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HEDL-SA-1769

CONF-790615--18

ANALYSIS OF PIPING SYSTEMS WITH NONLINEAR SUPPORTS SUBJECTED TO SEISMIC LOADING

D. A. Barta

March 1979

ASME P&PV THIRD NATIONAL CONGRESS

June 1979 - San Francisco, Ca.

HANFORD ENGINEERING DEVELOPMENT LABORATORY
Operated by Westinghouse Hanford Company, a subsidiary of Westinghouse Electric Corporation, under the Department of Energy Contract No. EY-76-C-14-2170

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D. A. Barta, Senior Engineer
Code Stress Analysis
Westinghouse Hanford Company
Richland, Washington

ABSTRACT

An analytical study of effects of nonlinearities in piping supports on response to seismic excitation is presented. Response calculations for simplified single degree of freedom nonlinear models are used to illustrate sensitivity to stiffness variations, lost motion and impact damping. Seismic responses of typical spans of various sizes of piping supported by both linear and nonlinear constraints are compared to assess the support load magnifications due to impacting.

The idealized nonlinear piping support models are integrated with a finite element model of a large piping system. Time domain seismic responses of the nonlinear piping system are compared to loads determined by a standard linearized seismic response spectra technique.

INTRODUCTION

The analysis of piping systems in the high temperature and seismic environment of nuclear plants, including the Fast Flux Test Facility (FFTF), has traditionally been carried out under assumed linear conditions. Piping supports were assumed to offer no resistance to the piping under normal thermal growth but, under seismic conditions, to be locked up as completely rigid struts. Dynamic characterization tests of available mechanical seismic supports have disclosed the existence of significant lost motion due to free play in the linkage between support and piping and within the mechanical support itself. In addition, flexibilities of the support, pipe clamp and civil support structure were disclosed which can significantly affect the piping system vibration characteristics and ultimately affect the seismic response behavior. Finally, the tests also disclosed large energy dissipation per cycle which far exceeds the standard 2% of critical damping which is customarily assumed in seismic response spectra generation for nuclear piping.

The primary effect of flexible supports is to lower the piping system natural vibration frequencies. Whether or not this will in turn increase or decrease the system response to seismic loading will depend on how closely the participating vibration mode frequencies become tuned to the peak seismic response spectra frequencies. The FFTF piping systems, when assumed to be rigidly supported, have natural frequencies higher than the peak seismic response spectra frequencies. Therefore, consideration of flexible supports in the seismic analysis generally effects an increase in the overall system response. Some localized decreases may occur, however, due to a redistribution of the loading.

The effects of gaps in the mechanical snubber and linkage system are not obvious. Possible effects are the lowering of the response frequencies, particularly at relatively low amplitude excitation, local magnification of load due to impact, and large energy dissipation at the impact locations.

This paper describes some of the piping models and the analysis techniques used to study the effects of support flexibility, free play and damping. Both time domain and frequency domain analyses were performed by using the general purpose finite element ANSYS [1][1] computer program and also a special purpose program which is a nonlinear adaptation of the phase plane method [2] for response solutions.

The objectives of this study are to establish the importance of piping support gaps and the associated impact damping effects on the response of piping systems subjected to seismic loading, to develop analysis methods for assessment of backlash effects, and to extend the analysis of a simple piping system to a typical FFTF large piping system.

PIPING AND SUPPORT MODELS

Nonlinear Spring/Mass Models

In order to determine the local effects of the flexibility, free play and damping parameters over a wide range of values, a simplified nonlinear spring/mass model with viscous damping, as shown in Figure 1, was used. A simulation of a mechanical snubber combined with civil structure and piping flexibilities with seismic accelerations applied through large ground masses is depicted in Figure 2. This model was used to evaluate seismic responses associated with actual snubber stiffness, free play and damping values measured during snubber characterization tests.

Three-Span Piping Models

In order to assess the effects of snubber gaps and impact damping on a system-wide basis, a finite element model was constructed which represents three piping spans simply supported at the extreme ends and supported by nonlinear snubbers between spans. This model is shown in Figure 3. Piping sizes chosen for this model are typical of the small-to-large diameter piping installed in FFTF and includes 1" (2.54 cm), 3" (7.62 cm) and 16" (40.64 cm) nominal diameters. The piping was considered to be insulated and to contain sodium at 700°F (371°C). The piping lengths and distances between supports for these models were chosen such that the fundamental vibration mode frequency would be at 2.5 Hz. while assuming linearized seismic supports.

FFTF Large Piping System Model

The schematic of a typical FFTF large piping system is shown in Figure 4. A total of 19 mechanical snubbers are used to support this system. The model was used as shown for the linear frequency domain seismic response spectra analysis. However, for the nonlinear time domain analysis, the model was modified by connecting each support to a large mass representing ground. This

[1] Numbers in parentheses indicate references listed ~~at the end of the paper~~

modification was necessary to enable application of the seismic loading as a base acceleration. The large ground masses were all assumed to be 1.0×10^6 mass units so that the applied forces at all support points could be scaled equally to produce the proper ground acceleration. In addition, the ground masses were sufficiently large to preclude interaction with the piping system masses, thereby preserving the piping system natural vibration frequency characteristics.

FAST FLUX TEST FACILITY SEISMIC MOTIONS

Response Spectrum

The seismic response spectrum used in this investigation corresponds to a horizontal acceleration at the operating floor of the reactor containment building. It was generated from a Design Base Earthquake (DBE) acceleration/time history using damping at 2% of critical. The calculated seismic response spectrum is shown in Figure 5. It is seen that, due to interaction between the soil structure and the building, the peak response occurs at a frequency of 2.5 Hz and the response spectrum diminishes very rapidly at higher or lower frequencies. Correlation of results obtained from seismic response spectra and from time domain analysis methods is therefore very sensitive to fine tuning of the structural vibration frequencies near 2.5 Hz.

Time Domain Acceleration

The horizontal acceleration/time history used to generate the response spectra is 20 seconds duration; however, less than 3 seconds of the history is needed to determine the maximum responses of the piping systems studied. The 3-second acceleration/time history used in this study is shown in Figure 6. A double integration of the acceleration/time history with respect to time will produce large absolute displacements in the rigid body modes, since the acceleration/time history is not base line corrected. However, the structural loads depend only on relative displacements and are not affected by the rigid body motions.

COMPUTER PROGRAMS

Modified Phase Plane

The phase plane method for response solutions is, because of its simplicity, accuracy and economy, a very powerful tool for analysis of a single dynamic degree of freedom system. This method, fully described in [2], is generally applied as a graphical solution of two simultaneous linear equations. For this study, the phase plane method was modified to permit use of any number of variations of stiffness versus displacement and to include both viscous and coulomb damping. A computer program was then developed to digitize the response solutions.

ANSYS Finite Element Program

The ANSYS computer program is a large scale general purpose program for the solution of several classes of analysis problems. The ANSYS computer code offers two analysis options which are applicable to the type of time domain nonlinear computation required in this investigation. Option 2.4, which is referred to in [1] as "Nonlinear Transient Dynamic Analysis," is a numerical integration method in which variations of stiffness as a function of time or position are readily included. The mass, damping and stiffness matrices are recalculated at each time interval, thus allowing variation in any desired manner. Option 2.4 is therefore not only versatile but relatively time consuming. Option 2.5, referred to as "Reduced Linear Transient Dynamic Analysis" can be used if the mass, damping and stiffness matrices are constant and the time interval is constant throughout the transient. This option offers a "semi-linear" variation which allows interfaces (gaps) between any of the dynamic degrees of freedom. These interfaces are described by specific forms of forcing functions for the linear analysis. Since the dynamic matrix is inverted but once, option 2.5 is far more economical than the former, and it was used throughout this investigation.

ANALYSIS RESULTS AND DISCUSSION

Single Degree of Freedom Results

The response of the simplified spring/mass model shown in Figure 1 to the FFTF horizontal acceleration was determined with damping assumed to be 2% of critical. Gap sizes were varied from zero to 1.0 inch (2.54 cm) and the oscillator frequency, calculated by disregarding gap effects, was varied from 1.0 to 30. Hz. The results, which are shown in Figure 7, reveal relatively small load magnification for all gap sizes at frequencies lower than the 2.5 Hz. seismic spectrum peak. At frequencies higher than 5. Hz. load magnifications due to impact against hard structure become increasingly larger with increases in both natural frequency and gap size.

The response results shown in Figure 8 illustrate the effect of 20% of critical impact damping on response attenuation. The nonlinear responses are less than the 2% of critical damped linear response spectrum at all frequencies lower than 5. Hz. Furthermore, the nonlinear responses remain lower than the peak of the response spectrum up to a frequency of 30. Hz. The value of 20% critical damping for impact was chosen arbitrarily for this study. However, some fuel assembly impact tests [3] show maximum rebounds of less than 30%. The impact damping coefficient was shown in [3] to be related to the coefficient of restitution by the following equation:

$$C_R = e^{(-2\pi\beta/\sqrt{1-\beta^2})}$$

Where, β = Coefficient of Impact Damping

C_R = Coefficient of Restitution

Maximum rebounds of less than 30% approximate a 20% of critical impact damping coefficient.

Simulated Mechanical Snubber/Piping Results

A simulation of the combined civil structure, snubber and piping stiffness, shown in Figure 2, was used to assess the seismic response characteristics over a range of snubber stiffness and damping values which were determined by snubber characterization tests. The assumed piping mass and stiffness correspond to a 1.0 inch (2.54 cm) nominal diameter pipe with insulation and filled with sodium, and with a 141.6 inch (360. cm) span simply supported at each end to ground. A mechanical snubber with variable stiffness and damping values was assumed to be attached at one end to the piping at mid-span and at the other end to ground through civil support structure with variable stiffness. The snubber gap was assumed to be .030 inch (.076 cm) as measured by test. A range of snubber stiffness and damping values were used which correspond to a small snubber of the type that are used to support small piping. The seismic loading was applied through large base masses representing ground. Forces applied through the ground masses were scaled to produce base accelerations identical to the FFTF horizontal seismic motion. The civil support structure stiffness values were chosen to tune the system natural vibration frequencies to 2.5, 5.0 and 9.0 Hz.

The maximum snubber load for the 2.5-Hz case was calculated to be 98. lb. (436. N.) as shown in Figure 9. By comparison, using the 2% damped seismic spectrum which has a 2.7 G acceleration peak at 2.5 Hz, a 313. lb. (1392.N) snubber load was obtained.

At a system frequency of 5.0 Hz, the maximum snubber load was calculated to be 85. lb. (378. N.) as shown in Figure 10. This compares to a 101. lb. (449. N.) snubber load determined by using the 2% damped seismic spectrum at 5.0 Hz.

Snubber loads determined for the 9.0-HZ. case are shown in Figure 11. In this case, the maximum snubber load, calculated to be 84. lb. (374 N.) is greater than the 73. lb. (325 N.) load obtained by using the 2% damped seismic spectrum at 9.0 Hz. This is attributed to load magnification due to impact which becomes increasingly larger with increases in natural frequency.

The implication of these results is that, with the use of mechanical snubbers to support piping systems, much larger damping coefficients than the 2% of critical may be justified. Additional more reliable evidence needs to be provided, however, on a system-wide basis for a large piping system, since the damping effect of the snubber could be very localized.

Three-Span Piping Results

The three-span piping models were chosen in order to assess the effects of snubber gaps and impact damping on a system-wide basis. The size of these models was a compromise between a large piping system and a small system which enabled the study of a wide range of parameters at a reasonable computer cost. The three-span piping responses to the FFTF horizontal base acceleration are shown in Figures 12, 13 and 14 for piping nominal diameters ranging from 1" (2.54 cm) to 16" (40.64 cm). The .120 in. (.305 cm) gap represents the maximum allowable lost motion during dynamic cycling of the combined snubber and linkage system. The expected range of support stiffness for each size of piping was enveloped by the support stiffness values chosen for this study.

The three-span piping response results lead to two conclusions: (1) the effect of impact damping is most pronounced with the piping supported at a frequency which coincides with the peak seismic spectra frequency, and (2) the gap effect on load magnification is of importance only in association with very stiff support structure.

FFTF Large Piping System Results

The finite element model of the piping system included 113 dynamic degrees of freedom and hence a like number of natural frequencies and associated mode shapes were computed for the linear seismic response spectra analysis. Of the total, only the 36 lower frequency modes provided significant contribution to the seismic response. These mode frequencies are listed in Table 1. The individual modal responses were combined according to [4] and account for all closely spaced modes. The total response was then determined as the square root of the sum of the squares of the responses resulting from seismic excitation in the vertical direction and in two orthogonal horizontal directions. The applied seismic spectrum is the 2% damped spectrum for the FFTF reactor containment building at the operating floor.

For the nonlinear analysis, snubber gaps were assumed to be .120 in. (.305 cm) and impact damping at the snubber locations was arbitrarily chosen as 20% of critical. The time domain seismic accelerations were applied simultaneously in the vertical and one horizontal direction and, in another separate computation, in the vertical and another horizontal direction orthogonal to the first. The greatest snubber loads of the two computations are compared to the loads determined by the linear method in Table 2.

The linear analysis loads exceed the nonlinear loads in all but two locations. These results indicate that the linear analysis is generally conservative, however, this is not entirely conclusive. Additional studies are needed to assess a wider range of gap, damping and stiffness parameters on a system-wide basis.

CONCLUSIONS

The effect of gaps on magnification of seismic support loads due to impact is minimal at support frequencies lower than five Hz. Load magnification increases rapidly with increases in support stiffness and also with increases in gap size at higher support frequencies.

Energy loss due to the impact damping associated with gaps is an important consideration in determining seismic loads throughout the entire range of support frequencies.

The effect of gaps on reduction of response frequency is negligible due to the transient nature of the seismic acceleration loading, however this effect could be significant in association with a more cyclic loading condition.

Large piping system analysis results suggest that the seismic response spectra method, which ignores the nonlinearities, is more conservative than the nonlinear time-domain method. However, a broader base of study on a system-wide basis is needed to support this conclusion. Additional studies should lead to the development of a cost effective quasi linear analysis method which would provide good approximations of the nonlinear effects but exclude repetition of the costly time-domain analysis procedure.

ACKNOWLEDGMENT

Performance of this study was made possible through funding provided by the Department of Energy for improved seismic design technology development utilizing FFTF experience. The author gratefully acknowledges the guidance and critical review provided by Mr. L. K. Severud, Plant Analysis Department Manager.

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2 Jacobsen, L. S. and Ayre, R. S., Engineering Vibrations, McGraw-Hill (London), 1958.

3 Morrone, A., "FFTF Scram and Nonlinear Reactor System Seismic Analysis," Westinghouse ARD Report FRA-1074, October 1973.

4 Regulatory Guide 1.92, "Combining Modal Responses and Spacial Components in Seismic Response Analysis."

TABLE 1

FFTF PIPING SYSTEM NATURAL FREQUENCIES

MODE MO	FREQUENCY HZ	MODE NO	FREQUENCY HZ
1	5.821	19	16.53
2	5.829	20	20.31
3	5.889	21	21.20
4	6.905	22	23.53
5	7.812	23	23.79
6	8.779	24	24.67
7	9.180	25	27.81
8	9.869	26	28.20
9	10.15	27	31.93
10	10.37	28	33.53
11	10.39	29	37.68
12	10.77	30	41.30
13	11.12	31	43.62
14	12.21	32	48.08
15	12.99	33	49.49
16	13.87	34	50.45
17	13.99	35	55.14
18	15.02	36	56.40

TABLE 2

COMPARISON OF LINEAR SPECTRA AND NONLINEAR ANALYSIS
FFTF PIPING SYSTEM SNUBBER LOADS

SEISMIC SUPPORT NO.	SNUBBER LOADS ~ LBF*	
	LINEAR SPECTRA	NONLINEAR ANALYSIS
1 - X	5047	4140
1 - Y	3289	1423
2 - Z	5071	3152
3 - X	2552	1315
3 - Y	2391	1776
4 - X	4422	4376
4 - Y	1327	486
5 - Y	1819	2876
5 - Z	5866	5514
5A - Y	2092	2708
5A - Z	5826	5273
6 - Z	10817	4716
7 - X	9369	8536
7 - Y	4862	3760
7A - X	9835	8994
7A - Y	6086	4021
9 - X	3670	2238
9 - Z	4227	3516
10 - Z	6888	3418

*1.0 LBF = 4.448 N.

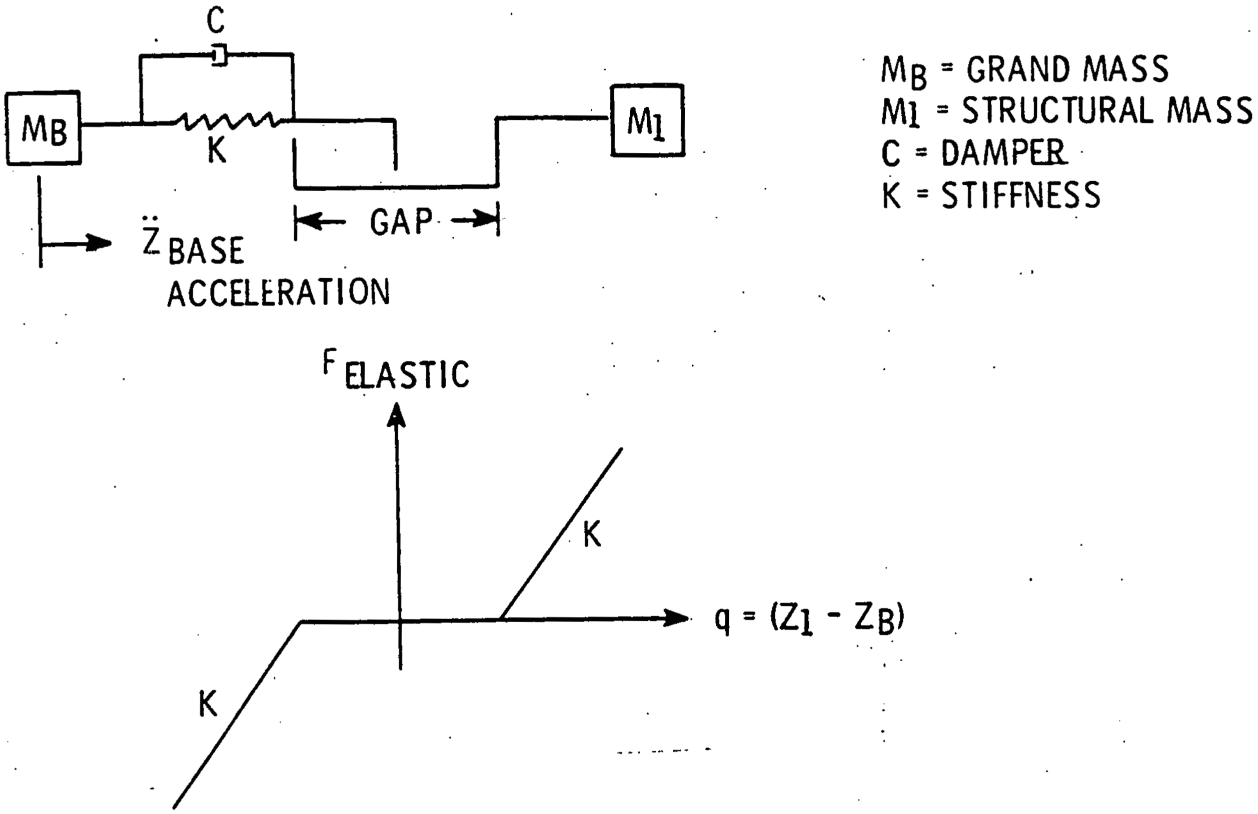

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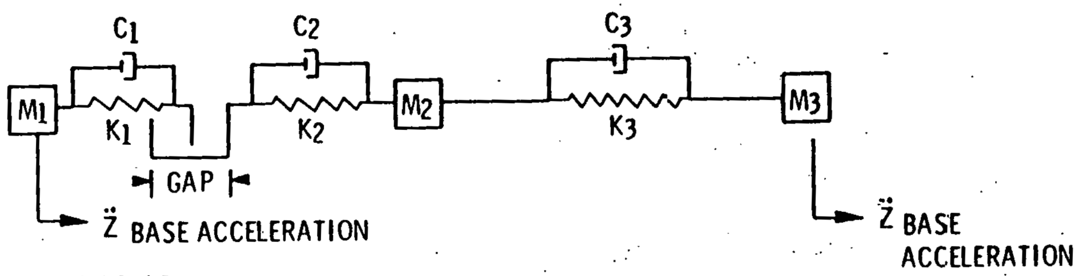
Fig. 1 Simplified Nonlinear Spring/Mass Model



M_1, M_3 = GROUND MASSES
M_2 = PIPING MASS
C_1, K_1 = CIVIL SUPPORT STRUCTURE DAMPING AND STIFFNESS
C_2, K_2 = SNUBBER DAMPING AND STIFFNESS
C_3, K_3 = PIPING DAMPING AND STIFFNESS

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Fig. 2 Combined Civil Structure/Snubber/Piping Simulation

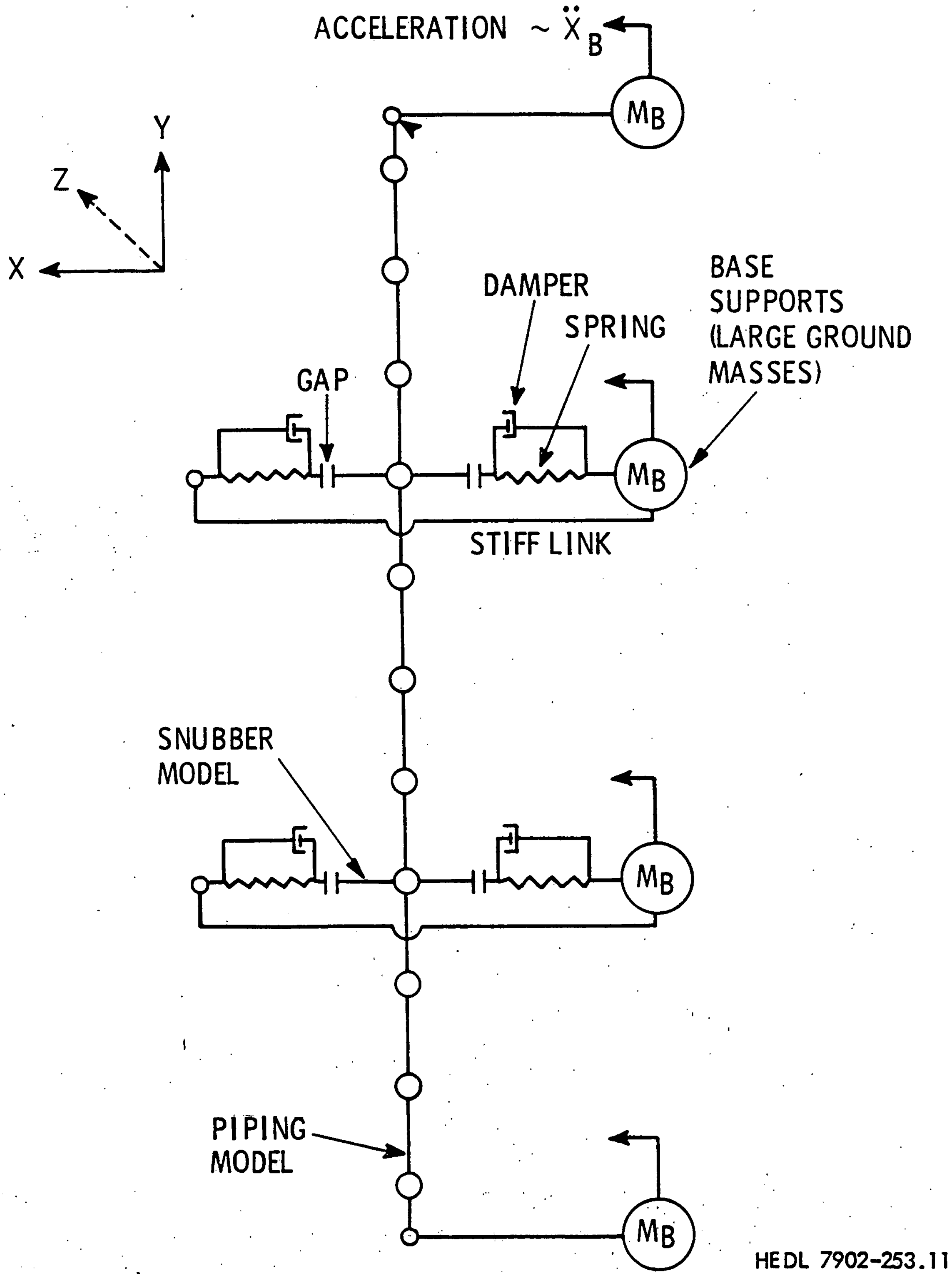

Fig. 3. Three-Span Piping/Support Model

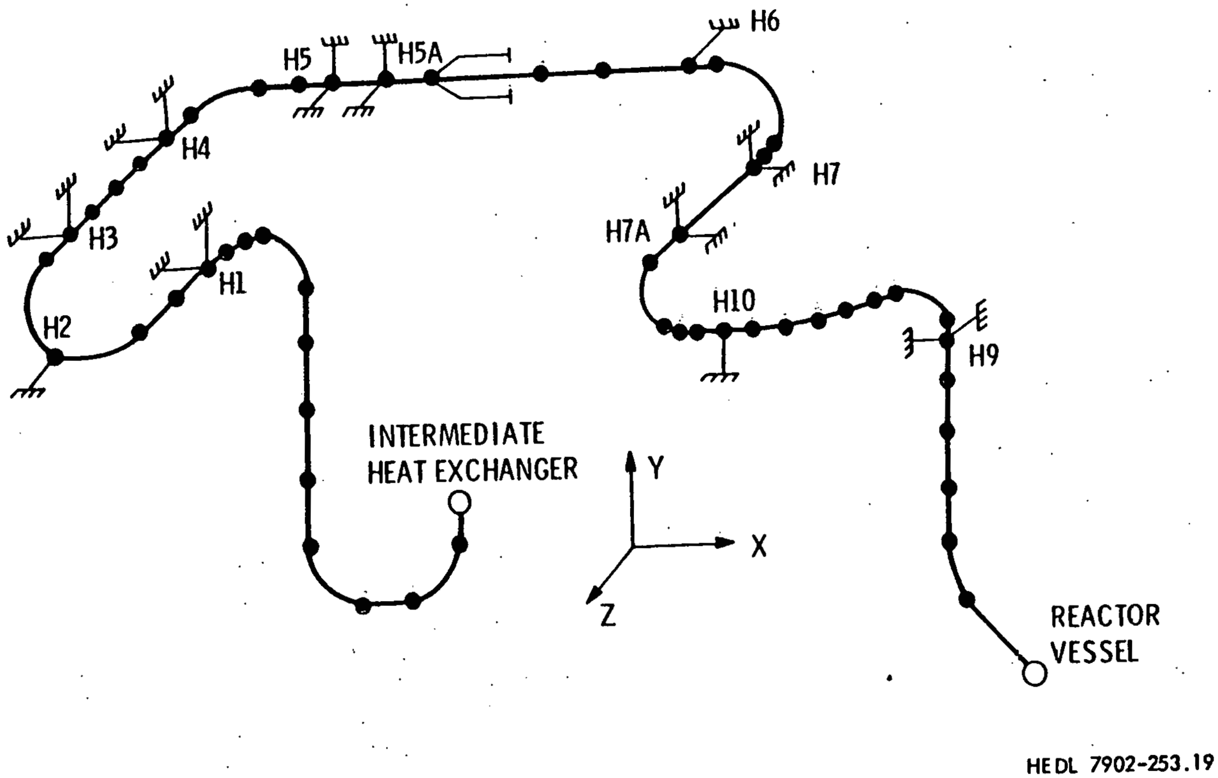

Fig. 4 Typical FFTF Large Piping System

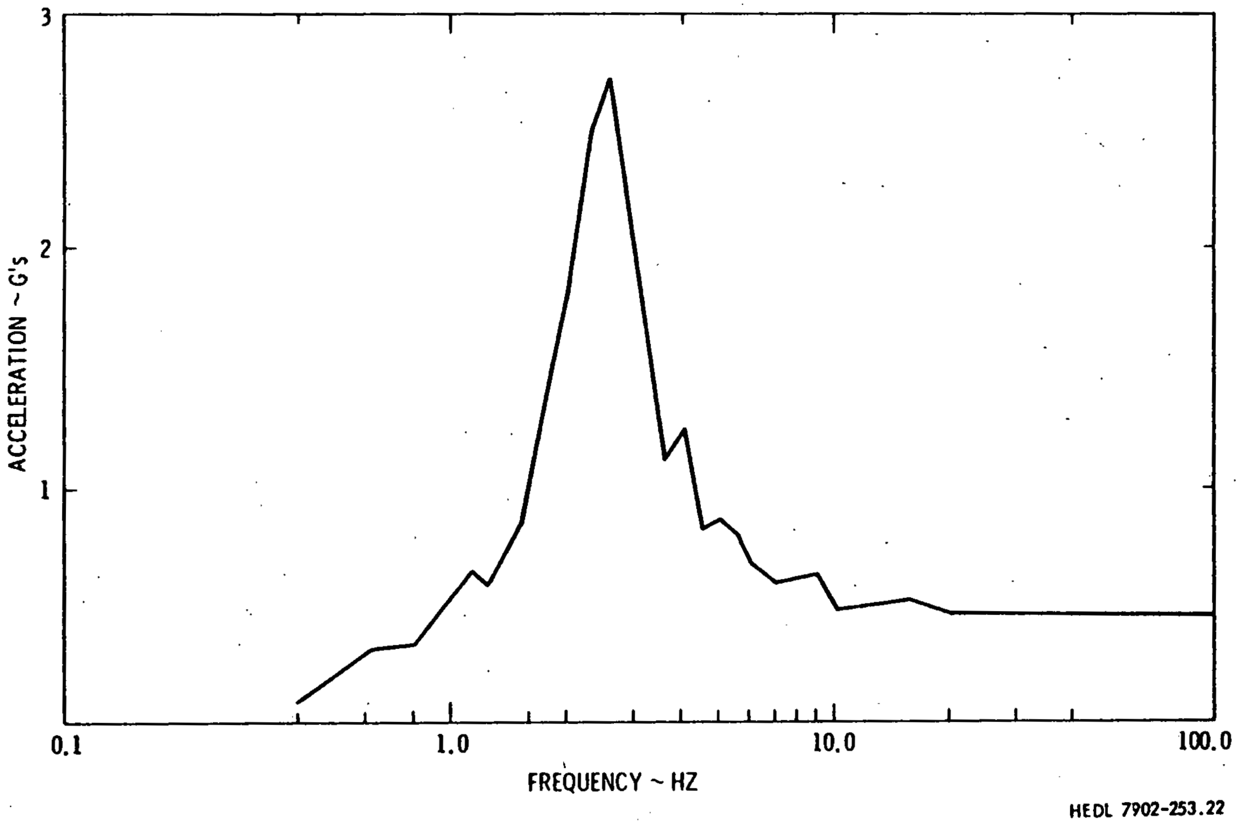

Fig. 5 DBE Horizontal Seismic Response Spectrum At The FFTF Reactor Containment Building Operating Floor 2% Damping

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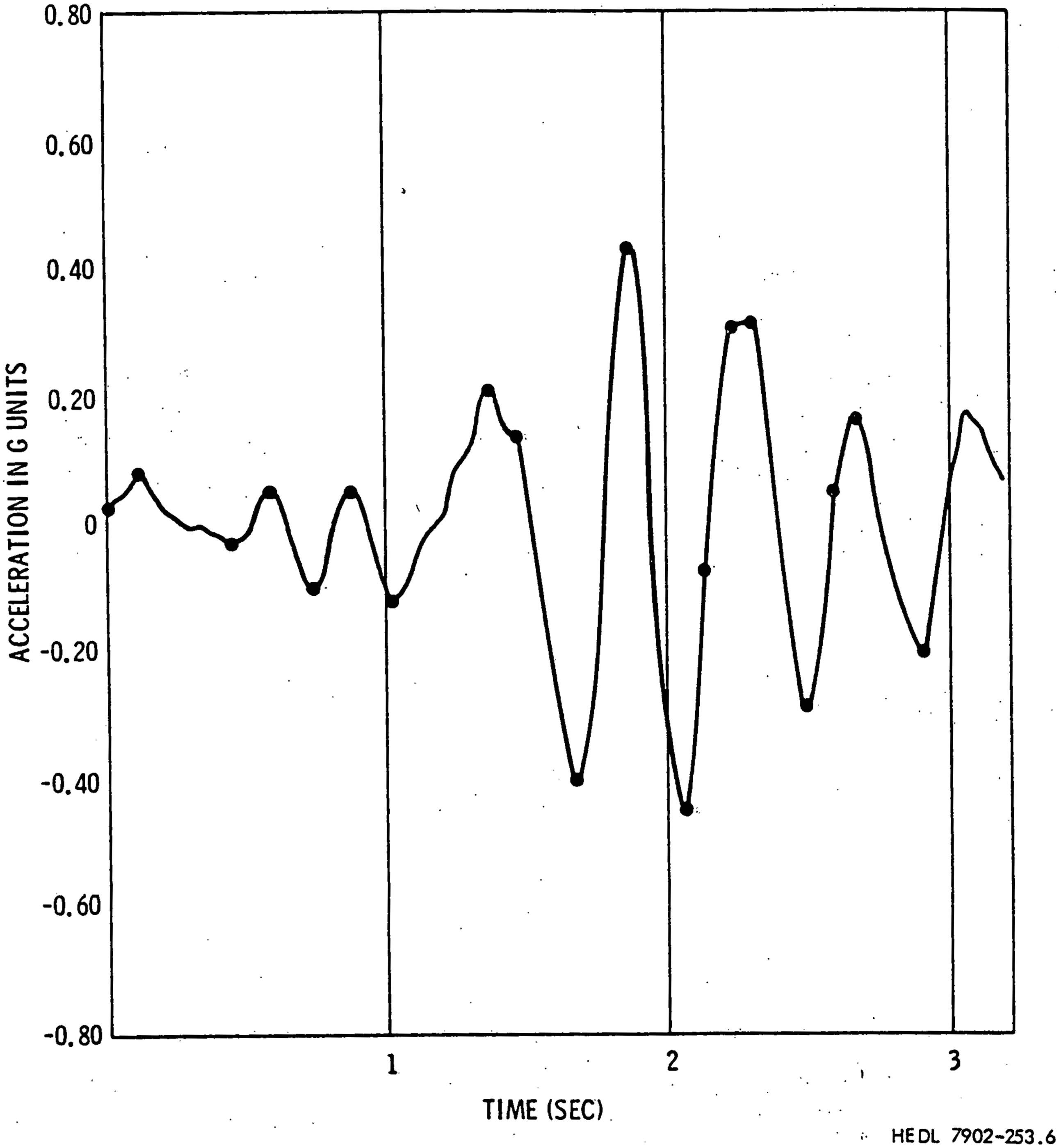

Fig. 6 Horizontal Seismic Acceleration/Time History At The FFTF Reactor Containment Building Operation Floor

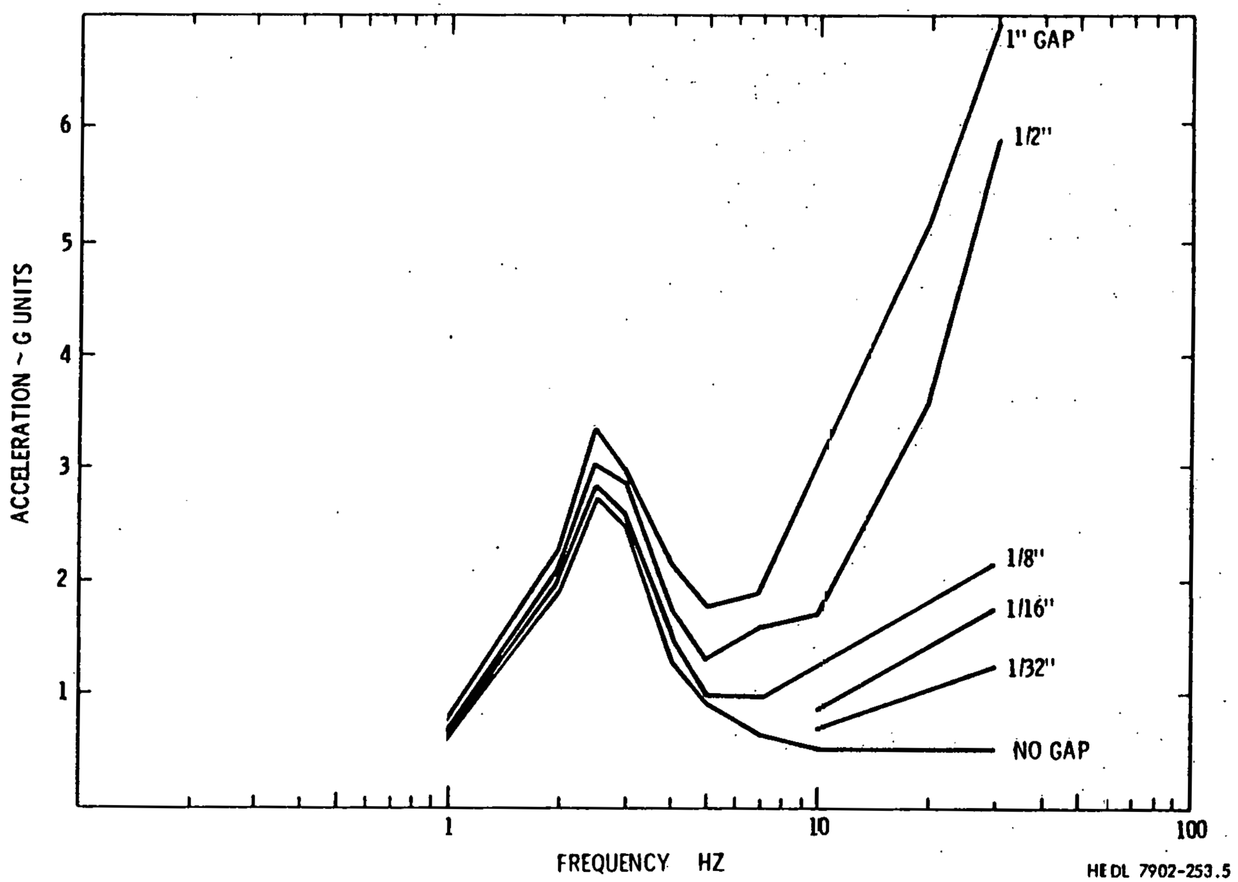

Fig. 7 Single Spring/Mass Response to FFTF Seismic Horizontal Acceleration
Damping = 2% of Critical
Note: 1" = 2.54 CM

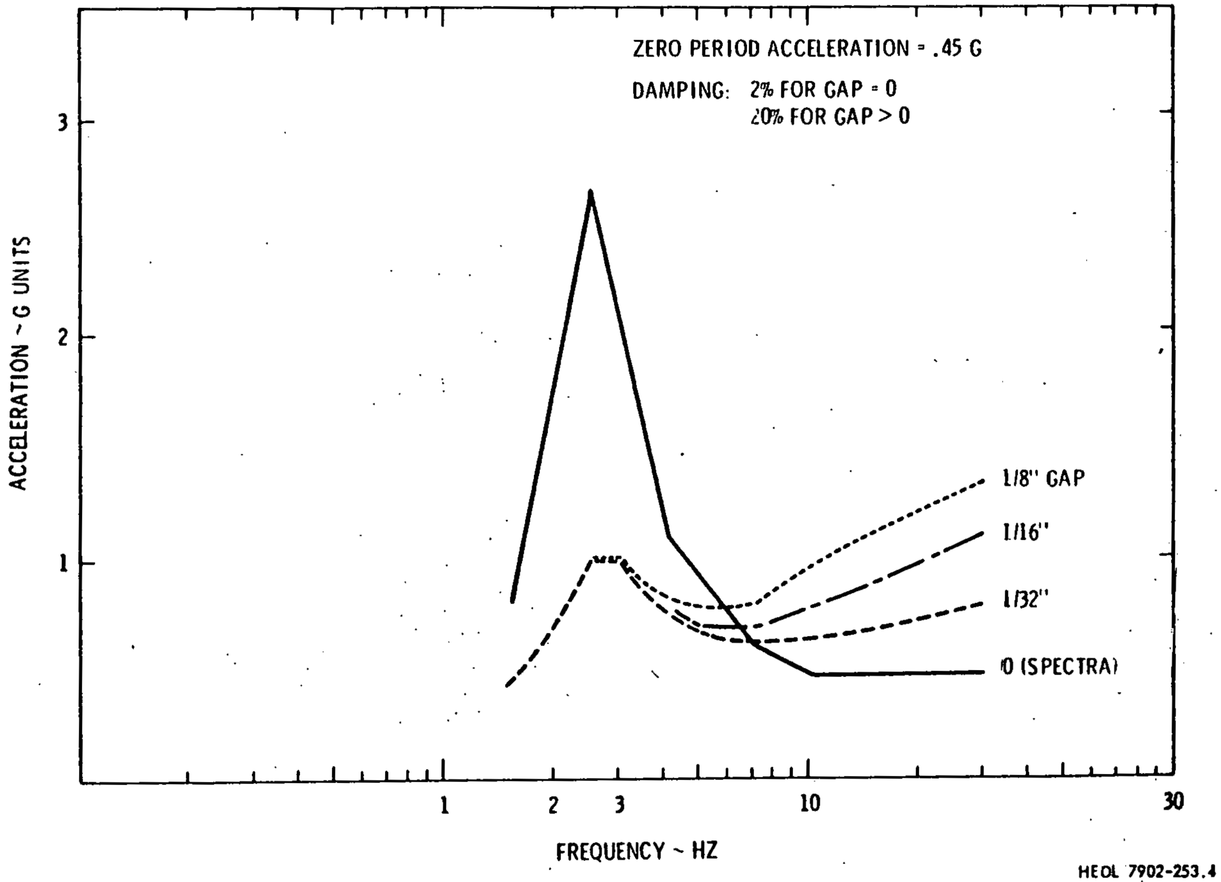

Fig. 8 Response Spectrum and Nonlinear Response To FFTF Seismic Horizontal Acceleration
NOte: 1" = 2.54 CM

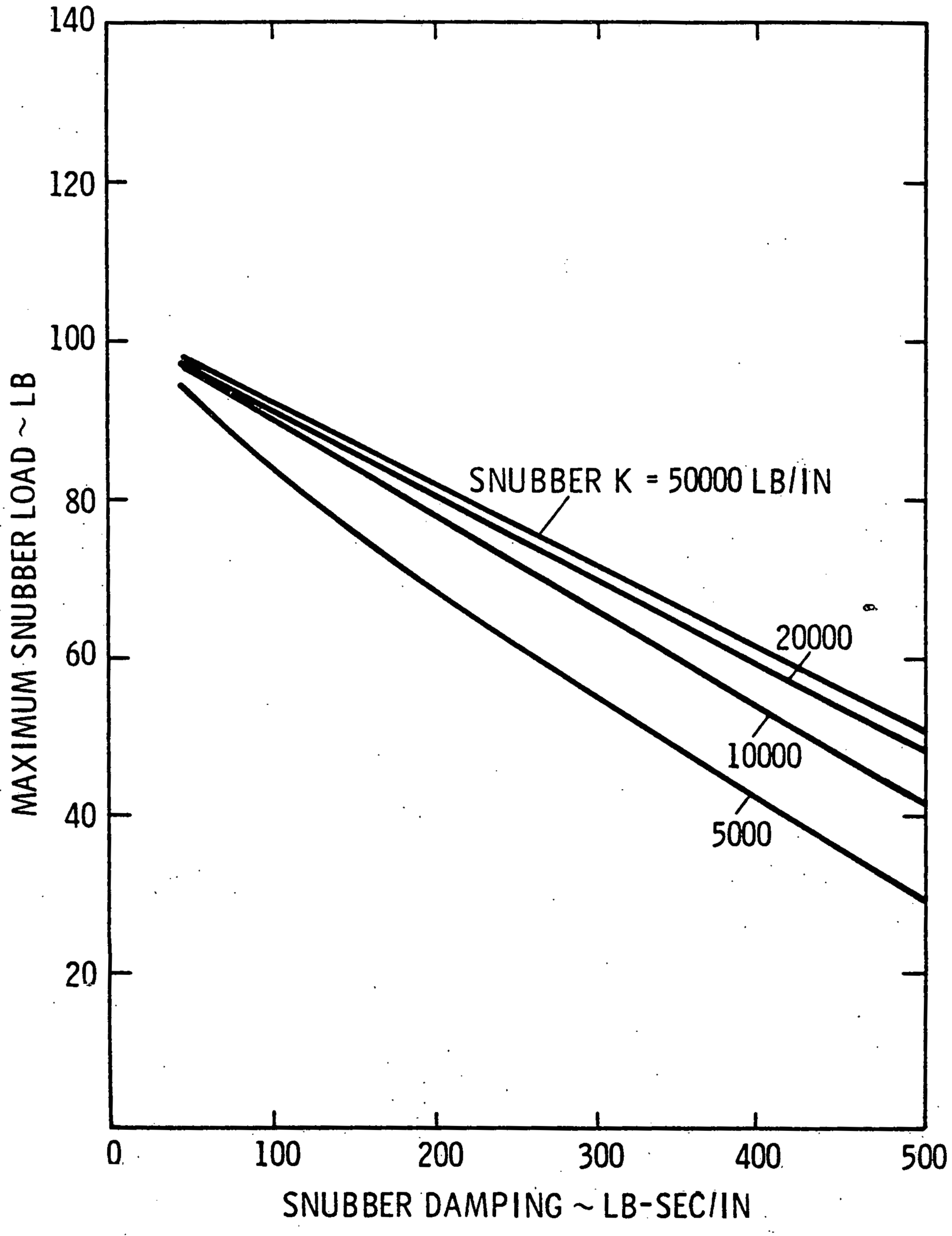

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Fig. 9 Piping/Snubber Response To FFTF Seismic Horizontal Acceleration/Time History
System Natural Frequency = 2.5 HZ
Piping Weight = 116. LB. (52.6 KG)
Snubber Gap = .030 IN. (.076 CM)
Note: 1.0 LBF. = 4.448 N.
1.0 LB/IN = 1.751 N/CM

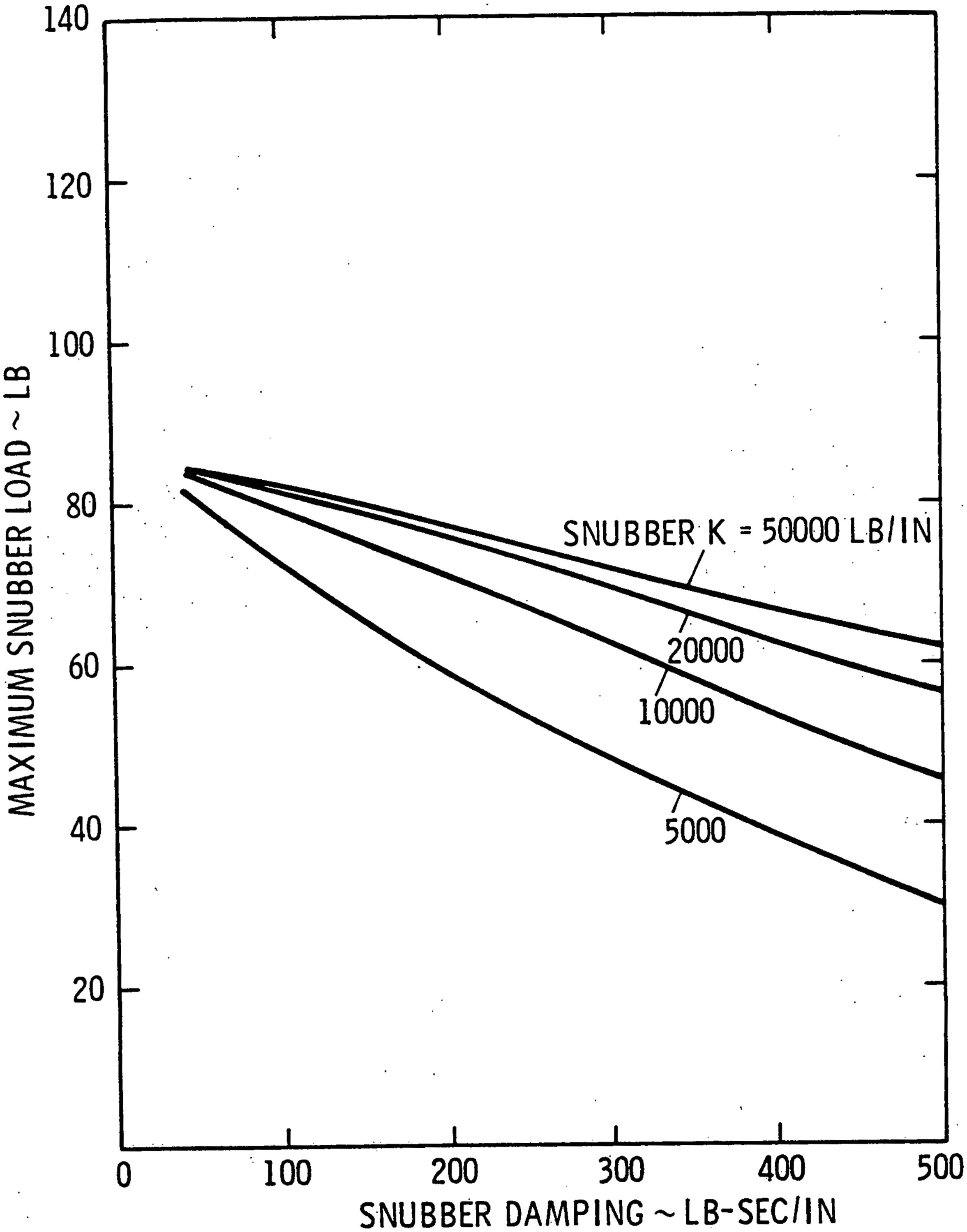

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Fig. 10 Piping/Snubber Response To FFTF Seismic Horizontal Acceleration/Time History
System Natural Frequency = 5.0 HZ
Piping Weight = 116. LB. (52.6 KG)
Snubber Gap = .030 IN. (.076 CM)
Note: 1.0 LBF = 4.448 N.
1.0 LB/IN = 1.751 N/CM

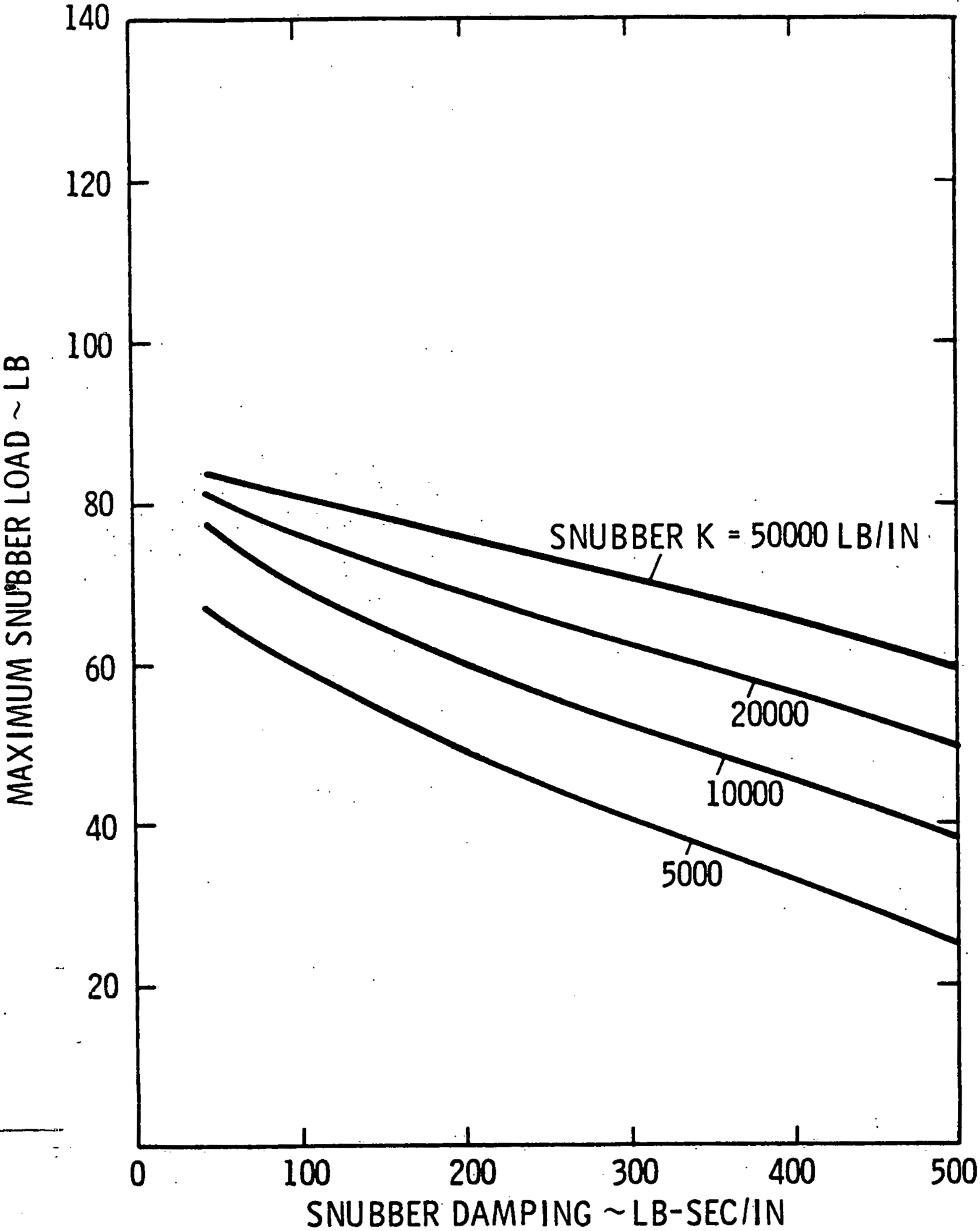

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Fig. 11 Piping/Snubber Response to FFTF Seismic Horizontal Acceleration/Time History
System Natural Frequency = 9.0 HZ
Piping Weight = 116. LB. (52.6 KG)
Snubber Gap = .030 IN. (.076 CM)
Note: 1.0 LBF = 4.448 N.
1.0 LB/IN = 1.751 N/CM

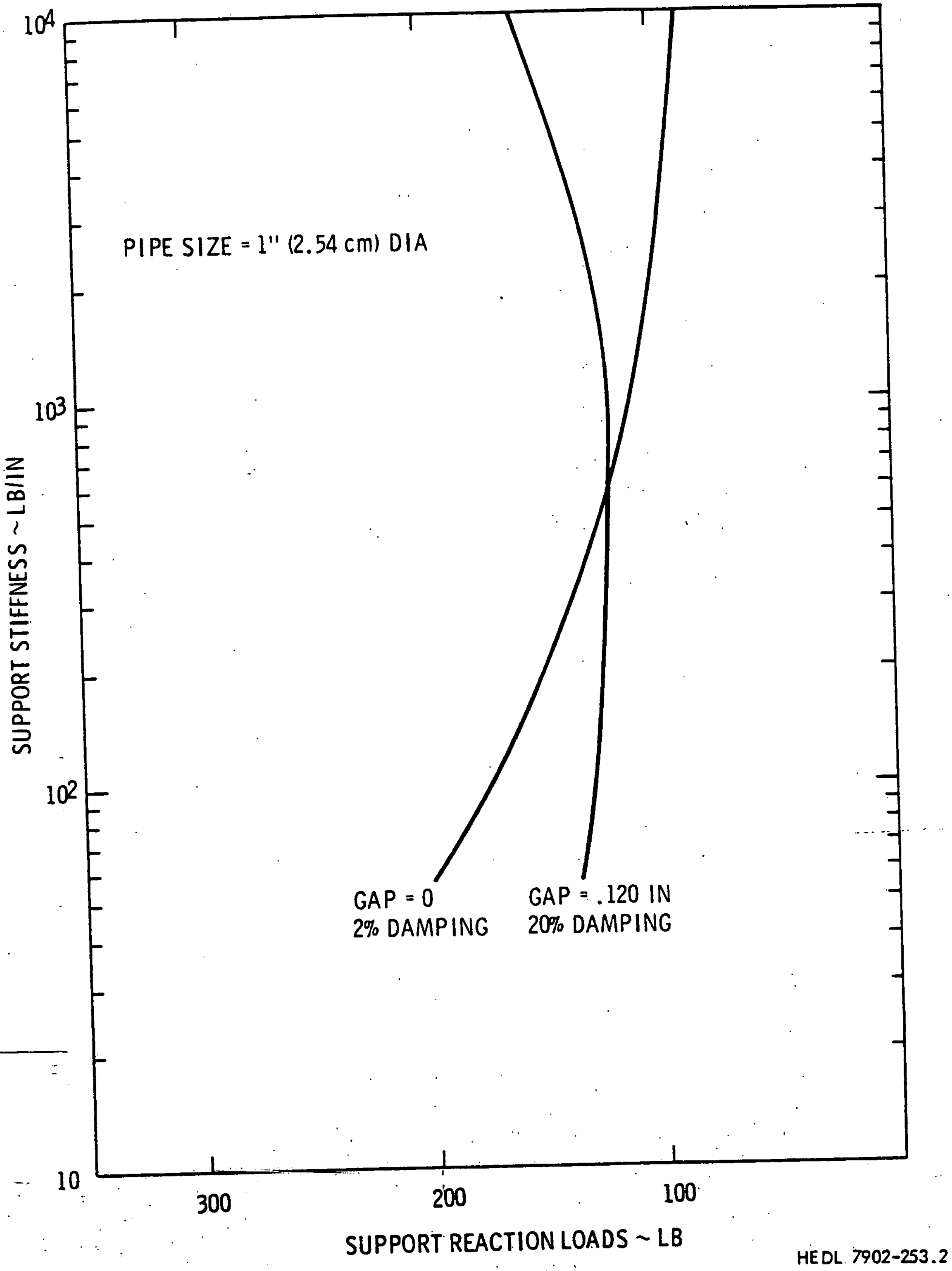

Fig. 12 Three-Span Piping/Support Response To FFTF Horizontal Acceleration
Note: 1.0 IN. = 2.54 CM
1.0 LBF = 4.448 N
1.0 LB/IN = 1.751 N/CM

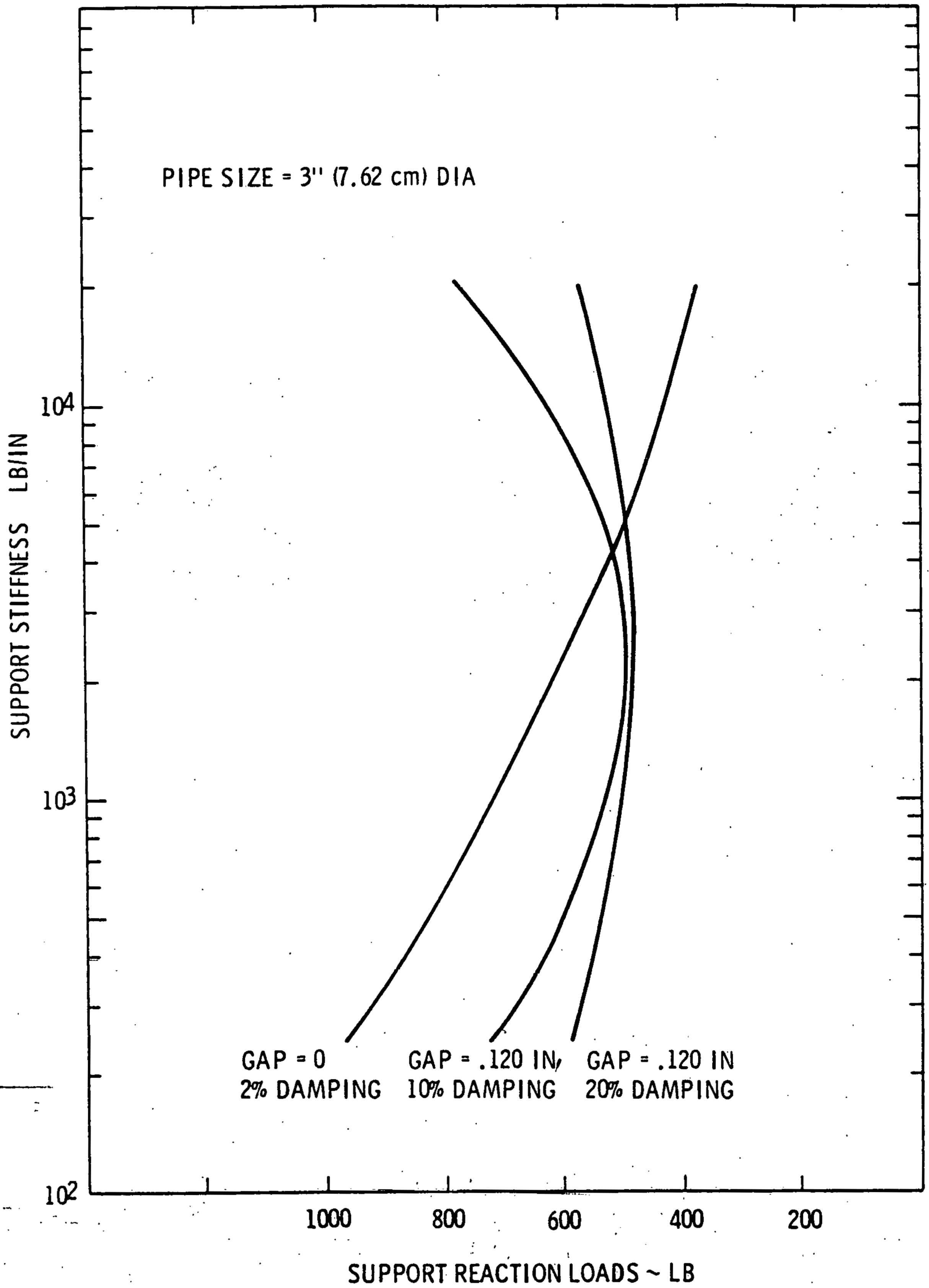

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Fig. 13 Three-Span Piping/Support Response To FFTF Horizontal Acceleration

Note: 1.0 IN. = 2.54 CM
1.0 LBF = 4.448 N
1.0 LB/IN = 1.751 N/CM

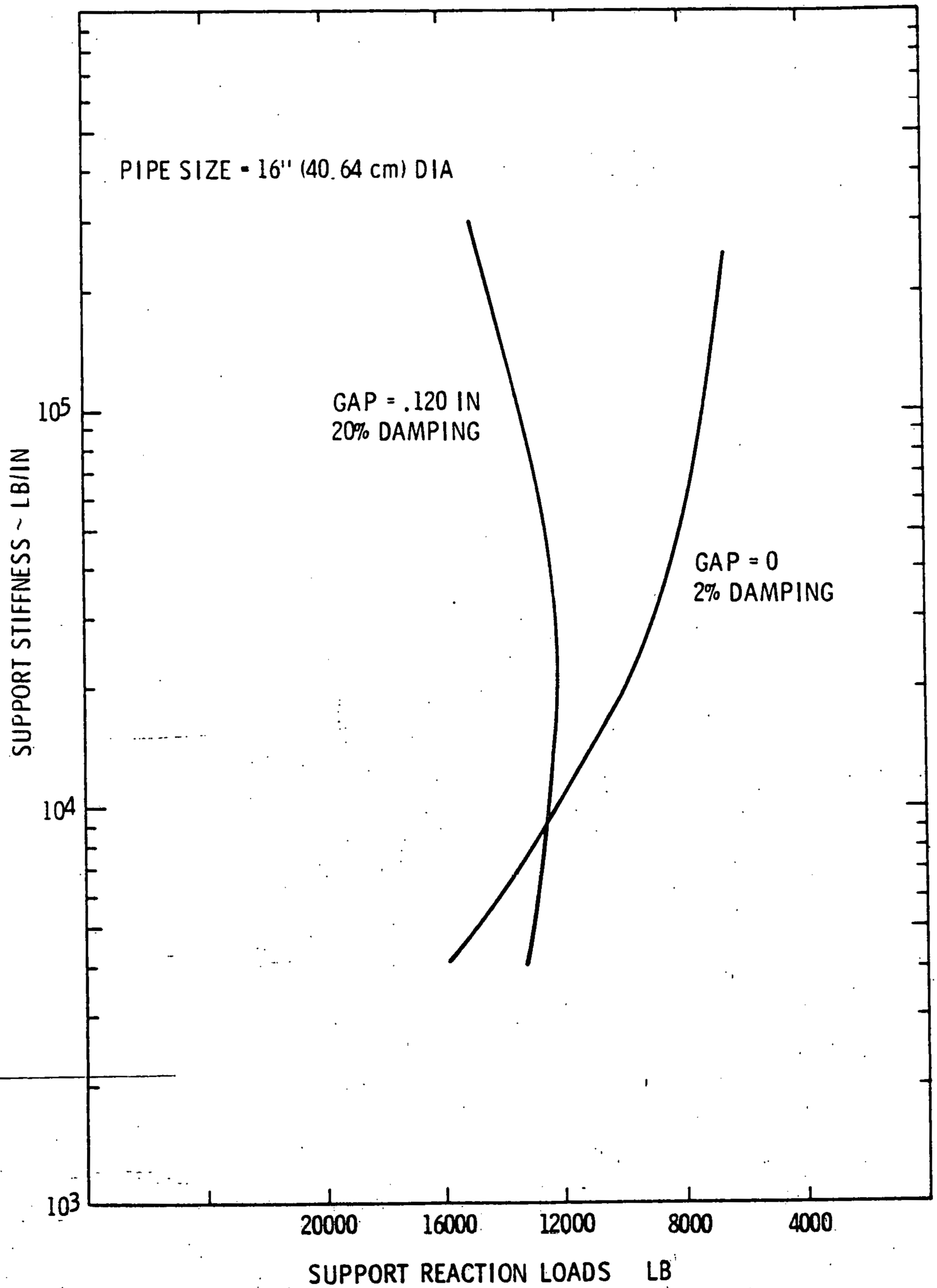

Fig. 14 Three-Span Piping/Support Response to FFTF Horizontal Acceleration

Note: 1.0 IN. = 2.54 CM
1.0 LBF = 4.448 N
1.0 LB/IN = 1.751 N/CM