Conf-910602--64

WSRC-MS--91-114

Received by OSTI
MAR 19 1992

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GUIDELINES FOR THE SEISMIC DESIGN OF FIRE PROTECTION SYSTEMS (U)

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A paper proposed for presentation at the
ASME PVP Conference
San Diego, California
June, 1991

and for publication in the proceedings

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ABSTRACT

The engineering knowledge gained from earthquake experience data surveys of fire protection system components is combined with analytical evaluation results to develop guidelines for the design of seismically rugged fire protection distribution piping. The seismic design guidelines of the National Fire Protection Association Standard NFPA-13 are reviewed, augmented, and summarized to define an efficient method for the seismic design of fire protection piping systems.

1.0 INTRODUCTION

In most regions of the country, current building codes impose fire protection requirements in the design of new commercial facilities. In critical applications, such as in nuclear facilities, fire protection systems (FPS) may be required to perform following a Design Basis Earthquake (DBE). As a minimum, portions of the systems which are determined to be essential for extinguishing fires are seismically qualified to survive a DBE event. These include water storage tanks and elements of the supply and distribution system.

The design standard which has been extensively used by industry for fire protection piping systems is the National Fire Protection Association Standard NFPA-13 (1). This standard defines a fairly comprehensive set of requirements for the design and installation of water distribution piping. Included are provisions which address the design for seismic events.

2.0 SEISMIC DESIGN OBJECTIVES

Although fire protection systems in nuclear facilities are expected to survive and be available following an earthquake, the functionality of the distribution pipe system is not necessary to safely shutdown the reactor. As such, these piping systems have usually been classified as Non-Nuclear Safety (NNS) or seismic category II equipment. The seismic design emphasis has been to ensure structural integrity so that the pipe system will retain its spatial position following an earthquake.

Earthquake experience data which have been assembled from earthquake surveys of industrial and commercial facilities around the world indicate that process piping systems in general have performed very well (2,3). Many of these pipe systems have never been designed for seismic inertia loadings, were rod hung, and hence possessed few lateral supports. The few failures have been attribbuted to the effects of seismic anchor movements, spatial interaction, and corrosion. The inherent seismic ruggedness of piping has also been substantiated by experimental test programs (4).

Fire protection distribution piping has not performed as well as other piping in earthquakes. Recent surveys of earthquake damage have found instances of failed overhead distribution piping although these systems had been presumably designed to NFPA standards (5,6). In general, the failures were due either to physical interaction with suspended ceilings resulting in damaged sprinkler heads or to leakage at non-welded joints. Such failures do not necessarily indicate deficiencies in the NFPA standard, but rather a need for a better understanding of the distribution piping environment.

As a consequence of potential seismic interaction effects in various environments, the design objective should be to focus on maintaining system pressure integrity and/or structural integrity. Based on experience data, the designer should consider the following:

Water Spray

Areas where water spray is a concern include rooms where electrical equipment is present. The water spray may be due to leakage at threaded pipe fittings or mechanical couplings caused by excessive sway, physical interactions, or seismic anchor motion. Water spray can also occur in deluge systems due to inadvertent system actuation.

Flooding

Aside from resulting in costly clean up, flooding due to pipe failure can represent a safety concern in the presence of electrical equipment.

Structural Impact

Impacting of distribution piping with adjacent structural features or equipment has sometimes had severe consequences on FPS piping. The most frequent cause of failure has been the interaction with suspended ceilings. The failure of FPS piping systems and neighboring suspended ceilings could have serious safety consequences on equipment and personnel. This suggests a need to control seismic deflection in both the piping and suspended ceilings. Seismic contact between distribution pipe system components and other NNS piping of an equal size or smaller should not be a concern.

3.0 SEISMIC DESIGN METHODS

Conventional design practice for FPS distribution piping has been to adhere to NFPA-13 guidelines. Commercial nuclear utilities have occasionally supplemented this design approach with computerized analytical methods comparable to those utilized in the design of nuclear safety class 2 and 3 piping. In a few cases shake table testing has been performed to experimentally validate the seismic survivability of prototypical FPS piping configurations. These test programs can provide useful information to supplement experience data in documenting credible failure modes and piping arrangements.

Due to the large amount of FPS distribution piping planned for reactor facilities, the use of an efficient and cost effective piping design method is appropriate. The authors of this paper believe it prudent to utilize the NFPA-13 approach supplemented by additional criteria to limit FPS pipe stress and deflection and to preclude the use of certain configurations which have been shown to be prone to seismic failure. A detailed pipe system analysis can be used as an alternative method (as provided in Section 3-5.3 of NFPA-13) but should generally not be necessary. In either case, the importance of a final as-built walkdown after system installation cannot be overemphasized. The use of the above mentioned design procedures combined with this spatial interaction field review will ensure the seismic adequacy of the distribution system.

4.0 PIPING SYSTEM SEISMIC DESIGN CRITERIA

4.1 CREDIBLE FAILURE MODES

Based on the failure modes indicated by experience data, seismic design criteria for FPS piping should focus on seismic anchor movements, spatial interaction, corrosion, and loss of pressure integrity. Most of these criteria are addressed by limiting pipe stress and deflection. Additional criteria are needed to ensure that pipe corrosion, loss of pressure integrity, and damage due to seismic anchor motion are precluded.

Corrosion

Corrosion related pipe failures manifest themselves by the occurrence of cracks and subsequent leakage at locations of a significant decrease in pipe wall thickness. In the design of new fire protection systems, the potential issue of corrosion can be addressed by stipulating the following:

- Use of corrosion resistant materials
- Good quality water
- Proper maintenance and periodic inspections

Pipe Fitting Pressure Integrity

Pressure integrity is maintained by limiting pipe stress together with an appropriate selection of connection fittings. The pipe fittings should be selected based on the pipe location relative to susceptible safety-related equipment. For example, welded pipe connections (not threaded fittings) should be used in critical areas such as the control room where the consequences of drip or spray could be severe. In addition, mechanical couplings should not be used in these areas. As an alternative, a dry system may be considered in these applications.

Seismic Anchor Motion

Seismic anchor motion may be imposed on distribution piping by attached equipment such as tanks which are sliding or rocking. Adequate anchorage of these attached equipment must be incorporated to preclude this phenomenon.

Another source of seismic anchor motion which has resulted in pipe structural failures is that which occurs when a relatively rigid small branch line, i.e., with lateral restraint provisions, restrains a much larger and flexible main run of pipe. A judicious selection of pipe support locations as described below should preclude this.

4.2 SUPPORT SPACING REQUIREMENTS

The potential for pipe system seismic failures due to anchor motion and spatial interaction effects diminishes when pipe stress and deflection are limited during the design phase. These seismic criteria are implemented through support spacing requirements which were derived based on a combination of NFPA-13 and ANSI B31.1 (7) pipe stress criteria. Analytical investigations have been performed to confirm the adequacy of these criteria using typical FPS piping configurations.

The support spacing requirements are as follows:

Vertical Support Spacing

1)

Pipe Diameter (in.)	Maximum Spacing (ft.)
≤3	12
4	14
5	15
6	17
8	19
12	23

2) On branch lines, the unsupported cantilever length from the last vertical support will be ≤3' for ≤1" diameter pipe or ≤4' for ≥1.25" diameter pipe. (See Detail "A" in figure 1).

3) On cross mains, there shall be at least one vertical support between each two branch lines. (See Detail "B" in figure 1).

Lateral Support Spacing

1) The maximum distance between adjacent lateral supports shall be 40 feet for ≥2" diameter pipe. For pipe <2" diameter the maximum span shall be 25 feet. The distance is measured along the pipe (See Detail "C" in figure 1).

   NOTE: In cases where this requirement cannot be met, a more detailed engineering analysis can be performed to investigate the effects of using longer lateral spans.

2) The maximum unsupported cantilever length of pipe shall be 15 feet. (See Detail "D" in figure 1).

3) On mains or cross-mains (non-branch lines), a lateral support must exist within one span length of a branch line on either side of the tee. A span length is the allowed distance between vertical supports. (See Detail "E" in figure 2).

Axial Support Spacing

1) The maximum linear span length between adjacent axial supports shall be less than 80 ft. (See Detail "F" in figure 2).

2) Risers or runs of one vertical span length or greater require at least one axial support. A span length is the allowed distance between vertical supports. (See Detail "G" in figure 2).

3) Supports which are positioned within 2' of the centerline of the piping to be braced longitudinally can act as an equivalent axial support. The diameter of the pipe to which this support is attached must be of equal or greater diameter than the longitudinal pipe run. (See Detail "H" in figure 2).

4) A connection to a rigid anchored nozzle or header acts as an axial support.

4.3 PIPE SUPPORT DESIGN CRITERIA

Support Loads

The loads on the pipe supports are calculated based on the seismic environment and the tributary weight of the supported pipe.

The seismic environment for facilities is described in terms of amplified response spectra for horizontal and vertical motions at various building elevations. The calculation of pipe support loads utilizes the peak horizontal spectral acceleration and Zero Period Acceration (ZPA) for 5% damping at the floor elevation to which the pipe supports are attached.

The tributary weight is the weight of all piping that contributes load to a given support. For a straight span of pipe with multiple supports, the weight of half the span length on either side of a support defines the tributary weight to that support. Figure 3 provides an estimate of tributary weight for various diameter pipes and spans.

Branch lines can contribute tributary weight to the attached mains or cross mains. Concentrated branch line weights and in-line equipment weights are distributed to adjacent supports using statics as shown in figure 4.

Support forces are calculated separately for each coordinate direction. The equations to be used for calculating individual support forces are as follows:

Vertical Support Design Load (Horizontal Pipe)

$$P_V = (5 * W) + 250 \text{ lbs.} \qquad (1)$$

where W= tributary weight of piping

Lateral Support Design Load

$$P_L = 0.75 S_H W \qquad (2)$$

where S_H is the peak horizontal spectral acceleration from the 5% damped building spectra.

Axial Support Design Load

For horizontal pipe, $P_A = S_{HR} W$ (3)

where S_{HR} is the ZPA (rigid) spectral acceleration for 5% damped spectra in the horizontal direction.

For standpipes and risers,

$$P_A = (1 + S_{VR})\ W \qquad (4)$$

where S_{VR} is the ZPA (rigid) spectral acceleration for 5% damped spectra in the vertical direction.

Support Criteria

The pipe support stress criteria are based on AISC (8) requirements using the load factor of 1.6 from the USNRC Standard Review Plan (9) guidelines for occasional loads. For example, the allowable tensile stress is $1.6 \times 0.6 \times S_y = 0.96\ S_y$.

The seismic criteria allow a variety of support types. Suitable types of supports include pinned rod hangers, both trapeze and single rod type, and ductile fabricated angle supports which are designed to ensure ductile behavior in an earthquake. All rod hangers should be pin-pin connection type. The use of eye bolts is recommended. Support design development can be performed very efficiently through the use of parametric data which implicitly incorporate the stress criteria and can be plotted or tabulated as shown in figures 5 and 6.

Several types of support hardware are not recommended because experience data indicate that they have exhibited poor seismic performance. Among those not recommended for use are:

- fixed end rod hangers
- friction hangers (vertical shelf supports)
- beam clamps

Note that beam clamps which rely primarily on friction are not recommended even though permitted by NFPA-13.

4.4 DESIGN PROCEDURE

The procedure documented below is a means of systematically developing a seismically adequate FPS distribution system. Given a fire piping layout:

1) Conceptualize the initial support configuration using the support spacing requirements defined in section 4.2 for vertical and horizontal seismic loading.

2) Determine displacements at header/branch connections to assess whether adequate branch flexibility exists. (See "Pipe Displacements")

3) Determine the displacements for piping spans which are supported by two adjacent buildings or structures. These displacements should be determined by absolute sum of the displacements expected for each individual structure.

4) Using the displacements determined in Steps 2 and 3 and a piping flexibility chart (figure 7), ensure that sufficient flexibility will exist at these locations. If required, reposition and/or modify lateral supports on branch lines to increase flexibility or add supports on the main line to reduce displacements. Repeat Steps 2 and 3 as required.

5) Determine the pipe clearance (or "rattle space") requirements to preclude detrimental interaction between the firewater piping and surrounding structures. (In general, implementation of the pipe support span requirements of this section will result in piping seismic displacements which are less than 6 inches for 0.2g PGA (Peak Ground Acceleration) sites).

   NOTE: It should be emphasized that this pipe clearance evaluation need only be conducted in instances where interaction (impact, spray, flooding) with safety-related equipment is possible or where personnel safety may be jeopardized. The areas of concern include potential impact to sprinkler heads, mechanical couplings, and threaded joints. Note that sprinkler head guards are commercially available which provide good protection for moderate impacts involving these otherwise fragile components.

6) Conduct a constructibility walkdown to assess whether the locations designated for supports can physically accommodate them. If applicable, assess whether the rattle space requirements determined in Step 5 are acceptable. Add supports or modify locations as required. Finalize the pipe and support layout.

7) Using the method presented in section 4.3, calculate the loads at all supports.

8) Based on the support load requirements and the knowledge of the pipe layout area from the constructibility walkdown, develop an appropriate support configuration using the support design criteria presented in section 4.3.

9) Conduct a final inspection of the completed fire piping installation to address interaction concerns caused by surrounding components.

Pipe Displacements

Piping displacements can be approximated using simple models for the piping system response. Pin-pin beam models produce conservative results for pipe seismic displacement and can be utilized to determine this component response. Spectral displacements can be estimated by calculating the fundamental frequency of a pipe span as follows:

$$f = \frac{9.87}{2x3.14} \left[\frac{EIg}{wL^4} \right]^{\frac{1}{2}} \qquad (5)$$

Where:

f = Pipe simple span fundamental frequency (cps)
w = Uniform weight of pipe (lbs/in)
g = Gravitational constant (386.4 in/sec^2)
E = Modulus of elasticity of pipe (psi)
I = Pipe moment of inertia (in^4)
L = Simple pipe span (in)

$$S_d = 1.27 \left[\frac{S_a \times g}{(2x3.14xf)^2} \right] \qquad (6)$$

Where:

S_d = Spectral displacement (in)
S_a = Spectral acceleration corresponding to calculated frequency (g)
1.27 = Participation factor for first mode response

The displacement generated from this equation will be conservatively high and represents the mid-span deflection of a pin-pin beam. If desired, less conservative deflection estimates can be made for positions away from the mid-span and closer to a support.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the seismic performance of fire protection system distribution piping in earthquakes, it has been determined that additional design criteria are needed beyond what is currently reflected in the applicable design standard. Pipe support spacing requirements are specified based on analytical results coupled with NFPA guidelines. Using seismic experience data, various design considerations are identified for pipe fitting selection, support details, and corrosion protection. An efficient design procedure is described which can be used to develop a seismically adequate distribution piping system.

Based on this investigation, it is recommended that design standard NFPA-13 be amended to incorporate appropriate additional design requirements which reflect the caveats identified by seismic experience data.

6.0 REFERENCES

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3) EPRI NP-6628, "Procedure for Seismic Evaluation and Design of Small Bore Piping (NCIG-14)", 1990.

4) S.W. Tagart, Y. K. Tang, H. L. Hwang, K. L. Merz and D. T. Guzy, "Seismic Analysis and Testing of Pipe Systems and Components", PVP Vol. 127, 1987 (p 229-236).

5) "The October 17, 1989 Loma Prieta Earthquake, EQE Engineering, San Francisco, CA, 1989.

6) "The July 16, 1990 Philippines Earthquake," EQE Engineering, San Francisco, CA, 1990.

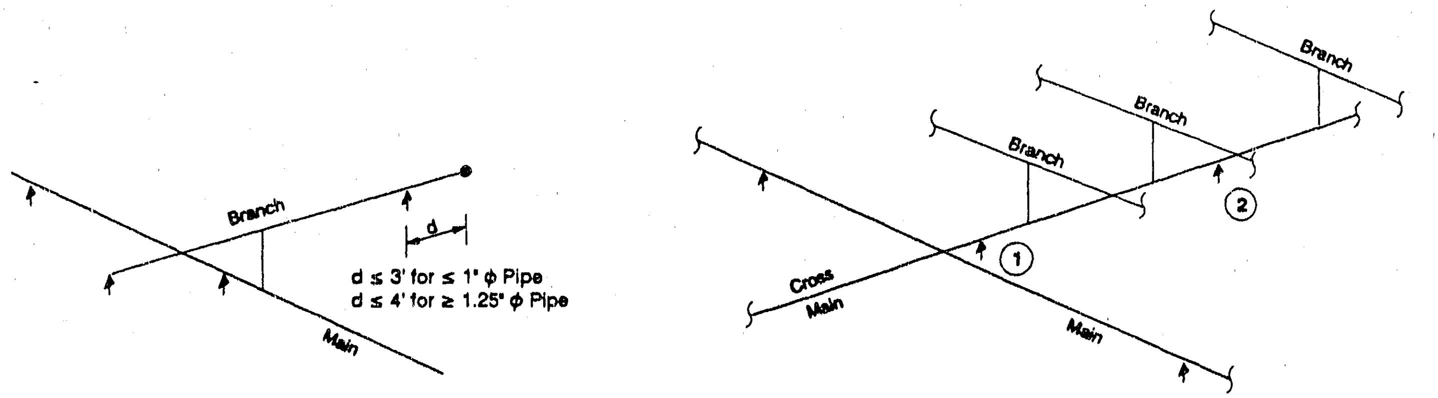
7) "Power Piping, Standard B31.1," American National Standards Institute (ANSI), New York, New York, 1987.

8) "Manual of Steel Construction," 9th Edition, American Institute of Steel Construction, Chicago, Illinois.

9) NUREG-0800, "USNRC Standard Review Plan".

SI Conversions

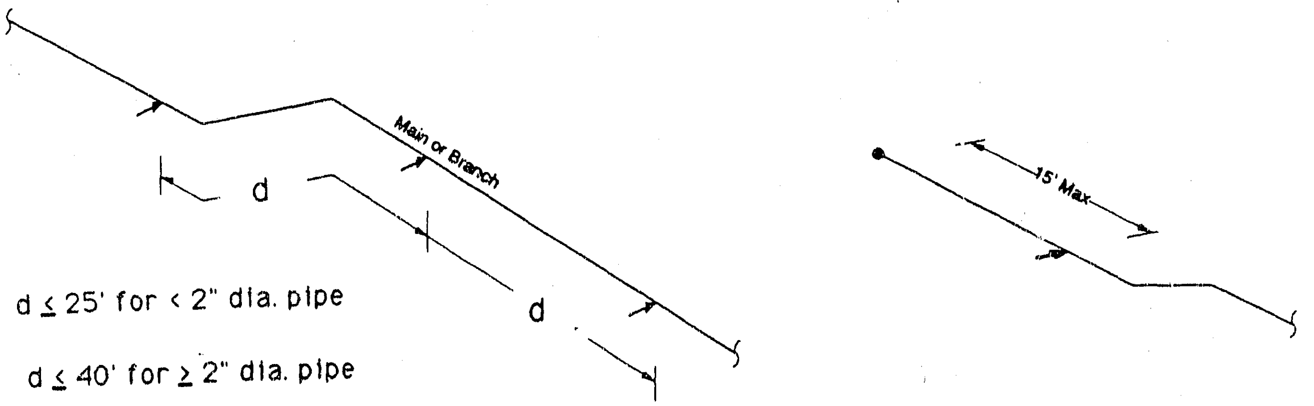
1 ft. = 0.3048 M
1 in. = 0.0254 M
1 psi = 6.895 KPa
1 lb = 4.448 N



① & ② are required between branch lines

Detail "A": Limits on Unsupported Cantilever Lengths, Vertical Supports

Detail "B": Vertical Supports Required Between Branch Lines on Cross Mains



Detail "C": Limit Between Lateral Supports is Measured Along Pipe

Detail "D": Limit on Unsupported Cantilever Length, Lateral Supports

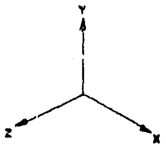
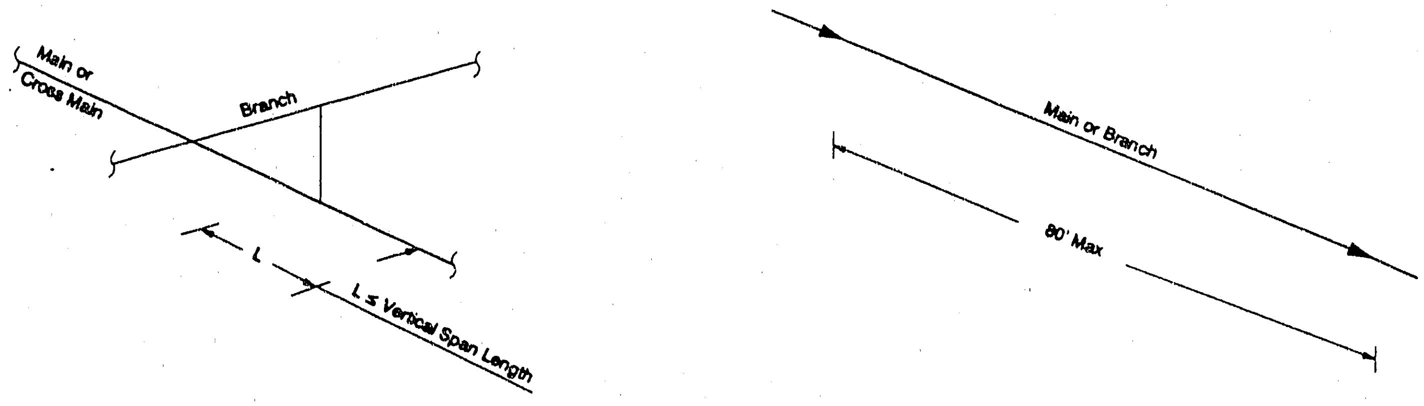
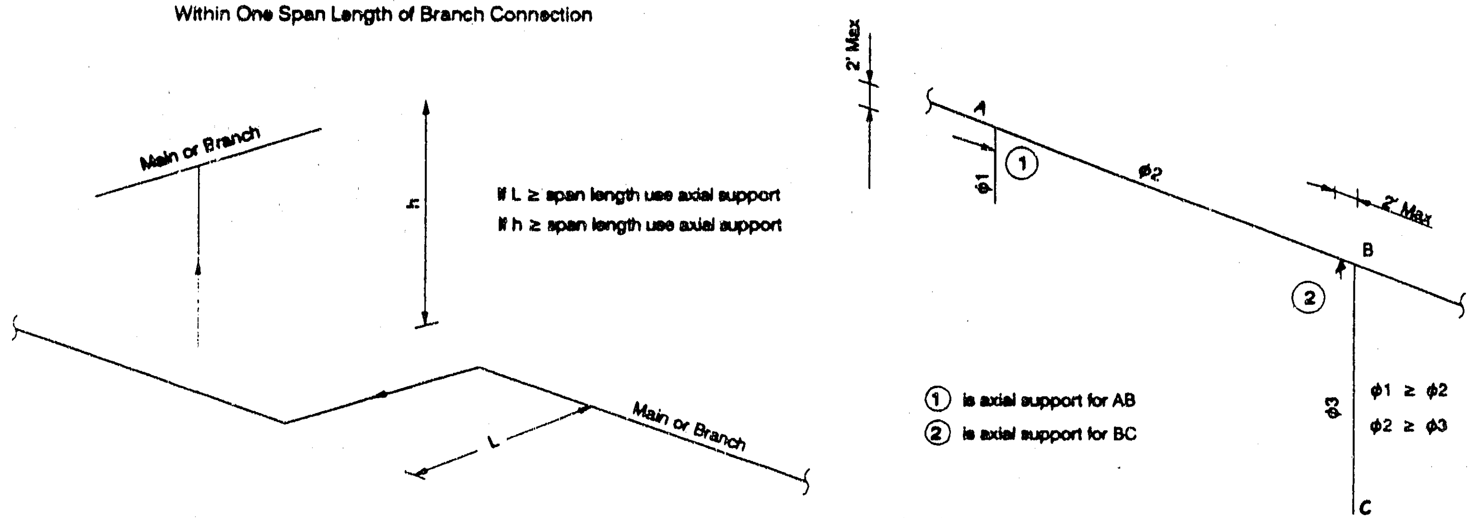


Figure : 1 Pipe Support Spacing Requirements



Detail "E": Lateral Support is Required on Main or Cross Main Within One Span Length of Branch Connection

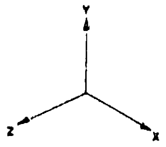
Detail "F": Maximum Span Between Axial Supports



Detail "G": Axial Supports Are Required If Riser or Run Exceed One Span Length

Detail "H": Lateral or Vertical Support Within 2' of the Pipe Centerline Can Act as Axial Supports

Figure :2 Pipe Support Spacing Requirements



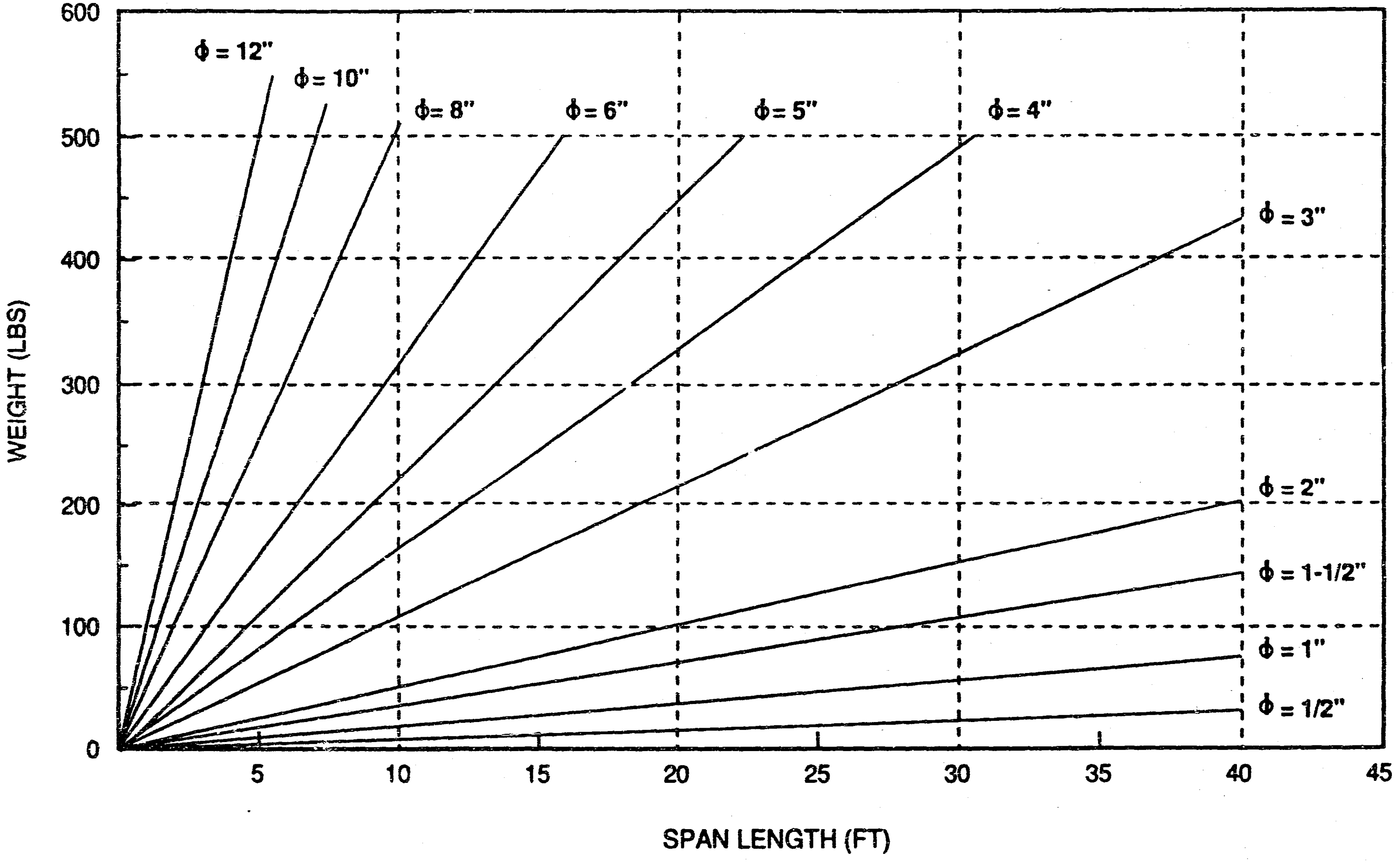
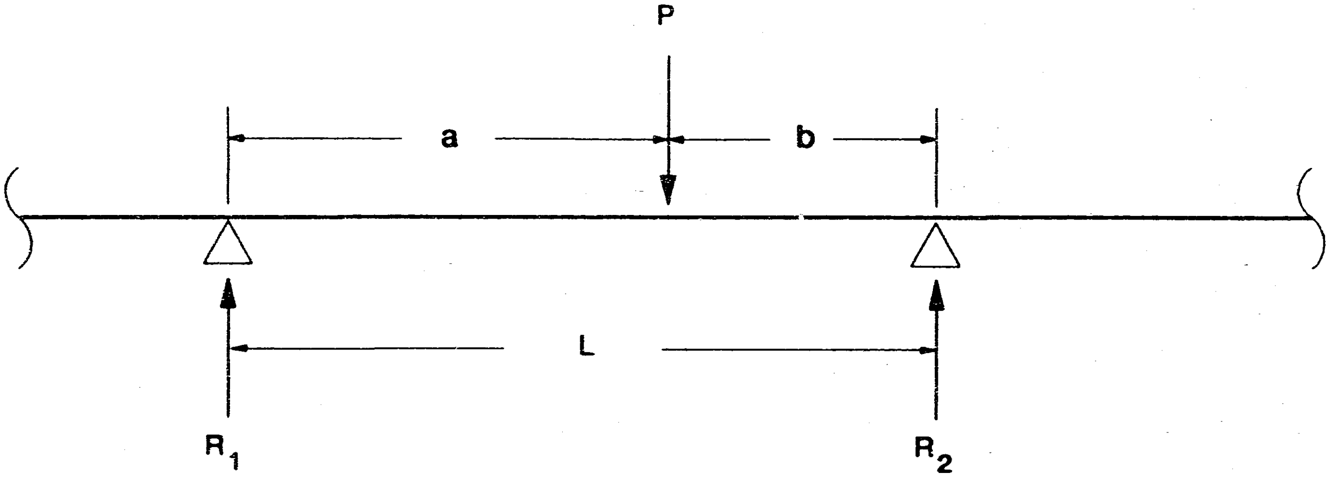


Figure :3 Piping Weight vs. Span, Schedule 40 Pipe + Water



$$R_1 = \frac{b}{L} P \qquad R_2 = \frac{a}{L} P$$

Figure :4 Distribution of Concentrated Loads to Pipe Supports

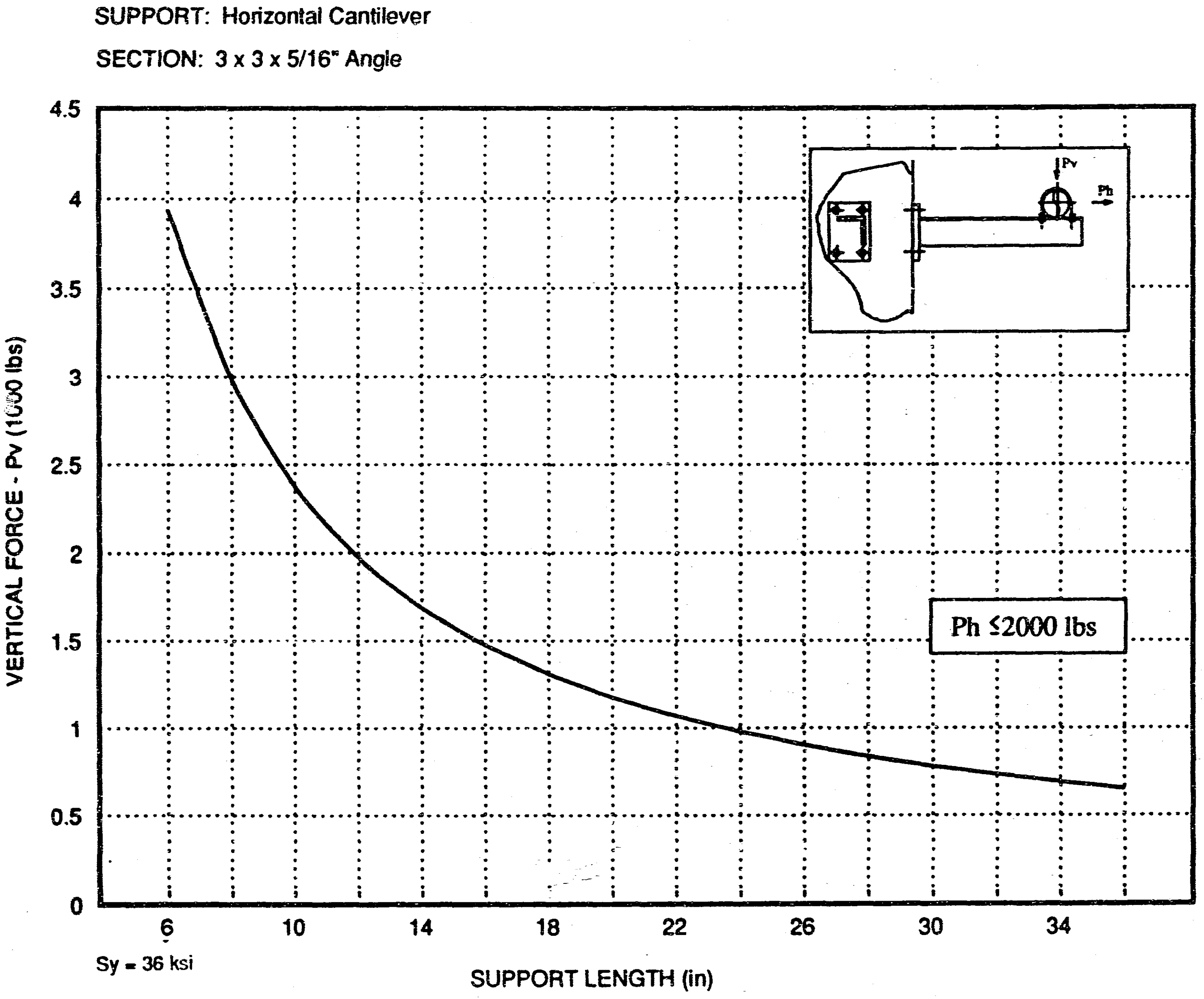


Figure :5 Acceptable Load Combinations for Fire Protection Piping Supports

SUPPORT: Horizontal Cantilever
SECTION: 3 x 3 x 5/16" Angle

VERTICAL FORCE Pv (lbs)

Support Length (in)	Horizontal Force Ph (lbs)										
	0	200	400	600	800	1000	1200	1400	1600	1800	2000
6	4072	4059	4045	4031	4018	4004	3990	3977	3963	3950	3936
8	3054	3044	3034	3023	3013	3002	2992	2982	2971	2961	2951
10	2443	2435	2427	2418	2410	2401	2393	2385	2376	2368	2359
12	2036	2029	2022	2015	2008	2001	1994	1986	1979	1972	1965
14	1745	1739	1733	1727	1721	1714	1708	1702	1696	1690	1683
16	1527	1522	1516	1511	1505	1500	1494	1489	1483	1478	1472
18	1357	1352	1347	1342	1337	1332	1327	1323	1318	1313	1308
20	1222	1217	1213	1208	1203	1199	1194	1190	1185	1180	1176
22	1111	1106	1102	1098	1094	1089	1085	1081	1077	1072	1068
24	1018	1014	1010	1006	1002	998	994	990	986	982	978
26	940	936	932	928	925	921	917	913	910	906	902
28	873	869	865	862	858	855	851	847	844	840	837
30	814	811	808	804	801	797	794	790	787	783	780
32	764	760	757	754	750	747	744	740	737	734	730
34	719	715	712	709	706	702	699	696	693	690	686
36	679	676	672	669	666	663	660	657	653	650	647

S_y = 36 ksi

Figure :6 Acceptable Load Combinations for Fire Protection Piping Supports

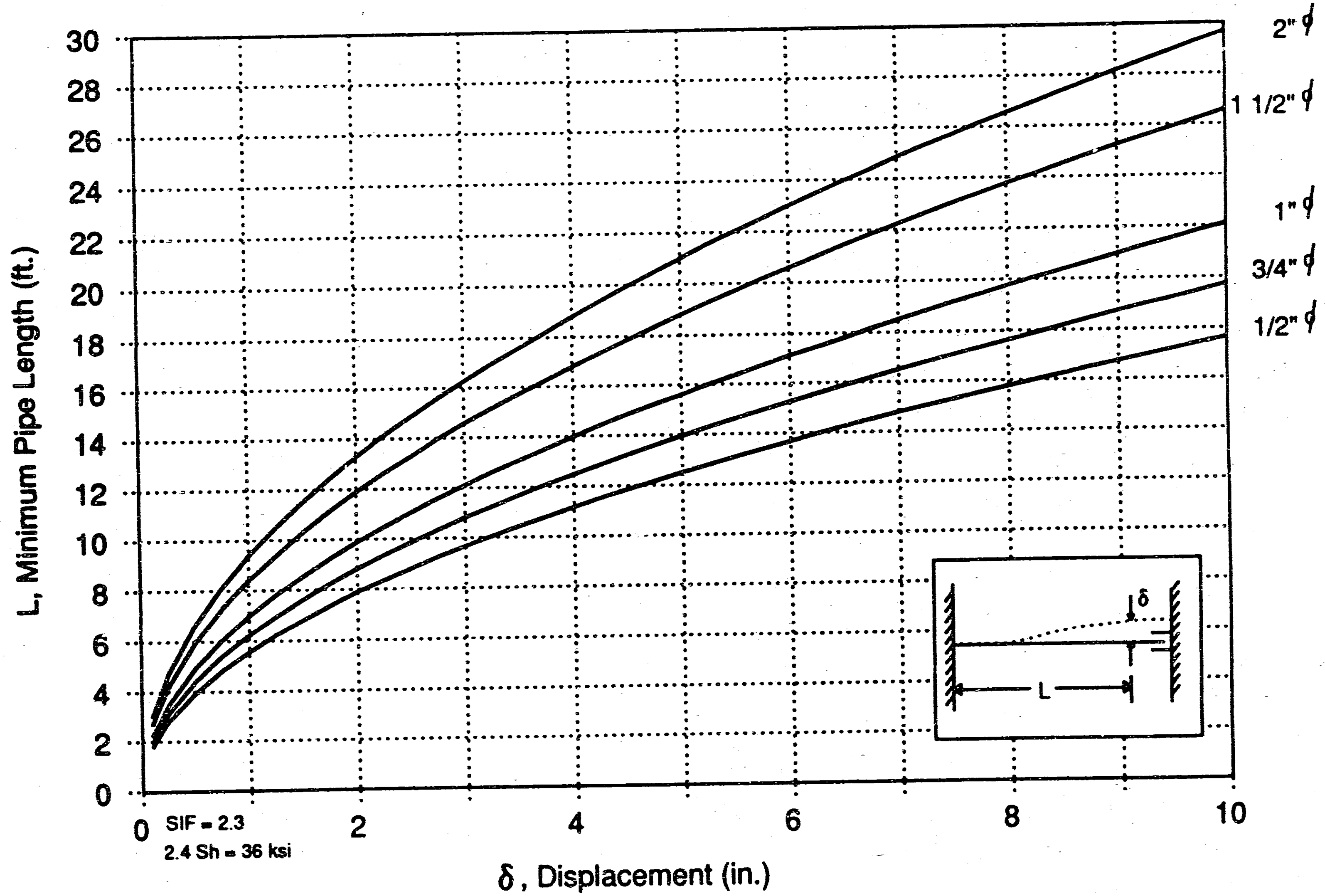


Figure :7 Flexibility Chart

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