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Analysis of the Effects of External Detonations on Piping Systems

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ABSTRACT

Nuclear facilities designed to confine explosion blasts and any associated release of radioactive particles must consider not only the integrity of the building structure but also of penetrating pipes, tubing and distribution systems. This is to assure that no unaccounted leak paths leading to release of radioactivity exist. This paper presents a method for analyzing the effects of external detonations on piping, tubing and electrical conduit systems in an old existing facility.

The structural evaluation effort faced quite a few challenges from both analytical and scoping point of view, viz.,

- Decades old facility, and ensuing difficulties in obtaining baseline or as-built design information.
- Piping/conduits of different sizes, routing, fittings, support designs and material (including PVC, Copper etc.)
- High blast peak pressures(in the thousands of psi range) with multiple explosive-to-target distances
- Selection of appropriate failure modes and analysis criteria for components, fittings and supports

Distance dependent blast pressure impulses (shape, duration, peak value) and component (piping/conduits etc.) spans and properties were evaluated to establish load regimes (impulsive, quasi-static, dynamic). Maximum deflection, stress/strain and support loads were computed and compared with limiting capacity (obtained primarily from review of test data on failed components) to determine survivability of components. Failed components and associated leak areas were estimated, and leak area optimization with cost-effective improvements were recommended.

INTRODUCTION

This paper analyzes the effects of blast pressure on wall mounted piping, tubing and conduits and draws conclusions regarding the failure of these systems under the anticipated blast loading conditions in an existing nuclear facility. Piping analyzed includes standard carbon steel pipe, copper tubing, plastic PVC pipe, and steel electrical conduits ranging in size from 3/8" to 2".

METHODOLOGY

Methods of Analysis

From the given the pressure impulse (shape, duration and peak pressure), and known pipe properties, the load regime is established: impulsive (pressure impulse much shorter than natural period), quasi-static (pressure impulse longer than natural period) or dynamic (intermediate between impulsive and quasi-static).

Then utilizing the specific impulse (the area under the pressure time-history curve, see Figure 1) the maximum deflection of pipe spans, the stress/strain, and the reaction load on supports are calculated.

The calculated deflections, stresses/strains and support reactions are then compared to piping and support capacities to determine whether the pipe or supports will fail.

Impulse Load Regime

Piping, represented as a series of beam spans, is dynamically loaded by a pressure impulse from an external blast. The span response will depend on the parameter ωt_l, the product of the natural pulsation ω of the span by the blast impulse duration t_l [1, p.277].

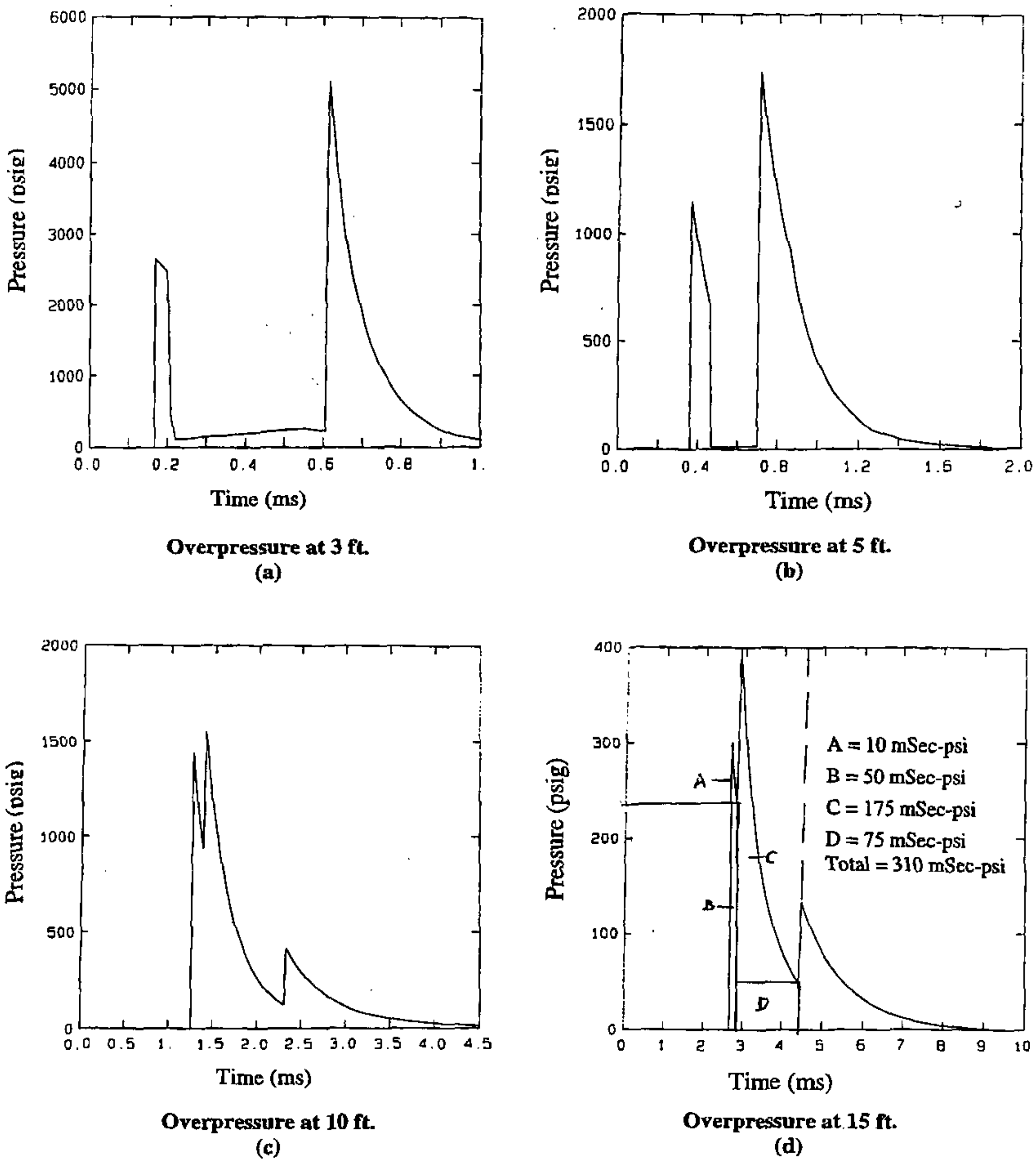
$\omega t_l > 40$, quasi-static regime [1, p. 278]: The dynamic load lasts significantly longer than the natural period of the span. The span has time to deflect while the impulse pressure is applied, and the deflection will reach up to twice the static deflection under the same side pressure.

$\omega t_l < 0.4$, impulsive regime [1, p. 278]: The blast is applied and removed so quickly that the span has little time to deflect before the blast pressure dissipates. The span deflection is much smaller than the static deflection under the same side pressure.

The natural pulsation of a pipe span of natural frequency f is $\omega = 2\pi f$, where

$$f = \frac{\pi}{2L^2}\sqrt{\frac{EI}{m}} \quad \text{[parameters defined in Nomenclature section]}$$

The applied specific impulse "i" is listed in Table 1-1, based on best estimates of the areas under the pressure time-history curves (Figure-1). A fourth, hypothetical case, for a small pressure impulse, has been added for information.



Overpressure at 3 ft.
(a)

Overpressure at 5 ft.
(b)

Overpressure at 10 ft.
(c)

Overpressure at 15 ft.
(d)

Figure 1 – Blast Overpressure Time History

Table 1-1 Specific Impulse "i"

Distance Blast source to Pipe	Max Duration t_I (msec)	Peak (psi)	*i* best estimate (psi-sec)	Figure
3 ft	0.8 - 0.6 = 0.2	5100	0.34	1a
5 ft	1.2 – 0.7 = 0.5	1750	0.36	1b
10 ft	2.3 – 1.3 = 1.0	1500	0.79	1c
15 ft	4.5 – 2.6 = 1.9	400	0.31	1d
Hypothetical	0.1	400	½(0.1)(400)/1000 = 0.02	-

Table 1-2 Maximum Value of Parameter ωt_I (with t_I = 2 msec).

	f10 (Hz)	f5 (Hz)	Omega/10 (Rad/sec)	Omega/5 (Rad/sec)	Omega*t_I (o)
3/8 tube	2.54	10.16	15.96	63.82	0.13
1 pipe	9.27	37.09	58.26	233.04	0.47
2 pipe	17.37	69.47	109.12	436.50	0.87
¾ conduit	5.88	23.53	36.96	147.82	0.30
1 conduit	7.30	29.21	45.89	183.54	0.37
¾ cu	4.47	17.88	28.09	112.37	0.22
1 cu	5.83	23.34	36.66	146.64	0.29
1.5 cu	9.76	39.03	61.31	245.24	0.49
3/4 pvc	2.07	8.26	12.98	51.93	0.10
1 pvc	2.63	10.52	16.53	66.12	0.13

From Table 1-2, it is apparent that the pipe will respond to the blast mostly in the impulsive regime ($\omega t_I < 0.4$). The load will be applied so quickly relative to the pipe's period that the pipe will deform less than under quasi-static loading.

RESPONSE COMPUTATION

Deflections and Strains

In the impulsive regime, the elastic-plastic deflection of a pipe span under a side-on blast pressure can be obtained from [1, eq.(4-70), p. 323]:

$$\frac{iDL^2}{\sqrt{24.576(2)\rho AEI}} = w_o$$

From [1, Fig.(4-26, p.321)] the maximum strain in the deflected pipe span is:

$$\varepsilon_{max} = \frac{Dw_o}{L^2\Psi_{w_o}} = \frac{w_o D}{L^2(0.2083)} = \frac{4.8 w_o D}{L^2}$$

The maximum deflections (at center of span) and corresponding strain are presented in Table 2-1, for 0.31 psi-sec and the hypothetical 0.02 psi-sec impulses (Table 1-1) for 5-ft and 10-ft spans.

Table 2-1 Maximum Deflections and Strains

	wo/0.31/5 (in)	wo/0.02/5 (in)	wo/0.31/10 (in)	wo/0.02/10 (in)	e/0.31/5 (%)	e/0.02/5 (%)	e/0.31/10 (%)	e/0.02/10 (%)
3/8 tube	84	5	339**	22	4.24	0.27	4.24	0.27
1 pipe	7	0.5	27	2	1.19	0.08	1.19	0.08
2 pipe	3	0.2	12	1	0.95	0.06	0.95	0.06
3/4 conduit	11	0.7	46	3	1.57	0.10	1.57	0.10
1 conduit	8	0.5	31	2	1.34	0.09	1.34	0.09

3/4 cu	25	2	98**	6	2.87	0.19	2.87**	0.19
1 cu	18	1	74**	5	2.77	0.18	2.77**	0.18
1.5 cu	5	0.3	21**	1	1.30	0.08	1.30	0.08
¾ pvc	186	12	743**	48	26.01	1.68	26.01**	1.68
1 pvc	126	8	503**	32	22.03	1.42	22.03**	1.42

Nomenclature: wo/0.31/5 = maximum deflection w_o, for a 0.31 psi-sec impulse, applied to a 5-ft span.
** Excessive deflections, beyond accuracy of bending equations.

Support Reactions

In practice, the direct blast will cause the supports of pipe runs along the wall to be in compression. However, a reflected blast wave could place the supports in tension, and an upward blast could place higher elevation supports in shear. The support reaction for a uniformly loaded, simply supported beam is

$$R^* = wL / 2$$

The maximum elastic deflection is:

$$w_o = 5wL^4 / (384EI)$$

Therefore, the elastically calculated support reaction due to a span deflection of w_o is

$$R^* = ((384\ EI)\ w_o / 5L^4)(L/2) = 38.4\ EI\ w_o / L^3$$

This support load corresponds well with the detailed analysis presented in Appendix B. Actual support load will be double this value due to added reactions from two adjacent spans.

$$R = 2R^* = 76.8\ EI\ w_o / L^3$$

Table 2-2 Support Reaction

	R/0.31/5 (lb)	R/0.02/5 (lb)	R/0.31/10 (lb)	R/0.0.2/10 (lb)
3/8 tube	494	32	247	16
1 pipe	6327	409	3163	204
2 pipe	21403	1384	10701	690
¾ conduit	3140	203	1570	101
1 conduit	4888	316	2444	158
¾ cu	2030	131	**	65
1 cu	3406	220	**	110
1.5 cu	9620	622	**	310
3/4 pvc	1126	73	**	36
1 pvc	1795	116	**	58

Nomenclature: R/0.31/5 = support reaction R for a 0.31 psi-sec impulse, 5 ft pipe span.
** Excessive deflections, beyond accuracy of bending equations.

COMPARISON WITH ALLOWABLES

Welded Steel

Welded steel pipe will reach the onset of plastic deformation at 0.2% strain.
The design limit for onset of buckling is $2.4(t/D)^{1.6}$ [2] which corresponds to the 95% lower bound [2].

Table 3-1 Calculated Bending Strain Compared to Buckling Strain, Metallic Pipe and Conduit

	e/0.31/5 (%)	e/0.02/5 (%)	e/0.31/10 (%)	e/0.02/10 (%)	Buckling Strain (%)
3/8 tube	4.24	0.27	4.24	0.27	5.3
1 pipe	1.19	0.08	1.19	0.08	6.14
2 pipe	0.95	0.06	0.95	0.06	3.01
¾ conduit	1.57	0.10	1.57	0.10	3.63
1 conduit	1.34	0.09	1.34	0.09	3.09

Threaded Steel

The 4-point bending of a 6-ft long, 2" sch.40, threaded pipe specimen [3] resulted in leakage through cracked threads at a cross head deflection of 1.4" to 1.8" and separation (break) at a center span deflection of approximately 3". For a symmetrical 4-point bending, the deflection under the load is [with X = a and L = 3a,]

$$\Delta_X = \frac{5Pa^3}{6EI}$$

The maximum deflection, at mid-span is

$$\Delta_{max} = \frac{23Pa^3}{24EI}$$

Therefore, the maximum deflection at mid span at thread leakage is $\Delta_{max} = (23/24)/(5/6)\ \Delta_X = 1.15\ \Delta_X = 1.15\ (1.4") = 1.6"$

The same rotation angle at mid-span is reached for a span length L when the mid-span deflection reaches the value $w_{oL} = w_{o6'}$ (L(in)/72"), or $w_{o5'}$ = 1.6(60/72) = 1.3" and $w_{o10'}$ = 1.6(120/72) = 2.7", these displacements limits at which the threaded joint will fail are compared to the calculated deflections in Table 3-2. Rupture (separation) of the threaded joint occurs at w_{s5} = 3(60/72) = 2.5" and w_{s10} = 3(120/72) = 5"

Table 3-2 Comparison of Span Deflections to Limit Deflection at Threaded Joint for Leak (leak) and Rupture

	wo/0.31/5 (in)	wo/0.02/5 (in)	wo/0.31/10 (in)	wo/0.02/10 (in)	$w_{o5'}$ leak/rupture (in)	$w_{o10'}$ leak/rupture (in)
3/8 tube	84	5	339**	22	1.3 / 2.5	2.7 / 5
¾ pipe	10	1	41	3	1.3 / 2.5	2.7 / 5
1 pipe	7	0.5	27	2	1.3 / 2.5	2.7 / 5
2 pipe	3	0.2	12	1	1.3 / 2.5	2.7 / 5
¾ conduit	11	0.7	46**	3	1.3 / 2.5	2.7 / 5
1 conduit	8	0.5	31**	2	1.3 / 2.5	2.7 / 5

** Excessive deflections, beyond accuracy of bending equations.

Nomenclature: wo/0.31/5 = maximum deflection w_o, for a 0.31 psi-sec impulse, applied to a 5-ft span.

Copper Tubing

The allowable stress at ambient temperature, for B-88 drawn (temper H) copper tubing is [4] S = 12 ksi, the yield S_y = 30 ksi, and the ultimate = 36 ksi. Therefore, the deflection at yield is

$$(w_o)_{max} = \frac{(30{,}000)L^2}{4.8DE}$$

For example, with L = 60", D = 1.90" and E = 17E6 psi, the deflection at yield is $(w_o)_{max}$ = 0.70", as reported in Table 3-3 under "CuYield5" for "1.5cu".

Unpublished test results [5] indicate that copper tubing could fail in a groove of the coupling (3 cases) or by crimping (1 case). In the first case, the deflection under load was 2", and therefore the center span deflection was 1.15(2') = 2.3". For the 5-ft span this deflection at rupture corresponds to 2.3(60/72) = 1.9" and for the 10-ft span 2.3(120/72) = 3.8".

Table 3-3 Comparison of Span Deflections w_o to Yield Deflection in Copper Tubing

	wo/0.31/5 (in)	wo/0.02/5 (in)	wo/0.31/10 (in)	wo/0.02/10 (in)	CuYield5 (in)	CuYield10 (in)	CuRup5 (in)	CuRup10 (in)
¾ cu	25	2	98**	6	1.51	6.05	1.9	3.8
1 cu	18	1	74**	5	1.18	4.71	1.9	3.8
1.5 cu	5	0.3	21	1	0.70	2.79	1.9	3.8

** Excessive deflections, beyond accuracy of bending equations.

PVC Pipe

The short term bending strength of PVC pipe is 11,000 to 15,000 psi [8, p.247], which corresponds to an elastically predicted (lower bound) strain of 11,000/460,000 = 2.4% to 15,000/460,000 = 3.3%. Bending fatigue tests by Scavuzzo et. al. [9] indicated failures in ~ 50 cycles at an alternating strain of ~ 20,000 μin/in = 2%.

Table 3-4 Maximum Strains in PVC Pipe

	e/0.31/5 (%)	e/0.02/5 (%)	e/0.31/10 (%)	e/0.02/10 (%)	e limit (%)
3/4 pvc	26.01	1.68	**	1.68	2.0
1 pvc	22.03	1.42	**	1.42	2.0

Nomenclature: e/0.31/5 = maximum strain, for a 0.31 psi-sec impulse, applied to a 5-ft span.
** Excessive deflections, beyond accuracy of bending equations.

Pipe Supports

6" Unistrut channel P1000, single load (1-5/8" height and width) capacity [8] = 1690 (24"/6")(0.50) = 3380 lb, with a safety factor of 2.4 on ultimate = 3380 (2.4) = 8122 lb. ~ 8000 lb.

48" Unistrut P1000, multiple load capacity [8] = 850 lb., with a safety factor of 2.4 on ultimate = 850 (2.4) = 2040 lb.

Conduit clamp design load [P2028, P2030, P2038] = 400 lb for ¾", 600 lb for 1", and 800 lb for 2", with a safety factor of 5 against rupture the ultimate load is 5(600) = 3000 lb and 5(800) = 4000 lb.

The tension capacity of embedded Unistrut inserts is 750 lb for a 6" long insert in 3000 psi concrete, which includes a safety factor of 3 [8]. Therefore, at ~ 3(750) = 2250 lb the Unistrut would fail.

Anchor bolts are 5/8" across flats (3/8" diameter bolts), unknown make, at 4" spacing. Based on [9], the anchor capacity for 3/8" bolts, unknown make, 4" apart (which is larger than 10diameters), is:

Tension allowable = (1460 lb)(0.5) = 730 lb, with a safety factor of 3 [9] = 2190 lb at rupture.

Shear allowable = (1420 lb) (0.75) = 1065 lb, with a safety factor of 3 [9] = 3195 lb at rupture.

Table 3-5 Support Reactions

	R/0.31/5 (lb)	R/0.02/5 (lb)	R/0.31/10 (lb)	R/0.0.2/10 (lb)	Channel Ultimate (lb)	Clamp Ultimate (lb)	Bolt Ultimate (lb)
3/8 tube	494	32	247	15	8000	3000	2190
1 pipe	6326	409	3163	204	8000	3000	2190
2 pipe	21402	1383	10701	690	8000	4000	2190
3/4 conduit	3140	203	1570	101	8000	3000	2190
1 conduit	4888	316	2444	157	8000	3000	2190
3/4 cu	2029	131	**	65	8000	3000	2190
1 cu	3405	220	**	110	8000	3000	2190
1.5 cu	9620	622	**	310	8000	3000	2190
3/4 pvc	1125	72	**	36	8000	3000	2190
1 pvc	1795	116	**	57	8000	3000	2190

Nomenclature: R/0.31/5 = support reaction R for a 0.31 psi-sec impulse, 5 ft pipe span.
** Excessive deflections, beyond accuracy of bending equations.

RESULTS AND CONCLUSIONS

The following conclusions apply to the actual 0.31 psi-sec pressure impulse for a 15-ft distant source. In parenthesis is the conclusion for a hypothetical 0.02 psi-sec pressure impulse.

1- Welded Steel: The strains are below buckling limits. The welded steel pipes would not fail from the blast pressure impulse. The Unistrut supports would fail, but the resulting longer span of pipe would not fail. (No failure for hypothetical 0.02 psi-sec impulse). Base metal and welded steel would not fail as a result of the pressure impulse.

2- Threaded Pipe and Conduit: The center span deflection of 5-ft and 10-ft span would exceed the measured deflection at rupture of threaded joints, in all cases except the 2" threaded pipe on 5-ft span. Also, the Unistrut supports would fail. The 2-ft long span deflections would be acceptable, Appendix D, but the resulting support loads would be excessive. (No failure for hypothetical 0.02 psi-sec impulse). Threaded joints would fail if located close to span center, as a result of the pressure impulse.

3- Copper Tubing and Pipe: The pipe and tubing deflections exceed the measured deflections at rupture of copper joints, and calculated yield and ultimate stress. The support loads would be excessive in all cases, except for the 5-ft span of ¾ tube. Copper tube joints would fail if located close to span center, as a result of the pressure impulse.

4- PVC Pipe: The center span deflection of 5-ft and 10-ft span would exceed the deflection at rupture for PVC pipe. The 5-ft span supports would not fail. (No failure for hypothetical 0.02 psi-sec impulse). PVC pipe will fail, as a result of the pressure impulse.

5- Predicted failure of threaded connections can be avoided by installing supports close to the connections. The supports should be sized to sustain the loads given in Table 3-5.

	5 ft span		10 ft span	
	0.31 psi-sec	0.02 psi-sec	0.31 psi-sec	0.02 psi-sec
Welded Pipe	ok	ok	ok	ok
Threaded Pipe/Conduit	No Good	ok	No Good	ok
Copper Tubing	No Good	ok	No Good	No Good
PVC Pipe	No Good	ok	No Good	ok

NOMENCLATURE

A = metal area of cross section
D = diameter
E = Young's modulus of material
f = natural frequency of simply supported span
f10 and f5 = natural frequencies for a 10-ft and a 5-ft simply supported span.
i = specific impulse, integral of the pressure-time function
I = moment of inertia of pipe cross section
L = span length
m = linear mass
P = peak pressure
R = total support reaction from two sides, twice R*
R* = support reaction from one side
w = distributed load
w_0 = deflection
Z = section modulus
α = dimensionless boundary condition parameter
ρ = mass density of pipe material
Ψ = dimensionless parameter
ω = natural pulsation

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APPENDIX A - PIPE STRAIN USING DIAGRAM [1]

We will calculate the dynamic strain and the support reaction loads for a 10 ft long pipe span of 1" standard (schedule 40) carbon steel pipe, subjected to a 400 psi, triangular pressure pulse of 0.31 psi-sec and 0.02 psi-sec respectively, using the solutions developed in [1].

It can be seen that the solutions in [1, Fig.4-26 and 4-27] apply to a cylindrical cross section if we set b = h = D the pipe diameter.

Strain Calculation

Applying the elastic-plastic solution of [1, Fig.4-26] we first calculate the strain in the pipe due to the blast load. The abscissa of the solution diagram is

$$\frac{PDL^2}{\Psi_P \sigma_Y Z} = 163$$

where, $P = 400$ psi
$D = 1.315"$
$L = 120"$
$\psi_P = 10$ [1, Fig.4-26]
$\sigma_Y = 35{,}000$ psi
$Z = 0.1329\ in^3$

The ordinate of the solution diagram is

$$\frac{iD\sqrt{EI}}{\Psi_i \sqrt{\rho A \sigma_Y Z}} = 8 \text{ (for 0.31) and 0.5 (for 0.02)}$$

where, D, Z, σ_Y are as above and
$i = 0.31$or 0.02 psi-sec.
E = 30E6 psi for carbon steel
$I = 0.0874\ in^4$
$\psi_i = 0.913$ [1, Fig. 4-26]
ρ = mass density of pipe material = (1.679)/[(12)(0.494)(386)] = 0.0007338 lbf/in^3 / (in/sec^2)
$A = 0.494\ in^2$

We enter [1, Fig.4-26] with (163,8) and (163,0.5) and read $IE\varepsilon_{max} / (\Psi_c DZ\sigma_Y)$ of >4.0 and ~ 0.2, which corresponds to ε_{max} > 1.2% and = 0.09%, which supports the values calculated in Table 3-1: e/0.31/10 = 1.19% and e/0.02/10 = 0.08%.

APPENDIX B - SUPPORT LOAD USING DIAGRAM [1]

Applying [1, Fig.4-27] we calculate the pipe support reactions due to the blast load. The abscissa of the solution diagram is

$$\frac{PD^2L^2}{\alpha_P EI} = 0.5$$

where P, D, L, I are as above and
$\alpha_P = 8$ [1, Fig.4-27]
E = 30E6 psi for carbon steel

The ordinate of the solution diagram is

$$\frac{iD^2}{\alpha_i \sqrt{\rho EIA}} = 1.2E\text{-}2 \text{ (for 0.31) or } 7.7E\text{-}4 \text{ (for 0.02)}$$

where, $\alpha_i = 1.4610$ and rest are as above

For the 0.31 psi-sec impulse, we enter [1, Fig.4-26] with (0.5,1.2E-2). The ordinate for an impulse of 0.31 psi-sec, is too large, beyond the range of [1, Fig. 4-27].

For the 0.02 psi-sec impulse, we enter [1, Fig.4-26] with (0.5,7.7E-4) and read $(\sigma_{max}/E)10^3$ ~ 0.7, and V = 8 x 0.0874 x (−0.7 x 30,000) / (120 x 1.315) ~ 93 lb, which supports the value calculated in Table 3-5, for a single span R* = R/2 = 204 lb / 2 = 102 lb.