EXPERIMENTAL EVALUATION OF THE NONLINEAR SEISMIC RESPONSE OF A NUCLEAR PIPING SYSTEM WITH DIFFERENT SUPPORT CONDITIONS

by

John C. Stoessel and Dr. Paul Ibáñez

ANCO Engineers, Inc.
9937 Jefferson Boulevard
Culver City, California 90230

ABSTRACT

Nonlinear analysis of nuclear power plant piping systems can be costly, and results can be questionable. However, reserve plastic ductility, evidenced in nonlinear effects, shows high reserve strength and is a very important consideration in design. Efforts are being made within the industry to benchmark analysis and observe nonlinear effects through testing. A series of tests performed on a piping system model subject to high-level seismic excitation produced much data useful to nonlinear analysis and plastic design techniques. The piping system was thin-wall stainless steel, subjected to a static pressure of 45 bar. Very high strains (in excess of 3 times yield) were observed with no catastrophic failure, contrary to what simple elastic analysis would predict. The pipe was subjected to biaxial independent motion in each of two planes. Several different spring hanger support configurations were tested, and many seismic events were run.

Also tested was the effect of a visco-elastic damper used to reduce seismic effects on piping systems. The damper was found to increase damping to 50-100% critical. Comparisons were made between damper, free, and rigid rod supports to observe changes in seismic stresses. The damper reduced stresses by up to 50%.

INTRODUCTION

Piping systems abound in nuclear power plants, and analysis of these systems occupies a great deal of manpower. Attempts to study the nonlinear effects analytically are costly, and results are often suspect. Exact modeling is cost prohibitive; therefore, assumptions are necessary which may reduce the accuracy of the mathematical model.

Laboratory testing can provide the necessary information about nonlinear dynamics of piping systems. Analytical approaches can be benchmarked, thereby uniting testing and analysis. Also, the confidence that goes along with testing is a definite factor, especially when reaching into the nonlinear, plastic region of materials.

One such example of laboratory testing of nuclear plant piping systems is presented herein. High-level seismic tests were performed on a thin-walled, stainless steel piping system, illustrated in Figure 1. Several different systems were utilized in order to observe the effects of these supports on pipe stresses. The pipe was filled with water and pressurized to 45 bar for all tests.

TEST SPECIMEN AND TEST PLAN

Figure 2 shows the layout of the piping system. Included in this figure are transducer locations and pipe dimensions. Pipe fixed points and spring hanger support points are highlighted*.

The piping system was subjected to independent biaxial motion in each of two planes. Motion was produced via hydraulic actuators fixed to a seismic mass floor (500 tons) and attached to a special fixture built to support the pipe. Motion was carried through the frame into the fixed points and hanger supports, and consequently into the pipe.

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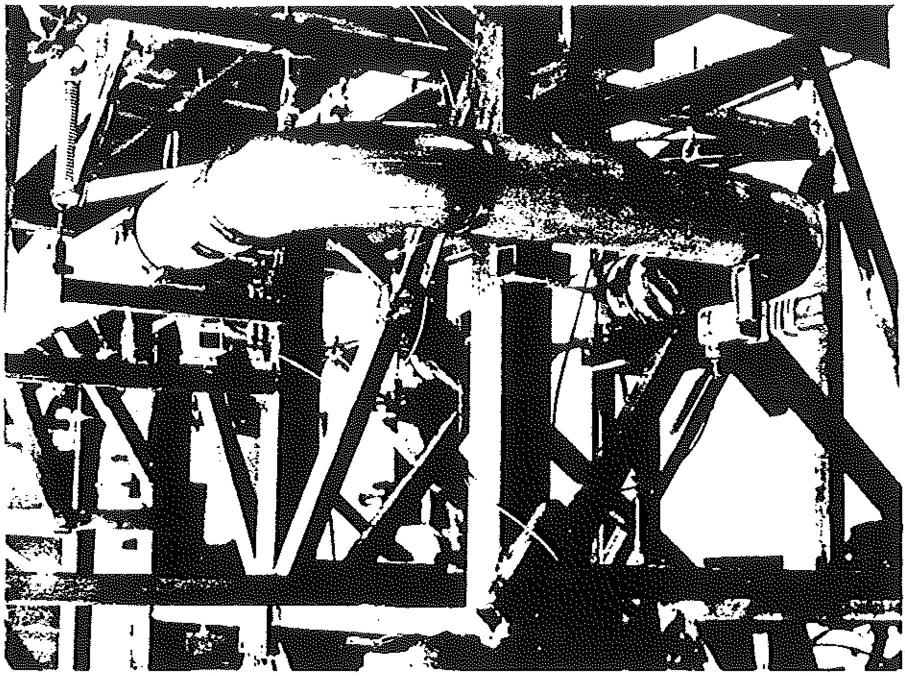
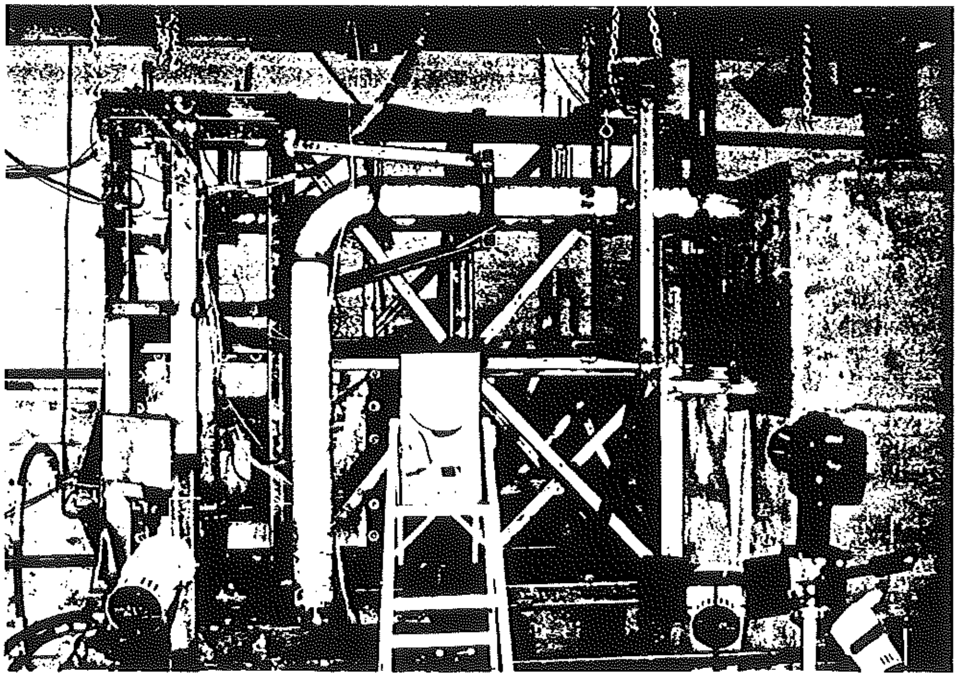
*Previous testing on this piping system was performed and summarized in ANCO Engineers, Inc., Report No. 2026-06.



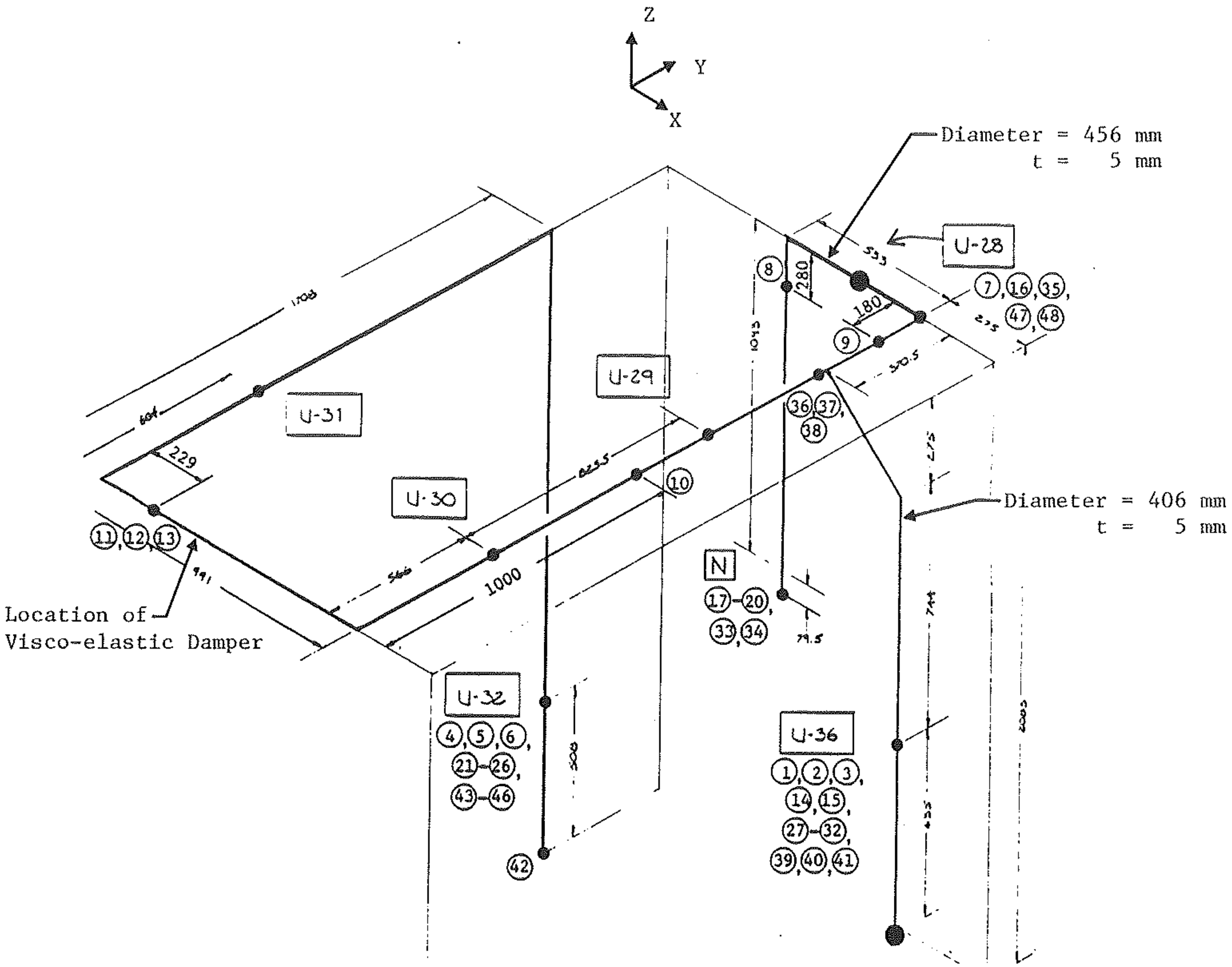
Pipe Section Between U30 and U31



Pipe Section From U31 to U32

<u>Modified TZ Pipe in Shaking Frame</u>

Figure 1



U36, U32 - Fixed Supports
U28, U29, U30, U31 - Spring Hanger Supports
N - Pump Nozzle Fixed Point

Channel No.	Description
1 - 7	Input Accelerations
8 - 10	Pipe Accelerations
11 - 13	Pipe Displacements
14 - 16	Dowel Forces
17 - 41, 43 - 48	Pipe, Support Strain Gages
42	Pipe Pressure

Figure 2

The required seismic criteria are in the form of response spectra. Figure 3 shows both the horizontal and vertical required response spectra, along with the bounded area representing test acceptance. These plots represent the 100% test condition.

TEST RESULTS

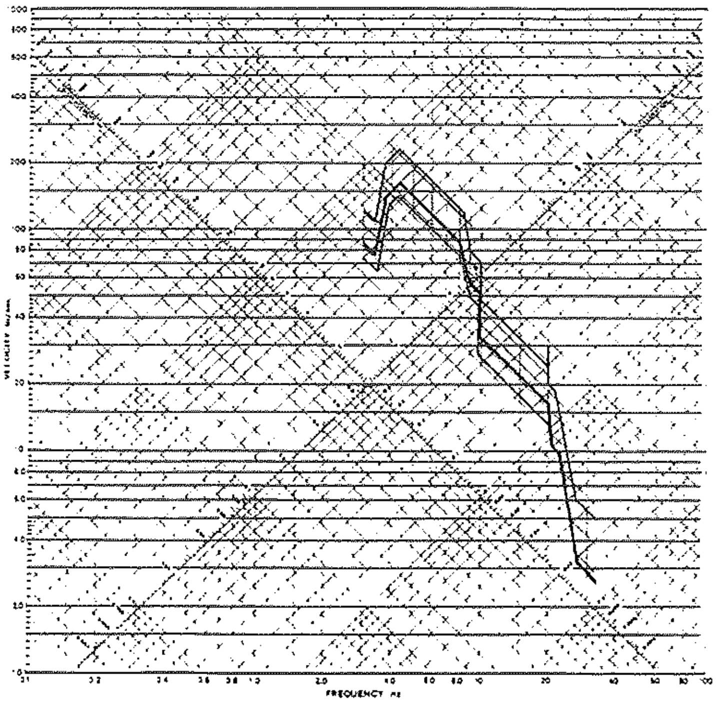
Table 1 summarizes the fundamental characteristics of the piping system in each of its three configurations. As evidenced, this system has resonances within the recognized seismic range (0-33 Hz) and also exhibits low damping (typically 1-3% of critical).

Table 2 lists the tests performed and summarizes maximum pipe strains, accelerations, and displacements for each test.

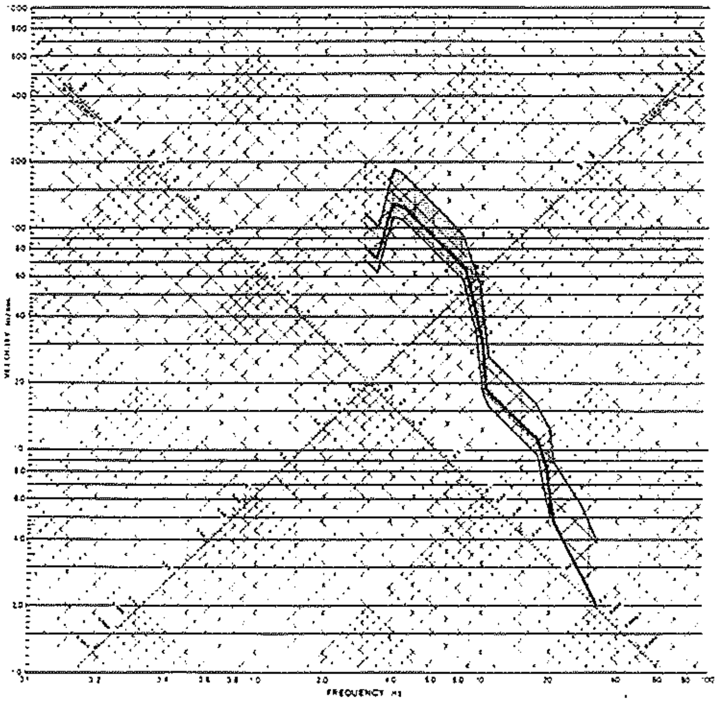
Results of these tests bear out the high plastic capacity of piping systems. In preliminary calculations, per ASME code, it was found that at 45 bar internal pressure the pipe was experiencing near yield conditions at several locations. Any dynamic stresses added were taking the pipe into its plastic region. Strain gage measurements showed that dynamic strains approaching 4,000 $\mu\varepsilon$ occurred during high-level seismic excitation, resulting in permanent deformation. High acceleration levels (in excess of 10 g) were measured on the pipe.

Several minor failures were recorded during testing. A spring hanger broke on one test. Another test resulted in a shear plug breaking at a fixed point pipe support. The third failure involved a cracked weld at the union of the 5-inch (12.7-cm) and 6-inch (15.25-cm) pipe. These tests were of maximum input, and failures occurred well into the test program, after numerous seismic events had already been performed.

Much strain gage, displacement, and acceleration data were recorded and reduced. However, its inclusion in this report would be too lengthy. The bottom line is: this piping system, typical to types found in nuclear plants,



Horizontal Required Response Spectra (RRS) (100%)



Vertical Required Response Spectra (RRS) (100%)

Figure 3

TABLE 1

Configuration	Transducer Orientation	Avg. Frequency, Hz	Avg. Damping, %	Comments
A (4 hangers)	X	8.8	2.0	
		14.8	1.5	
		18.0	3.0	
	Y	18.0	2.0	Participation of x-direction mode
	Z	7.0	2.7	
B (2 hangers)	X	8.4	3.3	
		8.9	1.5	
		14.8	3.0	
	Y	14.9	1.2	
		19.1	1.5	
		24.6	1.0	
	Z	7.2	4.3	
		29.3	1.2	
C (no hangers)	X	8.8	1.5	
		18.4	1.3	
	Y	18.4	2.0	Participation of x-direction mode
	Z	6.7	2.0	
		7.2	3.0	

TABLE 2: TEST DATA MAXIMUMS*

Configuration**	Excitation Direction	Level***	Pipe Accel., Ch. No.	Pipe Strain, Ch. No.	Pipe Displacement, Ch. No.
A	XZ	100%	4.4, 10X	1005, 39MX	37, 13Z
A	XZ	200%	11.2, 10X	1800, 38MX	68, 13Z
A	XZ	Max.	14.9, 10X	3400, 40MY	81, 13Z
A	YZ	100%	3.5, 8Y	768, 36MX	50, 13Z
A	YZ	200%	9.0, 8Y	4240, 18Y	91, 13Z
A	YZ	Max.	9.9, 8Y	5625, 18Y	104, 13Z
B	XZ	Max.	12.5, 10X	2304, 40MY	80, 13Z
C	XZ	Max.	12.0, 10X	4096, 39MX	89, 13Z

*Acceleration - g; Strain - $\mu\varepsilon$; Displacement - mm.

**A - 4 Spring Hangers: U28, U29, U30, U31.
B - 2 Spring Hangers: U29, U31.
C - No Spring Hangers.

***In percent of Required Response Spectra, Maximum ≃ 250%.

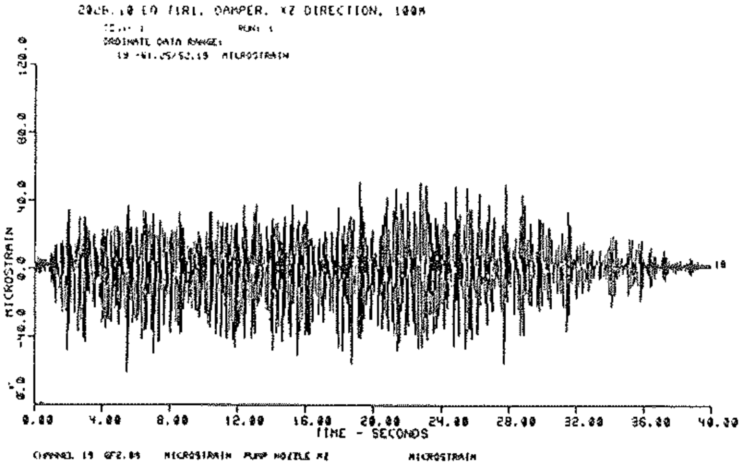
withstood seismic events at up to 250% of the required response spectra without catastrophic failure. Cumulative events exceeded 20 tests, resulting in a large number of stress reversal loadings that could lead to fatigue failures, had the pipe not exhibited high plastic reserve.

Another series of high-level seismic tests were performed on this piping system to observe the effects of a visco-elastic damper placed vertically near the pipe location of Channels 11, 12, 13 (see Figure 2). Figures 4 and 5 are strain and displacement time histories, respectively, of a point on the pipe. The addition of this damper produced damping near 50% of critical, and strain and displacement values were reduced by approximately 50% from the unsupported pipe configuration. Further study of this damper effect is under investigation in an upcoming publication.

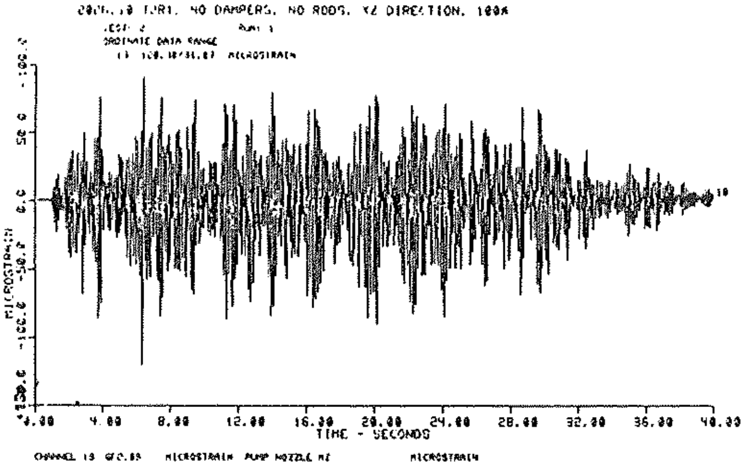
Lastly, a note is included on pipe natural frequencies and their relation to internal pipe pressure. Impact tests performed to measure fundamental frequencies of vibration of both pressurized and unpressurized pipe conditions showed lower order frequency increases of 10%. This warrants additional investigation.

CONCLUSIONS

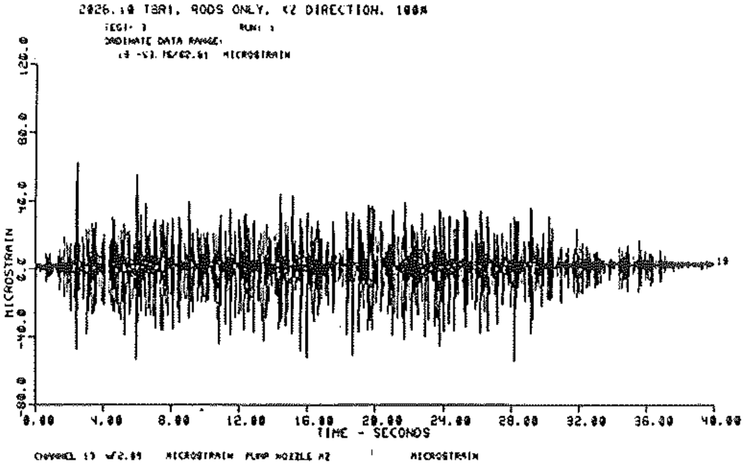
Piping systems such as these show remarkable capacity to withstand high-level seismic events. However, analytical models, limited to the linear elastic range, cannot bear out this capacity. It is tests, such as those described, that lead to better understanding of the true capacity of these systems. Ongoing work in this area is necessary in order to assure engineers/designers of the availability of sufficient data to allow efficient, economical design/analysis of complex, and oftentimes costly, nuclear power plant piping systems.



T1R1 - Channel 13
With Damper
(62 microstrain max.)

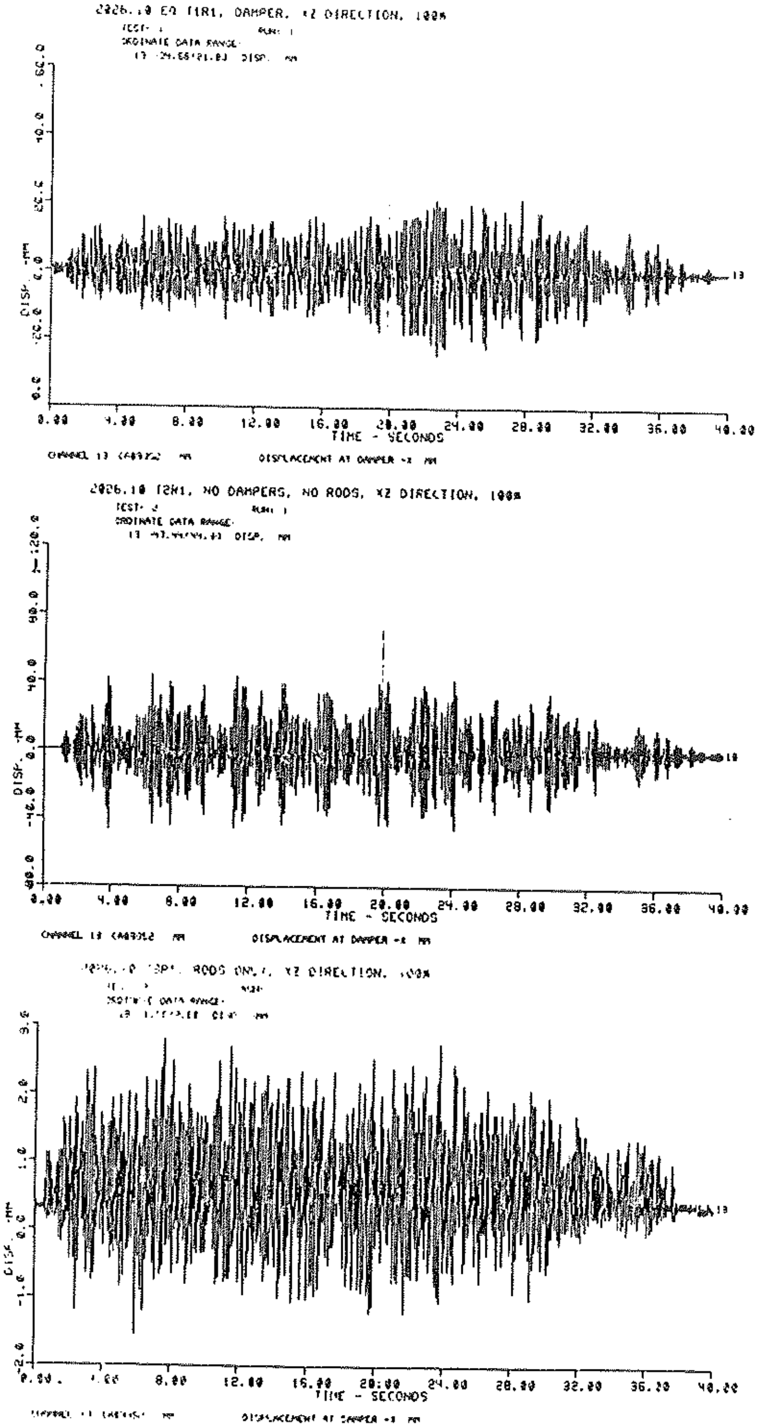


T2R1 - Channel 13
No Damper/No Rods
(120 microstrain max.)



T3R1 - Channel 13
With Rods
(63 microstrain max.)

Figure 4: Time Histories Pipe Strain
Pump Nozzle MZ



T1R1 - Channel 19
Damper Only
(25 mm max.)

T2R1 - Channel 19
No Damper/No Rods
(48 mm max.)

T3R1 - Channel 19
With Rods
(3 mm max.)

Figure 5: Time Histories Pipe Displacement at Damper Location