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PARAMETERS WHICH INFLUENCE DAMPING IN NUCLEAR POWER PLANT PIPING SYSTEMS

A. G. Ware

Idaho National Engineering Laboratory

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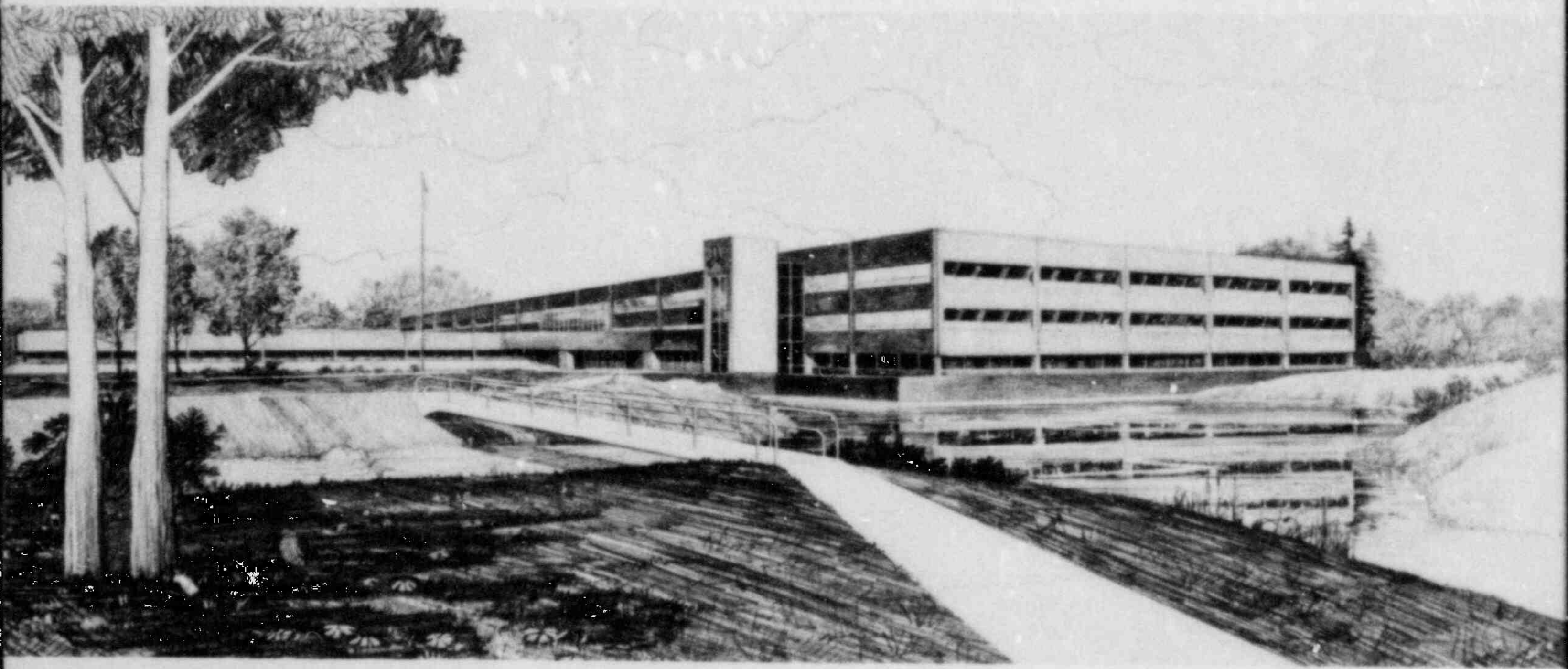

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Author(s):

A. G. Ware -- Engineering Analysis Division, Applied Mechanics Branch

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EG&G Idaho, Inc.
Idaho Falls, Idaho 83415

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INTERIM REPORT

ABSTRACT

This report gives the present status of the guidelines for structural damping in dynamic analyses of nuclear power plant piping systems. A brief description of the present state of knowledge of piping system damping in the U.S. is included, as are gaps in the overall understanding of the phenomenon. The report concludes with proposed EG&G Idaho efforts to contribute to the satisfactory establishment of reasonable damping values to be used in structural analyses.

SUMMARY

The present NRC guidelines for structural damping to be used in dynamic stress analyses of nuclear power plant piping systems are generally considered to be overly conservative and not in the best interests of the nuclear industry as a whole. In order to generate revised guidelines, solidly based on technical data, a good deal of new experimental data needs to be generated and assessed, and the parameters which influence damping need to be quantitatively identified. From data gathered to date, the relative importance of these parameters seems to be:

1. Strong Influence
    a. Type of Supports

2. Weak Influence
    a. Response Amplitude
    b. Response Frequency
    c. Insulation

3. Little or Unknown Influence
    a. Geometry
    b. Type of Excitation
    c. Direction of Excitation or Response
    d. Pipe Size.

As part of the NRC piping system damping study program, EG&G Idaho Applied Mechanics Branch will be actively involved in assessing and generating new data and in participating in revising the present guidelines. In FY-83 EG&G proposes to test a simple system with a variety of support configurations to gain a more basic understanding of the damping phenomenon. In subsequent years, more complex systems would be evaluated. The final goal of such a program would be to make "blind" predictions of reasonable values of damping for a given piping system.

ACKNOWLEDGMENTS

Gary Thinnes supplied Sections 5.1, 5.2, and Appendix A of this report.

Special thanks also go to Gene Heaton, Gary Thinnes, and Jim Arendts for providing figures.

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PARAMETERS WHICH INFLUENCE DAMPING IN NUCLEAR POWER PLANT PIPING SYSTEMS

1. INTRODUCTION

One of the more influential parameters used in dynamic stress analyses of nuclear power plant piping is the value of damping assigned to the particular piping system. In general, damping is a measure of energy dissipation in a structure.[a] The energy losses associated with higher damping values result in reducing the computed response motion of a piping system to a given excitation, and therefore can greatly influence the number and strength of supports required. At present, the damping in a system cannot be mathematically predicted accurately, but must be determined from vibration experiments. Since piping systems must be designed and analyzed to be structurally in compliance with industry requirements before they can be built and tested, damping values must be estimated from data obtained from existing systems or laboratory experiments. Unfortunately, the body of experimental data is sparse, there is a great deal of scatter in existing data, and conclusive representative values of damping for nuclear power plant piping have not been agreed upon. In lieu of best estimate damping values, the U.S. Nuclear Regulatory Commission (NRC) has established conservative values, discussed in Section 2.4, which would cause response amplitudes and the corresponding stresses to be overpredicted. This has resulted in piping systems which have more supports than would be required if more realistic damping values were used, in order to keep mathematically computed piping stresses below allowable values. These stiffer systems, although highly resistant to dynamic loads, become more severely stressed during thermal growth transients.

It is widely recognized that higher allowable damping values would be more reasonable, and would be beneficial to the nuclear industry by reducing

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[a] For a more complete discussion of damping, refer to Section 2.

the number of required piping supports. More accurate stress analyses would be possible; expenses would be reduced in design, analysis, procurement and installation of supports. There would be less chance of a support malfunction (since there would be fewer); and piping systems would undergo less stress when responding to thermal transients. However, the complexity of damping and the lack of consistency in available data have provided a substantial barrier to establishing a generally acceptable value or values of system damping to replace those presently allowed.

In response to this problem, a number of organizations have begun to assess the available data in order to make a recommended change, and to generate additional data to fill in the gaps in the present understanding of damping. With the recognized need to adjust the allowable values, data exchanges and cooperative testing efforts have been initiated between members of the nuclear industry.

An earlier EG&G report[1] presented recent experimental data from a number of sources, and described trends in damping values due to several influencing parameters. This earlier report has been cited extensively in many recent communications among government and industry experts who are active in revising the allowable damping values in structural analysis standards. Both the strengths and shortcomings of this report, the latter which relate primarily to the lack of data in answering vital questions, have been pointed out. This present report details some of the ongoing EG&G efforts designed to supplement the information in Reference 1.

The purpose of this report is to describe the EG&G involvement in the investigation of piping damping. Included are a brief summary of the present state of knowledge in the United States (U.S.), recommended short and long term goals for the U.S. program, and EG&G experiments which will be designed to supplement other test data and programs in clarifying the overall concept of piping damping.

2. BACKGROUND

This section presents a definition of damping, its causes, and how it is calculated. Since a discussion of these subjects would be quite lengthy, and since they are adequately covered in textbooks and manuals, only the basic concepts are outlined and references for more detailed reading are given. To complete the background, a discussion of the current Nuclear Regulatory Commission guidelines on damping is included.

2.1 Definition of Damping

The term damping refers to the energy dissipation properties of a material or system under cyclic motion. These energy losses are important because they reduce the response motion of the piping system when the system is vibrated. Damping is generally classified into two categories (1) material and (2) system damping. Material damping represents the phenomenon by which energy is dissipated within a volume of continuous solid matter. Examples are plastic slip or flow, and friction at grain boundaries. Under cyclic motion, these mechanisms lead to a stress-strain hysteresis. Material damping contributes only a small percentage to the overall damping, in the range of 0.04 to 0.2 percent of critical damping for steels stressed below the yield point.[2] This type damping becomes more pronounced at plastic stress levels. In contrast, system damping refers to energy losses between distinguishable parts. Examples are linear slippage between contacting parts, rotations at joints, and closing of gaps resulting in impacts. Lumping the system damping effects together can result in contributions of 1 to 2 orders of magnitude greater than material damping. In this report, damping refers to energy dissiption due to <u>all</u> sources, both material and system. Reference 3 gives a more detailed discussion on types of damping.

2.2 Mathematical Representation of Damping

Damping in a system is a complex phenomenon, and usually more than one type of damping exists in a system at a single time. The complex problem is generally reduced to a simplified mathematical description by assuming that if the damping is small, the effect can be represented by equivalent viscous dampers.[4] For a single degree of freedom oscillator, the equation of motion would be

$$M\ddot{x} + C\dot{x} + kx = F(t),$$

where

M = mass
x = displacement
C = damping
K = stiffness
$F(t)$ = applied force.

The coefficient C represents damping proportional to the velocity of the oscillator. The "critical" damping of the system (C_c) is defined as a function of the circular frequency ω

$$C_c = 2M\omega \, .$$

It is often convenient to express damping as the ratio

$$\zeta = \frac{C}{C_c} = \frac{C}{2M\omega} \, .$$

When expressed as a fraction, ζ is called the fraction of critical damping; when expressed as percent, ζ is called percent of critical damping.

The true damping characteristics of structural systems are very complex and difficult to determine. In fact, purely nonlinear systems cannot be characterized by parameters such as natural frequency and percent of critical damping at all, but only by response histories. However, it is common practice to express the damping of real systems in terms of ζ. This is reasonable if the system is only slightly nonlinear. In such cases a linear dynamic system analysis is commonly performed, with the nonlinearities approximated by a larger value of damping.

By transforming the equations of motion of the system into modal coordinates q_n by letting $x = \phi_n q_n$, the equations of motion for the n degrees of freedom can be written

$$\ddot{q}_n + 2\zeta_n\omega_n \dot{q}_n + \omega_n^2 q_n = \frac{F_{n(t)}}{M_n} ,$$

where

$$M_n = \phi_n^t M\phi_n$$

$$C_n = \phi_n^t C\phi_n = 2\zeta_n\omega_n M_n$$

$$K_n = \phi_n^t K\phi_n = \omega_n^2 M_n$$

$$F_n(t) = \phi_n^t F(t) .$$

Damping values are sometimes assumed to be constant under all conditions. This assumption has not been found to be realistic under some circumstances and other approximations have been formulated. For uniform mass damping, the damping force on each mass is proportional to the mass

$$(F_d)_j = \alpha M_j \dot{x}_j$$

where α is a constant.

$$C_j = \alpha M_j, \ \zeta_j = \frac{C}{C_c} = \frac{\alpha M_j}{2M_j\omega_j} = \frac{\alpha}{2\omega_j} ,$$

and

$$\alpha = 2\zeta_j\omega_j .$$

Thus the fraction of critical damping for each mode is inversely proportional to circular frequency. A second assumption is uniform structural damping in which the damping is proportional to the stiffness

$$(F_d)_j = \beta K_j \dot{x}_j .$$

Then

$$C_j = \beta K_j, \ K_j = \omega_j^2 M_j, \ \zeta_j = \frac{C}{C_c} = \frac{\beta K_j}{2M_j\omega_j} = \frac{\beta\omega_j}{2}$$

and

$$\beta = \frac{2\zeta_j}{\omega_j} .$$

In this case the fraction of critical damping is proportional to the circular frequency.

Rayleigh proposed a damping matrix consisting of both mass and structural damping. Damping of the form

$$\zeta = \frac{\alpha}{2\omega} + \frac{\beta\omega}{2}$$

is called Rayleigh damping.

2.3 Experimental Measurement Techniques

A number of techniques have been developed to estimate damping from experimental data. The simplest and most commonly used are the logarithmic decrement and half power methods.[4] In the logarithmic decrement method the ratios of the amplitude of vibration x_n at any time and the amplitude after m cycles x_{n+m} are used to form the logarithmic decrement

$$\delta_m = \ln \frac{x_n}{x_{n+m}} \quad .$$

Then

$$\zeta = \frac{\delta_m}{2\pi m \frac{\omega}{\omega_d}} \approx \frac{\delta_m}{2\pi m} = \frac{1}{2\pi m} \ln \frac{x_n}{x_{n+m}}$$

where ω and ω_d are the undamped and damped natural frequencies, respectively. If the damping is less than 20%, the approximate form which neglects the change in frequency due to damping is sufficiently accurate (the error in calculating ζ is less than 2%). The method is generally used with snapback testing, in which the structure is displaced, released, and allowed to vibrate freely. A typical experimentally determined time displacement history suitable for use with this technique is shown in Figure 1.

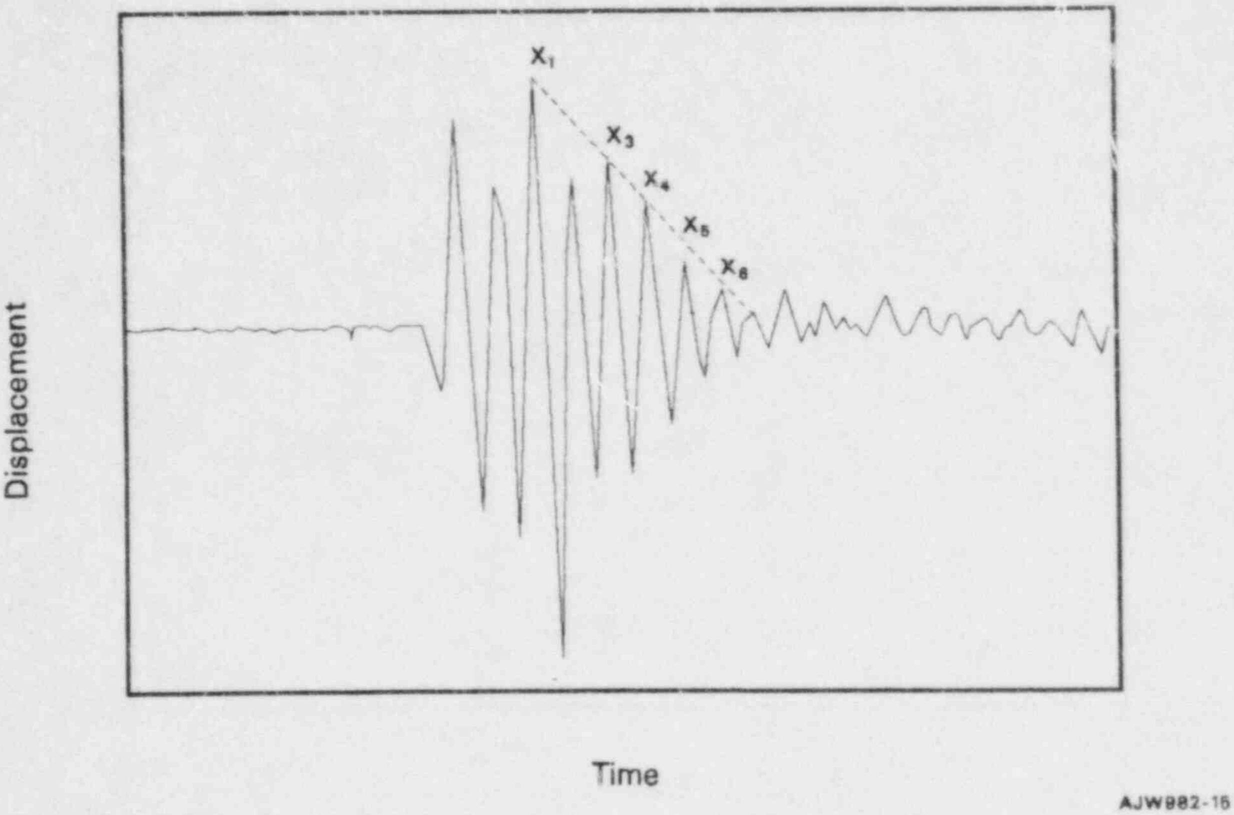

Figure 1. Typical logarithmic decrement curve.

The half power method uses a plot of response amplitude as a function of frequency to determine damping.[4] The damping ratio is approximately equal to

$$\zeta = \frac{f_2 - f_1}{f_2 + f_1}$$

where f_1 and f_2 are the frequencies where the response amplitude is 0.707 times the peak amplitude (see Figure 2). This method is useful for tests in which the excitation is sufficient to generate a frequency response curve, such as with shaker tests. Figure 3 shows a typical experimentally determined frequency response curve for a multiple degree of freedom system.

More precise (but also more complicated) procedures such as "curve fitting" and "circle fitting" have been developed and have been used to evaluate some of the data in the literature. A discussion and literature survey of these methods is contained in Reference 5. Reference 5 also describes some of the various methods used in structural dynamic testing.

One type of curve fitting method, which will be used by EG&G to evaluate some of the damping data discussed in Section 5 of this report, is called the complex exponential method. This method obtains the inverse Fourier transform of the transfer function (see Appendix A) to give the impulse response in the time domain. This response form, which can be written as the sum of complex exponential functions, is approximated by an interactive polynomial curve fitting procedure. The roots of this polynomial yield the natural frequencies and modal damping of the measured response.

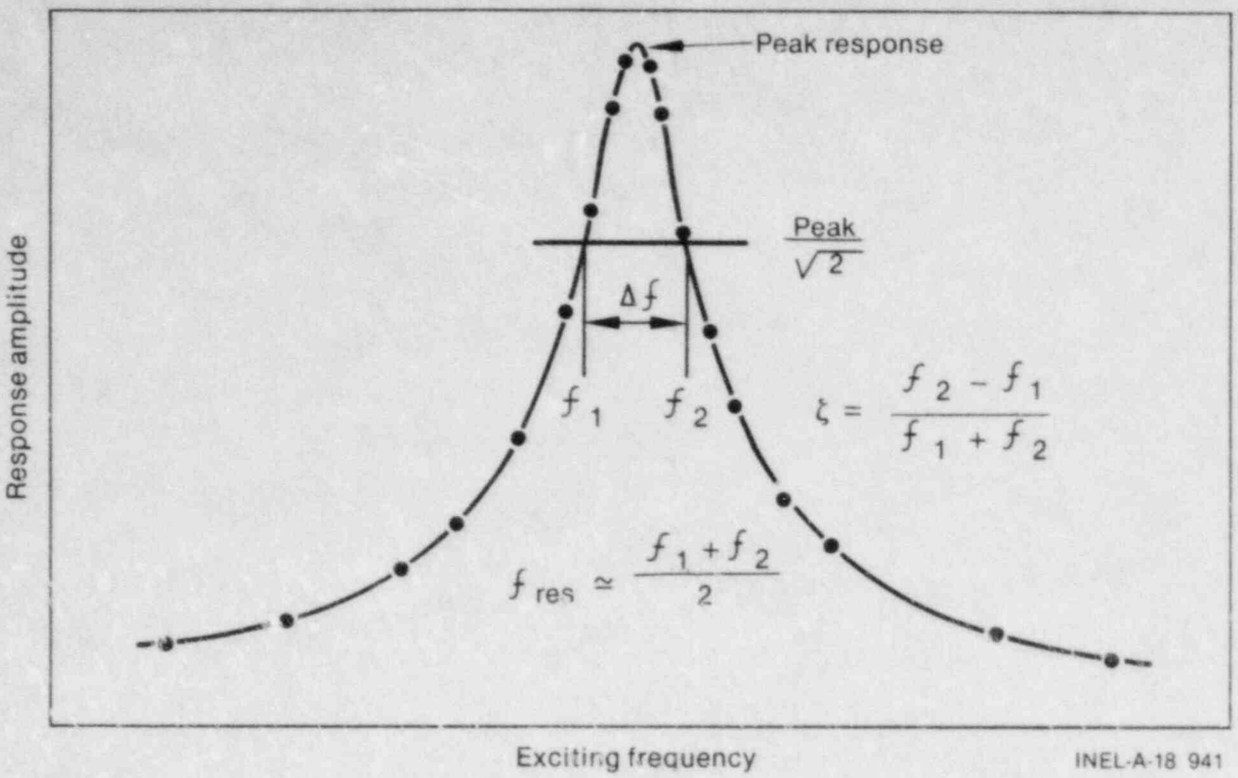

Figure 2. Half power method computation.

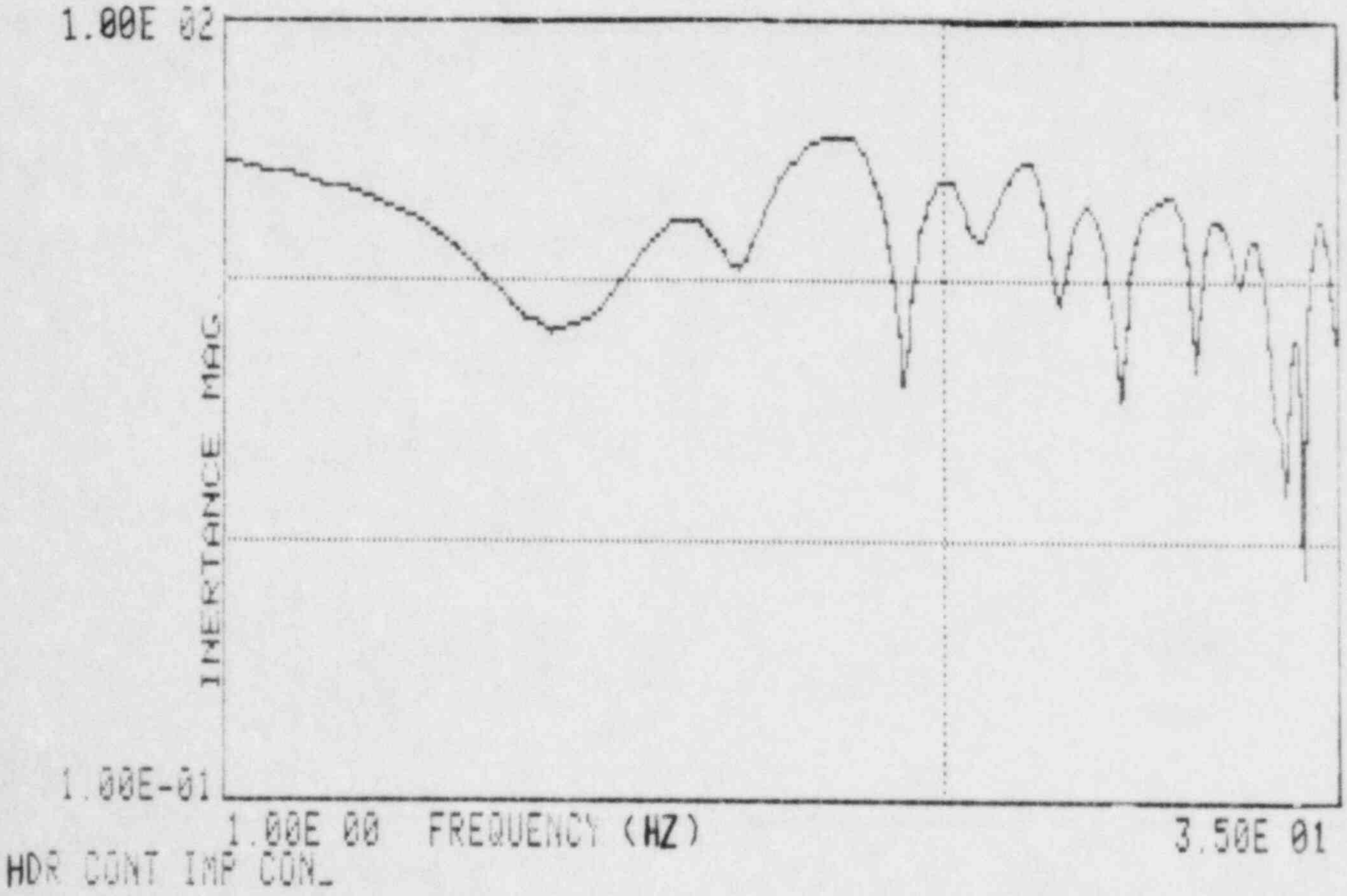

Figure 3. Typical frequency response curve.

2.4 Present Guidelines

The current Nuclear Regulatory Commission position on damping values to be used in dynamic structural modeling for the seismic design of nuclear power plant piping is set forth in Regulatory Guide 1.61.[6] The percent of critical damping for Operating Basis Earthquake (OBE) and Safe Shutdown Earthquake (SSE) load conditions are listed in Table 1 and are derived from recommendations given by Newmark, Blume, and Kapur.[7] Since the data base at the time the recommendations were made was limited, and since the values were designed to apply to a wide variety of piping systems, the values were deliberately set lower than the data would indicate. Lower bound damping values would ensure that response amplitudes and thus the corresponding stresses which would be compared to allowable values would not be underpredicted.

TABLE 1. DAMPING VALUES FROM REGULATORY GUIDE 1.61[6]
(Percent of Critical Damping)

Pipe Size	OBE or 1/2 SSE	SSE
Large diameter (greater than 12 inches)	2	3
Small diameter (equal to or less than 12 inches)	1	2

Since it was recognized that damping increased at higher response levels, the SSE levels were set at one percent of critical damping higher than OBE levels. Listing separate values for SSE and OBE allows a single analysis to be performed for each seismic event without first identifying system response and stress amplitudes. A more exact, but inefficient, method would be to first determine the amplitudes and then make use of the damping values associated with those amplitudes. Since damping affects response level, the process would have to be repeated a number of times until convergence was achieved.

Regulatory Guide 1.61 also allows an additional one percent of critical damping for piping over twelve inches in diameter than for piping equal to or smaller than this diameter. Experimental data indicates that the larger diameter piping systems typically have higher damping values. However, upon more extensive interpretation of experimental data, a conclusion can be supported that the higher damping values may be a function of piping supports rather than pipe diameter.[1] This would result from the fact that larger diameter piping is typically supported by devices which tend to dissipate energy (e.g., snubbers, constant force hangers) while smaller diameter piping would be more likely to be supported by rigid restraints and spring hangers in which less energy is dissipated.

The Regulatory Guide 1.61 values were approved on an interim basis in 1973, but due to a continued lack of consensus on what the values should be, a revision has not been agreed upon. The ASME Code,[8] presents a lengthy discussion of methods to incorporate damping into structural analyses, but contains the same values as Table 1. No values are recommended for transients other than seismic events, such as fluid induced vibrations, by either the Regulatory Guide or the ASME Code.

Although the Regulatory Guide allows damping values higher than Table 1 if documented test data are provided to support higher values, few, if any, attempts have been made to use other values in analyses. Thus the newest generation of nuclear power plants have their piping systems designed with the damping values of Table 1.

3. PARAMETERS WHICH INFLUENCE PIPING SYSTEM DAMPING-STATE OF THE ART

Since the issue of Regulatory Guide 1.61 there have been a series of summary papers which have contained experimentally determined damping values.[9,10,11] Actually, Ibáñez and the ANCO Engineers group have contributed a considerable number of state of the art papers on damping. For convenience, the previous ANCO papers have not all been referenced, since most are cited by Reference 11. It is not the purpose of this section to summarize all the damping data in previously published state of the art articles, but to concentrate on identifying those articles which specifically relate to parametric influences on damping.

In general, the previously cited references have tended to give an estimated range for damping applicable to the entire system rather than concentrate on parameters which may have an influence on damping. This is due to several reasons. First, there is considerable scatter in the damping data, so an average value is typically reported. Secondly, most of the data were not taken for the expressed purpose of computing system damping, but for characterizing the overall dynamic behavior of a specific piping system. Finally, some of the new data were reported as justification for changing the Regulatory Guide 1.61 values on a one-for-one basis, rather than considering parameters other than pipe diameter and type of earthquake, which are the only factors considered in Table 1.

There has been no comprehensive program in the United States which has varied one parameter at a time to systematically determine its influence on pipe damping. The Japanese have been working on their "Seismic Damping Ratio Evaluation Program" (SDREP) for several years in which parameters which influence damping were varied and existing data were evaluated using multiple regression analysis. The bulk of the data is unavailable in the U.S., and only brief summaries were presented in several SMIRT papers.[12,13,14] In the previous EG&G report,[1] data from German and U.S. sources were used to qualitatively assess factors which affect damping. This effort was only partially successful, because the data did not identify all parameters during the testing, (e.g. the stress amplitude was not generally computed) nor were the data generated specifically to evaluate damping.

In summary, there are insufficient data to effectively characterize the influence of various parameters on damping available in the United States at the present time. The following sections describe the present state of knowledge of parametric influences on damping, and discuss new data expected to become publicly available in the near future. To complete the overall picture, a discussion of what is not known, or gaps in the present knowledge, Section 4.1, should be reviewed in the context of the present section. To repeat, this section is not intended to be a complete state of the art discussion on damping itself, but to give a brief overview of the current knowledge on parameters which influence damping.

3.1 Parameters Which Influence Damping

In Reference 1, the author listed a number of parameters which were judged intuitively and from previous articles to be the principal factors influencing damping. Slightly modified, these are repeated below:

1. Excitation parameters

    a. Type of excitation (seismic, LOCA, etc.)

    b. Level of excitation (low, intermediate, high)

    c. Direction of excitation (vertical, along pipe axis, in support direction, etc.)

2. Physical parameters

    a. Type of pipe (diameter, material, thickness)

    b. System condition (hot or cold, filled or empty)
    c. Insulation
    d. Type of supports (spring hangers, snubbers, etc.)
    e. Geometry (support spacing, number of bends and elbows)
3. Response parameters
    a. Response frequency
    b. Response amplitude
    c. Response direction (vertical, longitudinal, transverse).

The two major attempts to answer a broad segment of these questions have been through the Japanese Seismic Damping Ratio Evaluation Program[12] and the previously cited EG&G report.[1] The Japanese results by Shibata are reproduced verbatim in Table 2. For a simple comparison between the EG&G results and a paraphrase of the Shibata results, refer to Table 3. A more detailed discussion of each parameter is provided below.

In Reference 1, EG&G reported a very slight trend that indirect methods, i.e., when the piping system vibration was induced through the supporting structure, produced lower damping than when the excitation was placed on the piping directly. However, the effect represented only about one half of one percent of critical damping which was judged to be insignificant. Shibata reported that the correlation was hardly observed. The EG&G report found that higher levels of excitation produced higher damping levels. The Japanese did not consider this parameter. Intuitively, larger excitation levels would be expected to produce higher stresses, and more impacting of supports and other non-linear effects, which would induce higher damping levels. Since excitation level is closely associated with response level, which is the parameter more often

TABLE 2. SHIBATA'S RESULTS (FROM REFERENCE 12)

Damping-Contributing Factor	Discussion About The Correlation Between Damping and Each Factor
1. Type of plant	The results show a strong correlation. It is considered that this is not only due to essential difference between BWR and PWR, but is due to that the damping characteristics is not explained enough with another factors.
2. Test method	The correlation with test method is hardly observed.
3. Pipe diameter 4. Thickness of pipe	The correlation is observed in some cases. These two factors have basically high correlations with many other factors such as "Fluid in pipe", "supporting conditions" and so on. Therefore, it is doubtful whether this result shows a true correlation.
5. Pipe material	The data of pre-operating tests were measured at small amplitudes where material damping is considered small, observed correlation with material is not easily conceivable. Results show CS pipings have slightly high damping than SS pipings.
6. Insulation	The correlation with damping is low.
7. Fluid in pipe	Weak correlation with fluid in pipe is observed. In other words pipings containing fluid have higher damping values.
8. Support-type	Strong correlation with support-type is observed. Contribution to damping becomes greater, in the order of rigid hanger, restraint, U bolt and oil snubber.
9. Deflection amplitude	The correlation with amplitude is weak. This results seems to be caused by that most of the data of pre-operating tests were measured at very small amplitudes.
10. Frequency	The weak correlation with frequency is observed. Damping value decreases as frequency increases.
11. Number of supports	The correlation with the number of support is hardly observed.

TABLE 2. SHIBATA'S RESULTS (FROM REFERENCE 12) (Continued)

Damping-Contributing Factor	Discussion About The Correlation Between Damping and Each Factor
12. Piping equipped with/without valve, pump	The correlation is observed in some groups of the data. It is considered to be caused by the effect of bias in sampling data.
13. Number of elbows	This factor is selected to be one expressing geometric effect. The distinct correlation with the number of elbow is not observed.

TABLE 3. PARAMETER INFLUENCE ON DAMPING AS REPORTED BY WARE AND SHIBATA

Parameters	Reference 1 (Ware)	Reference 12 (Shibata)
Excitation		
Type	No	No
Level	Weak	--
Direction	No	--
Physical		
Type of pipe	No	No
System condition	No	Weak
Insulation	--	Weak
Support type	Strong	Strong
Geometry	--	None
Response		
Frequency	Weak	Weak
Amplitude	Weak	Weak
Direction	No	--

reported by investigators, this parameter should also be considered in conjunction with of the discussion on response level below. Although neither source reported a correlation between excitation direction and damping, intuitively, response in the direction of an energy dissipating support would be expected to produce greater damping values than excitation perpendicular to the axes of supports.

Neither source concluded that the pipe size influenced damping. This is contrary to the philosophy of Regulatory Guide 1.61, which lists pipe diameter as one of the two parameters on which allowable damping for piping analyses is based. However, as previously stated, the supports themselves may be the parameter contributing to the damping, rather than the pipe size, since larger diameter piping systems typically have supports which dissipate more energy than the supports of smaller diameter piping. Shibata found that carbon steel piping had slightly higher damping than did stainless steel piping. Further, Reference 12 reported that fluid filled piping systems had higher damping values than empty piping; although in Reference 15, the effect was reported to be negligible in comparison to the effect provided by insulation. In the one case cited, EG&G in Reference 1 reported no change in damping values computed when the system was varied from empty to water filled. Intuitively, fluid friction in the piping system could dissipate more energy and thus produce slightly higher damping. However, based on available data, the effect may be negligible. While Reference 12 reported that the correlation of damping with insulation was low, Shibata in Reference 15 concluded that insulation makes a more substantial contribution to overall damping, and that the damping increases with the thickness of the thermal insulation. The EG&G report did not have sufficient information to investigate the influence of insulation on damping. The strongest contributor to piping system damping in both References 1 and 12 was the type of supports used. A consistent finding was that systems supported by snubbers and constant force hangers were judged to have higher damping values than systems supported by rigid restraints. The Japanese reported[12] than an effect due to the number of elbows was not observed, and that a correlation of damping with the number of supports was hardly observed. EG&G[1] did not have enough data to conclude if system geometry was an important factor.

In the EG&G report,[1] considerable effort was made to relate response frequency to damping. The response frequency is a parameter which includes support stiffness and spacing, mass distribution, pipe size, and geometry. Conveniently, it is also typically reported for all piping system dynamic characterization tests. In several cases, particularly that of the data from the Heissdampfreaktor (HDR) piping, an inverse frequency/damping correlation is seen. Shibata's data also shows a weak correlation of frequency with damping. In other data, damping seems to be constant with frequency. This anomaly is discussed in more detail in Section 4.1 which outlines the gaps in our present knowledge. Both the EG&G and Shibata results indicate that there is a weak correlation between response amplitude and damping. This seems to be an intuitively reasonable relationship because with larger amplitudes, the stress level increases and non-linear effects such as gaps become more pronounced. Unfortunately, most of the data was generated at low stress levels, and in addition, the actual stress levels were not reported. Other researchers have as a general rule concluded that damping increases with response level, although an applicable quantitative correlation has not yet been determined. This relationship is discussed in more detail in Section 4.1 which deals with gaps in our present knowledge. No correlation was found in the response direction by EG&G, although as in the case of the excitation direction, one might expect higher damping in the direction of the support axes.

Other investigators have commented on one or more of these parameters in their reports and papers.[9,10,11,17,18,19] These results will in part be discussed in the related material on gaps in our present knowledge in Section 4.1.

In summary, only a few qualitative trends have been observed which correlate damping with its influencing parameters, and the comprehensive task of defining the quantitative relationships which are necessary to fully understand the phenonemon is just beginning in the U.S. The following section describes some of the new data released and expected to be released during 1982, and early 1983.

3.2 New Data

Other than the substantial quantity of Japanese data which is not presently available in the U.S., the major U.S. test data completed by 1982 and not previously released are the EPRI/ANCO testing at the Indian Point plant and in the ANCO labs, General Electric (GE) safety/relief valve piping results, and U.S. Department of Energy (DOE) testing of thin walled liquid metal (LMFBR) nuclear grade piping. In addition, Battelle Institute in Frankfurt, West Germany, has released results from testing on a loop removed from the HDR plant.

The testing at the Indian Point plant was conducted on a feedwater line for EPRI by ANCO Engineers, who have the most experience performing large scale shaking of piping of all organizations in the U.S. Preliminary results can be found in Reference 16, but the final report has not yet been released. Summary papers of the testing[17,18] show that the data from these experiments will make a substantial contribution to the understanding of nuclear power plant damping. ANCO has also conducted tests on a "Z-bend" piping configuration in its laboratories for EPRI. The data, when released, is expected to be used both for analysis/experiment benchmarking purposes, and for pipe damping results.

A General Electric report[19] summarized the data for a number of safety/relief valve tests on Boiling Water Reactor (BWR) plants and subsystems. The significant conclusions from the report were:

1. The GE damping test data reported here (in Reference 19) showed no strong dependency upon either frequency or pipe size but did tend to increase with nominal pipe bending stress.

2. The GE damping data, when plotted as a function of stress, did indicate that the damping in these BWR piping systems was at least five percent (of critical damping) for measured stresses considerably less than the ASME Code service level A and B limits.

The GE data as it relates to response amplitude is discussed further in Section 4.1.

The Battelle Institute report[20] contains some damping values found during test rig experiments on piping performed at MPA Stuttgart and shows the influence of snubbers and hangers. An isometric of the system is shown in Figure 4, and the line diagram in Figure 5 identifies the measurement locations. Results are listed in Table 4. The most significant result is that for the main line, the damping for the X-Z plane mode dramatically increased when a hanger or snubber was added.

There are expected to be several additional tests conducted and reports issued in the U.S. in the 1982-1983 period which will further assist in contributing to the overall understanding of piping damping. In the LMFBR thin walled pipe area of research conducted through the DOE, Hanford Engineering Development Laboratory (HEDL) has been testing small piping systems.[21] Detailed results of this series and testing of a larger LMFBR line by Schott and Hulbert of Westinghouse Advanced Reactors Division (WARD) are expected to be made available in 1983. Further tests in the EPRI/ANCO series have been proposed, possibly in cooperation with the NRC. Finally, EG&G anticipates conducting a series of tests which would be run at the Idaho National Engineering Laboratory. The outline for these tests will be presented in Section 5 of this report.

TABLE 4. BATTELLE INSTITUTE MODAL DAMPING RESULTS (piping empty and unpressurized)

	Percent of Critical Damping						
	Without hanger or snubber			With hanger in Z-direction	With snubber		
					In Y-direction	In Z direction	
Bending Mode	X-Response	Y-Response	Z-Response	Z-Response	Y-Response	Z-Response	Frequency** (Hz)
Y-direction	0.35	0.5	0.4	0.5	--	0.4	5.08 - 5.28
X-Z Plane (+X/+Z)	0.4	0.45	0.45	9.3	0.6	11.2	6.13 - 8.88
X-Z Plane (-X/+Z)	0.4	0.3	0.25	*	1.4	--	14.01 - 15.31
Y-direction	0.35	0.4	0.4	0.42	1.8	0.5	15.08 - 15.79
Bypass in Y-direction	0.4	0.4	0.5	0.4	0.6	0.4	18.00 - 18.33
Bypass in X-direction	0.2	0.15	0.15	0.2	0.23	0.15	42.95 - 43.11
Bypass in Y-direction	0.3	0.25	0.40	0.4	0.3	0.4	45.49 - 45.54

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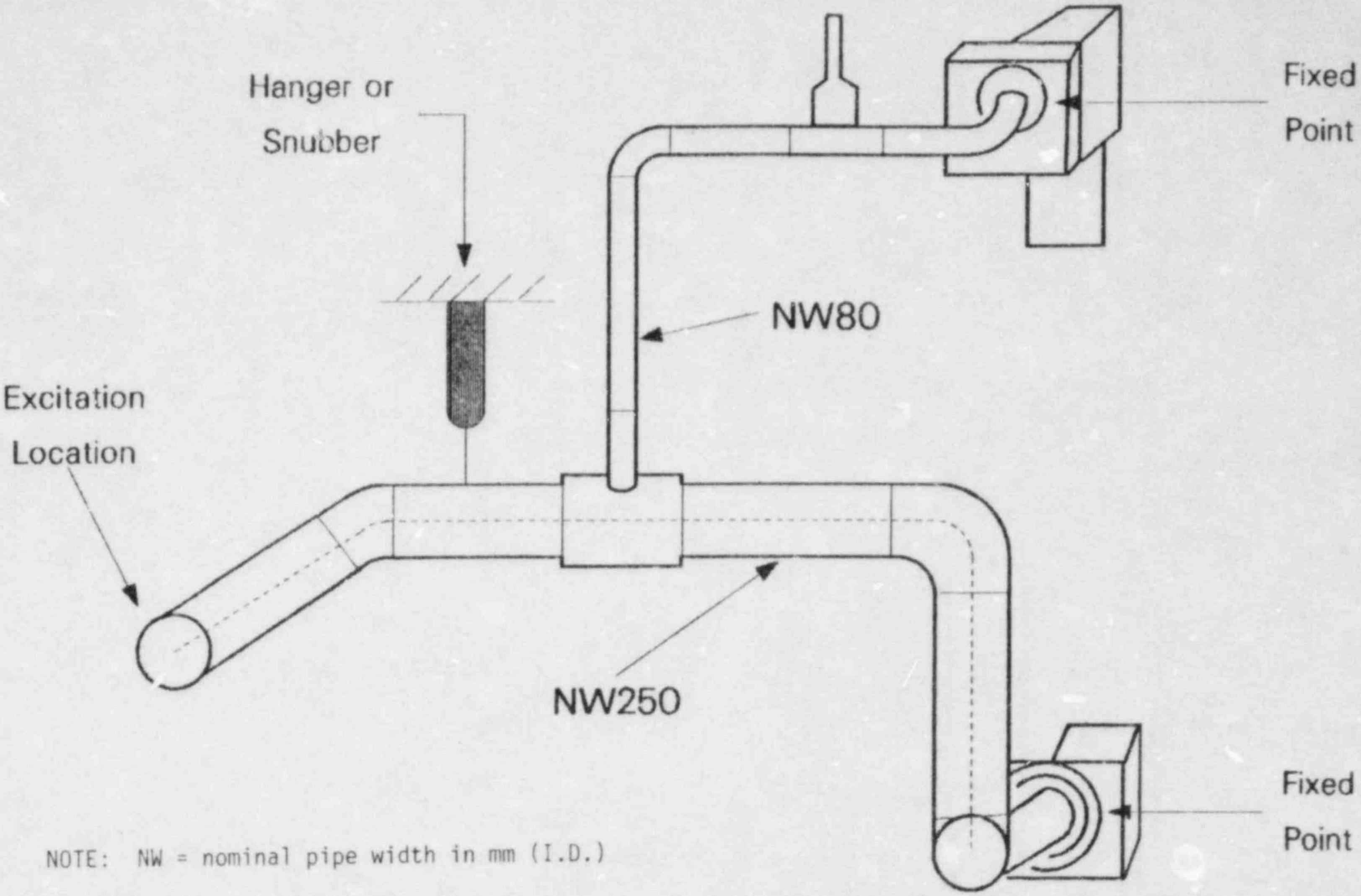
* Nonlinear resonance characteristic (higher damping)

** Varies slightly with support type



NOTE: NW = nominal pipe width in mm (I.D.)

Figure 4. Battelle Institute test system.

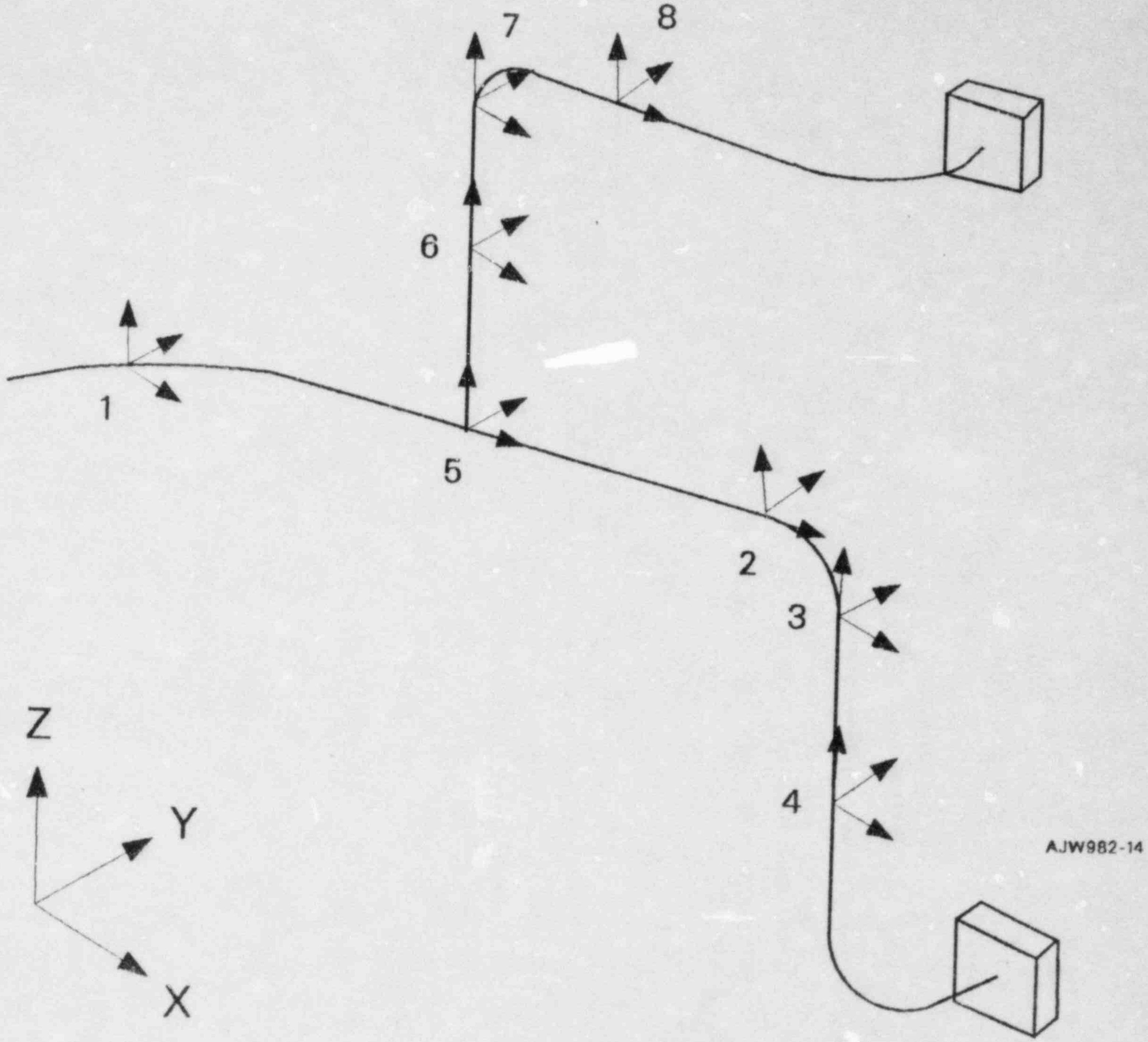


Figure 5. Schematic of Battelle Institute test configuration.

4. IDENTIFICATION OF PARAMETRIC EFFECTS

From the brief discussion on the state of the art in Section 3.1, it was concluded that from the sparse data base, only overall trends in parameters which affect damping have been identified. Most of the tests have been for general characterization of the dynamic response of piping systems rather than damping, so that the supplementary data necessary for a parameter study (such as stress levels) are not typically reported. This section gives a more detailed discussion of the gaps in the present overall understanding of piping damping, and identifies some goals that the U.S. program could strive to accomplish in the next several years.

4.1 Gaps in Present Knowledge

From the state of the art discussion, Section 3.1, overall trends from available data were identified. Qualitatively, the parametric influences in order of importance would seem to be:

1. Strong Influence
    a. Type of Supports
2. Weak Influence
    a. Response Amplitude
    b. Response Frequency
    c. Insulation
3. Little or Unknown Influence
    a. Geometry
    b. Type of Excitation

c. Direction of Excitation or Response

d. Pipe Size.

Even with these trends there are inconsistencies in the data, and a lack of quantitative information. To further clarify the gaps in knowledge some examples are given below.

4.1.1 Support Type

It has been conclusively demonstrated[12,20] that the addition of energy dissipating supports adds damping to a system. An example is shown in Figure 6, which is taken from Reference 12. However, data on the quantitative influence of the wide variety of types of supports (e.g., sway braces, rigid restraints, spring hangers, constant force hangers, snubbers, etc.) under varying levels of response amplitude are not currently available in the U.S. Further questions can be raised as to what effect multiple supports would have over a single support, and how various combinations of supports would change the damping of a system.

4.1.2 Response Amplitude

In general it has been established that increased response amplitude results in higher damping.[11,19] It was pointed out in Reference 1 that the relationship between excitation/response levels and damping is not altogether straightforward, since if the increased excitation causes higher damping, the higher damping would in turn inhibit response motion. Furthermore, the data are sometimes contradictory. Figures 7 and 8 (from References 22 and 19, respectively) show increased damping with response (stress) level up to and beyond yield stresses. On the other hand, Figure 6 shows that damping decreases with stress level. This anomaly can perhaps be explained by the fact that the Figure 6 data were taken at low response levels, and that the damping mechanism may have been Coulomb friction which would decrease with

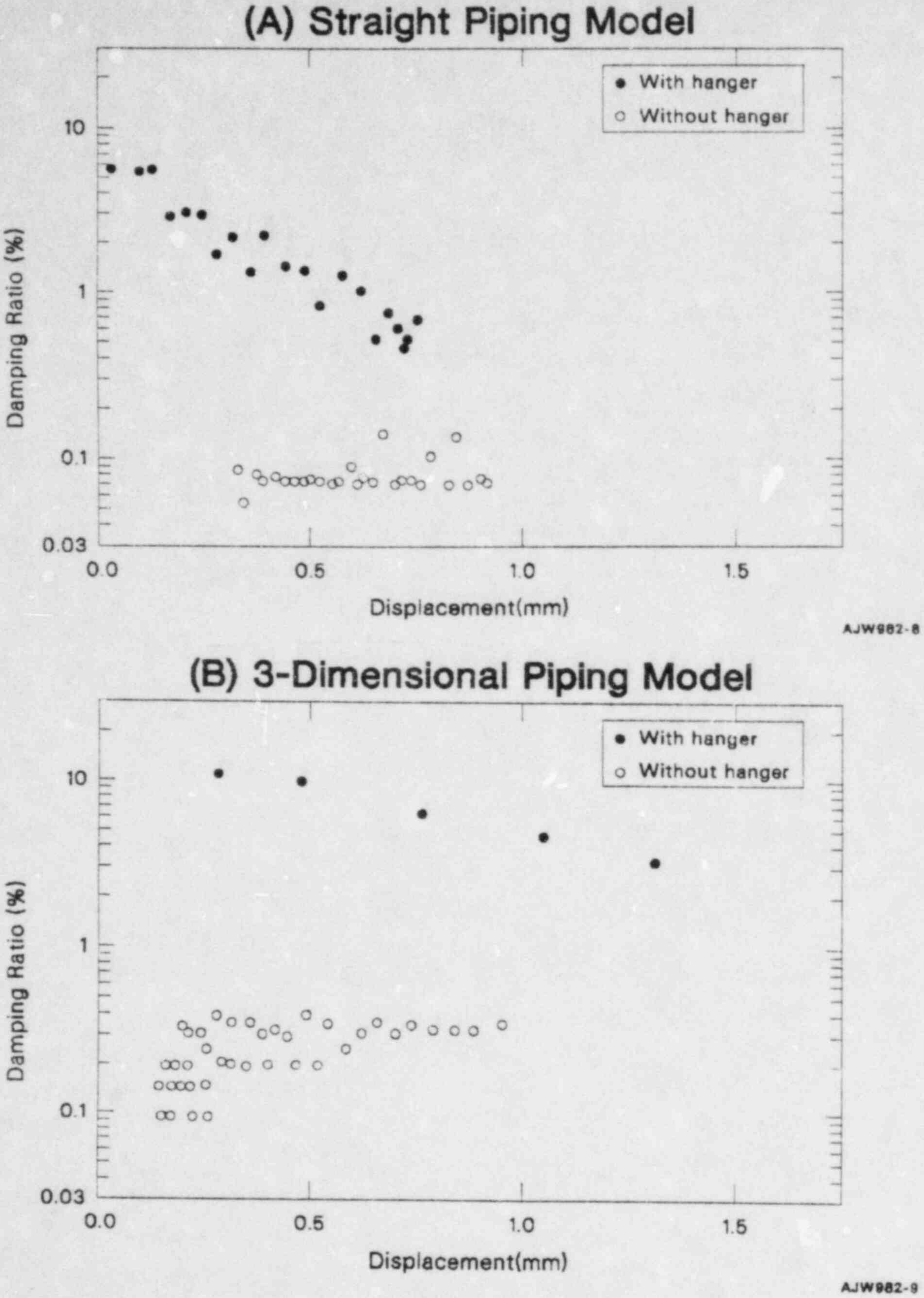


Figure 6. Effect of energy dissipating supports.

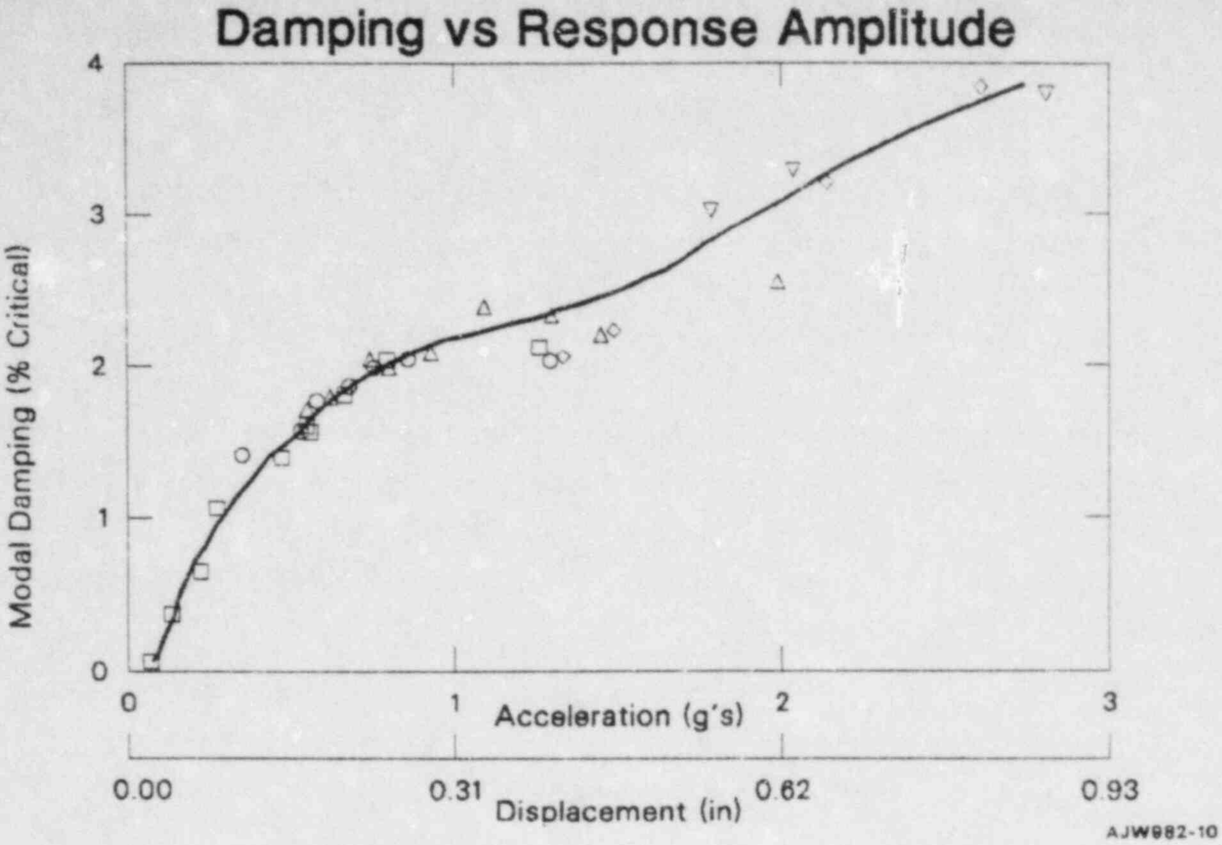


Figure 7. ANCO test data.

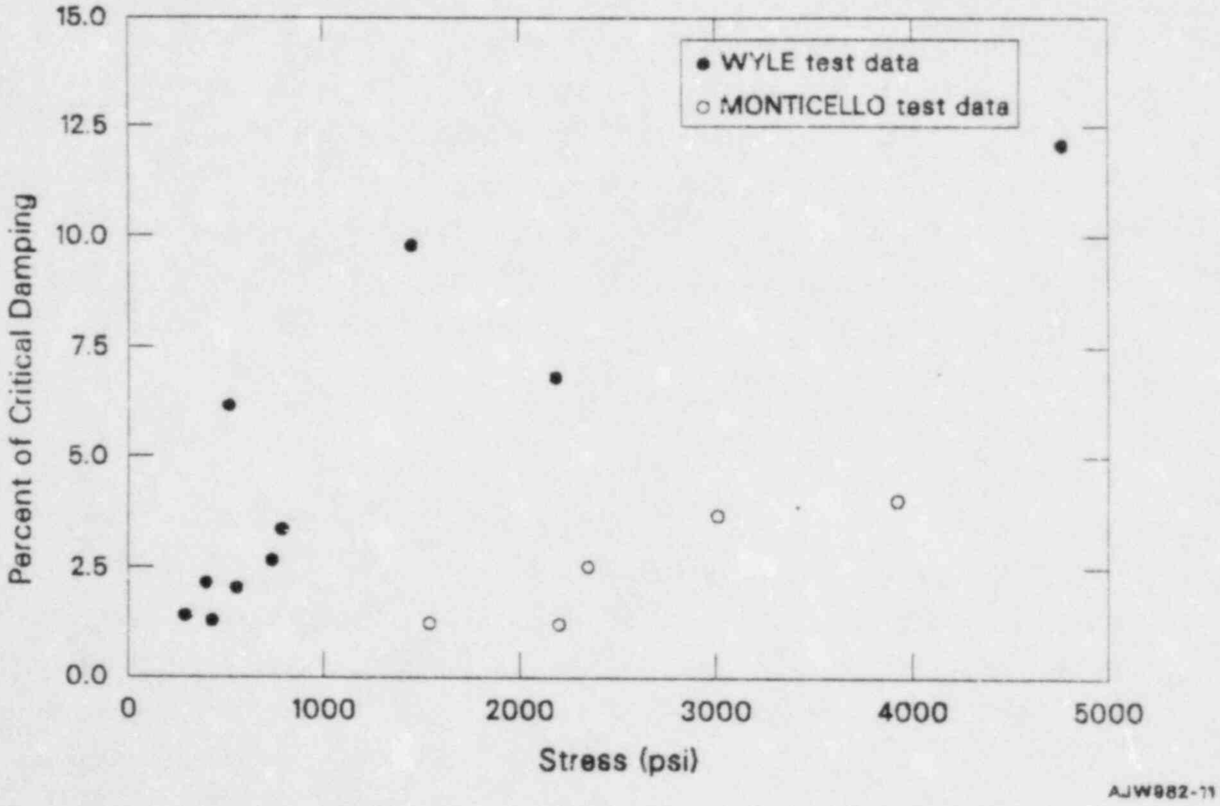


Figure 8. GE test data.

response level. Such a phenomenon was also observed by ANCO in testing a five inch pipe at the Diablo Canyon nuclear power plant[22] in which the damping decreased, then increased with acceleration level, as shown in Figure 9.

One constraint in determining the influence of response amplitude is that much of the test data was taken at low stress levels for safety reasons during in situ testing. Also, the stress level was not generally computed or reported. Consequently, the task of determining system damping at high stress levels must usually be determined in laboratory experiments. Reference 5 discusses various methods which could be used to extrapolate low level excitation damping results to high level excitation situations, but the lack of actual data is a present barrier to such an effort.

4.1.3 Response Frequency

Another parameter characterized by sometimes contradictory data is the response frequency. In Reference 1 the author postulated that this might be a parameter of convenience, since it related many of the stiffness and mass variables. Several of the piping systems surveyed in Reference 1 showed an inverse frequency/damping relation, especially below 10 Hertz, as demonstrated by Figures 10, 11, and 12. This phenomenon was also observed by the Japanese.[12] However, other data does not tend to support the premise that damping varies with frequency. The GE test data report[19] states that no such trend was observed, and the preliminary Indian Point data[1,16] shows that damping is relatively constant with frequency as shown in Figure 13. When the remaining EPRI/ANCO data from the Indian Point test series is finally released, this point may be further clarified.

4.1.4 Insulation

No program to thoroughly assess the affect of insulation has been carried out and reported in the U.S. Since the EPRI/ANCO tests at Indian Point were undertaken with both insulated and non-insulated conditions, the resulting data, when released, may shed more light on the subject. In the meantime, the Japanese conclusions reported in Reference 15 offer the best available insights at this time. These are quoted from Reference 15 as follows:

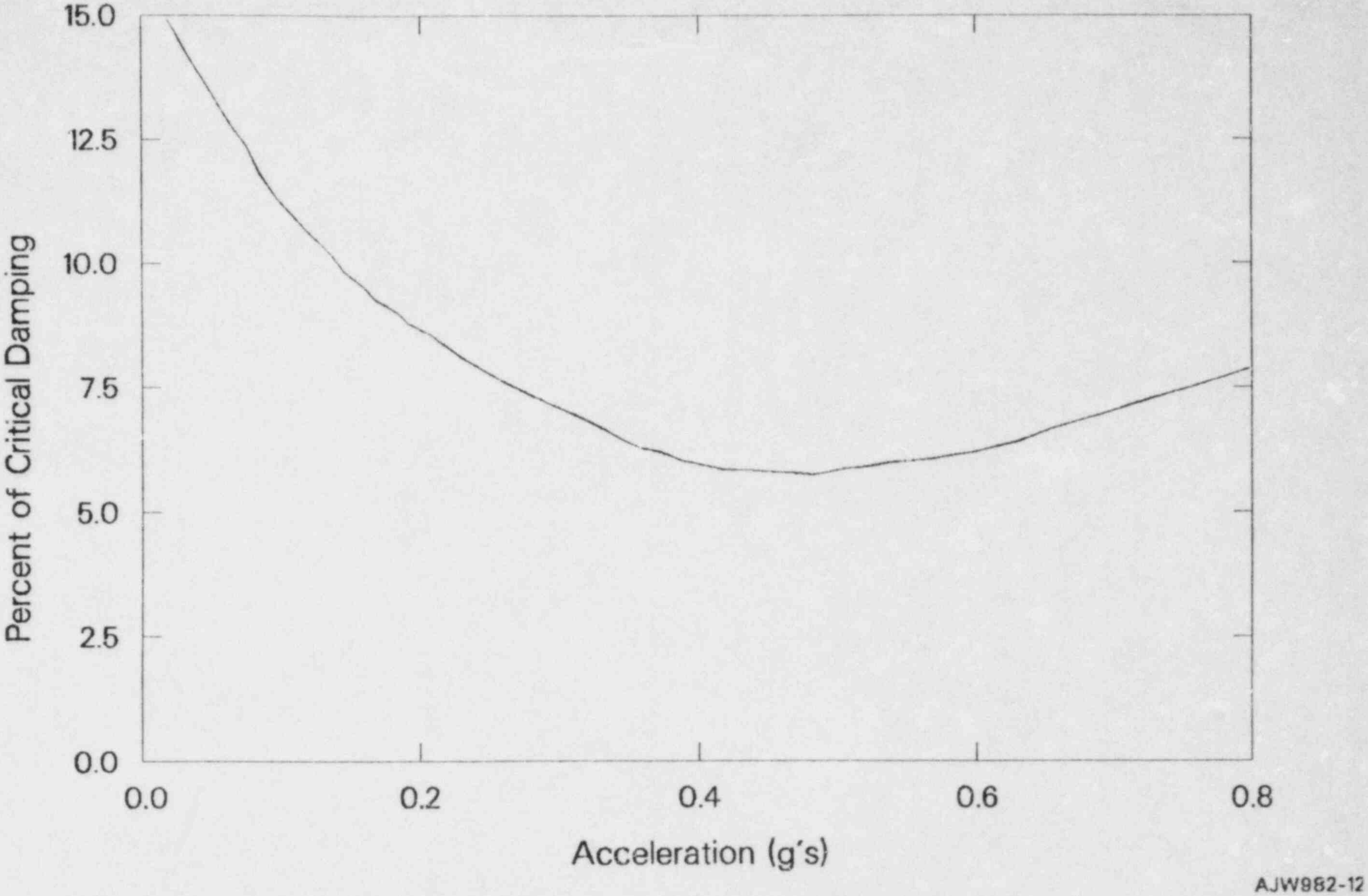


Figure 9. Diablo Canyon test data.

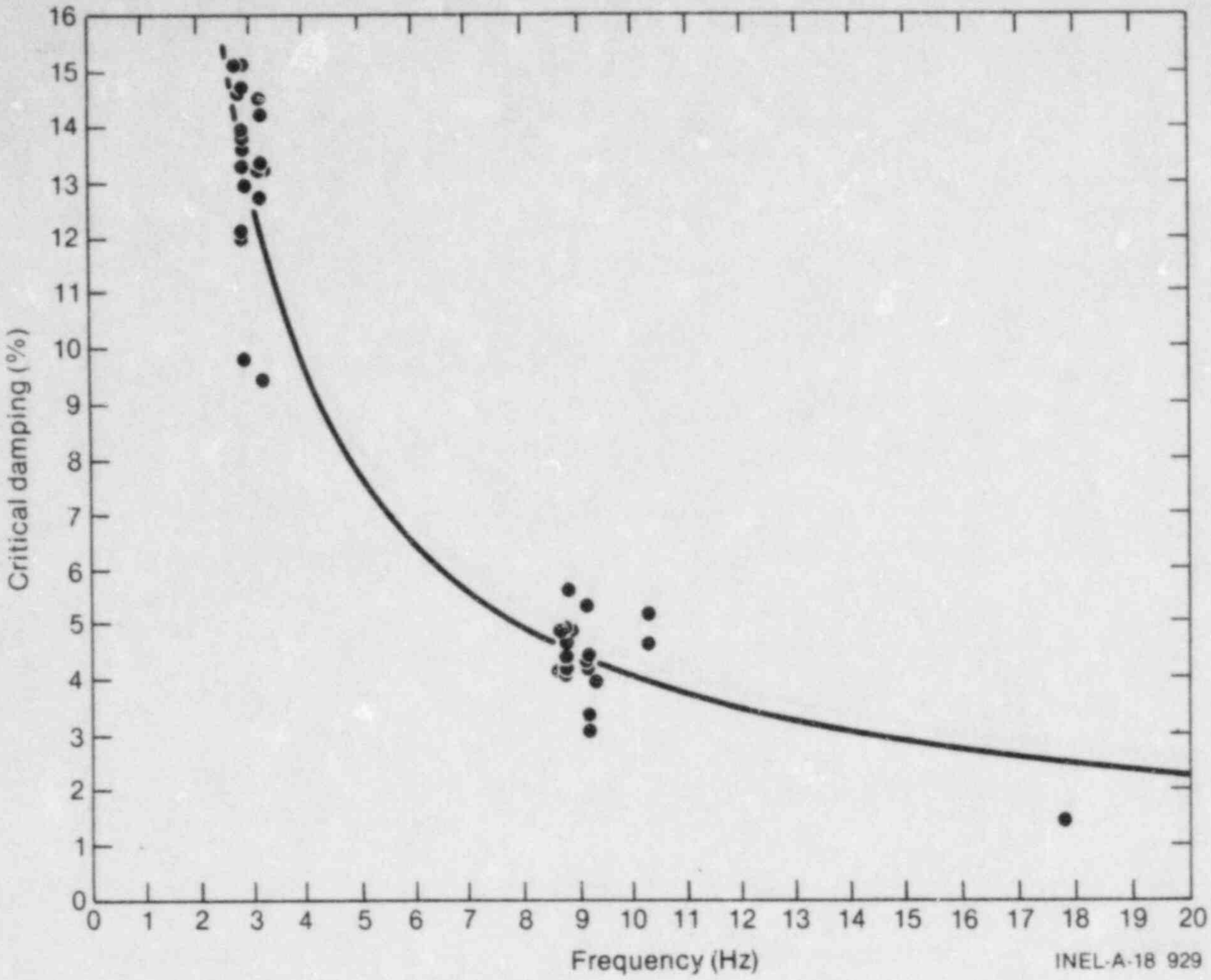


Figure 10. HDR PDL snapback test data

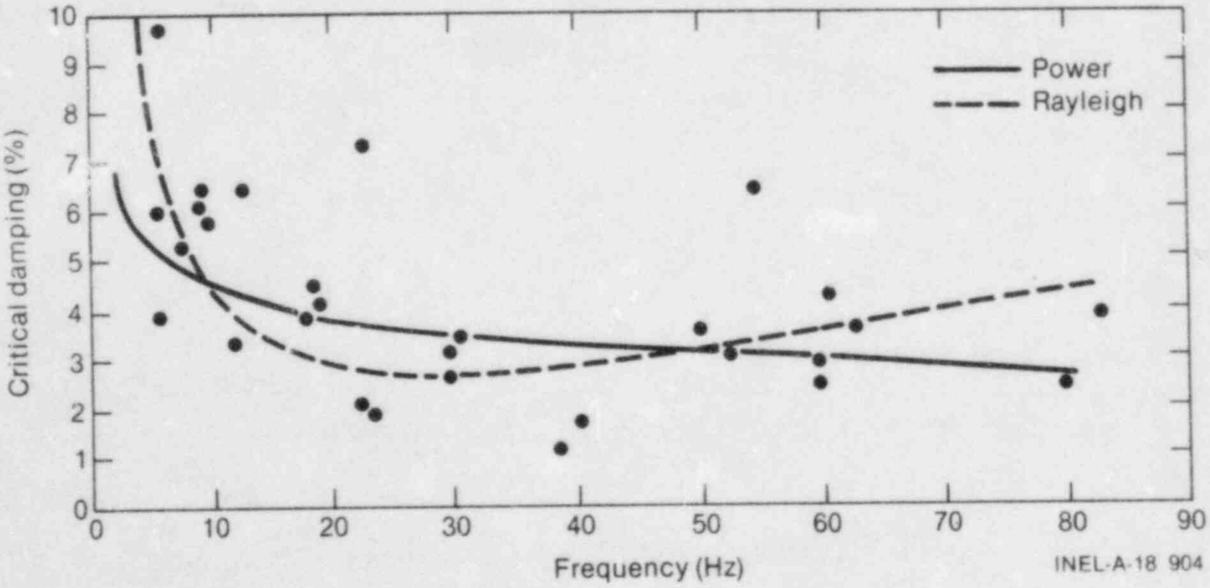


Figure 11. LaSalle recirculation line data.

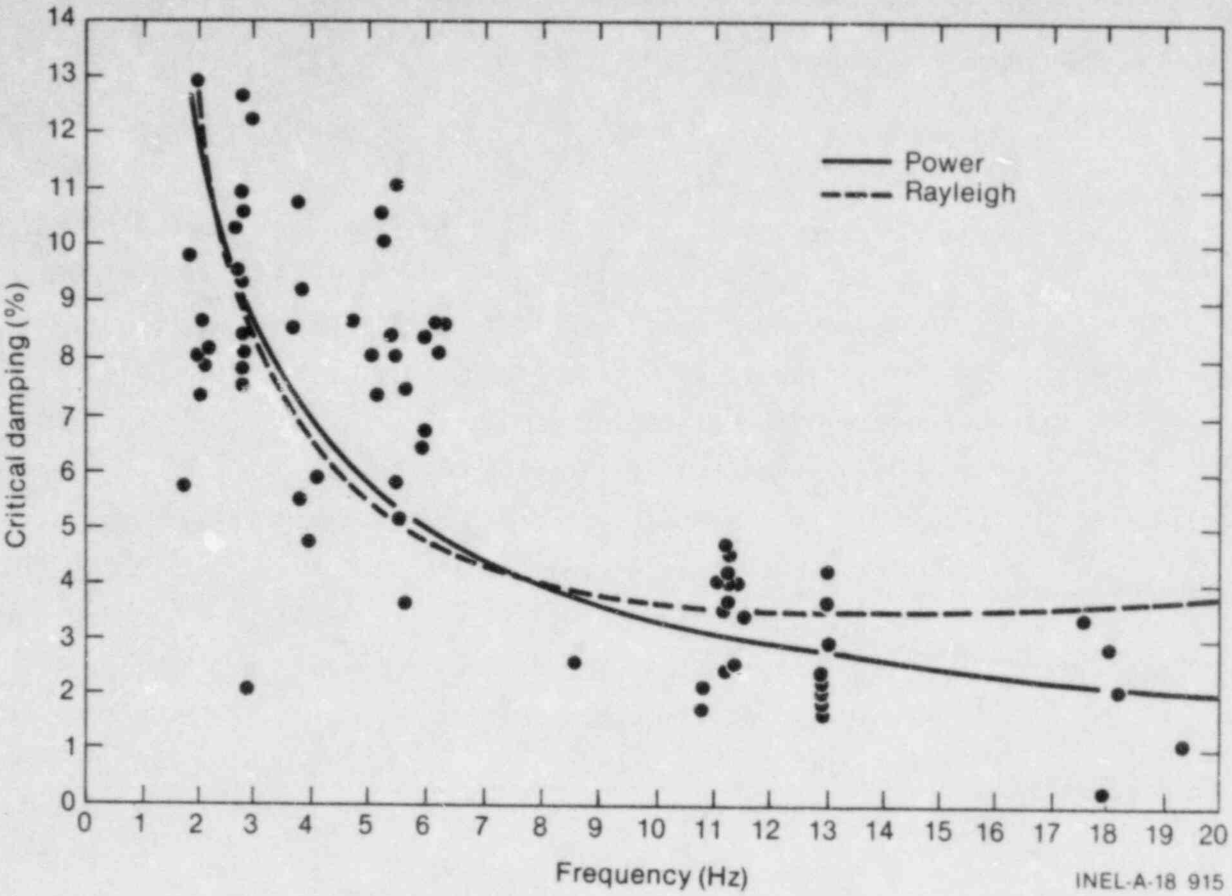


Figure 12. HDR URL snapback test data.

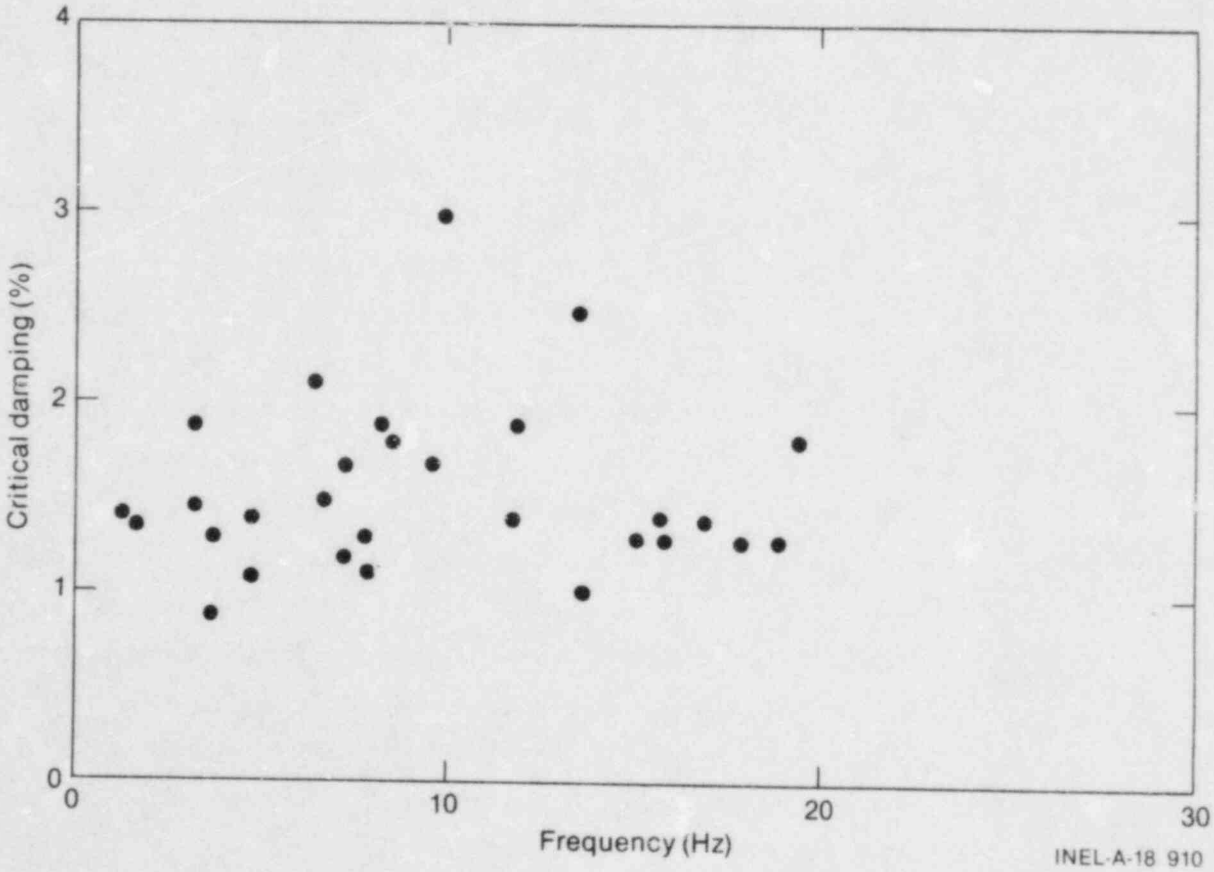


Figure 13. Indian Point feedwater line data.

"1. Thermal insulator (calcium silicate) contributes to increasing of the damping of piping system.

2. The component characteristics test of thermal insulator indicated that the damping ratio of piping with the calcium silicate thermal insulator increases as the thermal insulator becomes thicker and the pipe diameter becomes larger, and as the response acceleration becomes larger and the vibration frequency becomes higher. While the damping ratio of the reflective metal insulator is observed considerably lower than that of the calcium silicate thermal insulator.

3. As an example of an estimating formula for damping ratio of piping system with thermal insulator, the following equation was obtained from the component damping characteristics test.

$$\text{Log } h = 0.09\,D + 1.699\,Rm + 0.088\,d - 1.173$$

where

h = Damping ratio (%)

D = Nominal diameter (inch)

Rm = Mass ratio of thermal insulator to piping

d = Response displacement (mm).

4. The damping effect of internal fluid is negligibly small as compared with that of thermal insulator.

5. The simplified piping model tests showed that the damping effect of the thermal insulator is assumed to be 1/2 by the translational motion of piping and thermal insulator, and also to be 1/2 by the friction at the overlapped portions of aluminum plate. Furthermore, the restraint without gap does not affect

the damping, and conversely piping supported by the restraint with gap shows nonlinear behavior and the response acceleration does not develop more than a certain value.

6. The scale model test showed that the large damping ratio is obtained by gaps between piping and the thermal insulator, and by gap and friction at supporting parts of piping system.

7. In seismic design of piping system for nuclear power plant, the damping ratio, 0.5% is specified in Japan. From above-mentioned results, it may be concluded that the larger damping ratio than the specified value is applicable to actual design of piping system with thermal insulator."

4.1.4 Summary

Obviously, there are many gaps in our understanding of the phenomenon of piping damping, which can only be filled in by continued testing and data evaluation. A discussion of potential goals for the U.S. program is contained in Section 4.2 Anticipated EG&G contributions to such a program are presented in Section 5.

4.2 Potential Goals

For a program to keep on a consistent course, it is helpful for a set of goals to be established and followed as the outline of the program develops. The program should be flexible enough so that changes can be made to the goals, and new goals added, based on the information obtained from previous stages. This section outlines some potential short and long range goals for which the U.S. damping study program could strive. The Pressure Vessel Research Committee (PVRC) Technical Committee on Piping Systems has already established a Damping Value Task Group[23,24] to begin efforts to bring about revisions to the current guidelines. The following recommendations do not contradict the approach the PVRC Committee has adopted to date.

4.2.1 Short Term Goals

It will doubtlessly take several years to acquire the knowledge of damping values and their influencing parameters required to form an adequately justifiable basis, backed up by solid technical sources, for allowable damping values to be used in nuclear power plant piping analyses. Meanwhile, the nuclear industry would be saddled with the present guidelines, which are generally accepted to be too conservative and which are further considered not to be in the best interests of the country as a whole. For a number of years, there have been continued calls for revisions to the current guidelines.[25] Based on the available data, immediate changes have been recommended from an allowable of five percent of critical damping by GE[19] to ten percent by Rodabaugh (in a letter appended to Reference 24). J. D. Stevenson[26] compiled best estimates of mean values of damping below 10 Hertz and arrived at 5.8 percent of critical damping for the actual stress levels at which the tests were conducted, and 7.3 percent of critical damping at SSE stress levels.

In order to initiate a change before many more nuclear power plants are designed and built, it seems feasible that the present allowable percent of critical damping guidelines could be raised based on the data reported since the release of Regulatory Guide 1.61. However, it should be recognized that the pipe diameter and the seismic excitation level are not the only parameters on which such an immediate change might be based, and that due to the present lack of sufficient data which identifies the effect of the various influencing parameters, a good deal of judgement by the experts in the field would need to be injected into the decision making process. It should further be pointed out that although a single value might be the simplest way to set an allowable damping value, the result could be nonconservative for rigidly supported small piping lines, and overly restrictive for larger lines heavily supported by snubbers. A method of including the influencing parameters would seem to be both reasonable and achievable. Such a method is discussed in Section 4.2.2 below.

The PVRC will be actively pursuing such a recommendation by gathering available data and possibly applying regression analysis techniques.[24] A cooperative effort to revise the present guidelines involving electric utilities through EPRI, nuclear plant vendors and architect/engineers, and the Nuclear Regulatory Commission and its consultant EG&G is expected.

4.2.2 Long Range Goals

The long range goals of the damping program do not have the immediacy associated with the short term goals. Consequently, time can be taken to obtain a basic understanding of the interrelationships between damping in piping systems and the influencing parameters. From this research work, an expanded table of allowable damping values for various types of piping systems could be constructed to take the place of Table 1. As an example, Table 5 illustrates a conceivable format including a combination of factors which might be incorporated into such a table.

This table could be further modified by allowing certain Rayleigh damping coefficients for particular systems. Reference 1 showed that many piping systems could be characterized by Rayleigh damping and that several commonly used structural computer codes accept this type damping. Additionally, more response levels (other than simply OBE and SSE) could be allowed.

The ultimate goal of the program should be to provide for the engineer the ability to select a piping system, consider its geometry and supports, and make an accurate prediction as to what would be reasonable damping values to be used in an analysis. In achieving this goal, several "blind" predictions based on actual piping systems might be made, and parameters adjusted by trial and error until reasonable agreement of results could be obtained. This approach is similar to the tack now being used to improve finite element modeling of systems.

While EG&G expects to be an active participant in short term plans, the major thrust of activities will be concentrated on the long term goals, as discussed in Section 5.

TABLE 5. HYPOTHETICAL FORM OF ALLOWABLE DAMPING VALUES

Type of Support	OBE LF/HF	SSE LF/HF
Rigid strut	X1/X2	X11/X12
Sway brace	X3/X4	X13/X14
Spring hanger	X5/X6	X15/X16
Constant force hanger	X7/X8	X17/X18
Snubber	X9/X10	X19/X20
etc.		

For insulators add the following percentages: Calcium Silicate Y
Reflective Z.

Note: LF (low frequency, below 10 hz)
HF (high frequency, above 10 hz)

5. EG&G PROGRAM

There are several areas of interest to be undertaken in FY-83 by EG&G. As previously stated, it is intended that close cooperation will be maintained with the PVRC, EPRI, and others who are actively acquiring data on pipe damping. Further, efforts to share in the vast resources of the Japanese will be pursued.

To supplement these efforts and to fill in some of the gaps in damping knowledge discussed in Section 4.1, EG&G will perform a testing program of its own. The overall test plan will follow a basic building block approach in which simple configurations will first be tested in a laboratory environment, with the complexity gradually increased, until in future years, in situ testing of actual piping systems might be undertaken to verify "blind" predictions.

This section provides a general description of the proposed FY-83 test layout and configuration, the excitation and data acquisition systems, and the basic test plan. Some possibilities of potential tests beyond FY-83 are also included.

5.1 Damping Test Layout and Configuration

After surveying a number of sites at the INEL, it was determined that the best location for the proposed damping tests is at the Auxiliary Reactor Area III (ARA III). ARA III, located as shown in Figure 14, was originally the site of a gas cooled test reactor. After being decommissioned, the site has been used for various physics and materials tests. Building 608 at ARA III presently houses some of these tests and provides a space and services which would be needed for performing the contemplated damping tests.

Figure 15 indicates the arrangement of test equipment and test fixture set up within the area. The test area is approximately 40 ft long and

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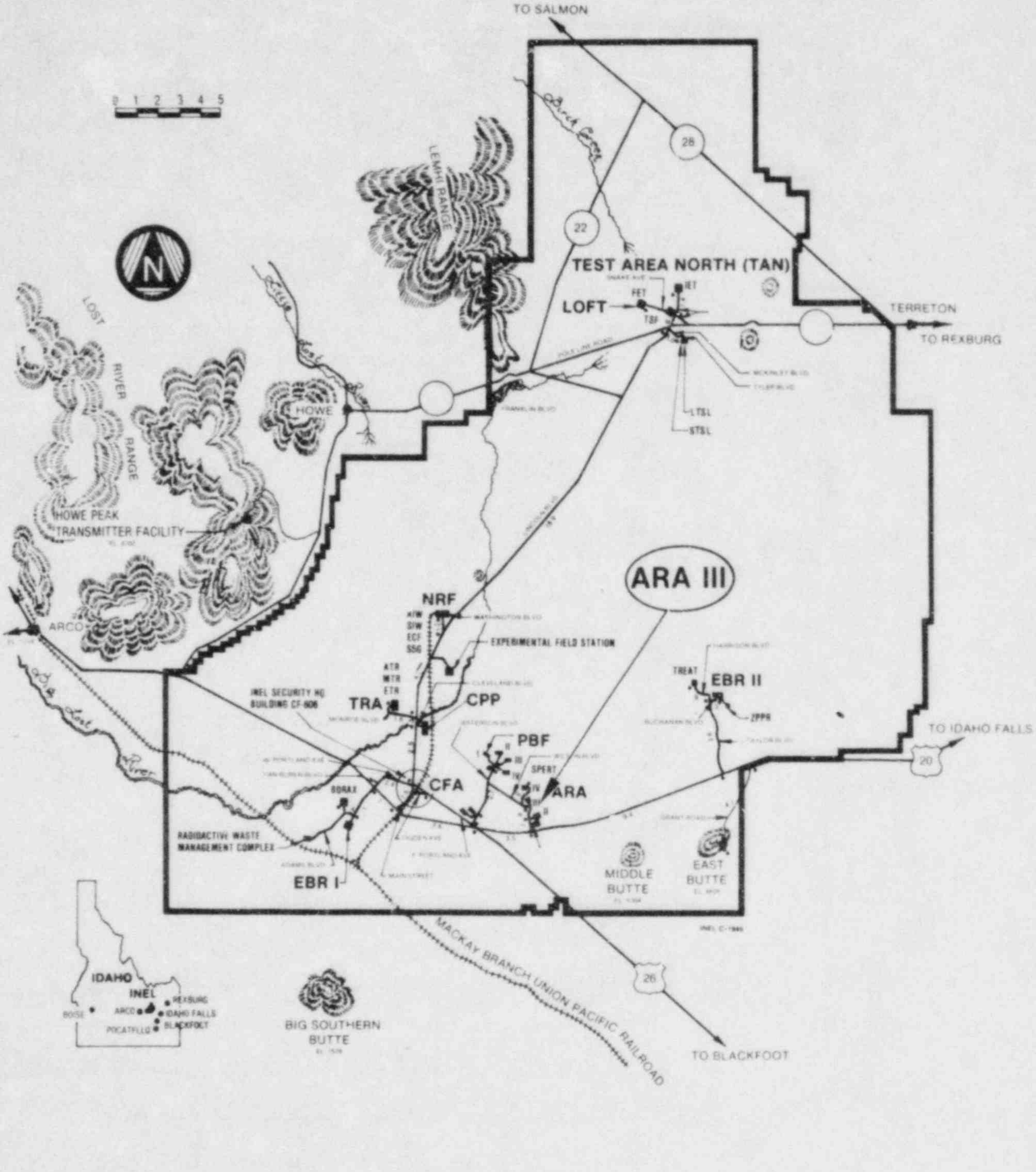

Figure 14. Location of ARA III.

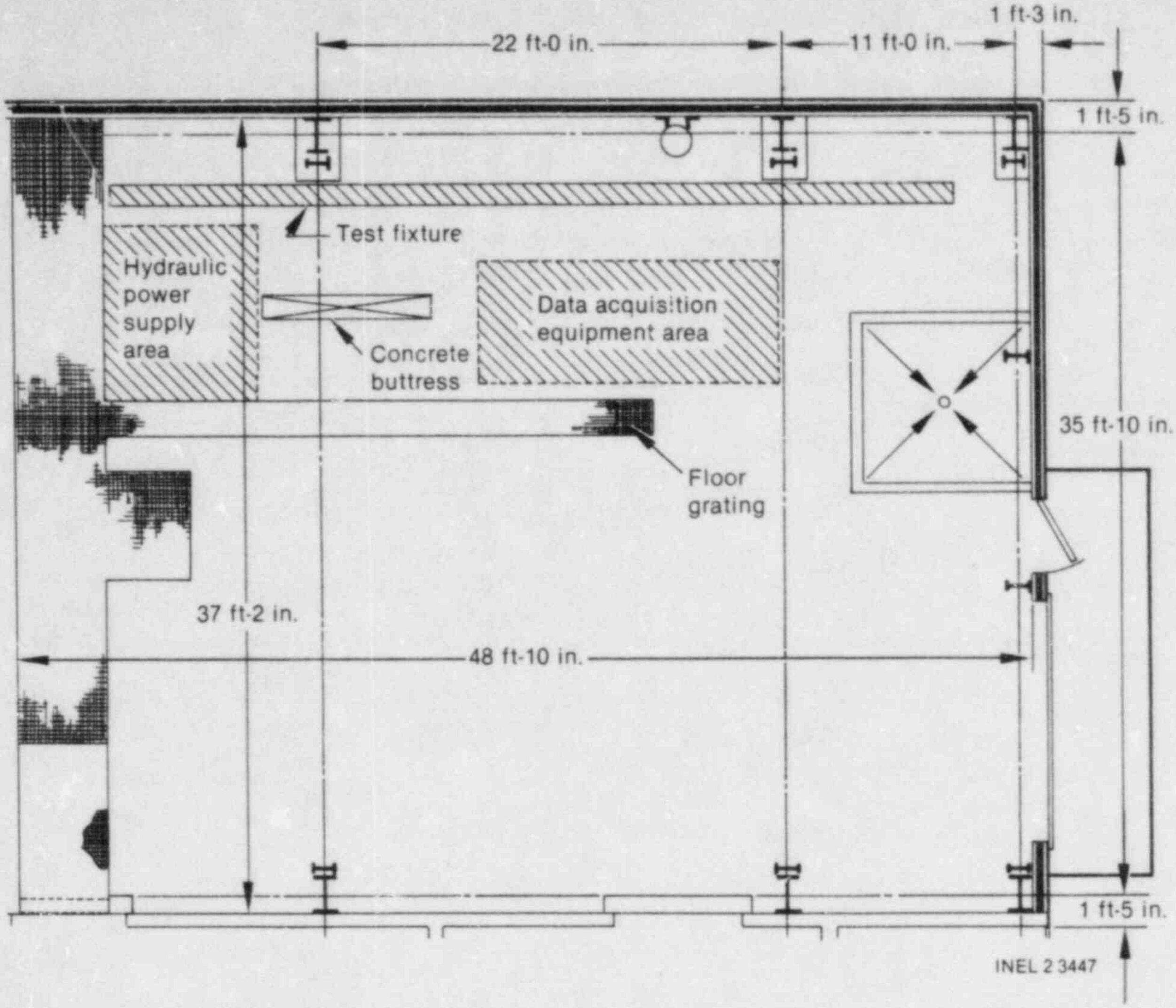

Figure 15. Arrangement of test equipment.

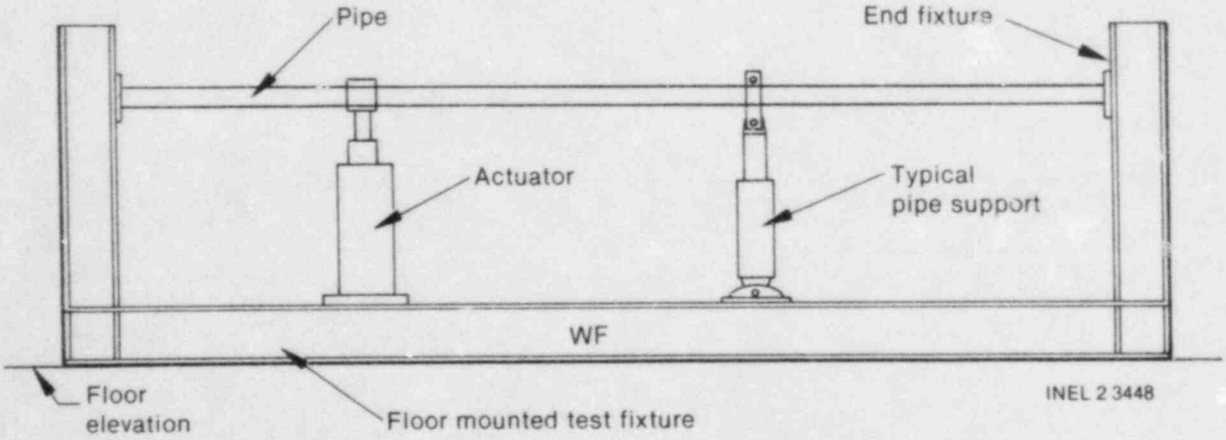

Figure 16. Typical test configuration.

15 ft wide. The test fixture will extend along the length of the area with the hydraulic power supply for the actuator and the modal analyzer to be located nearby.

The test fixture will consist of a rigid beam approximately 35 ft long anchored to the floor with moveable end fixtures mounted upon it. These end fixtures will be rigid in comparison to the stiffness of the test pipe and test supports. They will also provide end conditions for the pipe section varying from pinned to fixed conditions. A straight section of pipe will be supported between the end fixtures by typical piping supports such as snubbers, spring hangers, constant force hangers, and sway braces which will be anchored to the steel floor beam. The hydraulic actuator and snapback apparatus will also be anchored to this beam and attached to the pipe for excitation purposes. A typical test configuration is shown in Figure 16. There will be two sizes of stainless steel pipe used in the test arrangements, such as 3 in. and 8 in. nominal diameter schedule 40 pipe. It is anticipated that provisions can be made to test each pipe empty, filled with water, and insulated.

5.2 Excitation and Data Reduction

Several means of excitation will be employed. A hydraulic actuator will be used as the primary source of energy input. This actuator can either be attached to the test component with a reaction mass added or attached to a nearby rigid support structure with a force supplied between the support structure and the tested component. The latter arrangement would be used in these tests. The actuator weighs approximately 300 lbs. and can develop a maximum dynamic force of 2200 lbs. with good response characteristics well above the 33 Hertz range to be considered in these tests. The shaker operates on an oil pressure produced by a power supply consisting of a gear pump driven by an electric motor. Oil cooling is supplied via an oil/water heat exchanger which requires a water supply and drain at the test location. This power supply with its oil reservoir is mounted on a steel frame with casters. A third component of the hydraulic system is the hydraulic manifold which regulates the high pressure surges in the hydraulic lines. Hydraulic hose lines allow the power supply to be located up to 25 feet away from the hydraulic shaker. Electronics for this system consist of the hydraulic power supply control console, the servo controller for the actuator valve on the shaker, and an input signal wave generator.

Snapback tests will be performed by imposing an initial displacement on the system and then instantaneously releasing the imposed displacement. In this type of test, damping will be determined by the logarithmic decrement method applied to the structural response in the time domain. Impact tests using hammers will also be performed on the test set up. Pictures of the actuator, its hydraulic power supply, and the impact hammers are shown in Figures 17, 18, and 19.

Input forces to the system will be measured by load cells located between the actuator and the pipe for the shaker tests and in the head of the hammer in the impact tests. Response of the system will be measured by accelerometers, displacement transducers, and strain gauges attached at various locations on the pipe. Response signals will be sent from the transducers to the analyzer via coaxial cables with signal amplifiers. Strain gauge data will be transmitted to strain conditioners to be reduced and recorded for documentation of strain levels during the tests.

The structural analysis system which is to be used in the tests (see Figure 20) is capable of simultaneously recording eight channels of data and then analyzing each channel. Modal analysis testing utilizes a structure's calculated frequency response functions to determine modal frequencies, damping, and mode shapes.

During the tests, coherence functions will be calculated to determine the quality of the frequency response functions. Mathematical details of the transfer and coherence functions are given in Appendix A. Evaluation of the coherence functions during the tests allows for immediate correction or modification of the test procedure to ensure the best results possible.

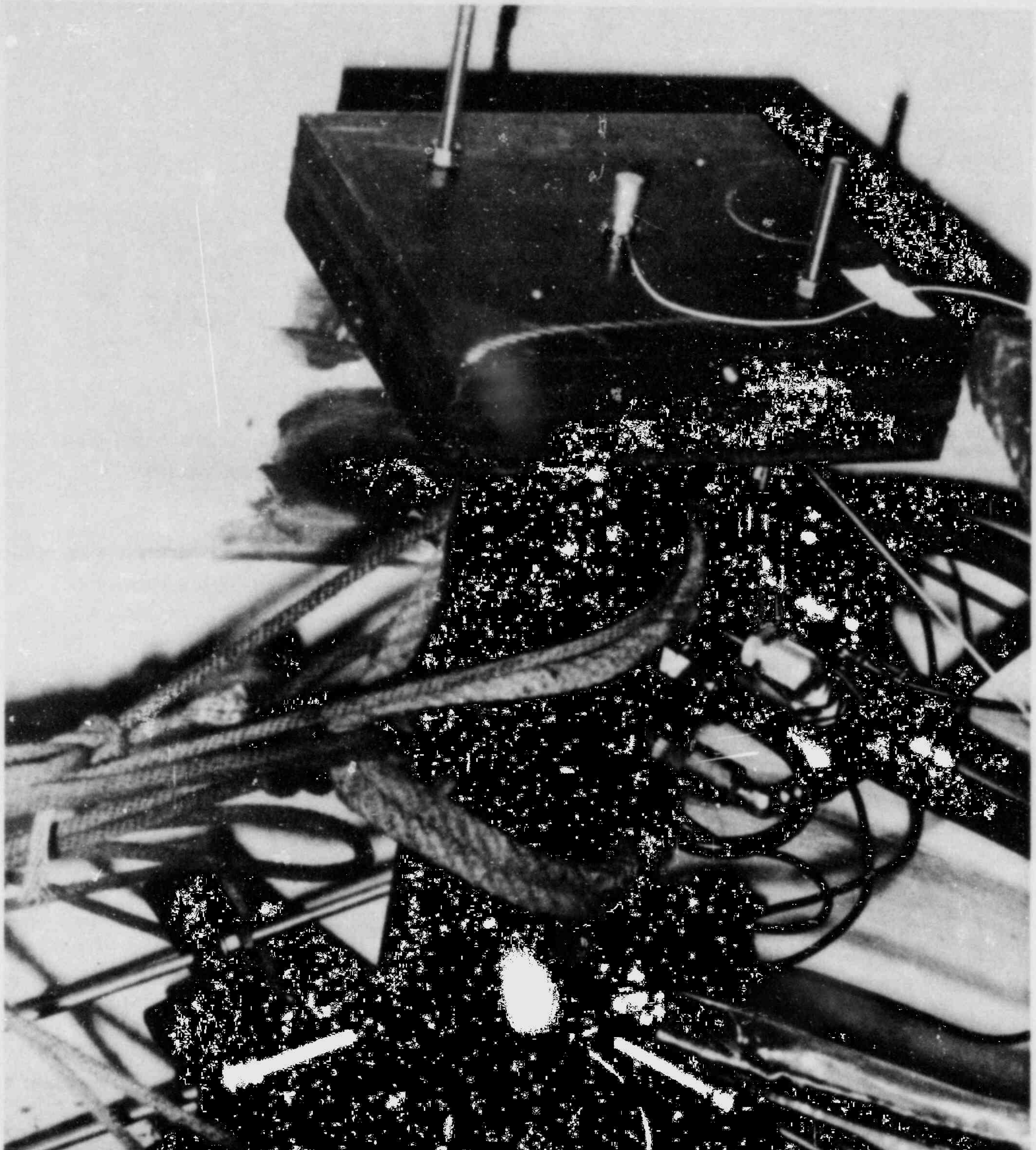

Figure 17. Hydraulic actuator.

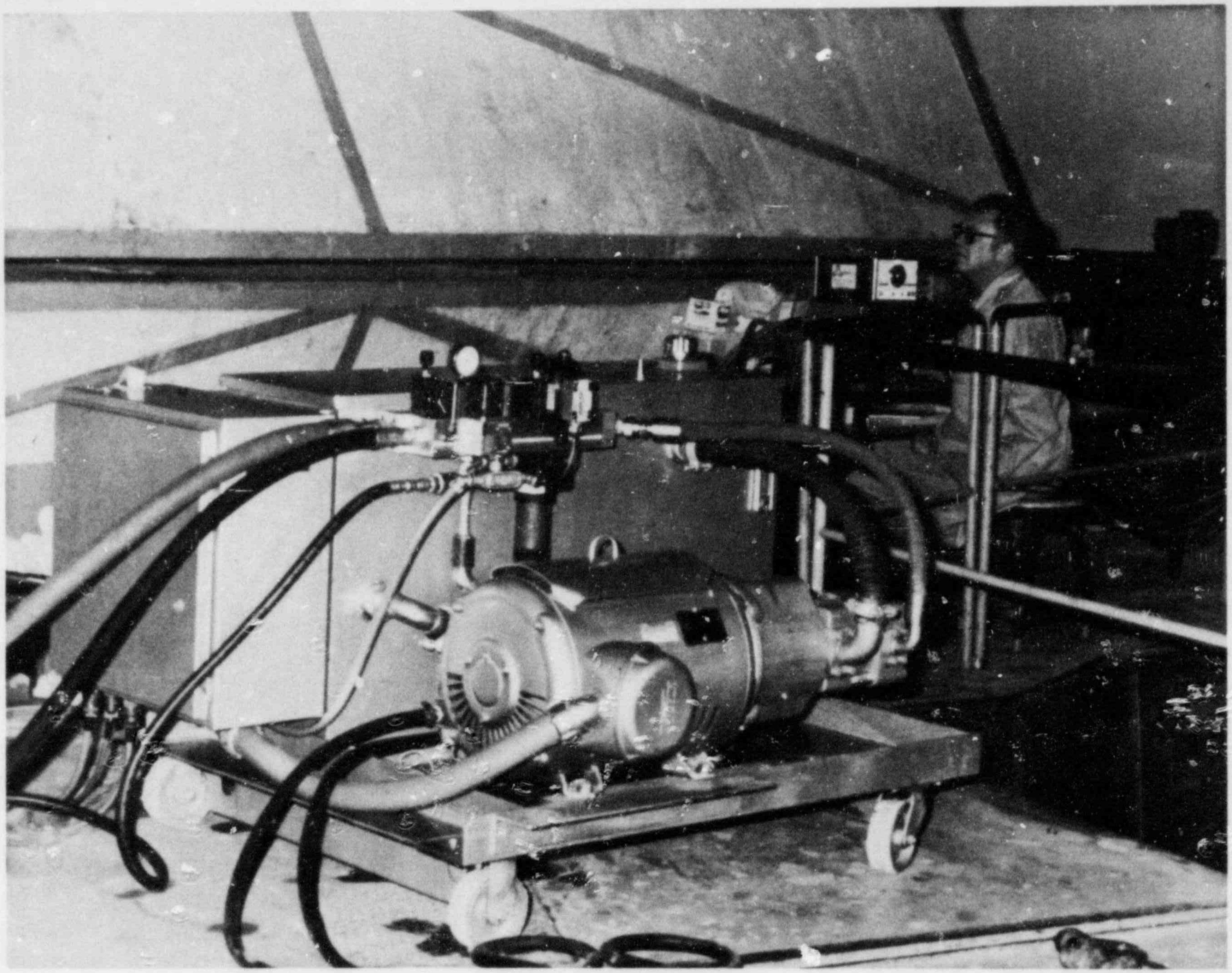

Figure 18. Hydraulic power supply.

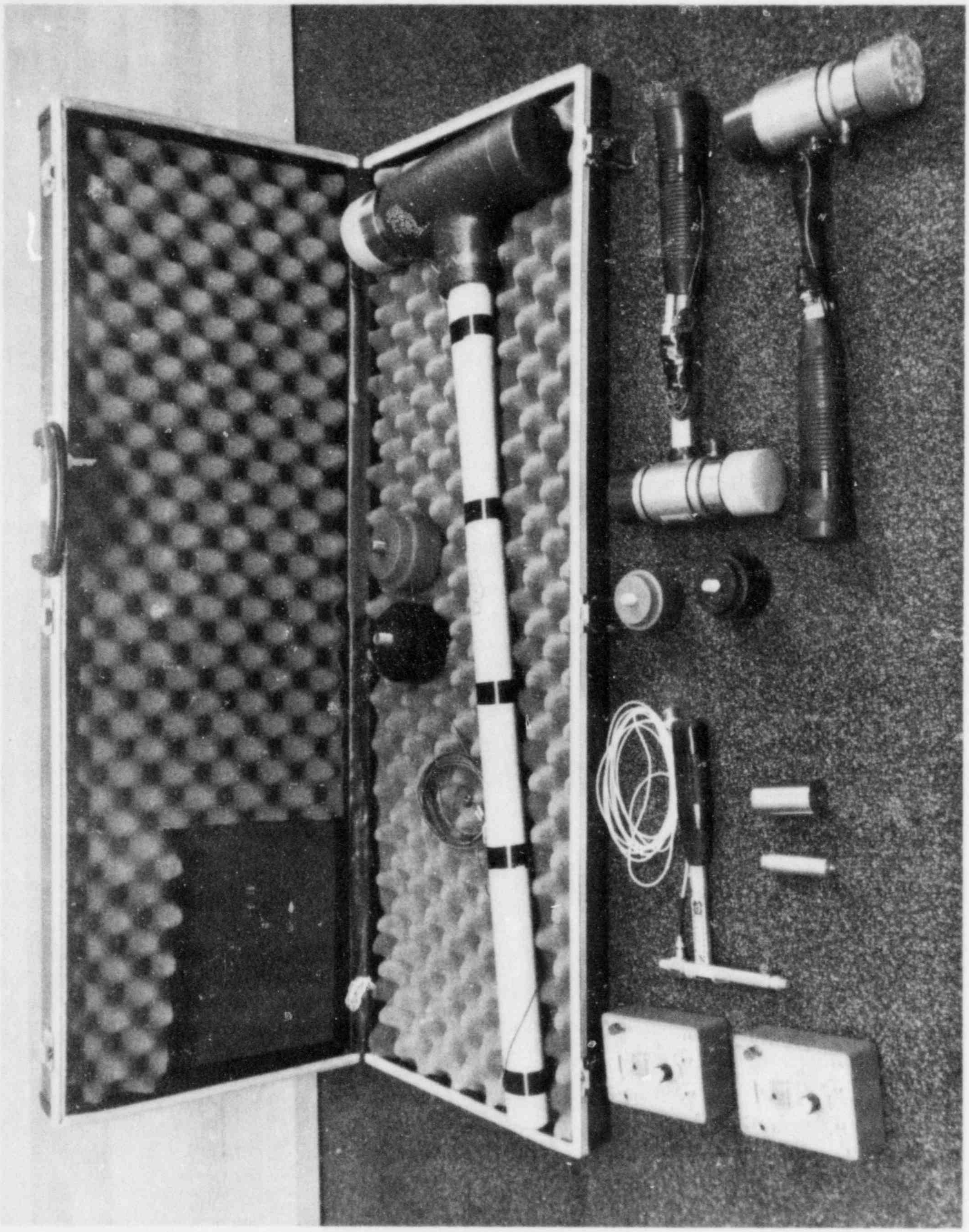

Figure 19. Impact hammers.

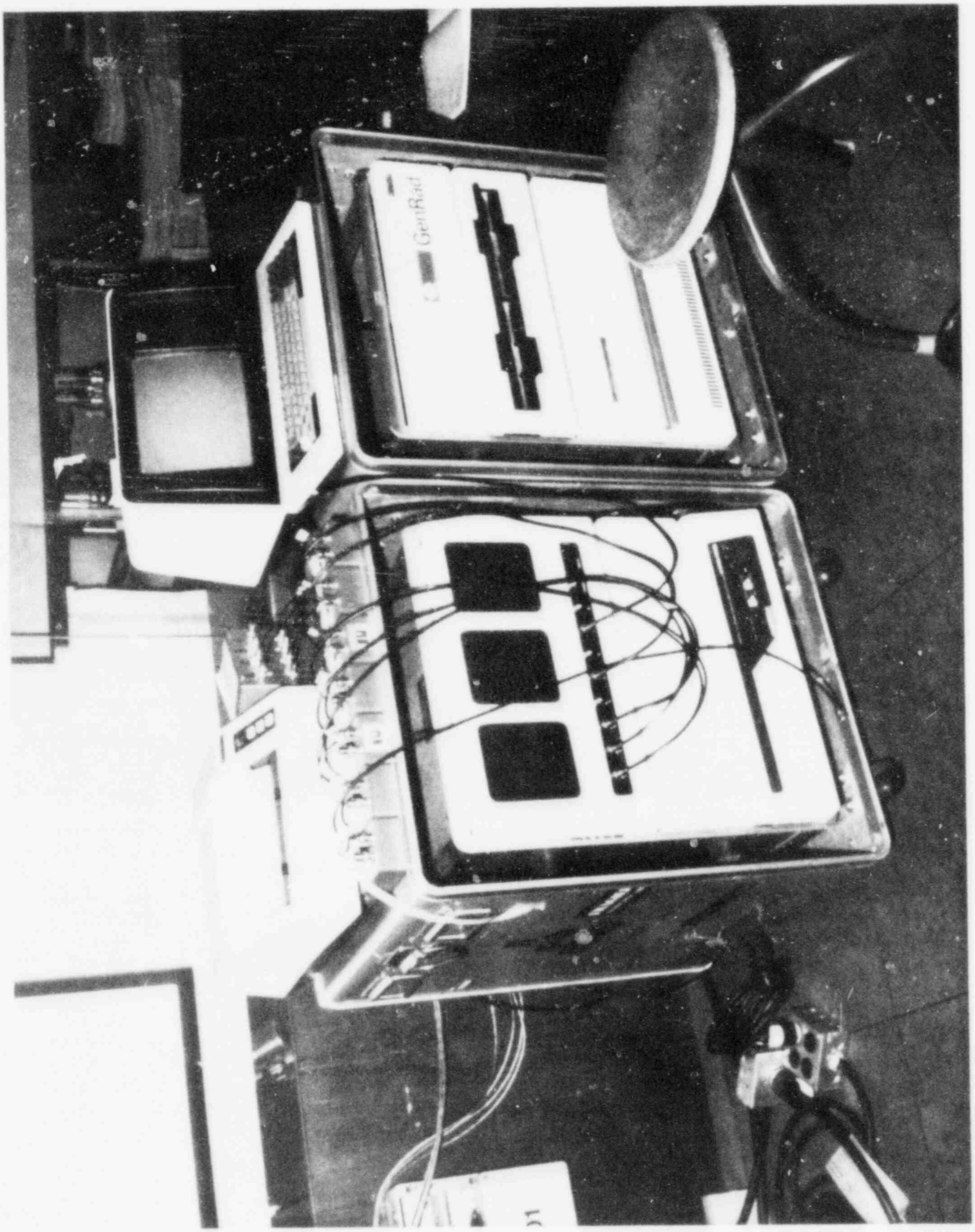

Figure 20. Data acquisition system.

The modal analysis techniques to be used for determining system damping utilize the complex exponential method and the frequency response function. This function is a ratio of the Fourier transform of the response output (displacement or acceleration in this case) to the Fourier transform of the input force. Therefore, this type of testing generally consists of some means of exciting the structure, electronic equipment to record input excitation and response, transmission lines from the recording equipment to the data storage device, and the analyzer/storage device.

5.3 Test Plan

The EG&G research program will start with simple test configurations and gradually increase their complexity. The goal of the initial phase is to first characterize the damping capabilities of individual supports. Data has been collected from a number of support vendors on the general stiffness characteristics of their products. Characteristics of specific supports which will be used in the test program will be further tested by EG&G.

The goals of the first phase of the program will be to investigate the following effects using the simple configuration described in Section 5.1:

a. Pipe with and without individual supports

b. Effect of adding additional supports

c. Effect of using two different types of supports

d. Effect of support spacing

e. Effect of adding water to pipe

f. Effect of changing pipe size

g. Effect of response amplitude

h. Effect of response frequency.

These parameters will be investigated by varying only one at a time whenever possible. The proposed sequence of events to be followed in carrying out the test plan is:

1. Design fixture, initiate procurement
2. Test individual supports
3. Install fixture
4. Test pipe with and without individual supports up to approximately 80% yield stress
5. Vary support types and spacing
6. Vary mass spacing
7. Increase response amplitude to beyond yield stress
8. Repeat 4-7 for different size pipe
9. Complete data reduction
10. Write report.

A detailed test plan and schedule will be issued before commencing testing.

5.4 Future Work

After completing the initial phase, a more complicated three dimensional test set up will be constructed. The next set of experiments will rely heavily upon the results of the initial phase of testing and the EPRI/ANCO results. Tentative plans would include large magnitude inertance testing.

Once the laboratory phase of the program has been carried out, parameters associated with damping in nuclear power plant piping systems would be characterized and "blind" predictions associated with in situ testing could be undertaken. A number of decommissioned facilities at the Idaho National Engineering Laboratory have been surveyed as part of this program, and would be suitable for such experiments.

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APPENDIX A

PROCEDURE FOR DETERMINATION OF TRANSFER AND COHERENCE FUNCTIONS

APPENDIX A

PROCEDURE FOR DETERMINATION OF TRANSFER AND COHERENCE FUNCTIONS

By definition,

$$H_{ij} = \frac{A(\omega)_i}{F(\omega)_j}$$

where H_{ij} is the transfer function for acceleration response at DOF i due to force at DOF j and the argument ω denotes functions of frequency.

During testing, measured quantities are

$a(t)_i$ and $f(t)_j$,

acceleration and force at, respectively, DOF i and DOF j as functions of time.

Then,

$A(\omega)_i = \mathcal{F}[a(t)_i]$ and

$F(\omega)_j = \mathcal{F}[f(t)_j]$

are, respectively, Fourier Transforms of $a(t)_i$ and $f(t)_j$.

The following equivalent definition of H_{ij} is used for computational purposes due to inherent noise cancellation properties:

$$H_{ij} = \frac{A(\omega)_i \; F(\omega)_j{}^*}{F(\omega)_j \; F(\omega)_j{}^*} = \frac{S_{ij}}{S_{jj}}$$

where

$$S_{ij} = A(\omega)_i \, F(\omega)_j^*$$

$$S_{jj} = F(\omega)_j \, F(\omega)_j^*$$

and $F(\omega)_j^*$ is the complex conjugate of $F(\omega)_j$.

The coherence function, γ^2, which is a measure of the quality of H_{ij}, is defined:

$$\gamma^2 = \frac{S_{ij} \, S_{ij}^*}{S_{jj} \, S_{ii}}$$

where

$$S_{ii} = A(\omega)_i \, A(\omega)_i^*, \quad 0 \leq \gamma^2 \leq 1$$

and

$$\gamma^2 = 1, \text{ implies perfect coherence.}$$

An additional improvement in the quality of H_{ij} is obtained by measuring a number of similarly obtained acceleration and force time histories, $a^n(t)_i$ and $f^n(t)_j$, and averaging. That is,

$$H_{ij} = \frac{\sum_{n=1}^{\bar{n}} S_{ij}^n}{\sum_{n=1}^{\bar{n}} S_{jj}^n}$$

The corresponding form of the coherence function is

$$\gamma^2 = \frac{\sum_{n=1}^{\bar{n}} S_{ij}^n \sum_{n=1}^{\bar{n}} (S_{ij}^n)^*}{\sum_{n=1}^{\bar{n}} S_{jj}^n \sum_{n=1}^{\bar{n}} S_{ii}^n} .$$

where, if

$$A^n(\omega)_i = \mathcal{F}[a^n(t)_i] \text{ and}$$

$$F^n(\omega)_j = \mathcal{F}[f^n(t)_j] \text{ , then}$$

$$S_{ij}^n = A^n(\omega)_i(F^n(\omega)_j)^*,$$

$$S_{jj}^n = A^n(\omega)_j(F^n(\omega)_j)^*, \text{ and}$$

$$S_{ii}^n = A^n(\omega)_i(A^n(\omega)_i)^* .$$

Equations 1 and 2 represent the computations that are performed during data acquisition. The value of $\bar{n}$ is typically equal to about 20.