEAT 3
TEST- YEQ3 RUN- C3R3 DATE-  6/13/83 TIME-  7: 7: 2


MAXIMUM AT      TIME
 CHANNEL         SEC         VALUE

   +17          12.42     -1.200E 00      G               S2V Y
   -17          24.64     -1.560E 00      G

   +18          14.83      9.000E-01      G               S3H Y
   -18          13.47     -2.100E 00      G

   +19           2.53     -1.920E 00      G               S3V Y
   -19           3.44     -2.250E 00      G

   +20          10.01      2.450E-01      G               S4 X
   -20           6.59      0.000E-01      G

   +21          16.65      1.590E 00      G               S4 Y
   -21          11.84     -1.155E 00      G

   +22           3.14      2.300E-01      G               S4 Z
   -22          10.04      9.000E-02      G

   +23           6.18      5.325E-01      INCHES          S1 Y
   -23           5.81     -4.850E-01      INCHES

   +24          14.11      1.300E 00      INCHES          P23 Y
   -24          19.67     -9.750E-01      INCHES

   +25          14.11      1.565E 00      INCHES          P43 Y
   -25          19.67     -1.355E 00      INCHES

   +26           8.26      7.500E-02      INCHES          S2H X
   -26          12.43     -6.750E-02      INCHES

   +27          19.56      1.790E 00      INCHES          P63 Y
   -27          12.48     -1.600E 00      INCHES

   +28          19.56      1.695E 00      INCHES          P71 Y
   -28          12.49     -1.525E 00      INCHES

   +29          19.55      1.190E 00      INCHES          P75 Y
   -29          19.66     -1.130E 00      INCHES

   +30          14.56      5.275E-01      INCHES          S3H X
   -30          14.44     -4.600E-01      INCHES

   +31          19.54      1.020E 00      INCHES          P93 Y
   -31          19.66     -9.900E-01      INCHES

   +32           6.17      4.575E-01      INCHES          S4 Y
   -32           5.79     -5.050E-01      INCHES
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06-13-83, 09:15
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                         DATA CHANNEL PEAK VALUES

NRC/EPRI  1  CONFIJ 3  Y  FORCING EARTHQUAKE 3 REPEAT 3
TEST- YEQ3 RUN- C3R3 DATE-  6/13/83 TIME-  7: 7: 2

MAXIMUM AT       TIME
 CHANNEL          SEC         VALUE

   +33           14.45       2.725E 02      MICROSTRAIN   ELBOW 1 Y A
   -33           14.54      -5.750E 01      MICROSTRAIN

   +34           14.47       3.700E 02      MICROSTRAIN   ELBOW 1 Y V
   -34           14.54      -7.750E 01      MICROSTRAIN

   +35           12.41       3.750E 02      MICROSTRAIN   ELBOW 1 Y C
   -35           14.24       1.700E 02      MICROSTRAIN

   +36           13.48       2.000E 02      MICROSTRAIN   ELBOW 1 Z A
   -36           11.87       4.500E 01      MICROSTRAIN

   +37           14.25       3.850E 02      MICROSTRAIN   ELBOW 1 Z V
   -37           14.55       9.750E 01      MICROSTRAIN

   +38           11.87       4.500E 02      MICROSTRAIN   ELBOW 1 Z C
   -38           14.17       2.425E 02      MICROSTRAIN

   +39           14.55       3.300E 02      MICROSTRAIN   ELBOW 1 -Y A
   -39           14.45      -3.000E 01      MICROSTRAIN

   +40           14.47       3.275E 02      MICROSTRAIN   ELBOW 1 -Y V
   -40           14.55       1.100E 02      MICROSTRAIN

   +41           14.43       4.575E 02      MICROSTRAIN   ELBOW 1 -Y C
   -41           14.53       1.575E 02      MICROSTRAIN

   +42           14.47       1.725E 02      MICROSTRAIN   ELBOW 7 Y A
   -42           14.34      -1.250E 01      MICROSTRAIN

   +43           14.47       2.800E 02      MICROSTRAIN   ELBOW 7 Y V
   -43           13.67       5.250E 01      MICROSTRAIN

   +44           14.46       4.900E 02      MICROSTRAIN   ELBOW 7 Y C
   -44           14.35       2.100E 02      MICROSTRAIN

   +45           14.23       3.575E 02      MICROSTRAIN   ELBOW 7 Z A
   -45           14.57      -1.250E 02      MICROSTRAIN

   +46           12.26       2.950E 02      MICROSTRAIN   ELBOW 7 Z V
   -46           14.13       1.725E 02      MICROSTRAIN

    47           14.34       5.675E 02      MICROSTRAIN   ELBOW 7 Z C
    .7           14.47       1.000E 02      MICROSTRAIN

   +48           14.34       1.975E 02      MICROSTRAIN   ELBOW 7 -Y A
   -48           14.46      -7.500E 01      MICROSTRAIN
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06-13-83, 09:15
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                         DATA CHANNEL PEAK VALUES

NRC/EPRI  1  CONFIG 3  Y  FORCING EARTHQUAKE 3 REPEAT 3
TEST- YEQ3 RUN- C3R3 DATE-  6/13/83 TIME-  7: 7: 2


MAXIMUM AT       TIME
 CHANNEL          SEC          VALUE

   +49           14.60       2.950E 02      MICROSTRAIN  ELBOW 7 -Y V
   -49           15.53       1.400E 02      MICROSTRAIN

   +50           14.46       6.100E 02      MICROSTRAIN  ELBOW 7 -Y C
   -50           14.35       1.500E 02      MICROSTRAIN

   +51           14.65       4.925E 02      MICROSTRAIN  ELBOW 10 Y A
   -51           14.56      -3.525E 02      MICROSTRAIN

   +52           19.44       2.625E 02      MICROSTRAIN  ELBOW 10 Y V
   -52            6.43       1.075E 02      MICROSTRAIN

   +53           14.54       4.850E 02      MICROSTRAIN  ELBOW 10 Y C
   -53           14.65       7.000E 01      MICROSTRAIN

   +54           14.33       1.875E 02      MICROSTRAIN  ELBOW 10 Z A
   -54            6.21       8.500E 01      MICROSTRAIN

   +55           14.13       3.150E 02      MICROSTRAIN  ELBOW 10 Z V
   -55           13.55       1.450E 02      MICROSTRAIN

   +56           14.66       3.650E 02      MICROSTRAIN  ELBOW 10 Z C
   -56           14.53       1.750E 02      MICROSTRAIN

   +57           14.56       5.125E 02      MICROSTRAIN  ELBOW 10 -Y A
   -57           14.66      -3.325E 02      MICROSTRAIN

   +58           14.56       5.475E 02      MICROSTRAIN  ELBOW 10 -Y V
   -58           14.45      -1.250E 01      MICROSTRAIN

   +59           12.52       5.075E 02      MICROSTRAIN  ELBOW 10 -Y C
   -59           14.13       2.675E 02      MICROSTRAIN

   +60           14.55       1.231E 03      PSIG         S4
   -60            6.52       1.151E 03      PSIG

   +61           12.70       6.000E 02      LBS          S2 V
   -61           14.30      -1.785E 03      LBS

   +62           14.03       4.350E 02      LBS          S2 H
   -62           14.67      -1.343E 03      LBS

    63           14.35       7.350E 02      LBS          S3 V
     3           14.64      -1.785E 03      LBS

   +64            6.42       1.065E 03      LBS          S3 H
   -64           14.64      -2.835E 03      LBS
```

APPENDIX F

PEAK RESPONSE FOR ALL DATA CHANNELS--HIGH LEVEL EARTHQUAKE FOR PIPELINE WITH TWO BRANCH LINES (TEST XQE7, RUN C2)

The peak (maximum) values of response, for each data channel, are given in this appendix for Test XEQ7, Run C2 for the second pipeline tested. A description of the transducer locations can be found in Figure 2.12 and Table 2.11. The strain gauge locations/orientations, given herein, are indicated by (1) node number, (2) direction of outward normal vector (to the pipe) at strain gauge location, and (3) the specification of the local orientation of a gauge as being either axial (A), "vector" (V), or circumferential (C). The direction of the normal vector (to the pipe) is either X, Y, or Z. The local orientations A, V, and C refer to the strain gauge being parallel to the pipe centerline, 45° from the A-direction, or in a circumferential direction (90° from the A-direction), respectively.

BAJ

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                              DATA CHANNEL PEAK VALUES

 NRC/EPRI 2  CONFIG 2  X FORCING  EQ 7  100% MAX
 TEST- XEQ7 RUN- C2   DATE-  5/11/84 TIME- 11:45:15

 MAXIMUM AT       TIME
  CHANNEL          SEC         VALUE

    + 1          15.73      4.752E 00      G              S1 X
    - 1          16.12     -3.391E 00      G

    + 2           2.95      4.892E-01      G              S1 Y
    - 2          20.30     -7.066E-01      G

    + 3           8.84      3.657E-01      G              S1 Z
    - 3            .07     -7.315E-01      G

    + 4          15.73      6.473E 00      G              S2 X
    - 4           7.72     -4.910E 00      G

    + 5           9.98      2.950E 00      G              S2 X LOWER
    - 5          16.11     -3.600E 00      G

    + 6          10.01      2.400E 00      G              S2 Z LOWER
    - 6          15.73     -3.800E 00      G

    + 7          16.98      1.883E 00      G              S3 X
    - 7           9.91     -2.071E 00      G

    + 8          10.30      2.425E-02      G              S3 Y
    - 8          22.13     -4.365E-01      G

    + 9          10.89      2.200E-01      G              S3 Z
    - 9           5.98     -8.800E-01      G

    +10           9.97      2.787E 00      G              S4 X
    -10          16.12     -2.763E 00      G

    +11           6.91      2.675E-01      G              S4 Y
    -11          23.72     -9.630E-01      G

    +12          17.15      2.114E-01      G              S4 Z
    -12           2.82     -3.483E-01      G

    +13          16.98      1.930E 00      G              S5 X
    -13           9.91     -1.930E 00      G

    +14          11.12      3.824E-01      G              S5 Y
    -14           3.20     -8.740E-01      G

    +15          10.37      4.637E-01      G              S5 Z
    -15          23.25     -4.300E-01      G

    +16          17.02      2.142E 01      G              PB31 X
    -16          17.11     -2.296E 01      G
```

BAJ

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                        DATA CHANNEL PEAK VALUES

NRC/EPRI 2  CONFIG 2  X FORCING  EQ 7  100% MAX
TEST- XEQ7 RUN- C2   DATE-  5/11/84 TIME- 11:45:15

MAXIMUM AT      TIME
 CHANNEL         SEC          VALUE

   +17          17.05       6.058E 00      G              PB31
   -17          16.97      -6.402E 00      G

   +18          16.30       1.354E 01      G              PB21 Z
   -18          15.76      -1.323E 01      G

   +19          10.00       7.880E 00      G              PM21 X
   -19          16.14      -8.479E 00      G

   +20          15.80       5.664E 00      G              PM31 Y
   -20          16.33      -4.461E 00      G

   +21          16.83       6.658E 00      G              PM33 X
   -21          13.70      -7.945E 00      G

   +22          15.80       5.391E 00      G              PM33 Y
   -22          16.34      -4.650E 00      G

   +23          12.23       7.747E 00      G              PM53 X
   -23          12.13      -6.682E 00      G

   +24          16.58       6.188E 00      G              PM53 Y
   -24          16.04      -5.278E 00      G

   +25          17.03       4.678E 00      G              PM63 Y
   -25          16.17      -4.826E 00

   +26          10.50       5.470E 00      G              PM63 Z
   -26          19.95      -5.445E 00      G

   +27          16.98       3.920E 00      G              PB61 Z'
   -27           9.92      -3.479E 00      G

   +28          16.74       4.637E 00      G              PB61 Y'
   -28          16.77      -5.314E 00      G

   +29          12.72       2.543E 00      INCHES         S1 X
   -29          13.14      -2.130E 00      INCHES

   +30          12.73       2.598E 00      INCHES         S3 X
   -30          13.15      -2.135E 00      INCHES

   +31          13.26       6.025E-01      INCHES         PM23 Y
   -31          13.17      -9.600E-01      INCHES

   +32          12.75       3.428E 00      INCHES         PM31 X
   -32          13.15      -3.183E 00      INCHES
```

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                         DATA CHANNEL PEAK VALUES

NRC/EPRI 2  CONFIG 2, X FORCING  EQ 7  100% MAX
TEST- XEQ7 RUN- C2   DATE-  5/11/84 TIME- 11:45:15

MAXIMUM AT       TIME
 CHANNEL          SEC          VALUE

   +33           12.73       3.362E 00      INCHES           PM33 X
   -33           13.14      -2.808E 00      INCHES

   +34           13.55       9.425E-01      INCHES           PM43 Y
   -34           13.16      -7.875E-01      INCHES

   +35           12.72       2.690E 00      INCHES           PM63 X
   -35           13.12      -2.258E 00      INCHES

   +36           12.98       9.925E 02      MICROSTRAIN     PM13 AX
   -36           13.05      -8.700E 02      MICROSTRAIN

   +37           13.14       5.950E 02      MICROSTRAIN     PM13 VX
   -37           13.06      -1.675E 02      MICROSTRAIN

   +38           13.05       5.900E 02      MICROSTRAIN     PM13 CX
   -38           12.97       9.250E 01      MICROSTRAIN

   +39           13.25       5.200E 02      MICROSTRAIN     PM13 A-Y
   -39           16.55      -1.650E 02      MICROSTRAIN

   +40           13.13       3.925E 02      MICROSTRAIN     PM13 V-Y
   -40           10.41       1.250E 02      MICROSTRAIN

   +41           16.54       3.950E 02      MICROSTRAIN     PM13 C-Y
   -41           16.33       1.900E 02      MICROSTRAIN

   +42           13.05       1.150E 03      MICROSTRAIN     PM13 A-X
   -42           12.98      -7.850E 02      MICROSTRAIN

   +43           13.05       6.950E 02      MICROSTRAIN     PM13 V-X
   -43           12.97      -6.250E 01      MICROSTRAIN

   +44           12.98       7.125E 02      MICROSTRAIN     PM13 C-X
   -44           13.05       1.925E 02      MICROSTRAIN

   +45           15.74       4.325E 02      MICROSTRAIN     PM15 AX
   -45           16.28      -2.275E 02      MICROSTRAIN

   +46           12.83       4.650E 02      MICROSTRAIN     PM15 VX
   -46           16.14      -2.250E 01      MICROSTRAIN

   +47           17.08       3.475E 02      MICROSTRAIN     PM15 CX
   -47           10.17       2.625E 02      MICROSTRAIN

   +48            9.99       3.050E 02      MICROSTRAIN     PM15 A-Y
   -48           16.14      -1.250E 02      MICROSTRAIN
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                         DATA CHANNEL PEAK VALUES

NRC/EPRI 2  CONFIG 2  X FORCING  EQ 7  100% MAX
TEST- XEQ7 RUN- C2   DATE-  5/11/84 TIME- 11:45:15

MAXIMUM AT       TIME
 CHANNEL          SEC          VALUE

    +49          13.15       4.300E 02      MICROSTRAIN     PM15 V-Y
    -49          13.54      -5.000E 00      MICROSTRAIN

    +50          16.15       5.000E 02      MICROSTRAIN     PM15 C-Y
    -50          15.74       1.800E 02      MICROSTRAIN

    +51          16.28       5.625E 02      MICROSTRAIN     PM15 A-X
    -51          15.74      -3.825E 02      MICROSTRAIN

    +52          16.28       4.600E 02      MICROSTRAIN     PM15 V-X
    -52          12.96       1.275E 02      MICROSTRAIN

    +53          15.74       6.800E 02      MICROSTRAIN     PM15 C-X
    -53          16.15       1.850E 02      MICROSTRAIN

    +54          16.15       4.625E 02      MICROSTRAIN     PM55 AZ
    -54          13.63      -1.975E 02      MICROSTRAIN

    +55           9.99       5.025E 02      MICROSTRAIN     PM55 VZ
    -55          13.04       8.250E 01      MICROSTRAIN

    +56          16.22       6.225E 02      MICROSTRAIN     PM55 CZ
    -56          16.15       1.725E 02      MICROSTRAIN

    +57          16.39       5.150E 02      MICROSTRAIN     PM55 AX
    -57          13.39      -2.300E 02      MICROSTRAIN

    +58          12.98       4.825E 02      MICROSTRAIN     PM55 VX
    -58          13.05       6.250E 01      MICROSTRAIN

    +59          16.16       5.300E 02      MICROSTRAIN     PM55 CX
    -59          13.63       1.625E 02      MICROSTRAIN

    +60          13.63       3.075E 02      MICROSTRAIN     PM55 A-Z
    -60          16.15      -7.250E 01      MICROSTRAIN

    +61           9.99       6.575E 02      MICROSTRAIN     PM55 V-Z
    -61          13.05      -8.750E 01      MICROSTRAIN

    +62           9.99       4.550E 02      MICROSTRAIN     PM55 C-Z
    -62          13.05       3.400E 02      MICROSTRAIN

    +63          10.13       3.700E 02      MICROSTRAIN     PM81 AX
    -63          19.94      -1.750E 02      MICROSTRAIN

    +64          12.92       5.525E 02      MICROSTRAIN     PM18 VX
    -64          13.62       4.500E 01      MICROSTRAIN
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                              DATA CHANNEL PEAK VALUES

NRC/EPRI 2  CONFIG 2  X FORCING  EQ 7  100% MAX
TEST- XEQ7 RUN- C2   DATE-  5/11/84 TIME- 11:45:15

MAXIMUM AT        TIME
 CHANNEL           SEC         VALUE

   +65            19.94      7.100E 02      MICROSTRAIN     PM18 CX
   -65            10.13      2.650E 02      MICROSTRAIN

   +66            16.17      2.650E 02      MICROSTRAIN     PM18 A-Y
   -66            13.49      7.500E 00      MICROSTRAIN

   +67            12.93      6.550E 02      MICROSTRAIN     PM18 V-Y
   -67            12.84      1.050E 02      MICROSTRAIN

   +68            10.13      6.050E 02      MICROSTRAIN     PM18 C-Y
   -68            16.26      3.750E 02      MICROSTRAIN

   +69            10.53      1.950E 02      MICROSTRAIN     PM18 A-X
   -69            10.49     -1.075E 02      MICROSTRAIN

   +70            16.16      6.450E 02      MICROSTRAIN     PM18 V-X
   -70            13.62     -1.100E 02      MICROSTRAIN

   +71            19.94      4.575E 02      MICROSTRAIN     PM18 C-X
   -71            16.22      3.300E 02      MICROSTRAIN

   +72            17.09      6.450E 02      MICROSTRAIN     PB11 AY
   -72            17.02     -2.500E 01      MICROSTRAIN

   +73            12.98      9.450E 02      MICROSTRAIN     PB11 VY
   -73            13.06     -7.275E 02      MICROSTRAIN

   +74            17.02      1.377E 03      MICROSTRAIN     PB11 CY
   -74            17.09     -1.537E 03      MICROSTRAIN

   +75            17.10      5.600E 02      MICROSTRAIN     PB11 AZ
   -75            17.02     -5.500E 02      MICROSTRAIN

   +76            17.09      1.245E 03      MICROSTRAIN     PB11 A-Y
   -76            17.02     -9.125E 02      MICROSTRAIN

   +77            16.35      5.050E 02      MICROSTRAIN     PB11 V-Y
   -77            16.90     -4.500E 01      MICROSTRAIN

   +78            17.02      6.200E 02      MICROSTRAIN     PB11 C-Y
   -78            17.09     -1.200E 02      MICROSTRAIN

   +79            13.63      6.300E 02      MICROSTRAIN     PB41 AX
   -79            12.91      5.750E 01      MICROSTRAIN

   +80            10.08      6.000E 01      MICROSTRAIN     PB41 VX
   -80            16.22     -2.975E 02      MICROSTRAIN
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                         DATA CHANNEL PEAK VALUES

NRC/EPRI 2  CONFIG 2  X FORCING  EQ 7  100% MAX
TEST- XEQ7 RUN- C2   DATE-  5/11/84 TIME- 11:45:15

MAXIMUM AT      TIME
  CHANNEL        SEC         VALUE

   +81         12.92       3.050E 02     MICROSTRAIN     PB41 CX
   -81         13.63       1.600E 02     MICROSTRAIN

   +82          8.97       3.025E 02     MICROSTRAIN     PB41 AZ
   -82          9.07      -1.000E 02     MICROSTRAIN

   +83         16.16      -2.500E 00     MICROSTRAIN     PB41 A-X
   -83         13.63      -6.150E 02     MICROSTRAIN

   +84         16.22       5.125E 02     MICROSTRAIN     PB41 V-X
   -84         16.16       2.975E 02     MICROSTRAIN

   +85         16.16      -5.000E 00     MICROSTRAIN     PB41 C-X
   -85         13.63      -7.600E 02     MICROSTRAIN

   +86         16.26       1.253E 03     LBS             S2 UPPER
   -86          9.18      -1.000E 03     LBS

   +87         16.40       1.772E 03     LBS             S2 LOWER
   -87         12.80      -1.880E 03     LBS

   +88         14.41      -1.083E 03     PSI             P1
   -88         13.55      -1.134E 03     PSI
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NRC FORM 335
(6 83)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1 REPORT NUMBER (Assigned by TIDC add Vol No if any)
NUREG/CR-3893

2 Leave blank

3 TITLE AND SUBTITLE
Laboratory Studies: Dynamic Response of Prototypical Piping Systems

4 RECIPIENT'S ACCESSION NUMBER

5 DATE REPORT COMPLETED
MONTH June YEAR 1984

6 AUTHOR(S)
Howard, G.E.; Walton, W.B.; Johnson, B.A.

7 DATE REPORT ISSUED
MONTH August YEAR 1984

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12a TYPE OF REPORT
Final Technical

12b PERIOD COVERED (Inclusive dates)
Jan 1983 - June 1984

13 SUPPLEMENTARY NOTES

14 ABSTRACT (200 words or less)

This report presents details of the test methods, specimens and a preliminary assessment of results. Two test configurations will be used to achieve the project objectives. Both were three dimensional configurations; the second configuration had branch pipes. The piping systems sustained no apparent damage after being subjected to an earthquake approximately four times greater than the SSE. Additionally, one of the piping system resisted five OBEs, nine SSEs and nearly thirty schocks.

15a KEY WORDS AND DOCUMENT ANALYSIS
Piping Seismic Capacity
Pipe Daming
Piping Benchmarks

15b DESCRIPTORS

16 AVAILABILITY STATEMENT
Unlimited

17 SECURITY CLASSIFICATION
(This report)
Unclassified

18 NUMBER OF PAGES

19 SECURITY CLASSIFICATION
(This page)
Unclassified

20 PRICE
$

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

120555078877 1 1AN1RM
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