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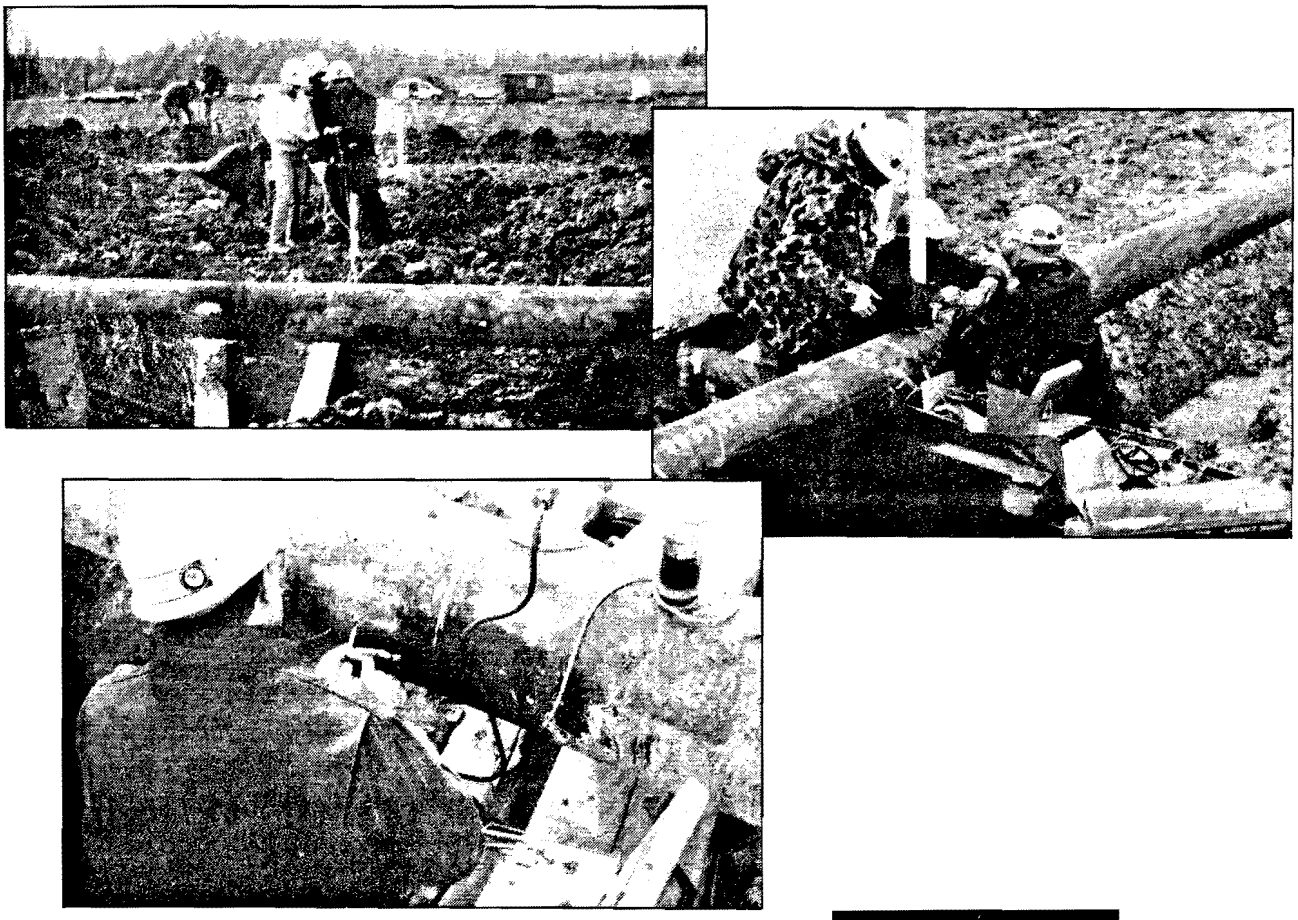
Surface Mine Blasting Near Pressurized Transmission Pipelines

By David E. Siskind, Mark S. Stagg, John E. Wiegand, and David L. Schulz



UNITED STATES DEPARTMENT OF THE INTERIOR

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BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Metric Units

cm	centimeter	m/s	meter per second
dB	decibel	min	minute
g/cm^3	gram per cubic centimeter	mm	millimeter
GPa	gigapascal	mm/s	millimeter per second (particle velocity)
h	hour	MPa	megapascal (million newtons per square meter)
Hz	hertz	ms	millisecond
kg	kilogram	Pa	pascal (newton per square meter) (pressure and stress)
km	kilometer	pct	percent
m	meter	s	second
$m/kg^{0.33}$	meter per scaled kilogram, cube root scaled distance	$\mu mm/mm$	micromillimeter per millimeter (microstrain)
$m/kg^{0.4}$	meter per scaled kilogram, 0.4 root scaled distance		
$m/kg^{0.5}$	meter per scaled kilogram, square root scaled distance		

U.S. Customary Units

cal/g	calorie per gram (specific energy)	in/s	inch per second (particle velocity)
ft	foot	lb	pound
ft/lb	foot per pound	lb/ft^2	pound per square foot (pressure)
ft-lb	foot pound (energy)	lb/in^2	pound per square inch (pressure and stress)
ft-lb/lb	foot pound per pound (specific energy)	$lb\text{-}s^2/ft^4$	pound second squared per foot to the fourth (mass density)
ft/s	foot per second (propagation velocity)		
in	inch	lb/yd^3	pound per cubic yard

Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

SURFACE MINE BLASTING NEAR PRESSURIZED TRANSMISSION PIPELINES

By David E. Siskind,[1] Mark S. Stagg,[2] John E. Wiegand,[3] and David L. Schultz[4]

ABSTRACT

The U.S. Bureau of Mines and the State of Indiana cooperated with AMAX Coal Co. and its consultants to determine the effects of coal mine overburden blasting on nearby pipelines. Five pressurized 76-m pipeline sections were installed on the Minnehaha Mine highwall near Sullivan, IN, for testing to failure. Four 17- to 51-cm-diameter welded steel pipes and one 22-cm PVC pipe were monitored for vibration, strain, and pressure for a period of 6 months while production blasting advanced up to the test pipeline field. In contrast to previous studies of small-scale, close-in blasting for construction, these tests involved overburden blasts of up to 950 kg per delay in 31-cm blastholes.

Analyses found low pipe responses, strains, and calculated stresses from even large blasts. Ground vibrations of 120 to 250 mm/s produced worst case strains that were about 25 pct of the strains resulting from normal pipeline operations and calculated stresses of only about 10 to 18 pct of the ultimate tensile strength. No pressurization failures or permanent strains occurred even at vibration amplitudes of 600 mm/s.

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INTRODUCTION

The U.S. Bureau of Mines (USBM) participated in a study of surface mine blasting impacts on gas and water transmission pipelines in a cooperative effort with the Division of Reclamation of the Indiana Department of Natural Resources (IDNR), AMAX Coal Co., and its consultants, Vibronics, Inc., New Mexico Institute of Mining and Technology, and Ohio Valley Pipeline, Inc. AMAX had concerns about blasting near active pressurized transmission pipelines at its Minnehaha Mine, near Sullivan, IN, as well as at other mines. As a result, the company approached the USBM and other cooperators in the fall of 1991 about the feasibility of conducting a study involving a variety of test pipelines subjected to full-scale overburden blasts at one of its surface coal mines.

This project provided an opportunity to study a problem of widespread concern. Numerous requests for advice on blasting near pipelines have been received by the USBM over the years, many related to mine or quarry operations. In a blast vibrations research planning document first prepared in March 1989, the USBM identified blasting near pipelines as a key research topic and industry need. Although some work was done in the 1970's and 1980's on blasting near pipelines, none to the authors' knowledge involved large-scale production mine blasting. Most, if not all, previous work examined close-in, small-scale blasts representative of excavation for pipeline installations next to existing lines. The industry and regulatory agencies need realistic guidelines for mine blasting near pressurized transmission pipelines to ensure both maximum resource recovery and the safety of such utilities.

The USBM role was to install and operate monitoring equipment for measuring strain and vibration and to interpret the results of those measurements. Other cooperators had responsibilities for pipeline installation (Ohio Valley Pipeline), supplemental vibration monitoring and continuous monitoring of internal pressures (Vibronics), and analysis, interpretation, and monitoring support (IDNR and New Mexico Tech.). AMAX provided the site, costs of pipeline installation, security fence and other facility improvements, and shot coordination.

Installation and monitoring began in March 1992, ensuring reasonable weather for the difficult installation phases. Monitoring locations were chosen so that initial vibration levels would be about 50 mm/s. Five total mining cycles of roughly 45 days each brought the blasting adjacent to the pipelines.

This report is an expanded version of a paper given at the Ninth Annual Symposium on Explosives and Blasting Research sponsored by the International Society of Explosives Engineers, January 31 - February 4, 1993, in San Diego, CA (*1*).[5]

BACKGROUND

PIPELINE IMPACTS FROM LARGE VIBRATION EVENTS

Some previous work has been done on vibration impacts on transmission pipelines. An examination of earthquake-induced pipeline responses concluded that buried pipelines move with the ground and not differentially. The most serious concern was for locations where the soil-rock characteristics abruptly change (*2*).

The U.S. Army Corps of Engineers tested pipeline responses to a concentrated 9,000-kg TNT blast (*3*). One end of a 15-cm-diameter, 67-m-long, pressurized pipeline was located only 24 m from ground zero. Although that end was in the crater and ejecta zone and experienced some permanent deformation, no visible breaks occurred. Internal pressure had dropped from 3.45 to 2.76 MPa, but no leaks could be seen. Peak dynamic strains, all measured longitudinally, were 1,100 to 1,400 μmm/mm, and estimated total strains, including those from pressurization, were about 1,550. The authors of the Corps report estimated yield stresses and strains of 414 MPa and 2,000 μmm/mm, respectively, and reported measured radial vibration of 4,270 mm/s (168 in/s).

SOUTHWEST RESEARCH INSTITUTE STUDIES

The most extensive studies of blasting and pipelines were those of Southwest Research Institute (SwRI) for the Pipeline Research Committee of the American Gas Association (*4-7*). SwRI and its sponsors were concerned with both mining and close-in construction blasts, particularly in the installation of new pipelines next to existing ones. However, because the initial soil tests and the followup tests involving blasting in rock all used small charges and short distances, there is a question of how applicable their results would be to the much larger mining blasts. Many if not all of the SwRI tests involved pipelines close to or

[5]Italic numbers in parentheses refer to items in the list of references preceding the appendixes at the end of this report.

within the zone of inelastic strain and permanent deformation. Appendix A describes the SwRI tests and results and also the adjustments made to the SwRI predictions in a more recent paper by Lambeth (*8*).

OTHER ANALYSES OF PIPELINES

Lewis L. Oriard, in his capacity as consultant for many pipeline projects, commented on the USBM's pipeline measurements given in Siskind's 1993 paper (*1*) in two personal communications to the senior author (*9-10*). His involvement with many large pipeline projects as well as roughly 350 urban pipeline and utility projects has led him to conclude that the blasting risk to pipelines is from block motion (permanent strain) or from having the pipeline in the actual blast crater zone. He suspects that no elastic wave (vibration velocity) criterion is needed, nor is it meaningful. Oriard also concludes that failure is initiated in the surrounding ground, which is weaker than the pipe, and that it is better to apply either vibration criteria or blasting criteria to the ground around the pipe rather than to the pipe alone. Oriard reported on a 2,000-km pipeline project adjacent to an existing high-pressure gas line. Blasting was as near as 4 m, with a safe-level criterion of 300 mm/s. Several unscheduled blasts were detonated, the largest consisting of nearly 27,000 kg (60,000 lb) of explosives along 2.1 km (7,000 ft) of trench, detonated instantaneously. Particle velocities were calculated to range as high as 2,500 to 3,700 mm/s. No damage occurred. Oriard also commented on very large strains (bending) observed during installation or relocation of pipes, even while the pipes were still pressurized, without damage.

Oriard's first communication also included a description of a blasting study he conducted on an unpressurized 37-m-long section of 91-cm pipeline with 11.13-mm wall. These were close-in tests with charges of 2.7 to 10.9 kg per delay. No damage was found even from the highest blast vibration: 318 mm/s, 1,494 μmm/mm strain, and calculated circumferential and longitudinal stresses of 248 MPa (36,000 lb/in^2) and 379 MPa (55,000 lb/in^2), respectively.

Jack L. Kiker who has consulted with Oriard on a variety of pipeline blasting projects, also commented on Siskind's 1993 paper (*1*). In a personal communication to the senior author, Kiker reported his experiences blasting within 3 to 6 m of an existing high-pressure pipeline (*11*). He reported one case in which a parallel ditch within 4 m of the blast had ground rupture cracks extending to the existing pipeline and in which peak particle velocities were 64 mm/s, without damage.

In another case, Kiker assisted on a project that involved blasting within 1.2 m of a 30-cm PVC sewer pipe. Vibration amplitudes up to 1,450 mm/s produced no damage. He also reported that vibration amplitude decreased 40 to 70 pct with depth at the typical pipeline burial depth of 1 to 1.2 m. Agreeing with Oriard, Kiker believes that risk to pipelines comes from ground rupture and movement of fractured rock into the pipe at high velocity, and not from vibrations per se. His reasoning is based on the short duration of these stresses, the strength of the pipe relative to the surrounding ground, and the limits on the amount of stress that can be transmitted from ground to pipeline because of these strength differences. As with the SwRI tests, all the tests of Oriard and Kiker involved small, close-in blasts.

Dowding's book (*12*) contains analyses of both unlined tunnels and buried pipelines. He addresses the cases where pipelines have low stiffnesses compared with the confining media, defining a flexibility ratio (J):

$$J = \frac{E/(1+\nu)}{\left[6E_P I_P/\left(1-\nu_P^2\right)\right]\left(1/r^3\right)},$$

where E and E_p = Young's moduli of ground and pipe, respectively,

ν and ν_P = Poisson's ratio of ground and pipe, respectively,

I_P = moment of inertia of pipe, $1/12h^3b$,

r = pipe radius,

h = pipe wall thickness,

and b = unit length along axis of pipe.

Citing work by Peck and others (*13*), Dowding states that, for J greater than 10, the restrained pipelines can be considered to be completely flexible and to deform with the ground. For lower J values, the strains in the pipes will be smaller than those in the surrounding medium. Using Dowding's values for soil of $E = 10^4$ lb/in^2 and $\nu = 0.25$, J values are 28, 8.3, and 2.7, respectively, for the 50.8-, 32.4-, and 16.8-cm steel pipelines studied by the USBM and 82 for the 21.9-cm PVC pipe. The two smaller steel pipelines do not appear to meet the flexibility criteria. Considering the very wet conditions for the USBM tests, an E of 10^4 lb/in^2 for the soil is probably too high, potentially reducing the J value. In addition, there are possible stiffening effects from internal pressurization that are not addressed here.

For cases of high J (>10), such as those of the larger steel and PVC pipelines tested by the USBM, Dowding gives formulas for bending and stretching strains (ϵ) for plane wave vibrations propagating parallel to the pipeline (worst case):

Bending:

$$\epsilon = \frac{u2\pi fr}{c_s^2},$$

where u = peak particle velocity,

f = frequency, Hz,

r = pipe radius,

and c_s = seismic S-wave velocity.

Stretching:

$$\epsilon = \frac{u}{c_P},$$

where c_P = seismic P-wave velocity.

For circumferential strains perpendicular to the axial strains and conditions of pure shear, Dowding gives a maximum strain:

$$\epsilon = \frac{u}{2c_S},$$

where c_S = seismic S-wave velocity.

The difference in stiffness between the steel and PVC is consistent with the significantly higher longitudinal strains (bending) measured by the USBM on the PVC. In this case, the strains are bending responses of the pipelines resulting from the components of compressional waves normal to the pipe axes or shear waves parallel to the axes.

O'Rourke and Wang give nearly similar relationships for bending and stretching of pipelines in totally confined and rigid conditions (*2*). For ground motion along the axis of the pipeline, they specify a maximum axial strain of

$$\epsilon = \frac{u}{c_p},$$

which is the same as Dowding's. For ground motion perpendicular to the pipeline, they give a maximum curvature (bending) of

$$\text{Bending} = \frac{2\pi fu}{c_s^2},$$

where velocity units are consistent. Because of the lack of the pipe radius term, it appears that "bending" is defined here as ϵ/r.

EXPERIMENTAL PROCEDURES

TEST PIPELINES

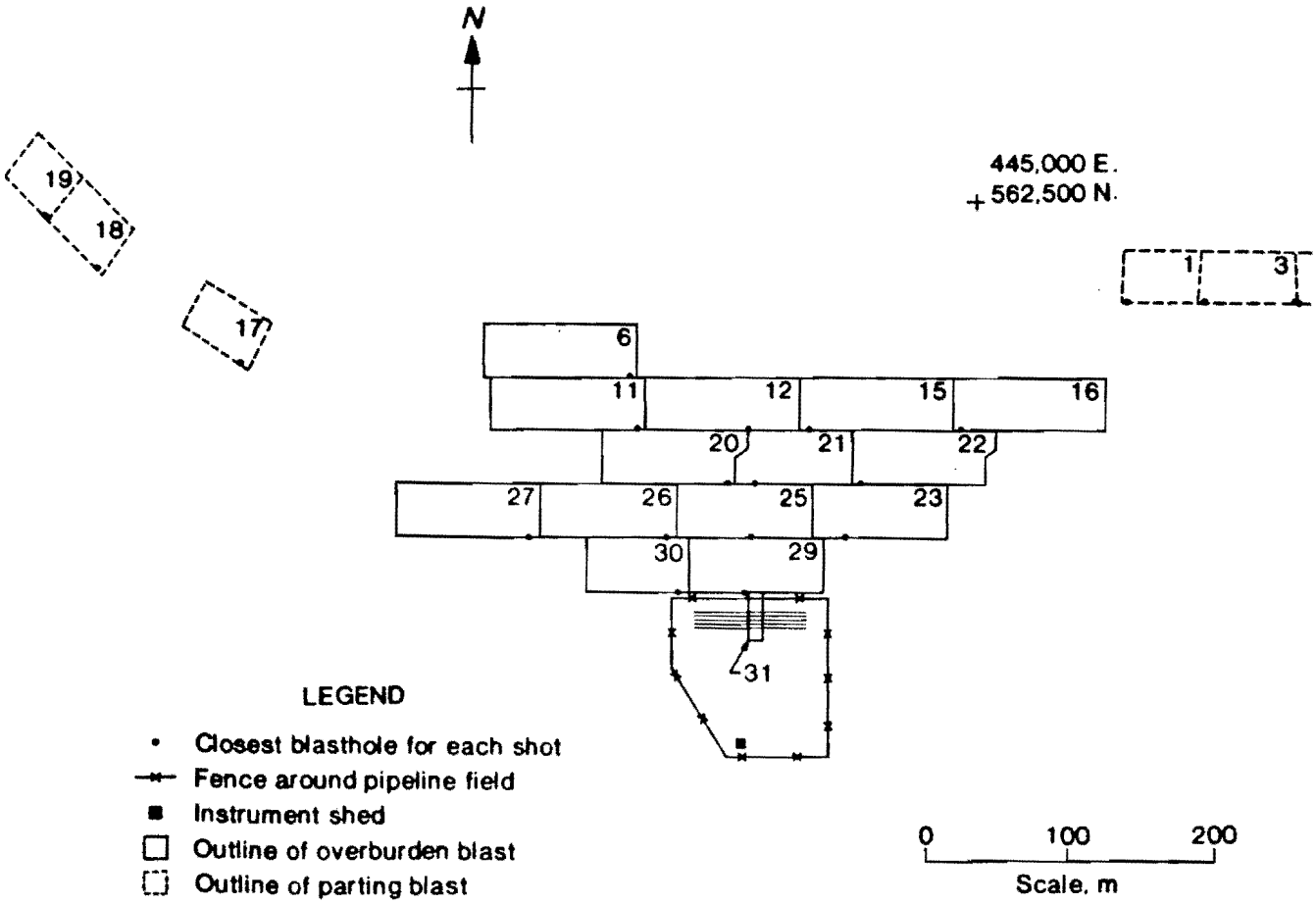
Five 76-m-long sections of transmission pipeline, with properties described in table 1, were installed on the AMAX Coal Co.'s Minnehaha Mine highwall bench for testing to destruction. They were all parallel to each other, with 3-m spacings, and also to the highwall face at an initial distance of about 150 m, as shown in figure 1. The pipe positions, in increasing distance from the highwall face, are in the same order as listed in table 1. Ohio Valley Pipeline crew welded and installed the pipelines, using their standard procedures, after the USBM workers attached longitudinal and circumferential strain gages and sensors for vibrations in the center areas of the pipelines. All pipes were placed in trenches and covered with about 1 m of the excavated clay soil. Some pipes, particularly the 50.8-cm pipeline, were installed under very wet conditions. The area was compacted by a loader and dozer; however, the soil did settle a few centimeters during the 7-month monitoring period. The pipes had three uprights each to provide access for pressurization and placement of pressure-measuring gages, and also to provide survey points to measure settlement and any other static-type responses. Figures 2 to 5 show pipe installation activities.

Table 1.—Pipeline characteristics

Outside diam, cm	Wall thickness, mm	Fill material	Age	Material type
Steel:[1]				
16.8	4.78	Gas	Used	X-42
32.4	6.35	Gas	Used	Grade B
32.4	6.35	Gas	New	X-42
50.8	6.63	Water	Used	X-56
PVC:[2]				
21.9	8.43	Water	Used	SDR26

[1]Initial pressurization 6.2 MPa (900 lb/in^2).
[2]Initial pressurization 0.62 MPa (90 lb/in^2).

Figure 1



Minnehaha Mine pipeline test area and the closer-in production blasts monitored.

MATERIAL PROPERTIES

The grade of steel pipe refers to its specified minimum yield strength (SMYS) in pounds per square inch. Therefore, X-42 means a SMYS of 290 MPa (42,000 lb/in^2). Grade B is equivalent to 241 MPa (35,000 lb/in^2). The PVC pipe has a yield tensile strength of 48.3 MPa (7,000 lb/in^2). Young's moduli for the two materials are 203 GPa (29.5 $\times$ 10^6 lb/in^2) and 2,760 MPa (4 $\times$ 10^5 lb/in^2), respectively. Poisson's ratio was assumed to be 0.3, consistent with SwRI analyses.

MONITORING

Measurements began as soon as the first pipeline was installed and the trench backfilled and continued until the final blast beneath the pipes 7 months later. After an instrumental shakedown period, complete monitoring of strains, vibrations, and pipeline pressures was done whenever overburden blasting occurred in front of the pipeline field (figure 1). Monitoring procedures were modified in response to a variety of problems, particularly water-caused failures of some strain gages and buried vibration sensors and two instances of lightning strikes in the test area. Toward the end of the study, recorders were moved from the instrumentation shack to a van for improved vibration isolation. Also, toward the end, Vibronics installed additional vibration equipment in the area, including two strong-motion three-component systems. By the time the blasting reached within 50 m of the closest pipeline, five seismic systems were in place on the surface and two on the pipelines.

MINE SITE AND PRODUCTION BLASTING

The Minnehaha Mine is a surface coal mine, which blasts overburden by casting and also blasts a thick parting, using hole diameters of 31 cm (12-1/4 in) and

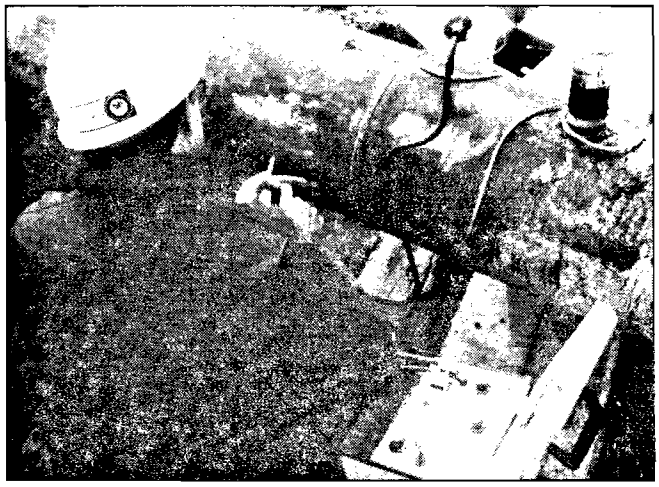
Figure 2

Pipeline test area.

Figure 3

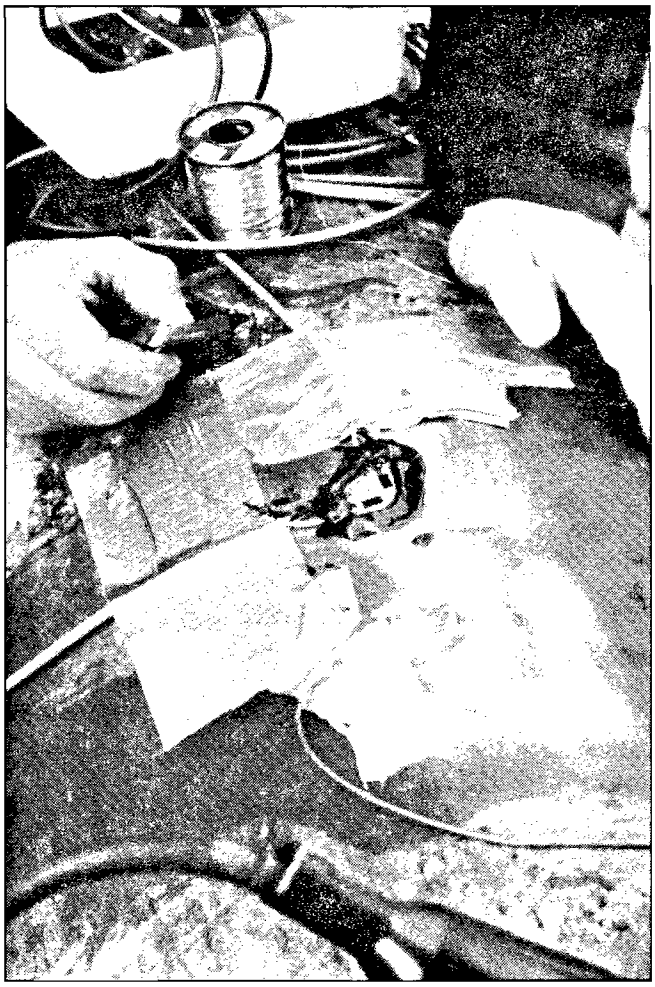
Placement of 16.8-cm pipeline in trench.

Figure 4



Installing weldable strain gages on large steel pipe.

Figure 5



Strain gage and vibration sensor.

27 cm (10-5/8 in), respectively. Charge weights per delay are as high as 950 kg. The highwall, including the pipeline field area, has about 2 m of clayey soil overlying about 12 m of shale. All nearby overburden blasts and a selected number of parting blasts were monitored over a 7-month period (figure 1 and table 2). The missed overburden blast (blast 28) was at the pit's far west end and not near the pipelines.

All blasts except the last (blast 31) were full-size overburden casting or parting rounds. No changes were made to account or adjust for the nearby pipeline field. The larger casting blasts were generally 5 rows of 10 holes each. As hole depths varied, charge weights per hole and per delay also varied; those listed in table 2 are the maximums. Hole depths were typically 20 m (66 ft) and 13 m (43 ft) for overburden and parting, respectively. Delays between rows and holes in a row were 126 and 25 ms, respectively. Smaller parting blasts also used relatively long between-row delays of 67 ms, likely intended to produce a modest cast.

Table 2.—Blasts monitored for pipeline response

Blast	Date	Time	Charge weight, kg		Distance,[1] m	Type of blast
			Total	Per delay		
1	3-18	11:07	9,162	435	338	Parting.
2	3-20	11:11	11,166	135	1,064	Overburden.
3	3-20	13:43	10,938	435	381	Parting.
4	3-20	13:53	9,841	435	436	Parting.
5	4-02	17:15	15,954	588	869	Parting.
6	4-02	17:40	30,547	751	180	Overburden.
7	4-02	18:41	10,202	218	933	Parting.
8	4-29	11:24	14,175	464	802	Parting.
9	4-29	19:20	13,561	539	347	Parting.
10 ...	6-02	11:20	22,482	626	756	Parting.
11 ...	6-02	17:21	24,398	639	146	Overburden.
12 ...	6-05	11:15	27,524	773	125	Overburden.
13 ...	6-05	11:24	7,399	301	920	Parting.
14 ...	6-05	14:07	8,073	181	951	Parting.
15 ...	6-05	17:14	29,162	689	131	Overburden.
16 ...	6-10	09:23	32,968	959	192	Overburden.
17 ...	8-03	14:13	10,408	465	387	Parting.
18 ...	8-05	11:14	14,804	828	506	Parting.
19 ...	8-06	14:55	17,245	600	552	Parting.
20 ...	8-06	17:09	30,373	731	88	Overburden.
21 ...	8-06	18:04	30,374	964	88	Overburden.
22 ...	8-07	18:18	31,741	884	116	Overburden.
23 ...	9-16	11:08	32,157	964	67	Overburden.
24 ...	9-18	14.33	ND	ND	ND	Parting.
25 ...	9-18	10:54	30,526	839	50	Overburden.
26 ...	9-19	14:25	27,072	872	74	Overburden.
27 ...	9-21	12:09	25,249	668	158	Overburden.
28 ...	10-21	Missed	ND	ND	ND	Overburden.
29 ...	10-23	11:18	34,457	839	15	Overburden.
30 ...	10-24	15:54	19,575	706	52	Overburden.
31 ...	10-24	16:25	2,880	743	1.5	Overburden.

ND Not determined.

[1]Distance is from closest blasthole to center of 16.8-cm (6-in) pipeline, which is closest to the highwall, measured on the ground surface.

STRAIN GAGES

All pipelines had longitudinal strain gages on the top and front, and the 16.8- and 50.8-cm pipes had circumferential gages as well. Two techniques for mounting strain gages on steel pipe were available, spot welding and adhesive bonding. Measurements Group type CEA-06-W250 C-350 weldable strain gages were initially chosen because of their ruggedness for the long monitoring period and the cold and wet field conditions. Weldable gages are precision foil strain gages bonded by the manufacturer to a metal carrier for spot welding to metal structures by the user. After surface preparation with a sanding disk, a sample metal carrier, supplied with each package of gages, was used to determine the proper energy setting and electrode force required to obtain a good spot weld. The two-element, 90° strain gage rosettes were aligned on the pipe and held in place with masking tape. The metal carrier was then tacked in place by a few spot welds on each side, and the tape was removed. The gage was then welded around the edges by two rows of spot welds.

Following welding, a layer of butyl rubber and a sheet of thick aluminum foil was added for mechanical protection. To keep out moisture, which causes most of the field installation failures in strain gages, a liquid sealant (M-coat FBT) was used around all the edges of the aluminum sheet and also around the lead wires, as recommended by the strain gage manufacturer. Two two-element strain gages were installed, one on top and one on the front face, at the approximate center of each 76-m length of test pipe, and were aligned with longitudinal and circumferential directions.

About a month before the end of testing, Measurements Group type CEA-06-250 UW 350 strain gages were epoxied to the 50.8-cm pipe. These were three-element 45° rectangular rosette configurations for principal strains. All strain gages used on the PVC pipe were also adhesive mounted. Figures 4 and 5 show instrumentation installation activities.

VIBRATION MEASUREMENT

Vibration transducers were attached to the top and front of the 50.8- and 16.8-cm pipelines. These were accelerometer-integrating amplifier systems with flat responses down to 1.0 Hz. The accelerometers on the larger pipe eventually failed from water intrusion in the saturated clay soil. They were replaced by an immersible Alpha-Seis velocity transducer with flat responses down to 2 Hz, starting with blast 22.

Vibrations were also measured on the ground surface above the pipelines with sensors in shallow-buried impedance-matching boxes. Both a Vibronics Alpha-Seis unit and a USBM three-component velocity gage were used throughout the study. Additionally, Vibronics installed two strong-motion systems (Dallas Instruments SR-4's) in the pipeline area starting with blast 20.

For all blasts, the radial direction was fixed as the horizontal perpendicular to the pipeline axes, with the transverse then being parallel to the axes. It was not possible to re-orient the monitoring systems for true "radial" and "transverse" with respect to the blasts nor was it desirable for assessing pipe responses.

SURVEYING FOR SETTLEMENT

Periodic surveying was done by AMAX using a laser transit to detect settlement, both natural settlement and any that could be attributed to the blasting. Of particular concern was strain-producing differential settlement of the type found by Linehan and others from pile driving near pipelines (*14*). Each pipe had three uprights extending above the ground surface, one near each end and one in the middle. Using these as indicators, eight surveys were done during the 7-month monitoring period with an emphasis on the last 5 weeks, during the heaviest blasting. Data are tabulated in appendix C.

PRESSURIZATION

Following installation, all five pipes were pressurized as shown in table 1. Pressures gradually increased in the steel pipelines, by 5 to 35 pct, as the ground warmed up from early spring to late summer. In the PVC pipe, by contrast, pressure dropped to less than half of initial (down to 0.276 MPa), consistent with information that O-ring-jointed water pipes such as this leak continuously. There was no way to visually verify leakage for the buried PVC pipe, and no joints were instrumented. Pressures were monitored and recorded every 15 min by an automated system installed by Vibronics.

VERTICAL WELL AND TELEPHONE CABLE

AMAX had arranged for the installation of a vertical well off the east end of the 16.8-cm pipeline and both coaxial and fiber-optic telephone cables in front of the pipeline field. The 37-m-deep cased well was cemented to the coal and shale formations and monitored continuously by Vibronics for pressure during the study period. On four occasions, cement bond logs were run to evaluate the bond quality between the cement and both the well casing and the formation. The four logs were done on March 19, June 11, September 24, and October 27, when maximum particle velocities had been obtained of 13, 121, 242, and greater than 600 mm/s, respectively.

Indiana Bell technicians spliced together the six individual 84-m fiber-optic strands to make a single 466-m-long telephone cable. The total cable was then long enough for light-loss measurements and also contained six additional weakness points. Tests were made by Indiana Bell before and after blast 29 using an optical time domain reflectometer and an optical attenuation meter.

MONITORING RESULTS

Up to 34 data channels, provided by both USBM and Vibronics, were used for each blast. Table 3 lists the highest measured ground vibrations, pipeline vibration responses, and strains for each blast. A complete list of all peak values is contained in the appendix B.

VIBRATIONS

Vibration amplitudes of the buried pipelines were less than corresponding motion components measured on the ground directly above. There was a consistent and significant reduction of about 40 pct at a depth of only about 1 m, which was surprising. However, it is entirely in agreement with other studies (*14*) including USBM RI 8969 (*15*), which compared vibration monitoring on the ground surface and basement walls and floors. Figures 6 and 7 compare peak values for ground vibrations and 50.8-cm pipeline vibration responses for the radial and vertical components of motion.

Table 3.—Highest vibrations and strains measured on any pipe

Blast	Vibration amplitude, mm/s		Strain, μmm/mm		
	Ground	Pipeline	Circumferential, steel	Longitudinal, steel	Longitudinal, PVC
1	13.2	9.4	5.3	4.3	6.9
2	3.8	1.8	2.8	1.18	2.5
3	10.7	5.3	2.2	2.9	4.9
4	9.1	6.4	8.0	1.6	7.0
5	9.1	3.8	3.6	1.1	2.0
6	67.1	30.5	28.0	12.5	30.3
7	5.1	1.8	2.5	0.7	1.0
8	7.9	NA	10.0	2.9	4.8
9	6.9	NA	6.3	1.8	3.6
10	5.3	NA	NA	NA	NA
11	93.5	NA	66.4	26.0	35.0
12	121	NA	51.3	31.0	47.3
13	3.3	2.3	1.8	1.4	2.0
14	3.8	1.5	NA	1.1	2.5
15	88.4	48.0	48.3	32.4	38.5
16	67.1	35.8	20.9	15.6	25.5
17	17.3	NA	13.6	6.0	10.1
18	17.0	5.8	2.7	3.5	9.6
19	16.5	6.9	10.7	4.8	15.9
20	136.1	86.9	63.0	31.1	97.5
21	166.6	102.1	33.5	51.7	102.5
22	126.0	57.9	55.8	30.8	76.2
23	205.7	148.3	43.2	50.8	92.9
24	NA	NA	NA	NA	NA
25	241.8	211.3	53.5	60.8	137
26	148.3	95.5	44.0	44.0	63.0
27	81.3	41.1	25.4	24.3	37.6
28	NA	NA	NA	NA	NA
29	647.7	274.3	94.8	156	499
30	530.9	146.3	55.8	77.5	NA
31	NA	NA	490	3,170	NA

NA Not available.

The "Background" section raised the question of how faithfully the pipelines move with the ground. Figures 8 to 10 provide an answer. They show time history record comparisons for the 50.8-cm pipeline for three blasts of increasing size. The smallest blast (figure 8) produced nearly identical waveforms for the pipe and the ground above blast. With amplitudes about five times higher, blast 27 (figure 9) had ground vibrations and pipe responses that were similar but not nearly so alike as those in figure 8. The third and largest blast of the three (blast 25, figure 10) shows considerable differences, particularly for the radial components. This blast also produced a much higher pipe response frequency. Apparently, the degree to which the pipeline response matched the ground vibration was vibration level dependent. Maximum accelerations for the three examples were 13, 53, and 340 pct of 1 gravity, respectively, suggesting a possible influence on response of pipe weight in addition to confinement.

Comparisons between responses of the two pipelines instrumented with vibration sensors are shown in figure 11. These pipes, representing both the largest and smallest steel pipelines tested, showed similar response amplitudes, although with some differences in the vertical waveforms.

Vibration frequencies were low for the relatively small blast-to-pipeline distances. This was likely a site phenomenon with a clay-soil layer over the shale. When blasts were in front of the pipeline (e.g., 15, 21, 25), the radial components had much 7- to 9-Hz energy. For these very close-in blasts, high-frequency vibrations were also present, which would normally be highly and selectively attenuated at any appreciable propagation distance in the clay-soil layer.

Propagation plots for maximum measured vibration amplitudes are shown in figure 12 for 0.4, square root, and cube root scaled charge weights. Maximums were used rather than individual components because radial and transverse components were aligned with the pipelines rather than adjusted for the direction to each blast. Over the range of distances and charge sizes represented in the plots, any of these plots can be reliably used to predict vibration amplitudes, with the scaling factor having no significant influence for this specific test site.

The cube root scaled propagation plot can be compared with the similarly scaled summary in Esparza's SwRI paper (7). The SwRI measurements go up to only 8 $m/kg^{0.33}$ (20 $ft/lb^{0.33}$), with the prediction line extrapolated to higher values. The attenuation exponent for USBM data is −1.33, compared with the SwRI value of −2.37. This is likely related to the relatively low attenuation of seismic energy in rock (USBM) compared with soil (SwRI) and possibly to seismic wave energy in contrast to plastic yielding. For conversion of the metric scaled distances shown (m/kg^x) to traditional engineering units of ft/lb^x use the following:

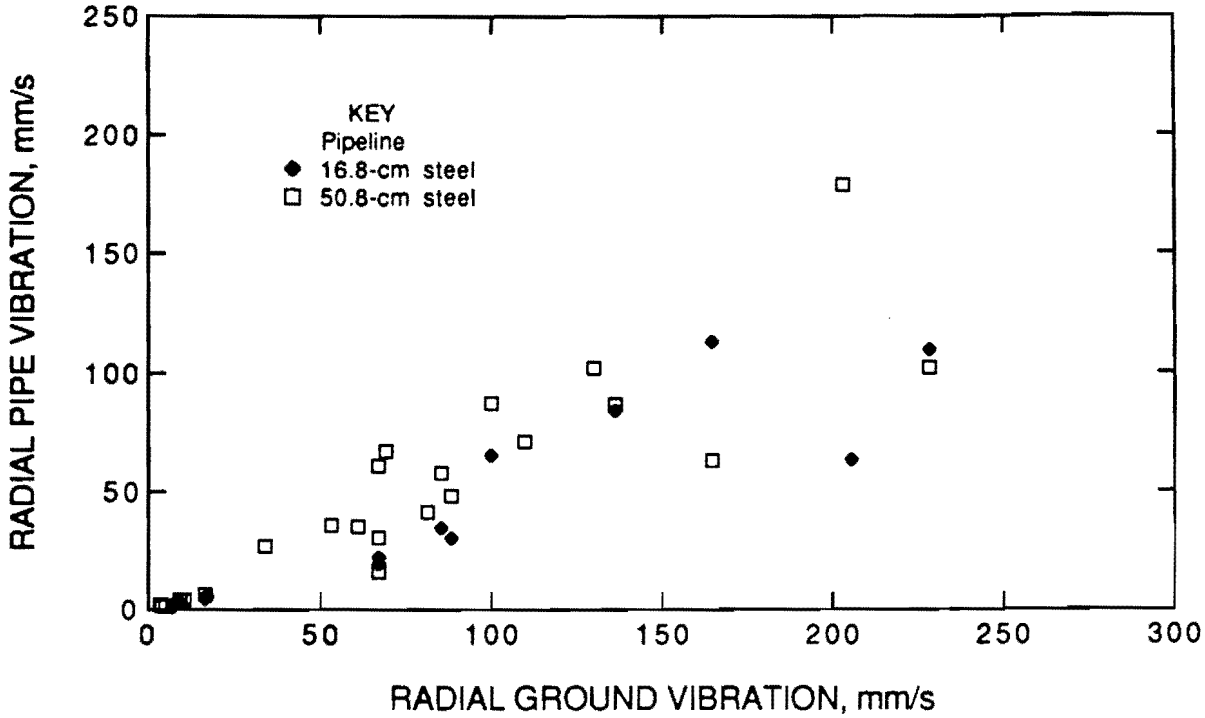
Scaling factor (x)	*Multiply by*
0.33	2.52
0.40	2.39
0.50	2.21

STRAINS

Sets of strain recordings from three of the larger blasts are shown in figures 13 to 15. For lower amplitude blasts, less than about 80 mm/s, the traces are symmetric about the zero line. Because tensions and compressions were about equal, bendings were approximately symmetrical and behavior was strictly elastic. Above this amplitude, some strain records show jumps that were either instrumental or represent real "adjustments" in pipeline positions, e.g., permanent vibration-induced displacements and settlements.

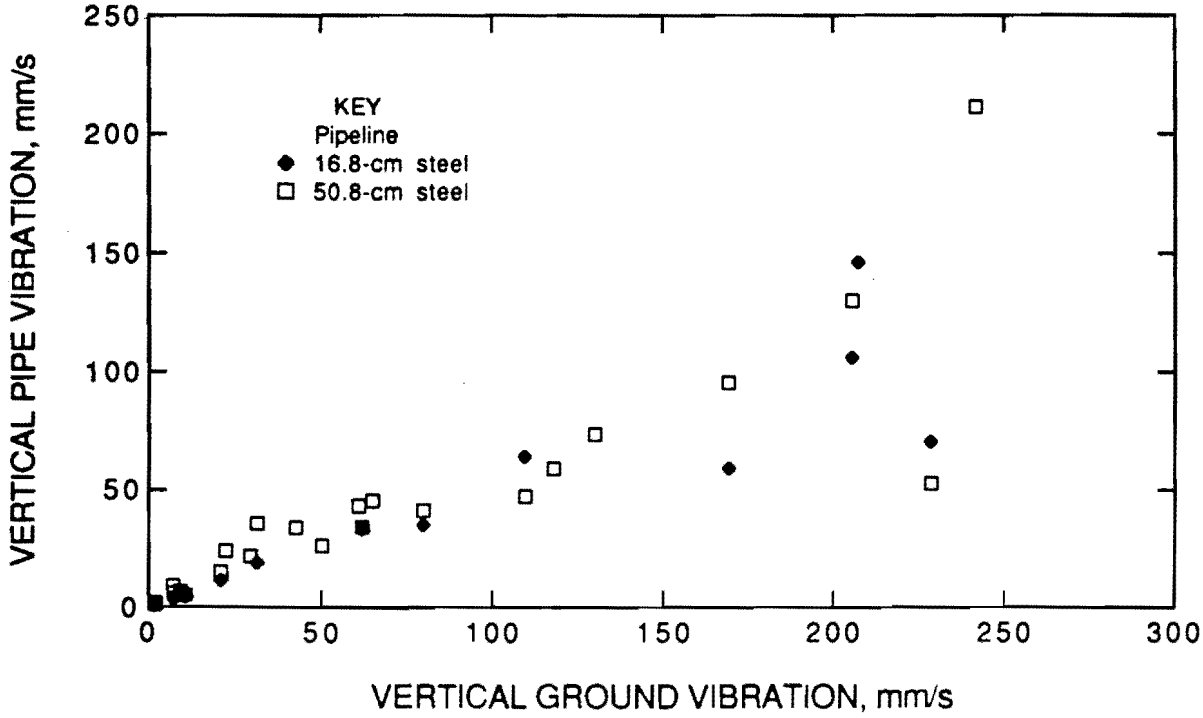
Strain propagation plots of strain amplitudes versus scaled distances are given in figures 16 and 17. These are strains from blasting alone and do not include the effects of pressurization. There is considerably more scatter than in the vibration propagation plots, probably because of response variations discussed previously, less than ideal coupling, and amplitude-dependent responses. At large distances (and relatively small vibration amplitudes), circumferential strains dominate. Closer in, there appears to be a limit on the amount of circumferential strain produced, and longitudinal strain becomes dominant. This limiting in circumferential strain could be related to imperfect coupling and relatively strong resistance to ovaling (out-of-round) deformation. Unfortunately, some strain gage failures late in the study hampered a more complete comparison (appendix B). For the 0.4-scaled plot, the USBM data can be compared with the SwRI prediction without "correction factors," which is similarly scaled. The SwRI stress and strain predictions depend weakly on pipe wall thicknesses. The lines representing their predictions and shown in figures 16, 17, and others were computed for their 61-cm pipe with a wall of 7.92 mm. A recomputed line corresponding to the USBM's 51-cm pipe (wall of 6.63 mm) would be only about 9 pct higher, an amount that would make it indistinguishable from the one shown on the figures. Within the range of the actual SwRI values (low scaled distances), USBM-measured strains are lower. At larger distances, corresponding to a large extrapolation of the SwRI prediction, USBM values exceed the SwRI prediction. A plot through the USBM data (excepting blast 31, the final ground-motion-producing blast at a scaled distance of 0.98 $m/kg^{0.4}$) would have a shallower slope than the SwRI equation. Most of this difference is

Figure 6



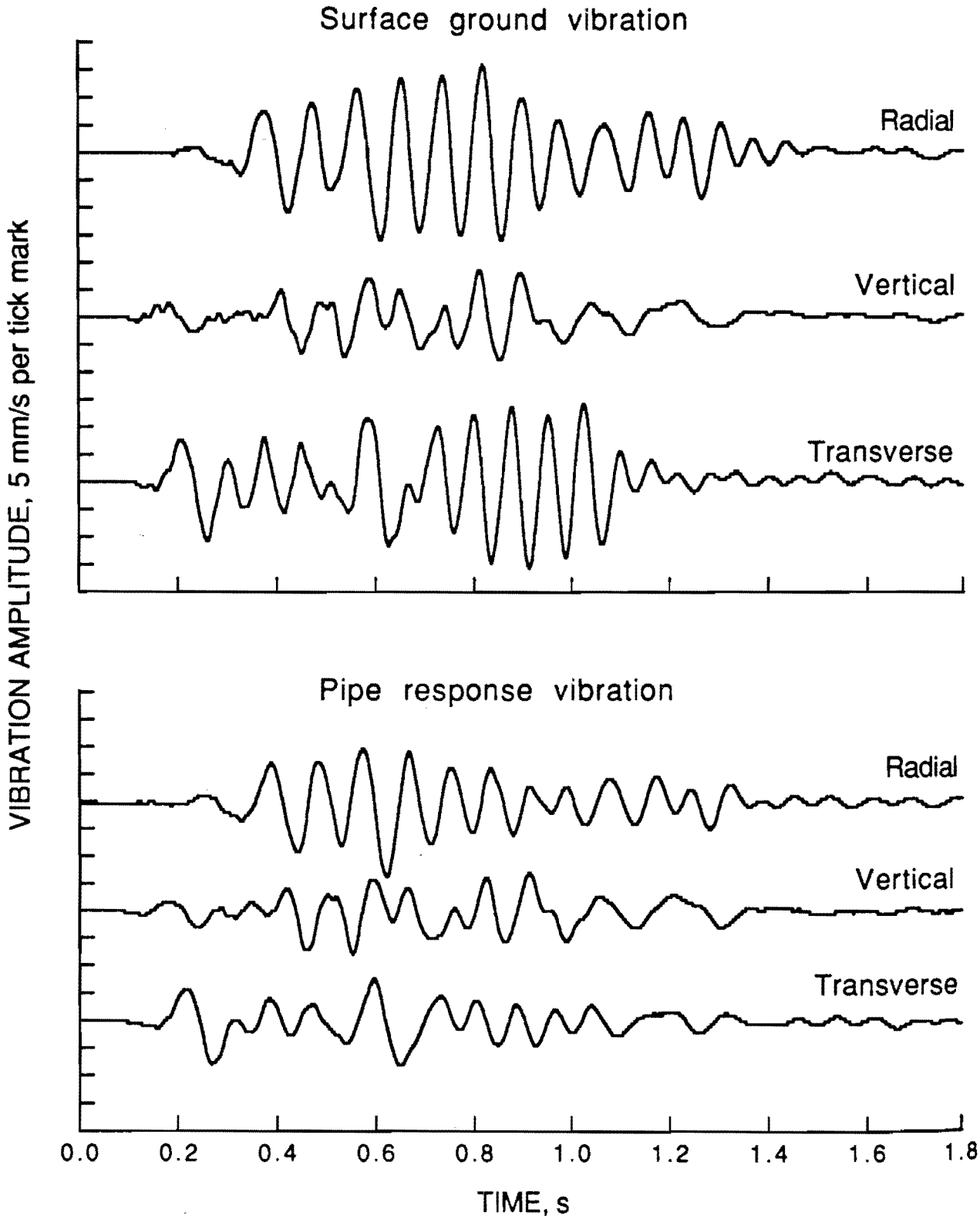
Radial ground vibration versus pipeline vibration response.

Figure 7



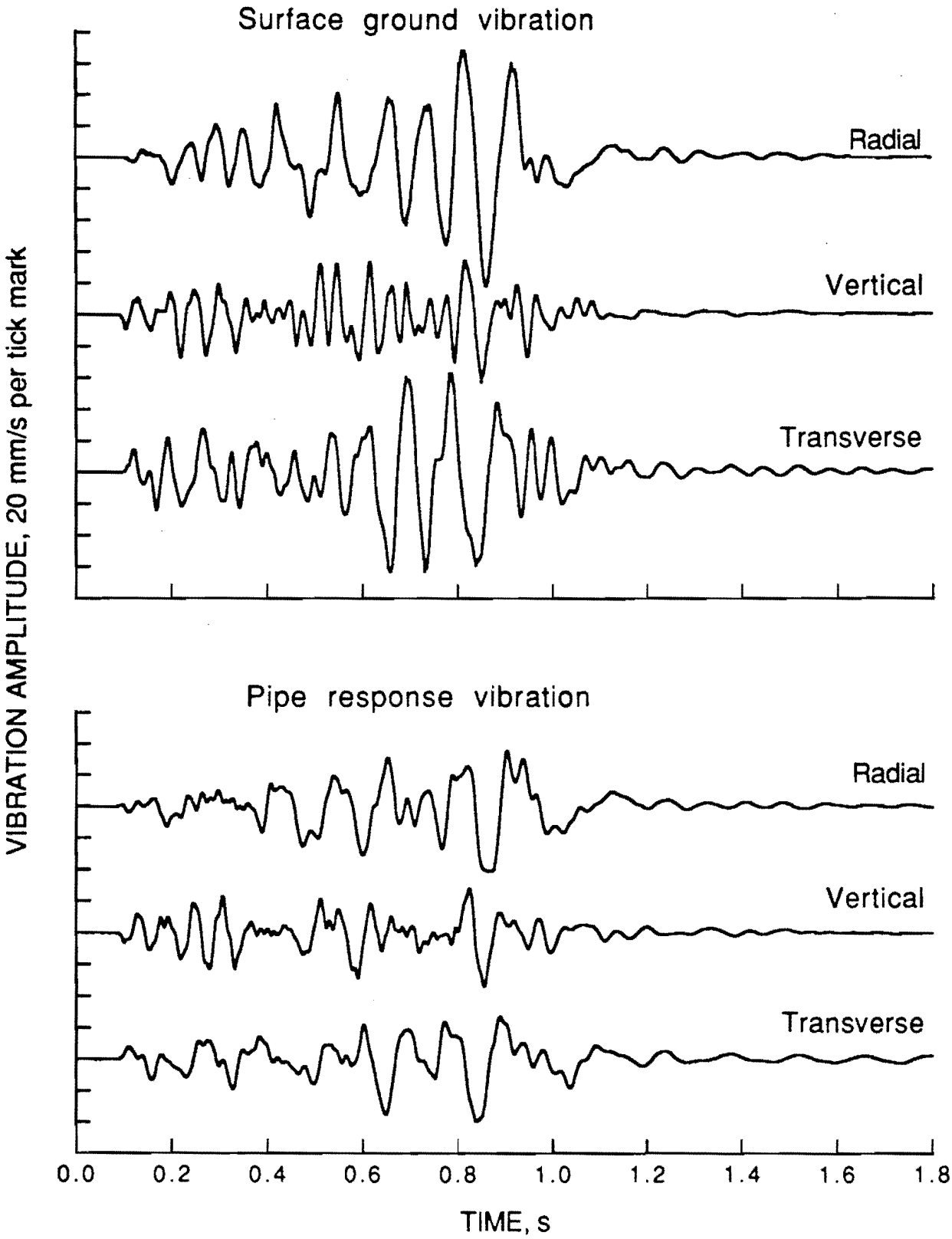
Vertical ground vibration and pipeline vibration response.

Figure 8



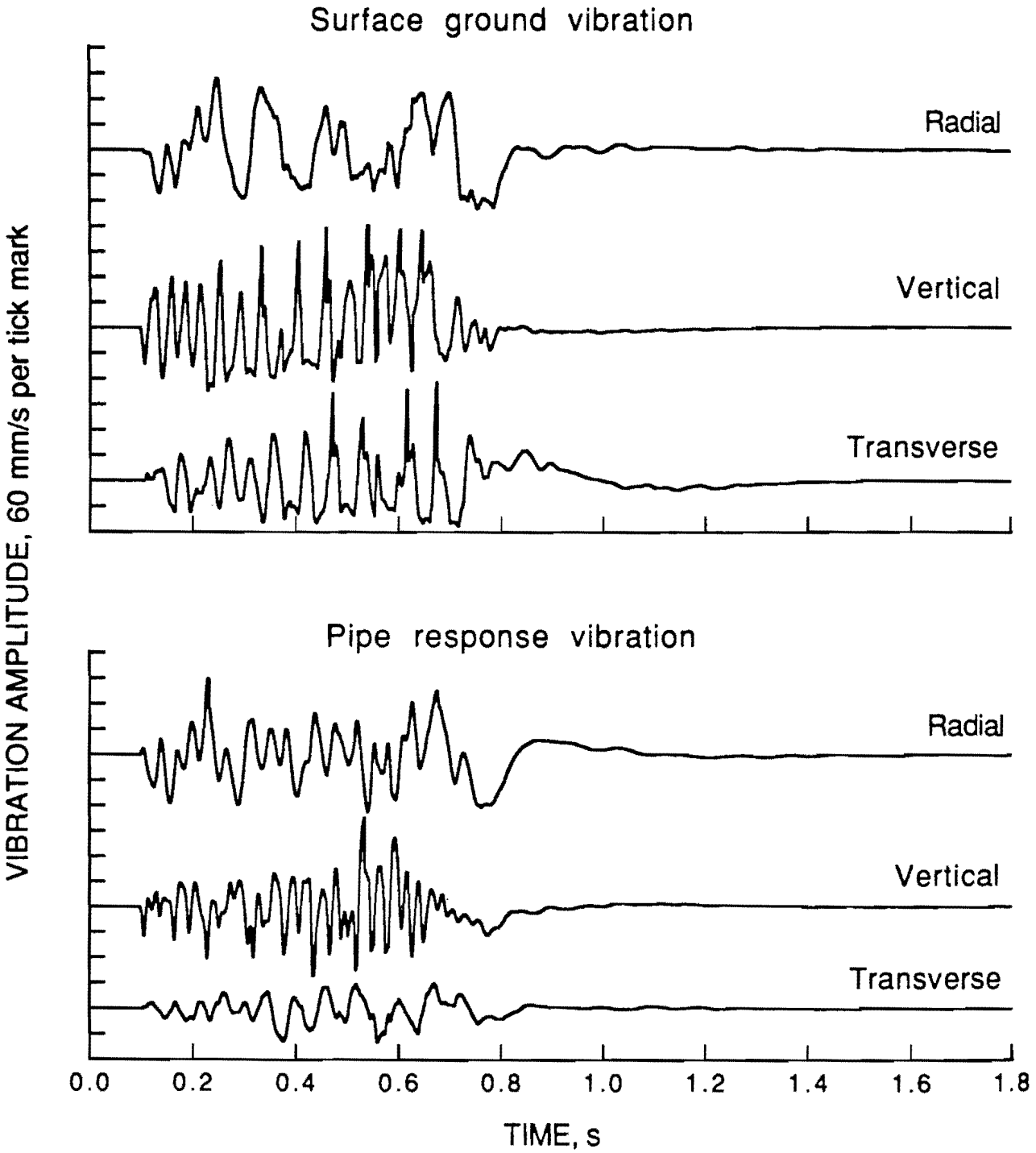
Vibration and response records for blast of September 28, 1992. This blast was part of a followup analysis.

Figure 9



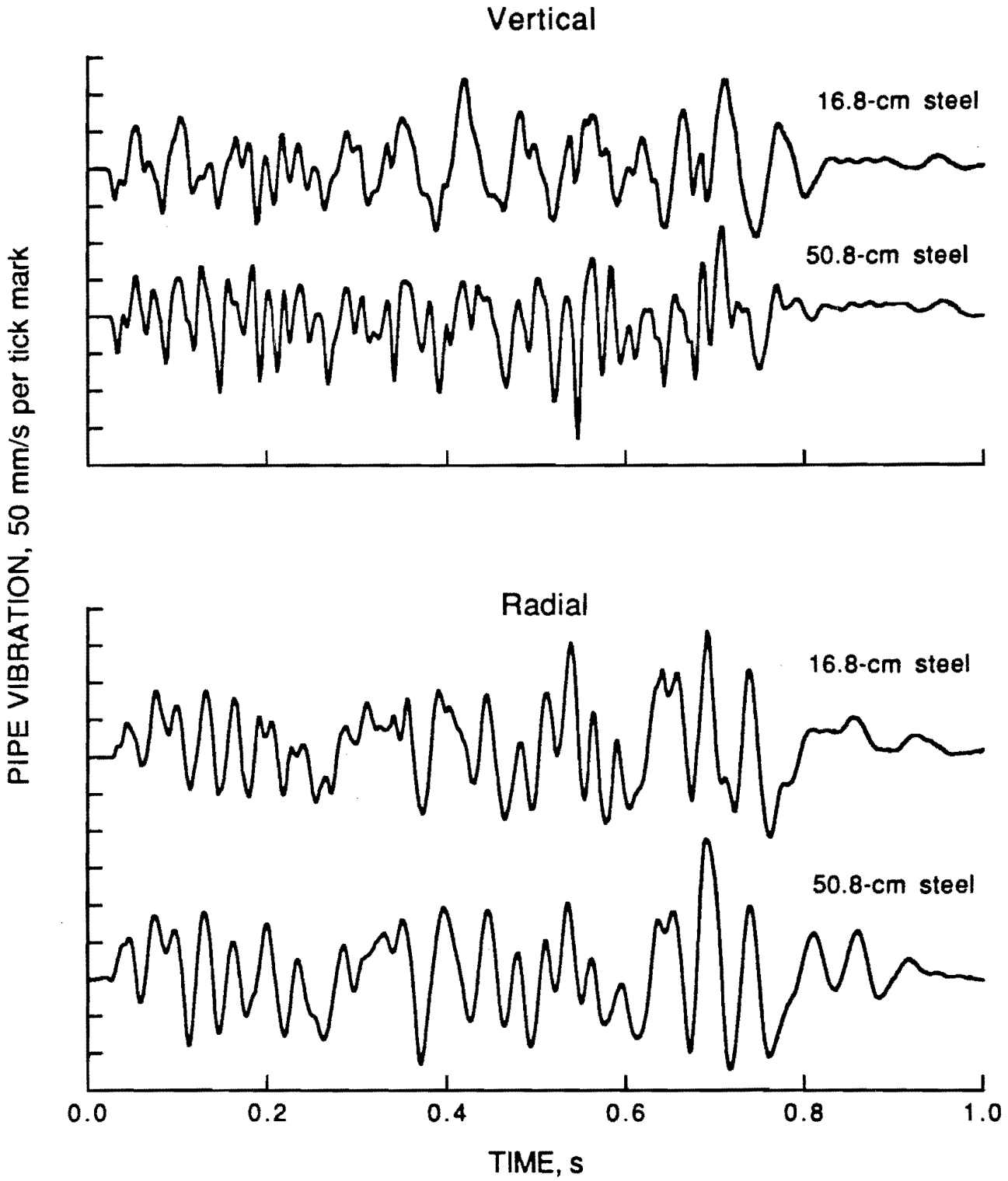
Vibration and response records for blast 27.

Figure 10



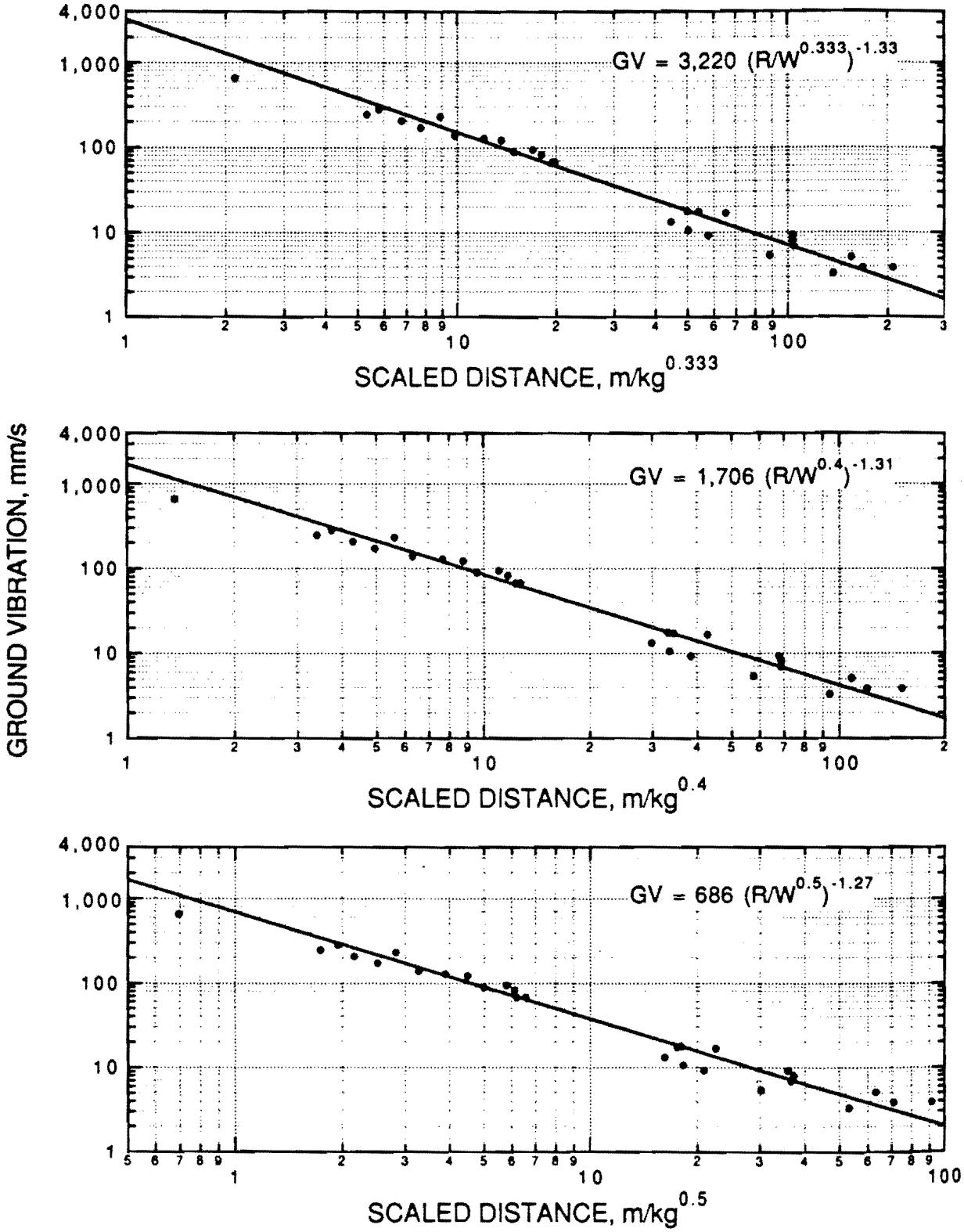
Vibration and response records for blast 25.

Figure 11



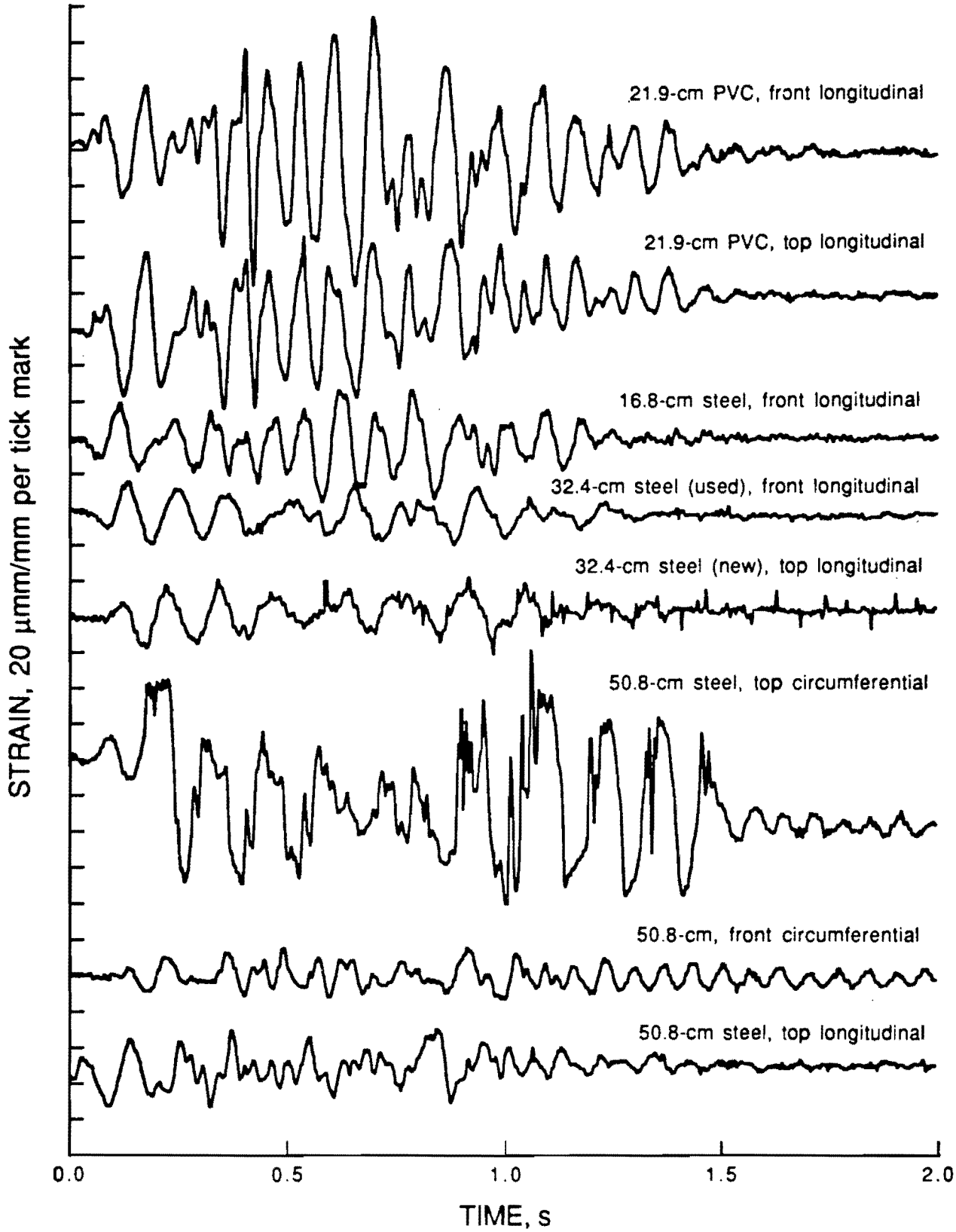
Comparisons of two pipelines' responses for blast 23.

Figure 12



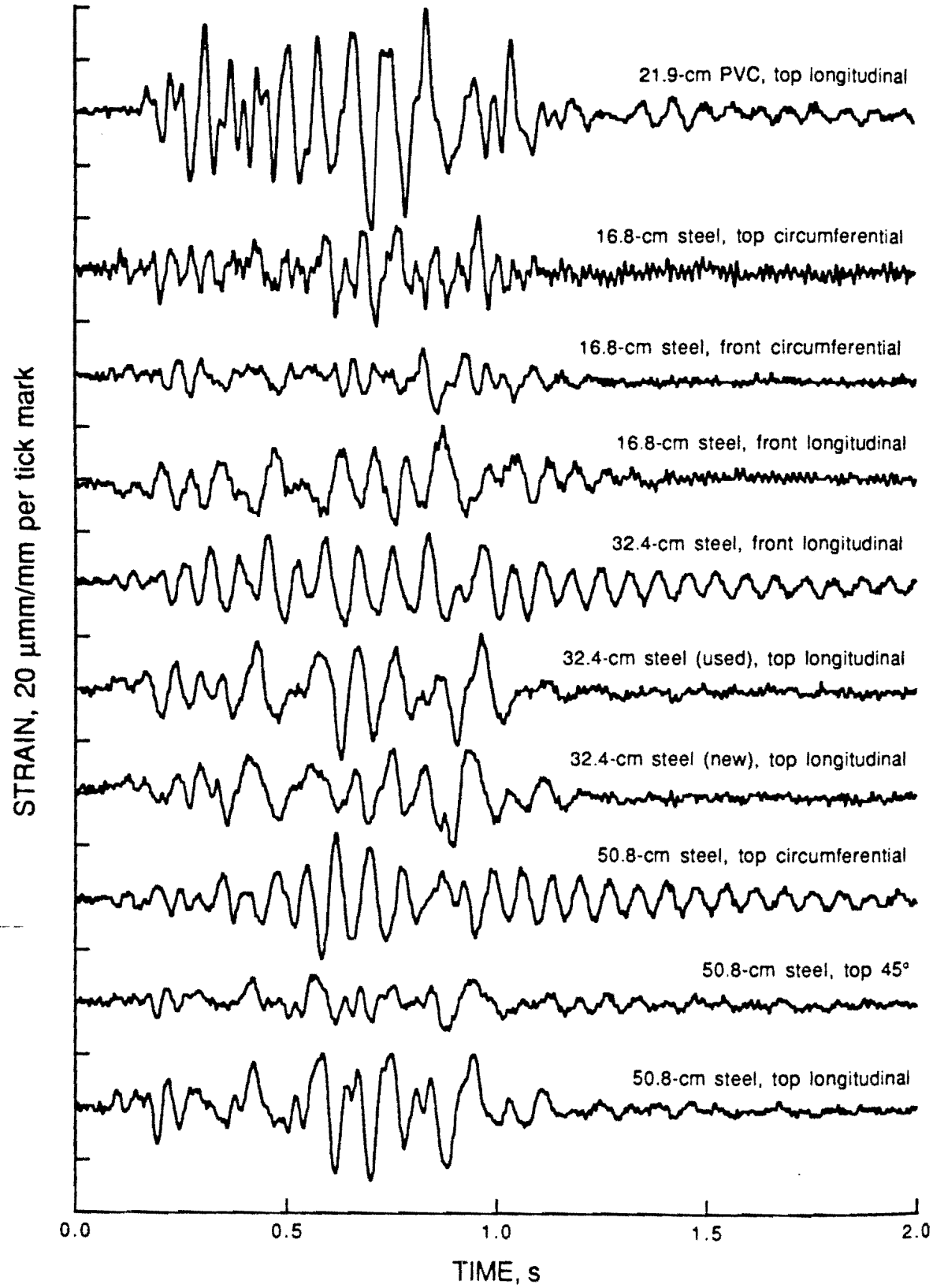
Propagation plots of maximum vibration amplitudes using cube root, 0.4 root and square root charge weight scaling. GV is ground vibration (mm/s), R is distance (m), and W is charge weight per delay (kg).

Figure 13



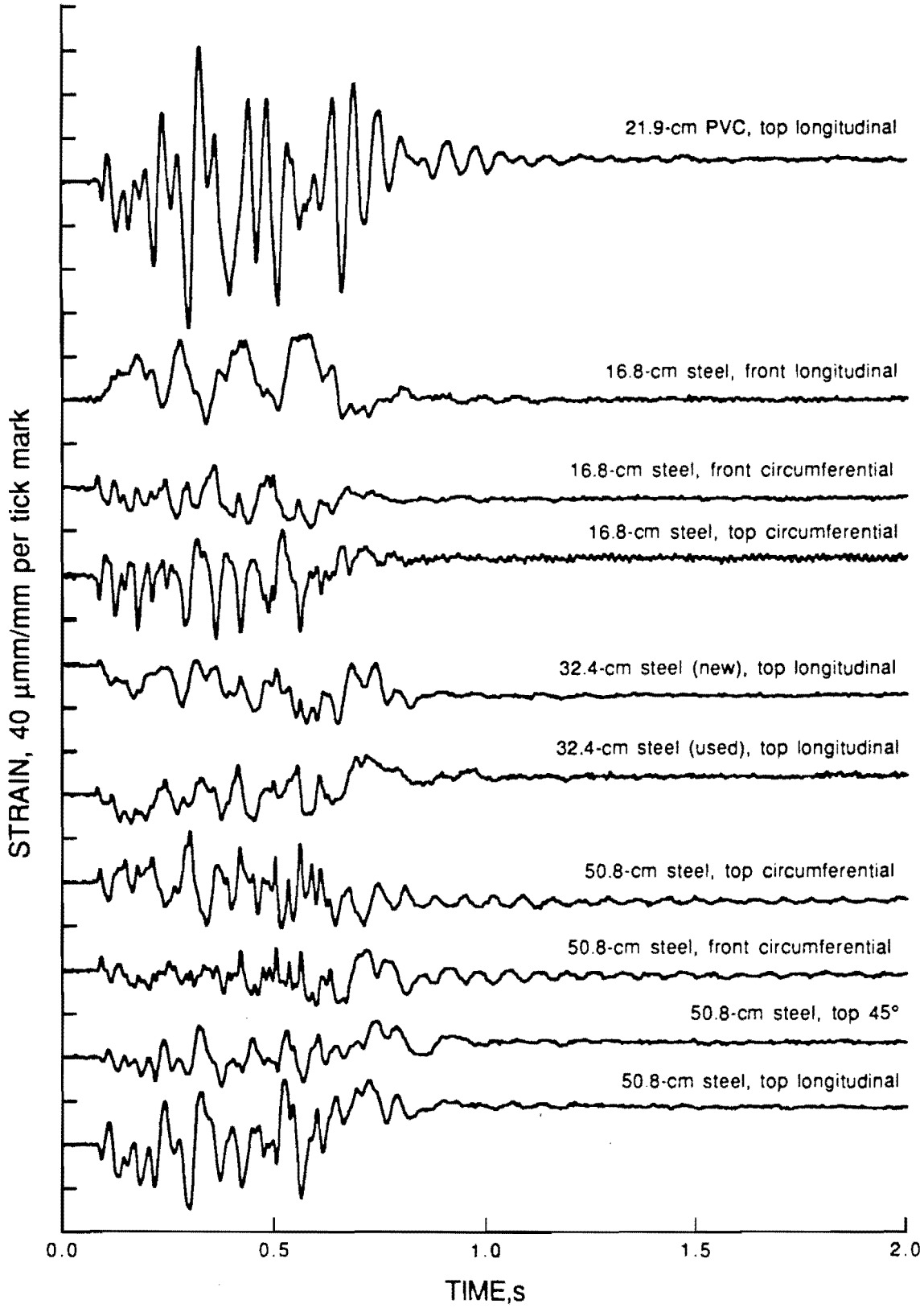
Pipeline strains for blast 22.

Figure 14



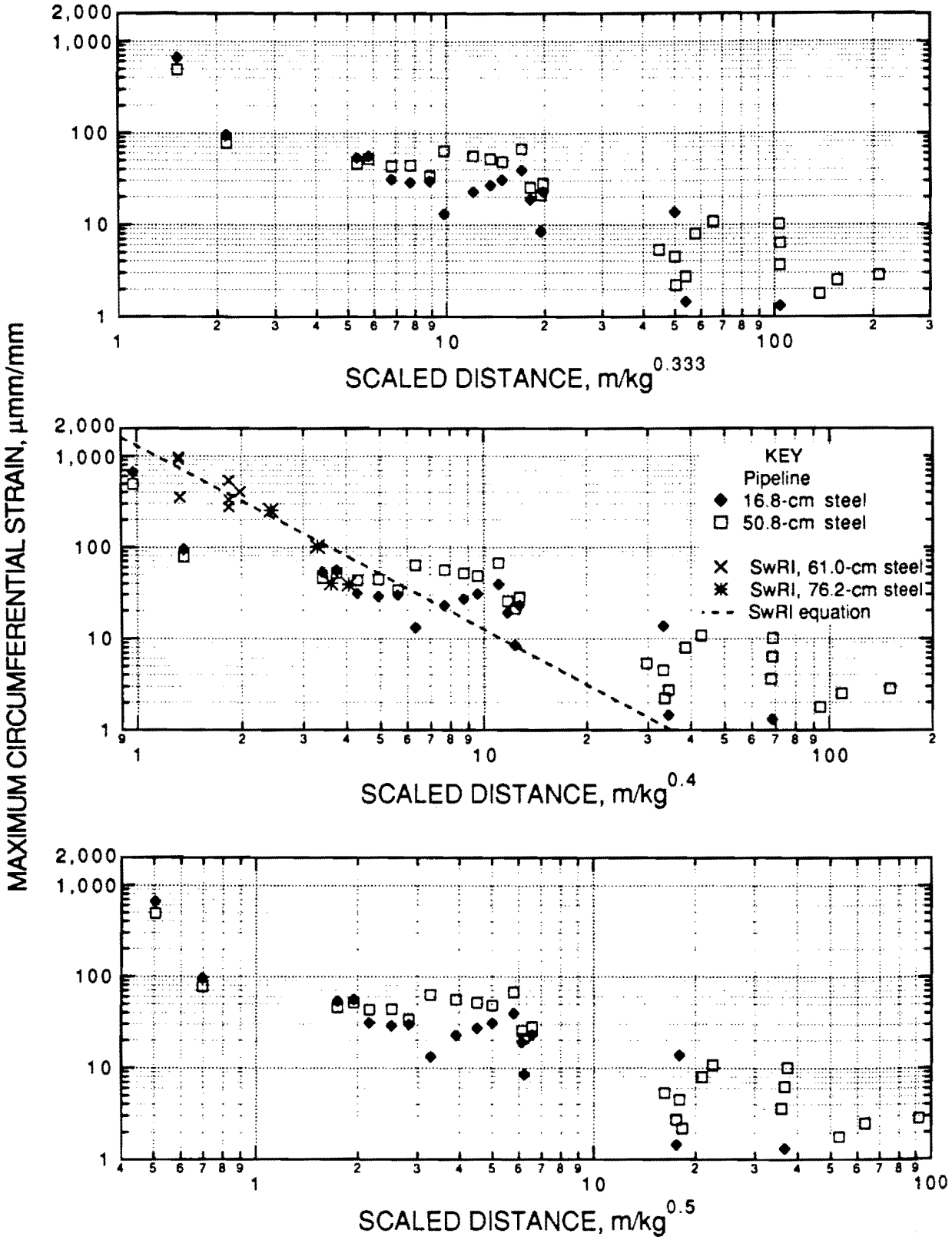
Pipeline strains for blast 27.

Figure 15



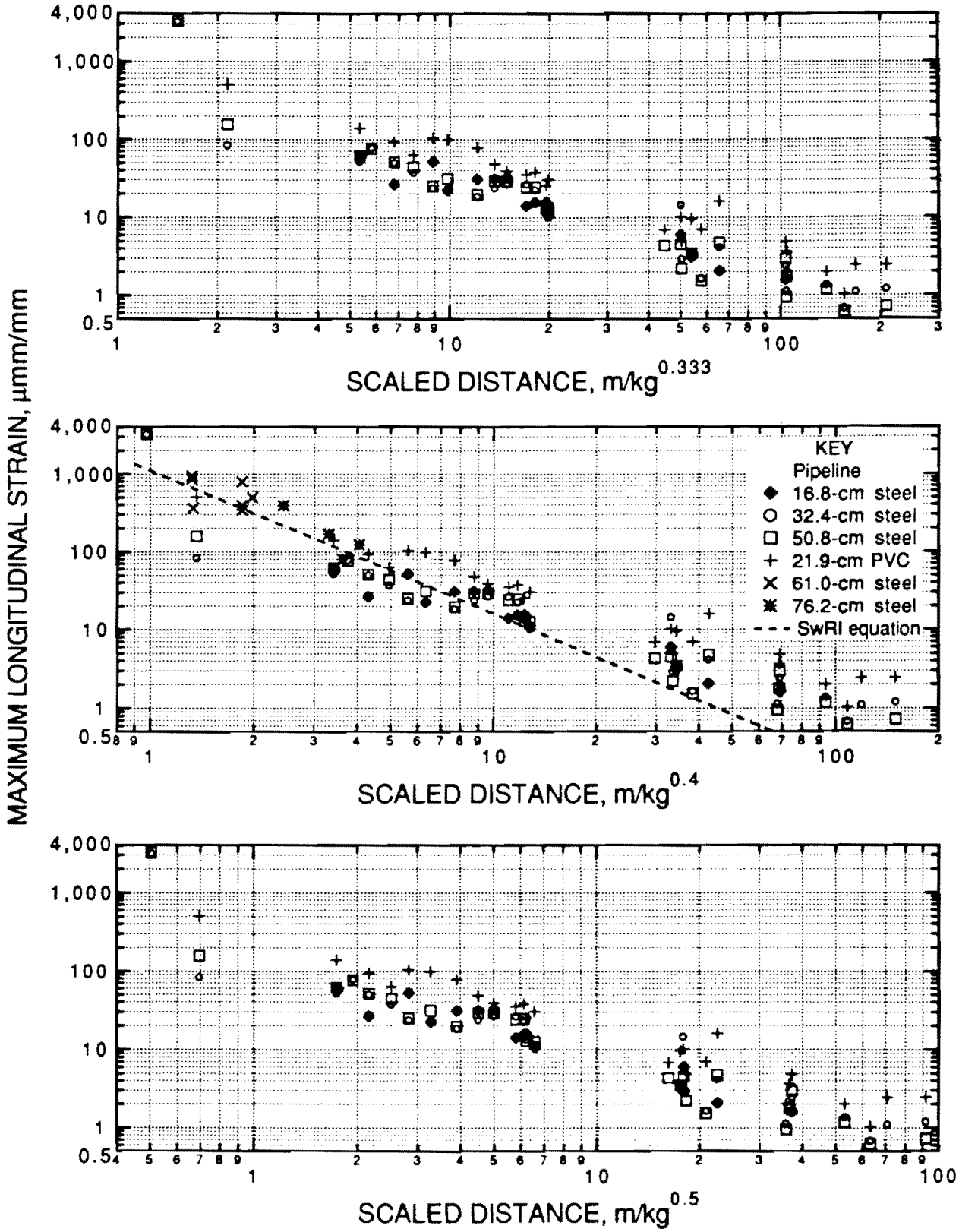
Pipeline strains for blast 25.

Figure 16



Propagation plots of circumferential strains.

Figure 17



Propagation plots of longitudinal strains.

likely because of the medium involved, rock instead of soil, and the extrapolation of the SwRI data to compare with mining-sized blast situations. The same conclusion was found for the vibration data. The USBM's final blast, blast 31, did match the SwRI prediction; however, this blast, which lifted both the ground pipes, was definitely not an elastic wave case, e.g., not a vibrations situation.

Measured peak strains versus ground vibrations are shown in figures 18 to 23 and strains versus pipeline vibration responses in figures 24 to 27, all strains being maximums. Comparisons shown in these plots are based on deformations expected to correlate with particular components of motion. For example, radial vibration compression waves (horizontal component perpendicular to the pipeline axes) are expected to flex the pipeline horizontally, causing maximum response on a longitudinal strain gage on the pipe's front (or back) side and to have little or no effect on a longitudinal strain gage on the top (or bottom). By contrast, a vertical vibration would produce exactly the opposite response.

There is also ambiguity about particle motion directions for close-in blasts. The depth of the explosive for blasts within about 60 m causes the true radial direction to have a significant upward angle. This situation makes the vertical component more important in this study than in actual production blasting where distances would not generally be so close. Relatively high longitudinal strains were measured on the PVC pipeline compared with strains on the four steel pipes, consistent with the lower PVC stiffness. If the pipelines were all fully coupled and moving with the ground, this difference should not exist. Generally, similar measurements on the steel pipelines gave similar amplitudes (e.g., the front longitudinal strain of one pipe agreed roughly with other front longitudinal measurements). Circumferential strains were often, although not always, the highest, particularly when measured on top rather than on the side.

Measured strains were relatively low for the given particle velocities. The large blasts involved in this study produced high particle velocities at relatively large distances. Hence, the pipelines experienced high vibration amplitudes at distances far enough to be clearly beyond the inelastic damage zone. By contrast, the SwRI studies measured high amplitudes only in the likely inelastic near zone. In addition, charges were in blastholes, vertical columns longer than the closest blast-to-pipeline separations. Again, this setup contrasts with that of the previous SwRI studies involving close-in "point" sources. Direct comparisons are difficult because of the vast differences in charge sizes and distances between the SwRI tests and the USBM tests, and for other reasons such as the ambiguity in some of the constants, as discussed in appendix A. Another complication in making comparisons is the possibility that the spatially extended mine charge with its relatively long detonation time impacts the pipeline less than a point-source-type blast. One comparison, using Lambeth's version of the SwRI prediction equations, is given in appendix A, table A-3.

For blasts 25 to 31, a three-gage strain rosette was used on top of the 50.8-cm (20-in) pipeline. Principal strains were calculated for these blasts, and in no cases did the peaks of the individual components occur in phase. Figure 28 shows an example of the principal strain analysis, with compression positive. In all cases measured, the components added in such a way that the principal strain peak was never much more than the maximum of those computed from single axes.

STRESSES

Stresses can be calculated from strains using the biaxial stress-strain equation given in the appendix A description of the SwRI analyses (*5*):

$$\sigma_c = \frac{E}{1 - \nu^2}(\epsilon_c + \nu\epsilon_l),$$

$$\sigma_l = \frac{E}{1 - \nu^2}(\epsilon_l + \nu\epsilon_c).$$

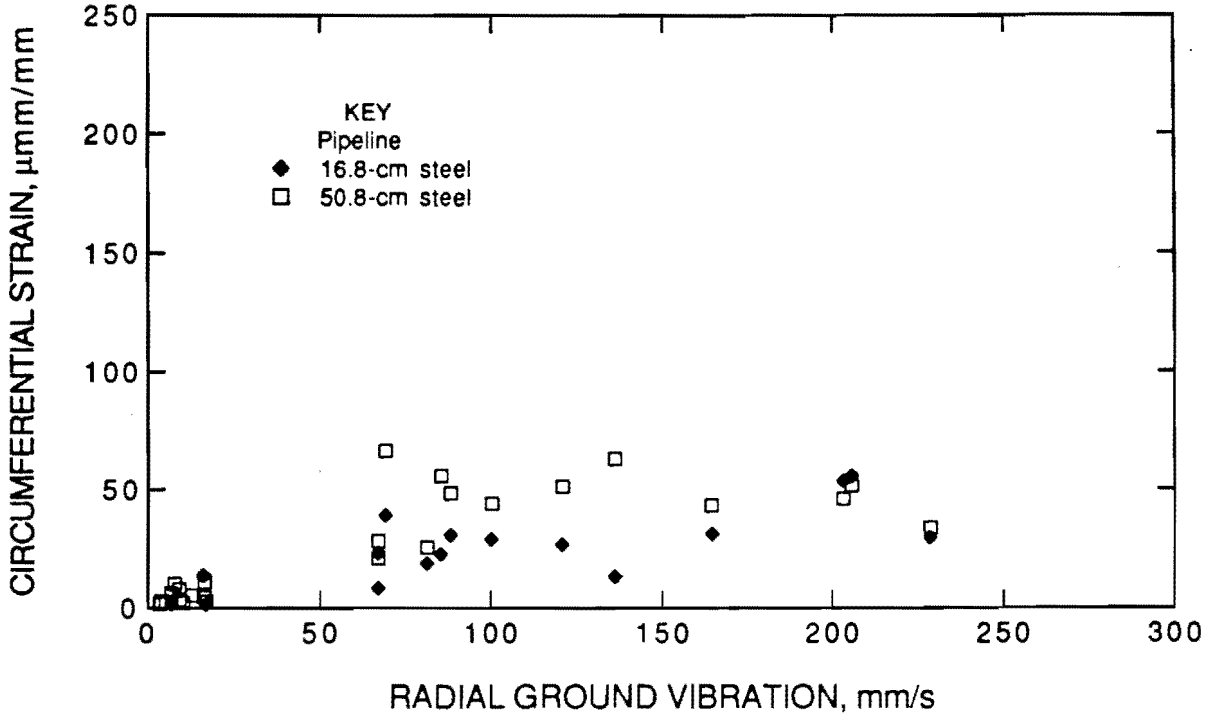
Use of these equations with the maximums rather than time-related values represents a worst case, assuming that circumferential and longitudinal peak strains occur at the same time and are of the same sense (both tensional or compressional). This computation of maximum possible stress is analogous to a pseudo vector sum compared with a true vector sum for three-component vibration analyses. Time-correlated strains should be employed to calculate true stresses. In addition, if ϵ_c and ϵ_l are of significantly different amplitudes, one will dominate the stress calculations. These equations generally overestimate stresses by up to 30 pct.

The principal strain analysis discussed previously showed that peaks did not coincide in time for the blasts analyzed and that simplified biaxial equations could be used:

$$\sigma_c = \frac{E}{1 - \nu^2}\epsilon_c,$$

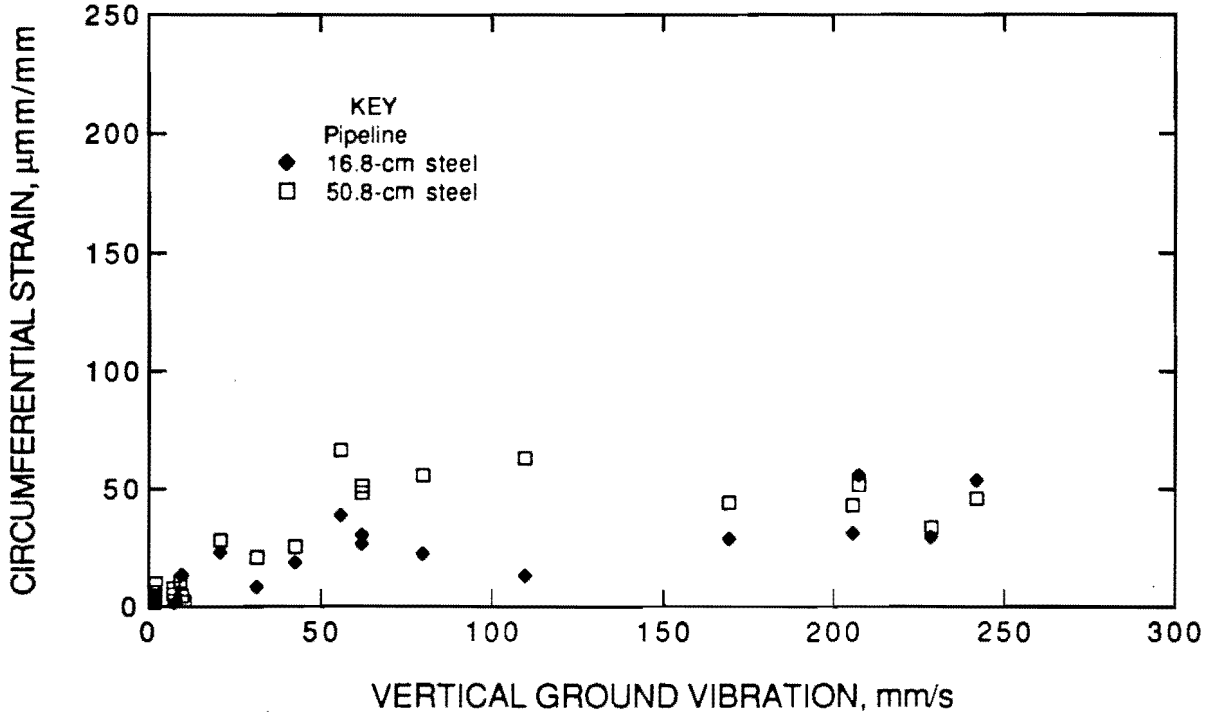
$$\sigma_l = \frac{E}{1 - \nu^2}\epsilon_l.$$

Figure 18



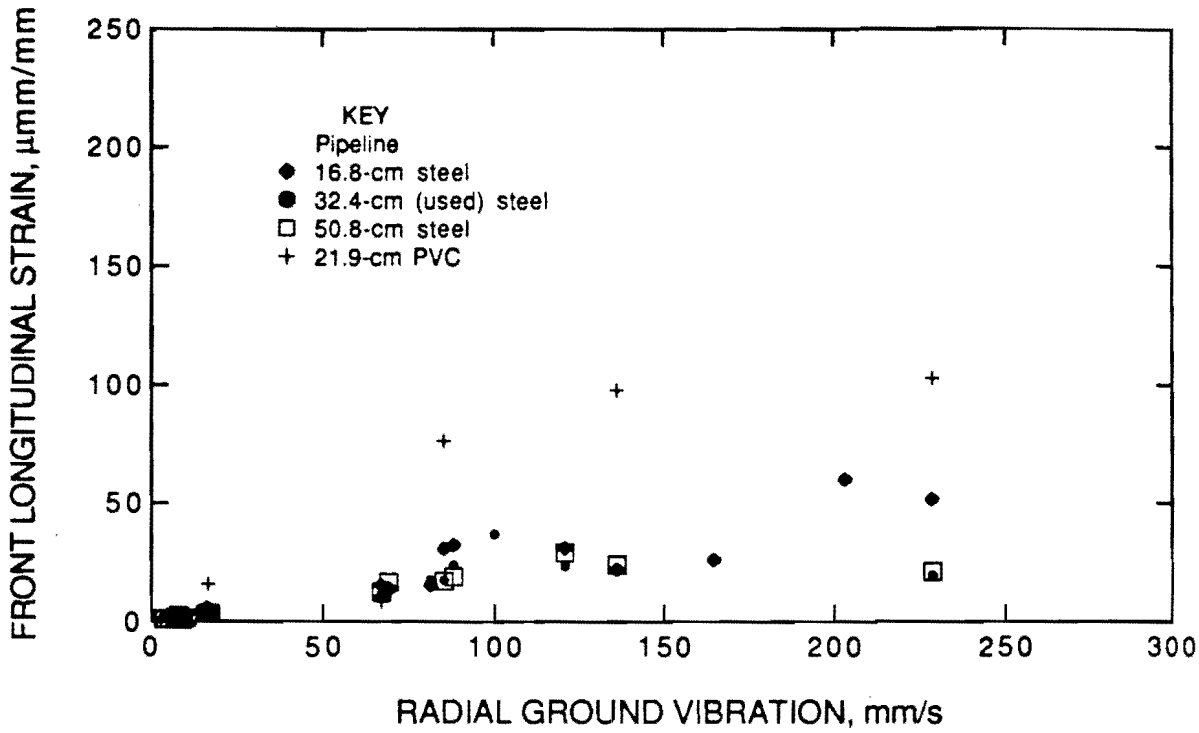
Circumferential strain versus radial ground vibration.

Figure 19



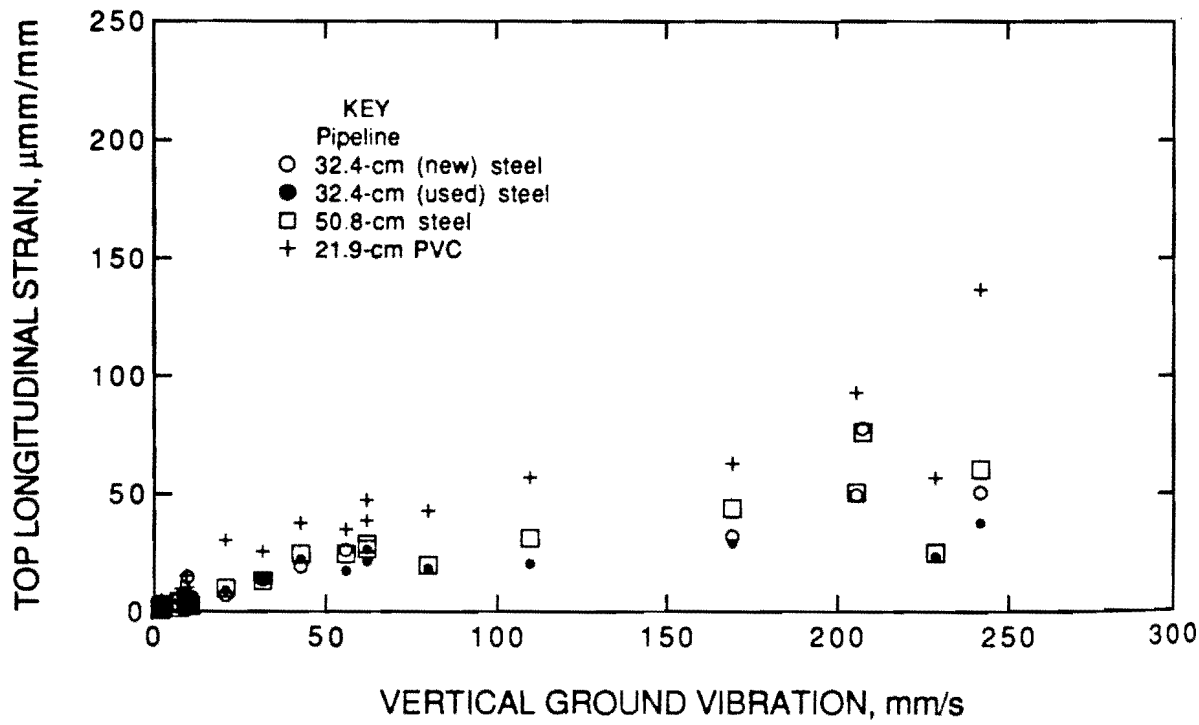
Circumferential strain versus vertical ground vibration.

Figure 20



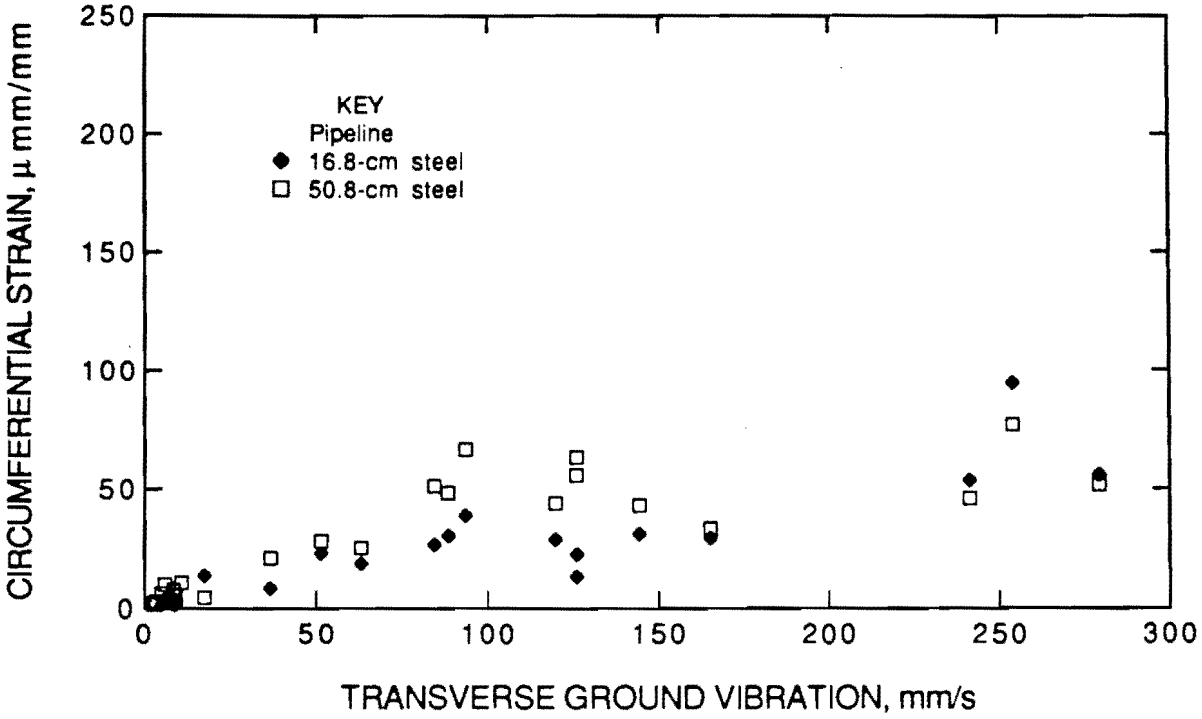
Front longitudinal strain versus radial ground vibration.

Figure 21



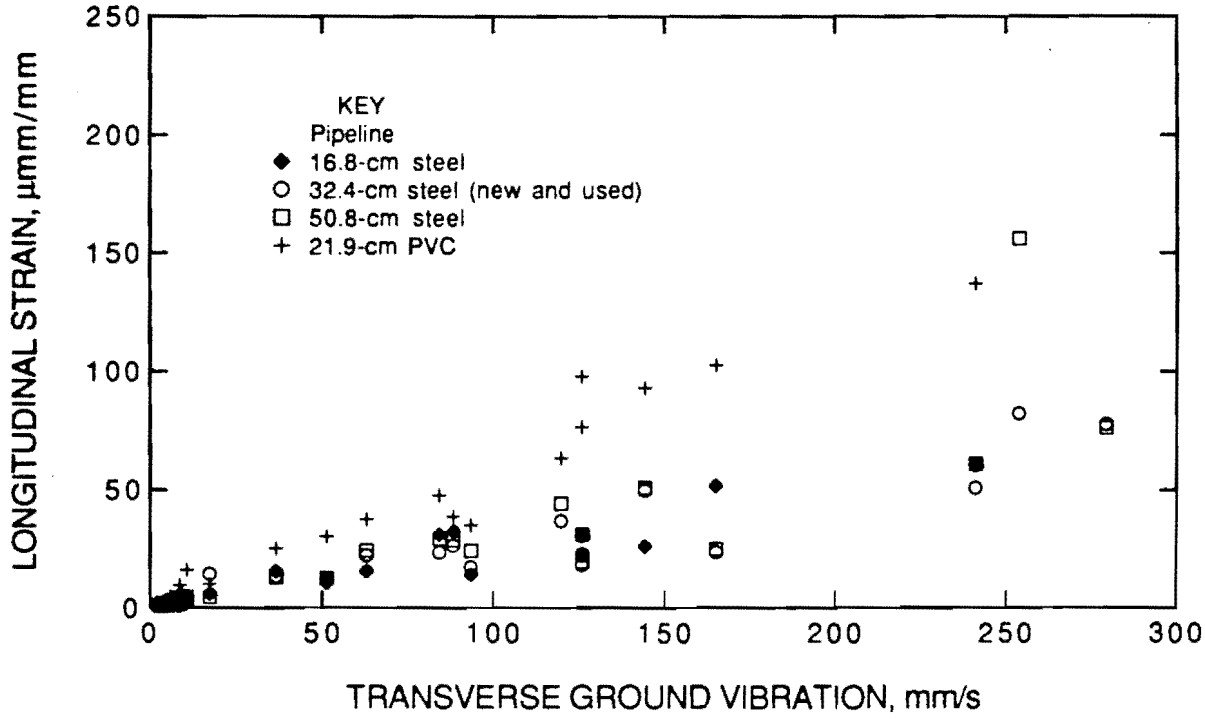
Top longitudinal strain versus vertical ground vibration.

Figure 22



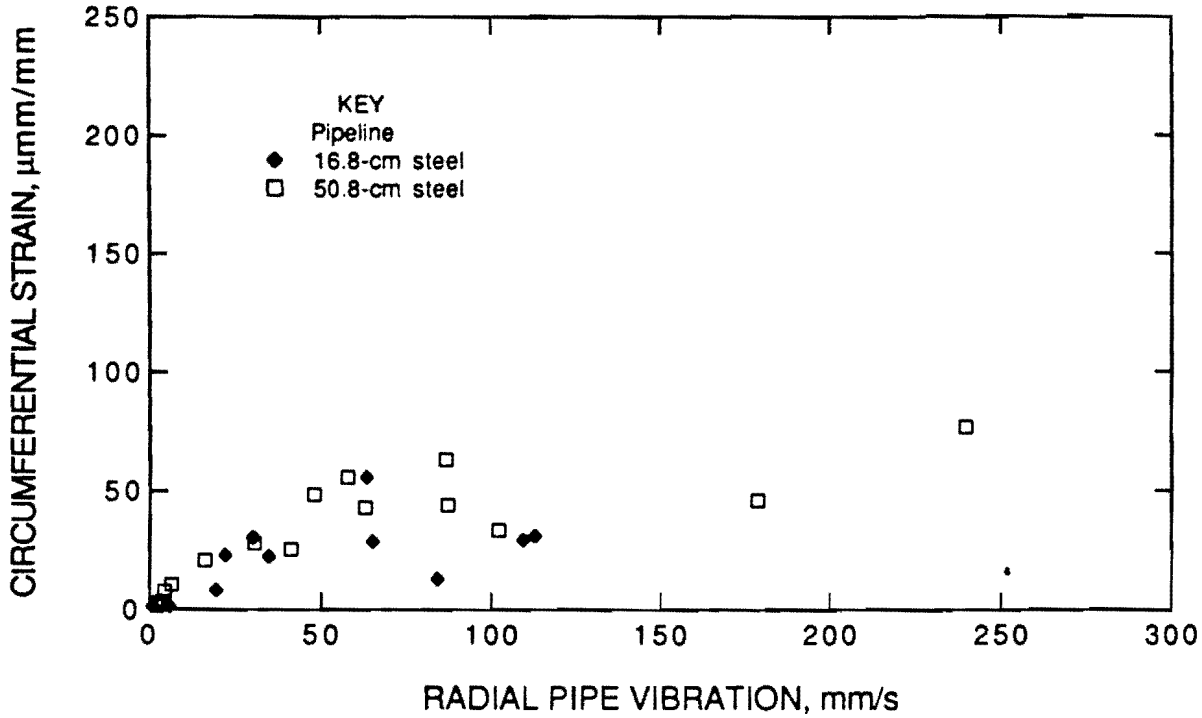
Circumferential strain versus transverse ground vibration.

Figure 23



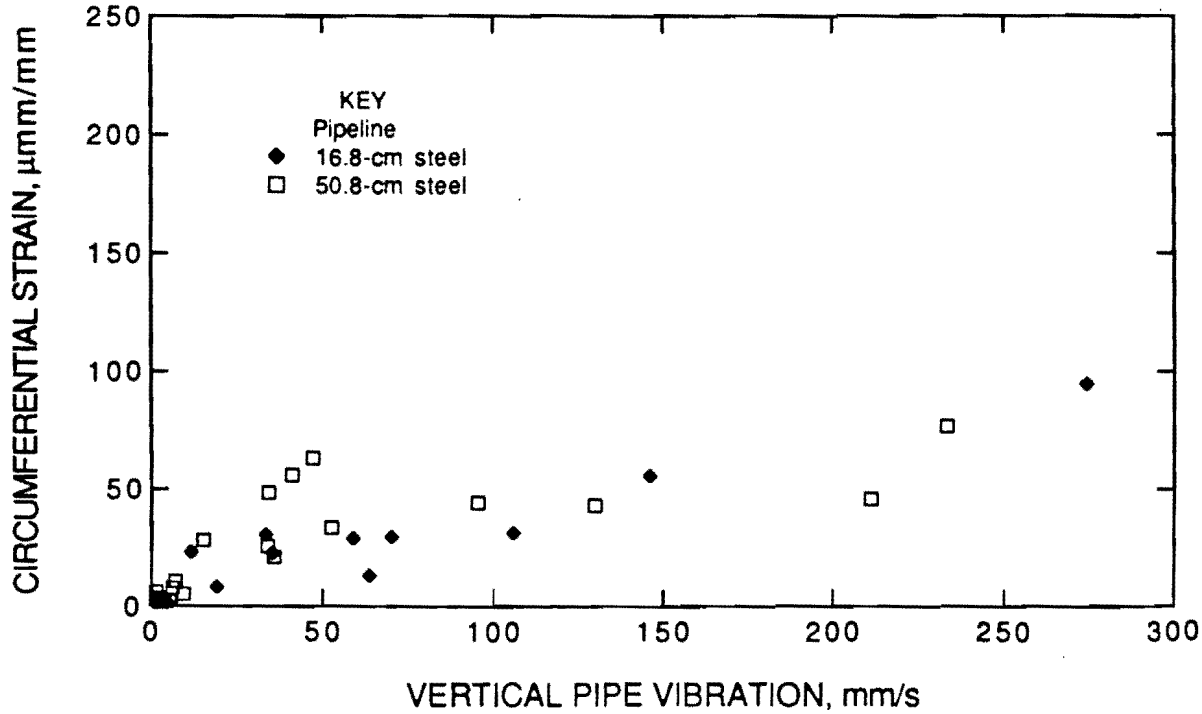
Longitudinal strain versus transverse ground vibration.

Figure 24



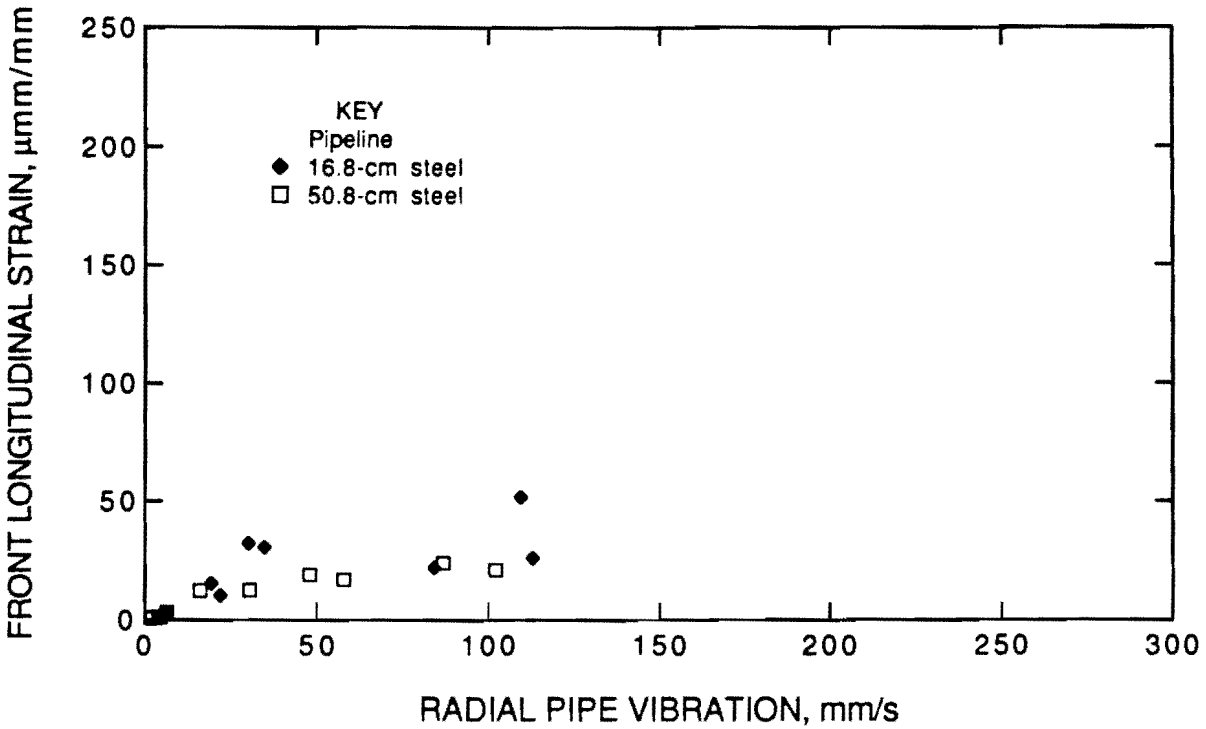
Circumferential strain versus horizontal pipeline vibration response normal to axes.

Figure 25



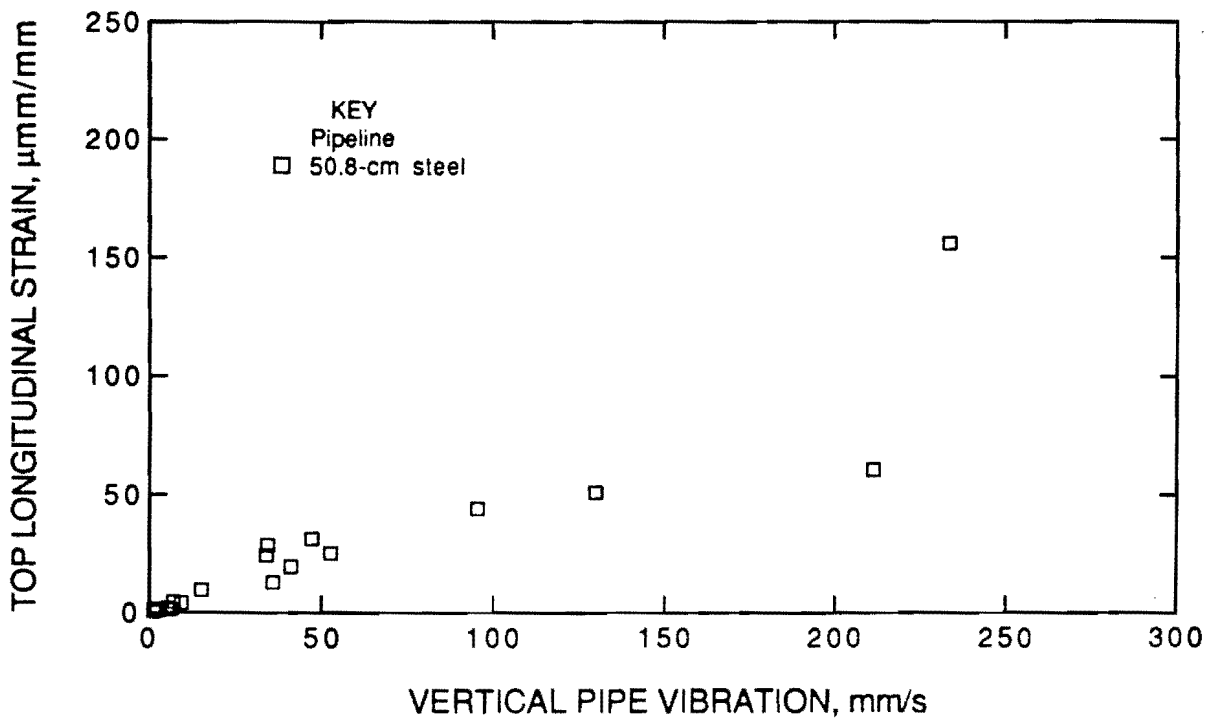
Circumferential strain versus vertical pipeline vibration response.

Figure 26



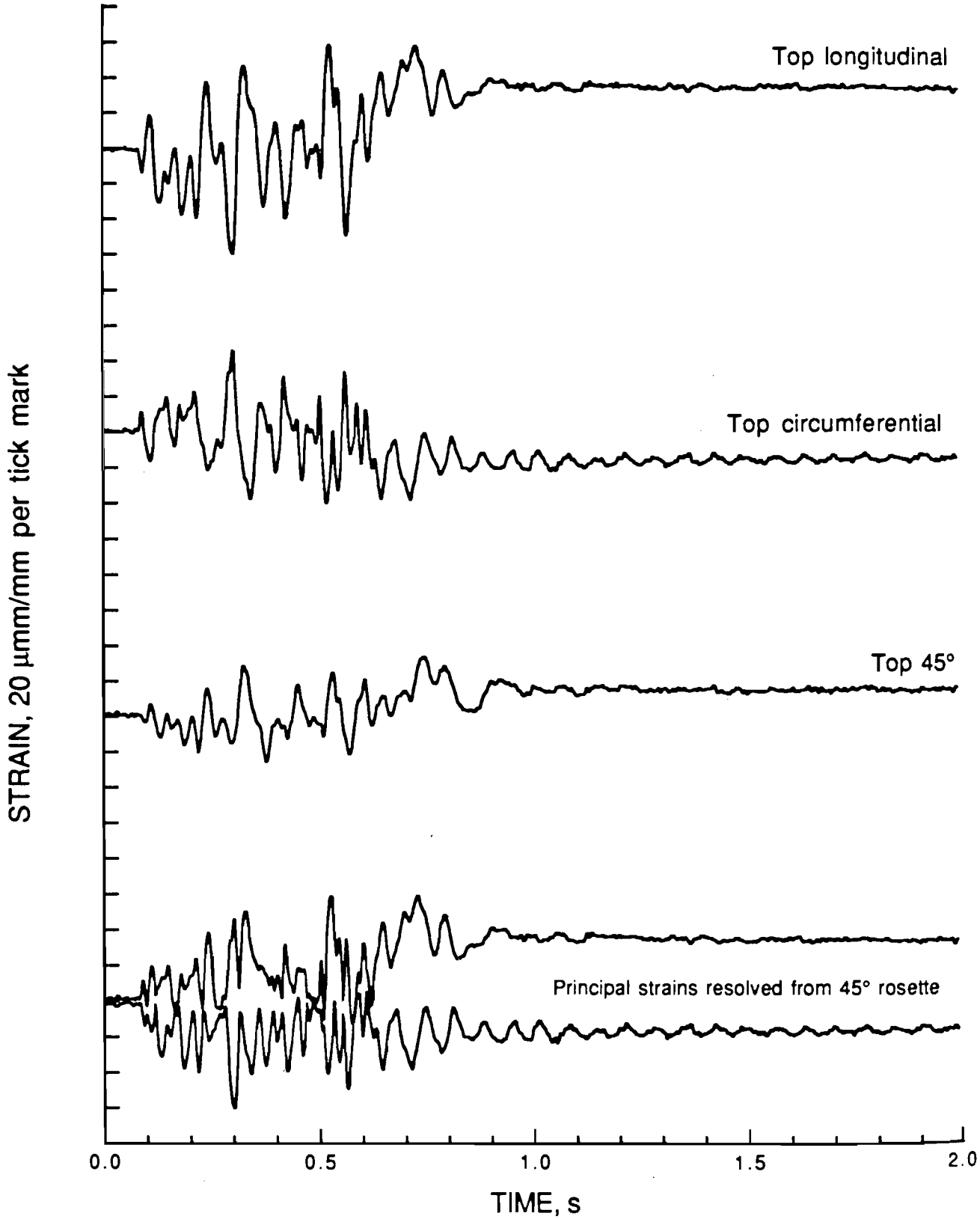
Front longitudinal strain versus horizontal pipeline vibration response.

Figure 27



Top longitudinal strain versus vertical pipeline vibration response.

Figure 28



Principal strain analysis for blast 25.

Figures 29 and 30 show the maximum strains and computed stresses using the SwRI values of 203 GPa (29.5 $\times 10^6$ lb/in^2) for Young's modulus and 0.3 for Poisson's ratio and based on the simplified biaxial equations. Also shown are the large-pipe SwRI measurements for these 0.4 scaled data and the SwRI prediction line extrapolated to large scaled distances. Generally, it is risky to use scaled distance plots to compare two sets of data with such different absolute distances. If comparisons are valid, the USBM data would be represented by a shallower slope than the SwRI prediction (rock versus soil), as already discussed. Close in, USBM stresses are relatively low except for the final blast (blast 31) just beneath the pipes and at a scaled distance of 0.98 m/kg$^{0.4}$. There was no question that permanent deformation of pipes and ground occurred with this final blast, and it is reasonable that responses were more similar to those found by SwRI than were the earlier, more distant, strictly elastic case USBM measurements. This blast is discussed in more detail later in the report in the section "Final Blast."

Circumferential or hoop stresses produced by internal pressurization can be easily calculated from the thin-walled cylinder equation:

$$\text{Stress} = PD/2t,$$

where P = pressure, Pa,

D = inside diameter,

and t = wall thickness, in consistent units.

Table 4 lists pipeline specifications and hoop stresses produced by internal pressurization. As the table shows, the pressurization-induced circumferential or hoop stresses for the two larger steel pipes are close to 72 pct of yield strengths (and would be exact if D was equal to the outside rather than inside diameters). The pressure used in the PVC pipe is considerably lower, probably because of the O-ring slip joints. Also in table 4 are both stresses and strains equivalent to 18 pct of yield strength. This 18-pct level is used by some transmission companies as an informal guideline for transient environmental effects such as traffic over a pipeline beneath a highway.

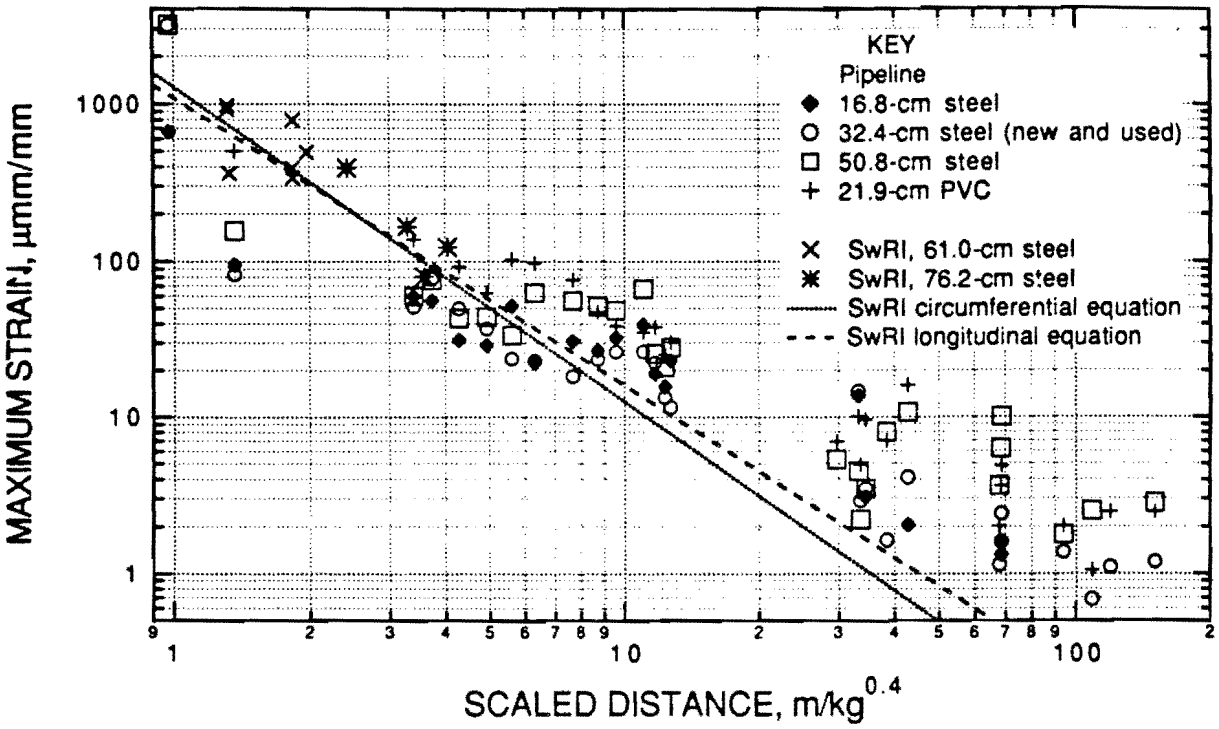
The minimum biaxial strain values in table 4 (last column) were calculated from the full biaxial stress-strain equation and represent the worst case assumption that the two strain components peak at the same time, are the same sense, and are the same peak amplitudes. They are minimums in that they are the lowest (most restrictive) values that correspond to the 18 pct of SMYS stress. More discussion of this 18-pct criterion follows in the section "Blasting Criteria for Steel Pipes."

Table 4.—Pipeline stresses

Pipe outside diam, cm	SMYS,[1] MPa	MAOP,[2] MPa	Hoop stress from internal pressurization, MPa	72 pct of SMYS, MPa	18 pct of SYMS, MPa	Minimum microstrain[3] at 18 pct of SMYS
Steel:						
16.8	290	3.86	64.2	209	52	179
32.4	241	6.82	167	174	43	150
32.4[4]	290	8.18	200	209	52	179
50.8	386	7.23	270	278	70	239
PVC:						
21.9	48	1.10	13.2	35	NAp	NAp

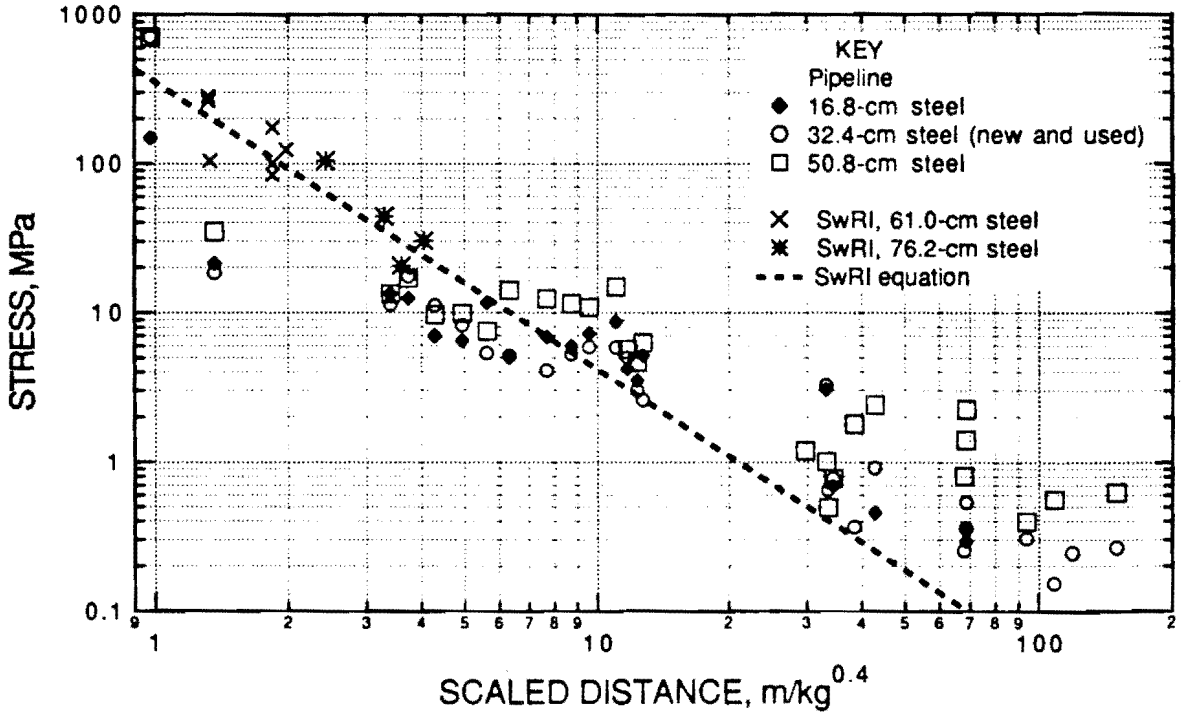
NAp Not applicable.
[1]SMYS = specified minimum yield strength (1 MPa = 145 lb/in^2).
[2]MAOP = maximum allowable operating pressure.
[3]Minimum strain that would produce stress equal to 18 pct of SMYS based on worst case biaxial equation prediction.
[4]New. All other pipes were used.

Figure 29



Maximum strains versus 0.4 scaled distance.

Figure 30



Maximum stresses versus 0.4 scaled distance.

SETTLEMENT

All transit survey data are given in appendix C. From elevation data, analyses were made of center-post settlement and maximum possible resulting strains based on Dowding's bending equation (*12*), as ground vibrations increased to over 600 mm/s. These results are given in tables 5 and 6 and figures 31 and 32, respectively. For this worst case analysis, the assumption was made that elevation changes did result only from vibrations, and not from natural compaction; water intrusion, the simple passage of time, or other causes. This is a significant assumption as clay soils are not particularly susceptible to vibration-induced settlement. To do justice to the settlement issue, a careful and controlled study is needed. Settlement and strains for vibrations below about 120 mm/s are small and irregular enough to be attributed to measurement scatter and normal "settling-in." The next two levels, up to 240 mm/s, appear to be more significant, with strains approaching 20 pct of those resulting directly from blasting vibrations (figures 18 to 27). The highest vibration, exclusive of blast 31, produced about 650 mm/s and appears associated with a significant increase in both settlement and predicted strains. However, at 12 to 55 μmm/mm, all strains were an insignificant fraction of an 830-μmm/mm level corresponding to the theoretical yield for Grade B pipe.

WELL AND TELEPHONE CABLE

For the well, three characteristics were evaluated: casing cement bond, zone isolation to control fluid migration, and casing integrity. The initial cement bond logs showed greater than 90 pct bonding to the well wall including the Coal VII and VI Seams. After the 120-mm/s blast at a distance of 124 m, some bonding loss was found for two zones of gray sandy shale. Overall, bonding was better than 85 pct and zone isolation was still maintained.

Another bond log after 240 mm/s (blast at 51 m) showed additional loss in one of these same shale zones. However, bonding was still better than 90 pct in intervals of 3 m directly above and below this zone, and zone isolation was maintained. The final test after all the blasting showed a total bond loss. The closest blast had been blast 29 at about 17 m, which produced a particle velocity of over 600 mm/s. In all cases, the well maintained pressure and the casing was undamaged.

Table 5.—Accumulative pipe settlement[1] of center upright post, millimeters

Maximum vibrations, mm/s	Steel				PVC,
	16.8-cm	32.4-cm	[2]32.4-cm	50.8-cm	21.9-cm
77.2	-0.91	-4.88	-0.305	-2.13	ND
120.9	0	-2.13	4.27	-0.91	3.05
103.6	4.00	0.91	7.01	1.22	7.62
166.6	7.32	5.49	11.3	6.10	11.3
241.8	5.79	4.57	11.6	8.84	9.75
647.7	30.8	32.0	41.1	37.8	38.4

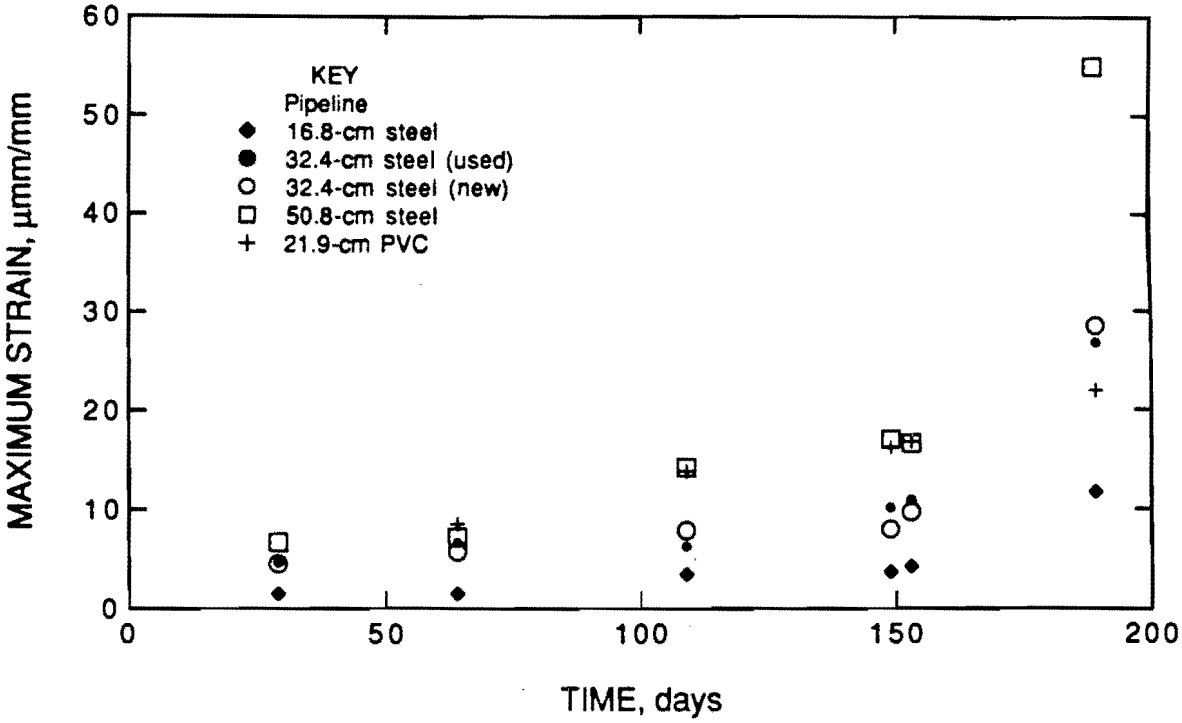
ND No data.
[1]Measurement accuracy is ±0.8 mm at the survey-to-midpoint upright distance of 53 to 55 m.
[2]New. All other pipes were used.

Table 6.—Maximum possible accumulative strain from vibration-induced settlement of pipes, micromillimeters per millimeter

Maximum vibrations, mm/s	Steel				PVC,
	16.8-cm	32.4-cm	[1]32.4-cm	50.8-cm	21.9-cm
77.2	1.5	4.6	4.5	6.7	8.5
120.9	1.5	6.6	5.7	7.2	8.5
103.6	3.5	6.3	7.9	14.2	13.8
166.6	3.7	10.1	8.0	17.0	16.2
241.8	4.3	10.9	9.7	16.6	16.8
647.7	11.7	26.7	28.4	55.0	21.9

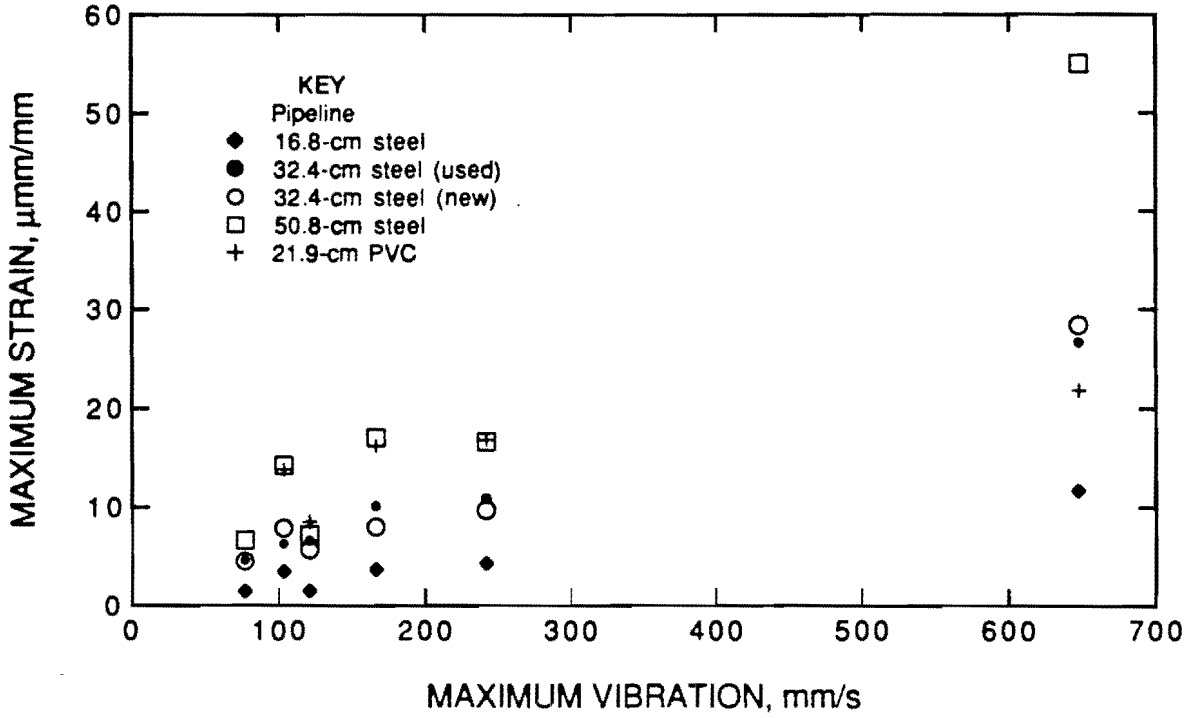
[1]New. All other pipes were used.

Figure 31



Strain from settlement versus time.

Figure 32



Strain from settlement versus vibration amplitude.

Indiana Bell's tests on the fiber-optic telephone cable found no breaks and an attenuation slightly lower after blast 29 than before (13.2 dB versus 13.9). This slight difference was attributed to warming from sunshine on both the equipment and exposed fiber ends. Admitting that the blast at over 600 mm/s had no immediate effect on the fiber optic, the Indiana Bell technicians could not guarantee that damage of an unspecified nature would not show up later. The buried copper coaxial cable was also undamaged by the blasting.

FINAL BLAST

Following production blasts 29 and 30 next to the fenced-in pipeline field (figure 1), a single row of four blastholes was drilled between the individual pipes to complete the testing program (blast 31). Figure 33 shows the results, with the severely bent but unbroken 16.8-cm pipe and the new 32.4-cm pipeline arching above the highwall swell. The largest pipe, the water-filled 50.8-cm pipe, was uplifted, parted, and fell back down, and the used 32.4-cm pipe was cleanly broken. The PVC pipe simply came apart at the O-ring joints. This blast produced severe uplift, with the explosive being below rather than next to the pipes. The distance listed in table 2 for blast 31 is the horizontal or surface projection; the true distance from each pipe to the closest explosive column top was 5 to 6 m.

This blast was clearly different from the previous 30, producing permanent ground and pipe strain. Vibration levels were above 900 mm/s, although not meaningful for this situation, representing non-elastic responses. Strains shown in table 6 are possibly underestimates, as pipeline movement eventually parted the signal wires. All pipes lost pressure. The two unbroken pipes sheared off the end uprights as the center uplift pulled the ends closer. Pressure was then lost at the upright joints.

Strain values and computed stresses from this blast are included in figures 16, 17, 29, and 30 for comparison with the SwRI prediction equations, as discussed in the section on stress. They were not included in the strain-versus-velocity plots (figures 18 to 28) because they were not true elastic wave particle velocities.

Following blasting, Texas Gas Transmission Corp. removed samples from the four steel pipes and tested them for strengths. All pipes had yield strengths above design minimums (table 7). In particular, the two that did not rupture from shot 31 had considerable margins, suggesting a significant factor of safety in the SMYS specifications.

Figure 33

Uplifted pipes following blast 31.

Table 7.—Postblast tests of steel pipe by Texas Gas Transmission Corp., megapascals

Outside diameter, cm	SMYS[1]	Measured strengths	
		Yield at 5-pct elongation	Ultimate tensile
16.8	290	456	610
32.4	241	267	354
32.4[2]	290	436	521
50.8	386	417	494

[1]SMYS = specified minimum yield strength (1 MPa = 145 lb/in^2).
[2]New. All other pipes were used.

ANALYSES OF FINDINGS

The last mining cycle brought the production blasting within 15 m of the closest pipeline (blast 29). There was little backbreak and no apparent permanent ground displacement at this minimum distance of 44 hole diameters. Vibration levels were 635 mm/s for this blast on the ground surface and 234 to 274 mm/s on the two instrumented pipelines, with no loss of pipe integrity (pressure drops). Figures 18 through 28, showing measured strains, are composites from two types of blasts, parting and overburden, different azimuthal directions, and five pipelines of two different materials. It is not surprising that considerable scatter exists in the summary figures, and a pipe-by-pipe analysis reduces this scatter. Also in common with other studies, there were problems with continual use of strain gages and electronics in an unfriendly environment for an extended period of time. Generally, circumferential strains were higher than longitudinal by a rough factor of 2 for the lower vibration levels and were comparable or lower in amplitude at high vibrations (table 3). PVC pipe strains were slightly higher, probably because of their lower stiffness and more faithful conformance to ground displacement.

BLASTING CRITERIA FOR STEEL PIPES

Criteria are needed for blasting near pipelines that will ensure that damage will not occur and yet be reasonable with regard to resource recovery and other requirements for blasting. The pipeline industry itself must deal with this problem whenever blasting is needed for repair, replacement, or installation of an adjacent new pipeline. "Damage" is defined here as any failures leading to pressure or product loss and any plastic deformation (yield or permanent bending).

The Enron standard (*6*) specifies allowable stresses of 6.9 MPa for electrically welded and 3.45 MPa for gas-welded or mechanically joined steel pipes. Corresponding strains are 30.8 and 15.4 μmm/mm, considerably less than many measured values in table 3.

The previously mentioned criterion of 18 pct of yield strength is applied to transient excitation such as traffic on a highway crossing a buried pipeline. If this is adopted as a blasting criterion, the stresses and strains listed in table 4 would apply. It is not unreasonable to allow such a criterion for blasting, as it is unlikely that a pipeline would simultaneously be subjected to traffic stress and high-level blast vibration.

Internal pressurization at the MAOP produces circumferential stresses corresponding to about 72 pct of yield or the SMYS (table 4). The addition of a maximum dynamic stress of 18 pct brings this total to 90 pct. Esparza's SwRI final report includes five yield theories for biaxial states of stress (*5*). He says "many engineers tend to use the distortional energy criteria, sometimes called the Huber-Hencky-Mises Theory, as they believe it is the most accurate." The appropriate yield equation is then given as

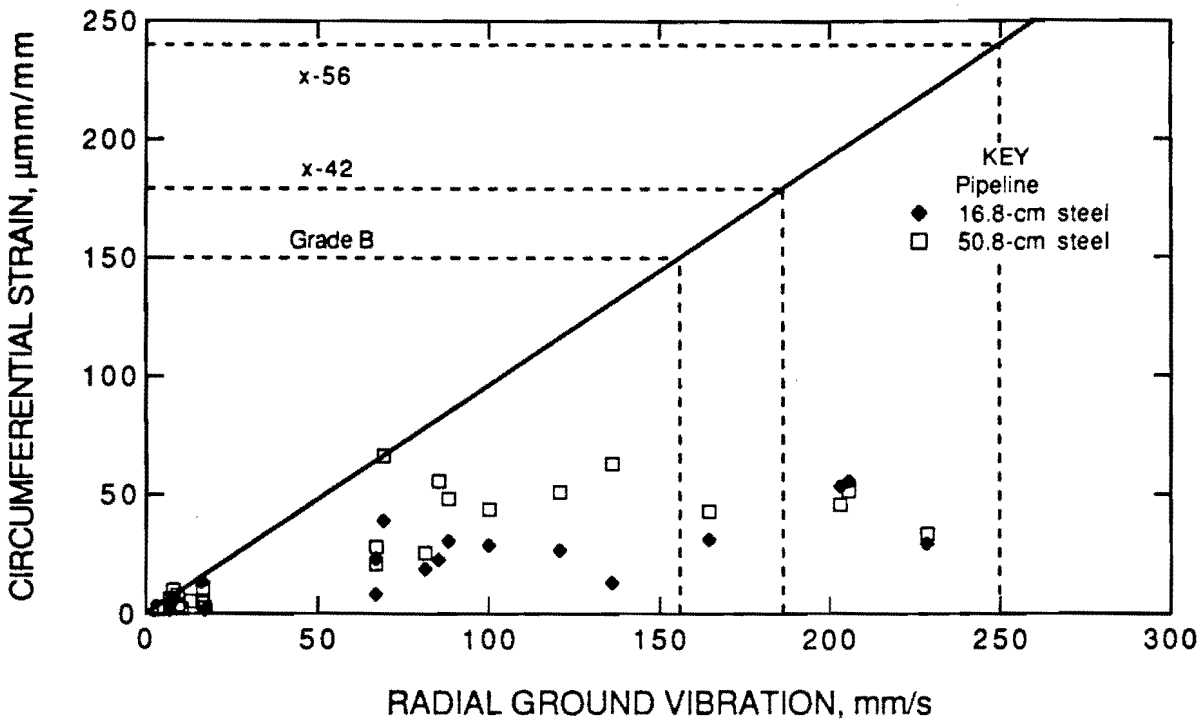
$$\left(\frac{\sigma_c}{\sigma_y}\right)^2 + \left|\frac{\sigma_c}{\sigma_y}\right|\left|\frac{\sigma_l}{\sigma_y}\right| + \left(\frac{\sigma_l}{\sigma_y}\right)^2 = 1,$$

where σ_c, σ_l and σ_y = circumferential, longitudinal, and yield stresses, respectively.

For a total circumferential stress of 90 pct of SMYS ($\sigma_c = 0.9\sigma_y$), the equation gives a maximum total longitudinal stress (σ_l) of 0.18 or, again, 18 pct of SMYS. This means that both stresses are limited to 18 pct of SMYS.

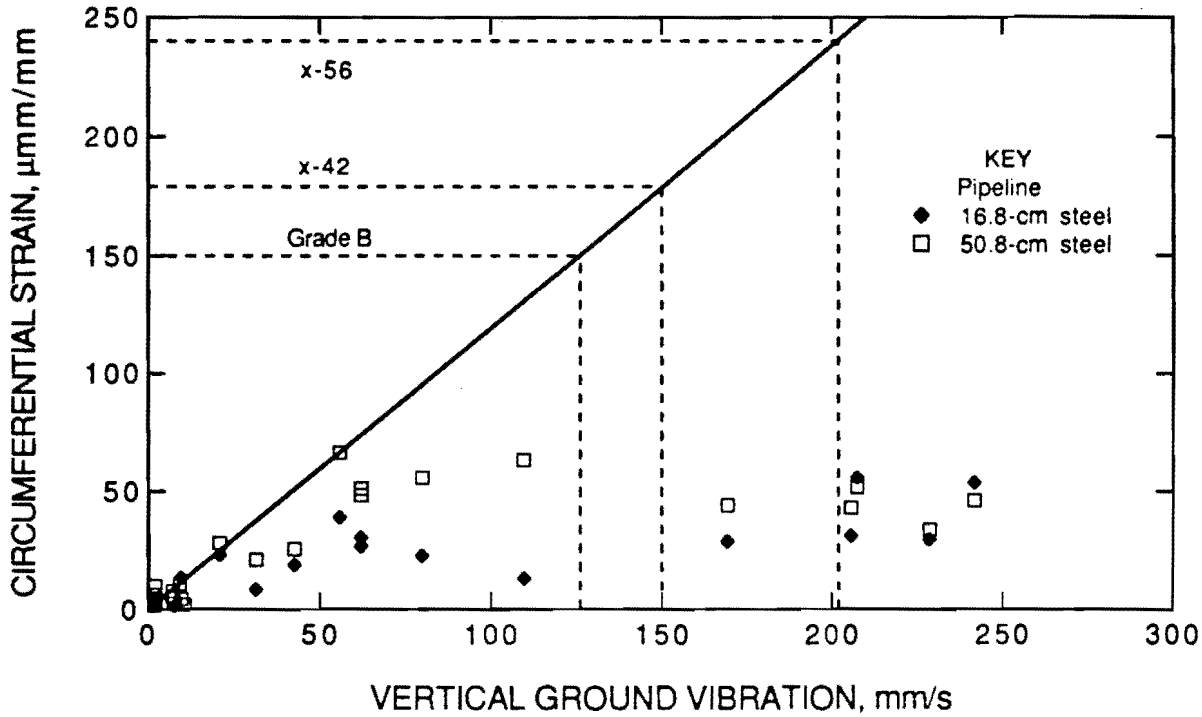
An initial estimate of a safe-level criterion for blasting is possible from the particle velocity strain comparisons from figures 18 to 23 and extrapolating particle velocities corresponding to 150 to 239 μmm/mm from table 4. The vibration amplitudes corresponding to Grade B, X-42, and X-56 pipelines are then 127, 150, and 200 mm/s, respectively, for vertical vibrations and slightly higher for radial. These are shown in figures 34 and 35.

Figure 34



Radial velocity criteria based on maximum circumferential strain and grade of pipe.

Figure 35



Vertical velocity criteria based on maximum circumferential strain and grade of pipe.

It is important to consider if this approach is conservative. The 18-pct criterion allowed for traffic still includes a safety factor; the SMYS itself has a safety factor in that it is a "minimum"; and the blast data are well contained by the maximum value envelopes. Strains are calculated as worst case biaxial. Furthermore, the low frequency (and potentially higher strain-producing vibration) found here (5.6 Hz) is about as low as could be expected for such close-in blasting (*16*). On the other hand, the pipeline may not yet be fully coupled after only 6 months in the ground. The soil over the pipelines was softer than nearby undisturbed ground even after 6 months, despite the use of standard installation procedures. The problem of incomplete coupling and reduced responses at higher vibration amplitudes was addressed by developing an envelope of maximums by extrapolating strains from lower level responses (figures 34 and 35). Any additional work on pipeline responses from blasting should include consideration of improved or ideal coupling, or alternatively, a simple and practical way of directly monitoring pipe response under backfilled conditions.

All the analyses in this study are based on elastic waves and the total absence of any permanent ground deformations or block movements into the pipeline vicinity. Distances between pipes and blasting must be sufficiently large to preclude direct blast-produced ground cracks, on the order of 100 blasthole radii. For a typical large surface mine blast, this would be about 16 m (52 ft). Blasting for construction, excavation, and new pipeline installation would likely be within this range, and there the concerns of Oriard and Kiker (*9-11*) and SwRI analyses (*4-8*) would apply.

BLASTING CRITERIA FOR PVC PIPELINE

Unlike the steel pipeline, the PVC pipe at the specified maximum pressure experienced far less hoop stress than 72 pct of SMYS (table 4). It is likely that there is some other limiting factor, such as the O-ring couplings. The strain corresponding to the maximum operating pressure 1.1 MPa (160 lb/in^2) is 4,800 μmm/mm, a fraction of the yield failure strain of 17,500. Again, a rough estimate of particle velocity is possible from the strain figures and a doubling for circumferential strain, which was not monitored on the PVC pipe. Assuming a maximum environmental strain equal to 5 pct of that produced by pressurization, or 1.35 pct that of yield, and the worst case maximum strain envelope (from figure 20), the corresponding strain would be 240 μmm/mm and velocity would be about 250 mm/s. Because of the lack of actual circumferential strains and uncertainty about failure modes for PVC pipe, this level should be further reduced until more data are available. Again, a 125-mm/s (5-in/s) criterion seems reasonable. Possibly, users of PVC pipe have an environmental criterion similar to the 18-pct SMYS suggested for steel.

CONCLUSIONS

This report describes a study of full-scale blasting near pressurized pipelines. Although particle velocities of over 600 mm/s were sustained without loss of pipe integrity, it is recommended that 125 mm/s measured at the surface is a safe-level criterion for large surface mine blasts for Grade B or better steel pipelines. The same criterion is recommended for SDR 26 or better PVC pipe. The basis for this recommendation is that the pipes can tolerate a dynamic load equal to 18 pct of SMYS. It is suggested that this criterion not be applied at construction sites if experience has shown that higher or lower particle velocities are tolerable or appropriate. Also, no adjustment is believed needed for pipeline age, assuming the protective coating is intact, unless the pipeline is known to be at higher risk from previous damage or other causes. The same safe-level criterion also appears applicable, at a minimum, to vertical wells and telephone lines.

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APPENDIX A.—SOUTHWEST RESEARCH INSTITUTE STUDIES

The extensive studies of blasting near pipelines by Southwest Research Institute (SwRI) for the Pipeline Research Committee of the American Gas Association (*4-7*) were primarily for construction blasting for the installation of new pipelines next to existing ones. The original SwRI comprehensive "final report" authored by Westine and others in 1978 (*4*) was superseded by a more comprehensive report by Esparza and others in 1981 (*5*), which included additional tests, analyses, and revised stress prediction equations.

SwRI EXPERIMENTAL RESULTS

Six series of tests involved pipelines and blasting in soil (*5*). Pipeline sizes and other test parameters are listed in table A-1. The two smallest pipes were approximately 1/8- and 1/4-scale models of a 61-cm (24-in) diameter pipeline. Those two and the 40.6-cm pipe were specially installed for the study (test series A). The 61- and 76.2-cm pipelines were located in Kansas City, MO, and Madisonville, KY, respectively, with only the latter pipeline pressurized (to 2.76 MPa, 400 lb/in²) during the blasting tests (series B and C). Except for the in-service Madisonville pipeline, all tests were on relatively short pipe sections of 2.1 to 13.7 m. For all tests, the pipe lengths were at least twice the distance to the explosive charge.

Test series D and E studied lines and grids of charges oriented parallel and at various angles to the pipelines. The distances in table A-1 correspond to the closest charge, with each individual charge so small as to be a point source. Only a few of the grid tests used delays between charges of 3 to 6 ms.

The two-media tests (series F) had small point charges in holes in a 3- by 3- by 0.9-m-thick concrete slab 0.9 m from a test section of pipeline. This was intended to simulate blasting in rock, which was also addressed more seriously by SwRI in a followup study (*7*).

None of the SwRI tests approximated mine or quarry blasting, both of which have larger and more distant explosives, are fired in rock, and have mostly rock travel paths for the vibrations. Strain and vibration records from SwRI tests were very highly damped (e.g., 30 pct) with only one to two cycles of motion at extremely long periods of 60 to 250 ms, despite the closeness of the blasts. Some of the strain and vibration measurements had only one pulse and no rebound at all, suggesting permanent ground strain rather than elastic waves. SwRI ground vibrations were measured off to the side or on the opposite side of the blast from the pipe rather than above, next to, or on the pipelines. The authors avoided measuring in the disturbed ground but at the cost of an easy comparison with directly measured strains and vibrations. Because some directionality is possible for all blasts and likely for those done with multiple charges, this monitoring procedure could have contributed to the vibration amplitude scatter.

Only a few SwRI measurements involved pipelines under internal pressurization, mainly test C in table A-1. This large pipeline in Madisonville, KY, is rated at 414 MPa (60,000 lb/in²) specified minimum yield strength (SMYS) and was being operated at a reduced pressure of 2.76 MPa (400 lb/in²) during the blasting tests. A maximum allowable operating pressure (MAOP) of 6.8 MPa (990 lb/in²) for this pipeline would produce circumferential stresses of about 290 MPa, corresponding to about 70 pct of SMYS. Blasting-induced stresses ranged up to 103 MPa (15,000 lb/in²) from particle velocities of roughly 500 mm/s (20 in/s), without damage. This represents about 25 pct of the pipeline's SMYS to be added to stresses from pressurization. The pipe-to-charge distance was 2.74 m, and the actual measured velocities were 1,831 mm/s at 1.83 m and 358 mm/s at 3.66 m. It is not known if the pipe would have failed if it had been operating at MAOP.

Table A-1.—SwRI pipeline blasting experiments in soil (5)

Test	Pipe diam, cm	Pipe wall, mm	Distance range, m	Charge size, kg
A. Point source	7.5	1.50	0.23-3.35	0.014 -0.50
	15.1	2.36	0.30-6.86	0.014 -1.82
	40.6	13.1	0.30-0.91	0.014 -0.027
B. Point source	61.0	7.92	1.83-3.96	2.27 -6.82
C. Point source	76.2	8.74	2.74-4.57	1.36 -2.27
D. Line of charges ...	7.5	1.50	0.45-4.57	[1]0.0153-0.182
	15.1	2.36	0.45-4.57	[1]0.0153-0.182
E. Grid of charges ...	15.1	2.36	0.45-1.22	[2]0.025 -0.153
F. 2-media tests	15.1	2.36	1.52-3.35	0.114 -0.182

[1]Weight of explosive per hole, seven holes in a line.
[2]Weight of explosive per hole, three rows of four holes.

SwRI THEORETICAL ANALYSES OF VIBRATION

The SwRI authors derived relationships for ground motion and strains based on similitude theory, theoretical energy, conservation of mass and momentum, π theorem, and shock front propagation (*5*). Because the authors used empirical vibration data to define the equations' terms, it is not clear how predictions from these equations differ from the USBM's traditional and relatively simple charge weight scaling. The SwRI authors call any charge weight scaling other than cube root scaling "dimensionally illogical." The SwRI equations are complex, contain some difficult terms and parameters difficult to measure, and sometimes predict unrealistic amplitudes. Their equation, in its original U.S. customary units is

$$\left[\frac{U}{c}\right]\left[\frac{p_o}{\rho c^2}\right]^{0.5} = \frac{0.00617\left[\dfrac{W_e}{\rho c^2 R^3}\right]^{0.852}}{\tanh\left[26.0\left[\dfrac{W_e}{\rho c^2 R^3}\right]^{0.3}\right]}.$$

For easy comparison with the referenced reports, all units in the following discussions are being kept in the authors' original measurement system. A similar equation was also derived for displacement. Equation parameters are

U = peak radial ground particle velocity, ft/s,

R = standoff distance, ft,

W_e = explosive energy release, ft-lb,

ρ = mass density of soil or rock, lb-s^2/ft^4,

c = seismic P-wave velocity in soil or rock, ft/s,

and p_o = atmospheric pressure, lb/ft^2.

The explosive energy release (W_e) requires some calculation. For example, ANFO is 912 cal/g, which is equivalent to 1.28×10^6 ft-lb/lb (SwRI uses 1.52×10^6). Multiplication by the amount of explosive (in pounds) gives the appropriate W_e value. Mass density (ρ) and propagation velocity (c) are not typically known with any precision or even adequately defined for this analysis. For the SwRI tests, they pertain to the soil. For more distant blasts (e.g., >10 m), it is not clear if they would pertain to the surface soil or the medium that provides most of the vibration propagation path. Most situations will include a mixture of rock and surface soil.

Predictions from this SwRI equation were compared with measurements from single-charge blasts reported in USBM RI 9226 (*15*). Particle velocities were reasonably close for ρ and c of 2.7 g/cm^3 (5.23 lb-s^2/ft^4) and 3,000 m/s (10,000 ft/s), respectively, but far too low for soil-type values of these two parameters. The plot of the SwRI equation velocity parameter also suggests two range regimes with a shallower propagation slope for the distant tests (left side) than for the close-in tests (right side) in their figure 64 (*5*). This again suggests a different strain mechanism close in or at least a different seismic wave type.

SwRI authors also derived simplified versions of their propagation equations for cases where

$$6 \times 10^{-5} < \frac{W_e}{\rho c^2 R^3} < 6.4 \times 10^{-2}.$$

Few, if any, mining-type blasts fall within this range because of their relatively large distance (R); therefore, the simplified equations appear applicable only to construction blasts.

SwRI THEORETICAL ANALYSIS OF STRESS AND STRAIN

Two types of pipeline responses can occur, out-of-round deformation (ovaling) and bending, represented by circumferential and longitudinal strains, respectively. The circumferential strain is a measure of pipe deformation by ovaling. SwRI developed an equation for pipe ovaling natural frequency:

$$T = 8.11\sqrt{\frac{\rho_s R r^4}{E h^3}},$$

where T = period ($1/f$),

ρ_s = soil density,

R = standoff distance,

r = pipeline radius,

E = Young's modulus,

and h = pipe thickness.

The above equation assumes perfect ground-to-pipeline coupling. It also assumes that all the ground between the source and the pipeline contributes to the pipe's natural frequency, that is, all the ground within the distance specified by the R term. This equation must apply to only close-in cases (e.g., <10 m). It is not reasonable to expect a pipe's response period to increase without limit for increasing R, nor for the ground at 100 m or more distance to contribute to the stiffness of a ground-pipeline system. The SwRI authors also say that the equation "may not apply for media with a significant elastic constant (perhaps rock)" (*5*). Applying this equation to the USBM's pipelines gives long periods of 6 to 50 s for even the closest blasts at 15 m.

Others (*2, 13*) subscribe to the assumption that a buried pipeline is relatively flexible and therefore will deform with the medium. If so, the dominant period of the motion is only a function of the wave propagation effects of the surrounding medium and the excitation motion itself. Interaction of delays will affect the excitation motion and is a function of delay interval, location, and the propagation medium.

The SwRI-developed strain relationships were based on theoretical considerations and contained constants that the authors said could not be explicitly evaluated. This required a statistical fit approach to their experimental data. Their resulting equations were

$$\epsilon_{cir} = 4.78\ \chi^{0.805},$$

$$\epsilon_{long} = 1.98\ \chi^{0.735},$$

where, for point sources,

$$\chi = \frac{nW}{\sqrt{Eh}\ R^{2.5}}.$$

The terms in the χ equation are as follows:

n = equivalent energy release (nondimensional, equals 1 for ANFO),

W = charge weight, lb,

E = modulus of elasticity, lb/in^2, typically 29.5 $\times 10^6$ for steel,

h = pipe wall thickness, in,

and R = distance between pipe and charge, ft.

For stress determination, SwRI used the biaxial stress-strain equation as a reasonable approximation for the relatively thin-walled pipes:

$$\sigma_1 = \frac{E}{1-\nu^2}\left(\epsilon_1 + \nu\epsilon_2\right),$$

where ν = Poisson's ratio,

and 1 and 2 = either the circumferential or longitudinal directions.

Depending on the particular strains used, such as maximums or real-time, the computed stresses can be true values or worst case maximums, analogous to pseudo vector sums in vibration analysis. Using the biaxial equation, SwRI produced a stress prediction equation:

$$\sigma = 4.44\ E\ \chi^{0.77},\ \text{lb/in}^2,$$

which they report provides a good match for both circumferential and longitudinal stresses, having standard errors of about 34 pct.

In addition to point sources, SwRI developed strain and stress equations for lines and grids of charges. These required some adjustments to the charge (W) and distance (R) parameters in the χ equation. With a minor exception, all these arrays used simultaneous initiation and, therefore, were not comparable to traditional delayed mining-type blasts.

SwRI authors also developed an adjustment factor for the strain and stress prediction equations to account for charge depths. Their concern was with the amount of soil backing up and stiffening the pipeline. This depth factor (F) is added to the χ equation, which then becomes

$$\chi = \frac{nW}{\sqrt{EhF}\ R^{2.5}}.$$

The F factor is determined as follows:

$$F = 1 \text{ for } R/H \le 4,$$

$$F = \left[\frac{H}{R} + \frac{\rho_p h}{\rho_s R}\right] \text{ for } R/H > 4,$$

where R = actual charge-to-pipeline distance, ft,

H = amount of soil behind pipe along same line as R, ft,

ρ_p = pipe material density,

ρ_s = soil density (density units are arbitrary),

and h = pipe wall thickness, ft.

They also warn that this factor is based on only four measurements with 20-lb charges at 70 to 200 ft and should be used very cautiously for stresses greater than the values corresponding to $\chi = 10^{-6}$ (σ = 3,142 lb/in²).

A sensitivity analysis was performed by the SwRI authors that shows some of the problems with their prediction equations. They found parameters R and W strongly influencing strains and stresses (and these parameters will also strongly influence vibration amplitudes). However, ρ and c had no influence at all on strains and are not included in either the strain or the stress prediction equations. By contrast, the complete vibration prediction equation given previously does include both ρ and c, as do the simplified versions. For vibrations, a doubling of c in the SwRI equation roughly doubles computed peak particle velocity, making it about as strong an influence as charge weight W. Using a simplified and approximate relationship for ground displacement, the SwRI authors were able to eliminate the dependence of stresses on ρ and c. This differs from many USBM and other studies that generally found particle velocity amplitudes unrelated (or, at best, weakly related) to these parameters. By contrast, frequency, and therefore by inference, displacement, was found to be strongly dependent (*15*). The reason for this disparity between blasting experience and SwRI predictions is not clear, as strains should in some way be proportional to particle velocity amplitudes or, at the very least, to displacements.

Based on the comprehensive 1981 SwRI report (*5*), the Enron Gas Pipeline Group published a standard for allowable blasting near buried pipelines (*6*). They used the SwRI stress equation along with the depth adjustment factor F. The Enron standard also provided two safe-level criteria of 6.9 MPa (1,000 lb/in²) for welded pipeline and 3.45 MPa (500 lb/in²) for jointed or acetylene welded pipelines. The reason for these particular and very restrictive limits was not specified.

SwRI EVALUATION OF BLASTING IN ROCK

A highway construction project enabled SwRI to collect data on pipeline response that are more applicable to traditional millisecond delayed rock blasting (*7*). This study of two large pipelines involved larger sized charges, larger pipeline-to-blast distances (table A-2), and delays between charges of 25 ms for 21 production blasts. The pipes were placed in trenches that were backfilled with sand and coarser material. Production blasting was in rock as was virtually all of the seismic wave travel path.

Table A-2.—SwRI pipeline blasting experiments in rock (*7*)

Pipe diam, cm	Pipe wall, mm	Distance range, m	Charge sizes, kg
30.65	9.53	25 -59	4.5-9.09
76.2	11.9	1.2-43	4.5-9.09

The resulting strain records have the appearance of elastic wave responses with many cycles of motion, in contrast to the results of the previous highly damped and close-in soil tests. Unfortunately, this appearance could be due to the multiple delayed charges and not to the elastic versus plastic responses. The one exception showing subdued response was from a blast at only 1.2 m, which, like the soil tests, appeared to produce soil permanent deformation strains. Stresses were computed from strain measurements and compared with the stress prediction equation previously presented for point sources in soil. Charge weights used were the amounts per delay because the delay intervals were long compared with the pipeline natural frequencies. This time relationship also justified using the point source rather than the array source equation. No depth factor (F) was used.

Stresses obtained were considerably less than those from the soil tests; in many cases they were single digit microstrains and barely larger than record noise. SwRI authors attribute this difference primarily to the larger distances. They also suggest an effect from the partitioning of explosive energy between fragmentation and vibrations, more relief for the rock blasting, and the use of delays in the rock tests. However, an alternative explanation is that the soil tests were so close as to involve nonelastic and permanent deformation responses while the rock blasting tests are more representative of responses to elastic waves. This possibility was presented in the earlier discussion of SwRI vibration monitoring in the main text (*5*).

SwRI recommends that the soil prediction equation also be used for rock cases with a free face parallel to the explosive array. The soil tests provide an almost perfect upper bound on the scatter from the rock blasting tests. It is likely that the measurements from the rock blasting tests are more realistic than the measurements from the soil tests for evaluating surface mine and quarry blasting, although still only addressing small charge weights.

Alan Lambeth presented a paper at the 1993 American Gas Association Conference, which contained some new pipeline monitoring data and an analysis based on the modified version of the SwRI stress prediction equation (*8*). The monitoring was done on an out-of-service 61-cm pipeline with 1.6- to 12.5-kg charges at distances of 3.4 to 7.6 m. Again, there is a question of close proximity and whether elastic waves or plastic deformation were measured. Lambeth's paper showed no strain or vibration time histories to provide an evaluation of this question. Lambeth's stress amplitudes did reasonably agree with the SwRI prediction curve (*5*) for close-in blasts in soil.

Desiring to provide a universal blasting criterion, Lambeth started with the SwRI stress prediction equation version that includes the soil backing factor (F). To this, he added additional adjustments for powder factor, larger distances, skill of the blaster, and confinement, to predict a stress upper bound.

$$\sigma = F_c F_p F_L \; 4.44E \left[\frac{W \, F_w n_s / 900}{\left(E \, t \, F_h\right)^{0.5} R^{2.5}} \right]^{0.77},$$

where F_c = confinement factor,

F_p = powder factor,

F_L = large-distance factor,

E = Young's modulus, lb/in^2,

W = maximum charge, lb,

F_w = "who is blasting factor,"

n_s = specific energy of explosives, cal/g (ANFO = 900),

t = pipe wall thickness, in,

F_h = soil backing factor,

and R = distance, ft.

The confinement factor (F_c), is 1.0 for blasting with free faces and 2.0 if movement is restricted.

Powder factor (PF) is also assumed to relate to vibrations. When in the range of 2.0 to 3.5 lb/yd^3, there is no penalty (F_p = 1). If PF is >3.5, then F_p = PF/3.5. If PF is below 2.0, than $F_p = (2/PF)^{0.5}$. While it is possible that high powder factors can increase vibrations, penalties for low values are less justified. Weak rock can be effectively blasted with low powder factors, with specific powder factors chosen for appropriate fragmentation and throw. Both the confinement factor (F_c) and charge weight (W) already account for the amount of energy and relief. Extensive studies of blast parameters for mining found these confinement factors to be of no significance to ground vibration, although important for airblast (*17*).

The large-distance factor (F_L) was developed from Lambeth's analysis of USBM measurements. It is unity for distances under 200 ft and [0.009 (R - 200) + 1] for greater distances. This factor increases without bounds (e.g., 1 for 200 ft, 4.6 for 600 ft, 10 for 1,200 ft). Possibly it cancels out some of the excess distance attenuation represented by the $R^{-1.925}$ factor elsewhere in the equation (based on $F_h \approx H/R$; see below). A more direct approach would be to drop the F_L correction and use a more appropriate attenuation exponent.

The "who is blasting" factor (F_w) assigns a small penalty of 1.2 if someone other than the pipeline company is responsible for the blasting.

The soil backing factor (F_h) comes into use when the charge depth is more than five times the pipe depth and was previously given in the SwRI report discussion. This multiplying factor increases indefinitely with increasing charge depth. For cases of potential permanent ground strain (close-in blasts), a good backing may constrain differential pipeline movement. However, its need is not evident in the more distant elastic-wave-only cases. At the same time, SwRI authors and those adapting the SwRI analyses have assumed perfect ground-to-pipeline coupling, which is not necessarily true because coupling can be highly variable. Although a free-surface multiplying factor of two times is justified from dynamics theory, there is no rationale for an unbounded factor. For the USBM tests, described in table A-3, the depth ratios are about 10, and the corresponding stress increase factor from this F_h term is about 2.43.

Lambeth's version of the SwRI stress equation was tested on three of the largest USBM blasts, and the results were compared with measured values. Using the various adjustment factors, the predicted stresses greatly exceeded the measured values (based on worst case stress-strain conversions), the extrapolated worst cases based on ideal coupling, and theoretical stresses computed from Dowding's equations (*12*) (table A-3). Eliminating the questionably applicable factors gives more comparable results. For example, a blast 21 prediction with F_p, F_L, and F_h equal to unity gives 25.8 MPa. This is exactly the USBM value for a worst case extrapolation from the measured strains, assuming they represent an ideal-coupled pipeline (table A-3). A similar computation for blast 29 was only about two times too high.

Table A-3.—Predicted stresses for three USBM blasts based on the SwRI equations, megapascals[1]

Blast	Predicted stresses		Stresses from measured strains		Calculated stresses	
	Full equation	$F_p, F_h, F_L = 1$	Actual maximums	Extrapolated from envelope	Bending	Ovaling
21 . . .	208	25.8	9.15	26	51	126
25 . . .	232	59	16.5	65	73	147
29 . . .	1,360	346	40.0	154	135	226

[1]MPa = 10^6 N/m^2.

Lambeth's paper (*8*) included some stress criteria for pipelines. One criterion, from a 1981 pipeline research committee panel, recommended that total stresses from pressurization and blasting should not exceed the MAOP stress envelope plus whatever adjustments are judged appropriate for the individual pipeline. Since stress from pressurization is usually limited to 72 pct of MAOP, the blasting plus adjustment part could equal the remaining 28 pct in the absence of other stresses. For a Grade B pipe with a SMYS of 240 MPa (35,000 lb/in^2), this would be 67.6 MPa (9,800 lb/in^2). Lambeth also mentioned an allowable additional stress of 55.2 MPa (8,000 lb/in^2) on a 61-cm (24-in) pipeline based on additional circumferential stresses from external load (transients) compared with the slow loading rate of internal pressurization (grade unspecified).

In reviewing the draft of this USBM RI, Lambeth stated the F_h should not be used in conjunction with F_L, since F_L was developed empirically from the USBM data and the F_h factor could not be applied because of insufficient data. As a result, F_L already includes the effects of charge depth and backing. However, Lambeth's stress prediction equation does include both factors (*8*).

Summarizing Lambeth's study, his experimental values appear to correspond only to close-in blasts and his adjustments to the SwRI prediction equation appear unjustified from blasting studies. They produce unrealistic stress values when applied to large-size mining-type blasts.

APPENDIX B.—VIBRATION AND STRAIN DATA

The following data table summarizes the peak values of all the USBM and key Vibronics, Inc., measurements. Blank spaces mean no reliable reading was obtained. This Cricket Graph table was used to summarize all the collected data and also to produce the plots comparing the various parameters of vibration and strain. Following the table is a key to column headings.

Shot	Date	Hour_Min	20_GV_V	20_GV_R	6_GV_V	6_GV_R	MB_R	MB_V	MB_T
1	31892	1107	9.3				13.08	7.06	8.76
2	32092	1110	1.5	1.7	1.42				
3	32092	1343	5.28	3.94	4.42				
4	32092	1353	6.22	4.29	3.33				
5	40292	1715	1.55	3.81	1.19	3.05			
6	40292	1740	15.24	30.48	11.68	22.1			
7	40292	1841	1.22	1.8	1.07				
8	42992	1124			1.27		7.62	1.98	
9	42992	1920	1.32		0.81	0.91	6.1	1.42	
10	60292	1120					3.86	1.45	
11	60292	1721							
12	60592	1115							
13	60592	1124	2.11	2.18	0.66		2.92	1.6	
14	60592	1407	1.4	1.3	0.99		2.36	1.45	
15	60592	1714	34.29	48.01	33.53	30.23	88.14	50.8	
16	61092	923	35.81	16	19.05	19.3	67.06	30.99	
17	80392	1413							
18	80592	1114			4.57	5.84	17.09	7.52	
19	80692	1455	6.91	6.3	5.59	4.6	16.51	5.59	
20	80692	1709	47.24	86.87	63.75	84.33		97.28	
21	80692	1804	52.58	102.11	70.36	109.47	147.83	130.56	
22	80792	1818	35.81		35.31	34.8		79.76	44.2
23	91692	1108	121.41		105.92	113.03	125.98	205.74	
24	91892	1433							
25	91892	1054					187.96	209.8	
26	91992	1425			59.18	65.28	97.79	169.42	
27	92192	1209					65.28		
28	102192	1255							
29	102392	1118			274.32				184.15
30	102492	1554			146.3	63.5	205.74	219.96	222.5
31	102492	1625			2252.98	1653.54			

Shot	Alpha_S_R	Alpha_S_V	Alpha_S_T	PVC_TL	PVC_FL	20_S_TL	20_S_TC	20_S_FL	20_S_FC
1	13.08	7.06	8.76	6.9	4	4.3	5.3		
2	3.81	1.52	3.3	2.45		0.73	2.81	0.73	
3	10.41	10.67	7.87	4.9	3	2.2	2.2	1.5	
4	9.14	7.11	8.38	6.98	3.62	1.54	7.98	1.04	
5	9.14	2.03	7.11	2	1.59	0.6	3.62	0.95	
6	67.06	20.83	51.31	30.3	8.61	9.8	28	12.5	
7	5.08	1.52	3.05	1.04		0.45	2.5	0.63	
8	7.87	2.03	5.84	4.81		2.94	10	2.54	3.76
9	6.86	1.52	4.83	3.62		1.77	6.25	1.59	2.45
10	4.32	1.52	5.33						
11	69.09	55.88	93.47	35		24.2	66.4	16.7	
12	120.9	61.98	84.33	47.3		26.5	51.3	29.1	
13	3.3	1.02	2.54	2		1	1.77	1.18	
14	3.81	1.02	1.78	2.45					
15	83.31	61.98	88.39	38.5		28.6	48.3	19	
16	60.96	31.5	36.58	25.3		12.8	20.9	12.4	4.35
17	16.26	5.08	17.27	10.1		4.49	4.22	3.67	
18	16.26	7.52	8.64	9.61		3.36	2.72	3.45	2
19	14.22	9.14	10.67	15	15.9	4.76	10.7	3.4	
20	136.14	109.73	125.98	57.1	97.5	31.1	63	24	25.8
21	166.62	119.89	156.46	57.1	102.5	24.9	33.5	21.3	
22	85.34	67.06	125.98	42.6	76.2	19.5	55.8	17.2	13.1
23	164.59	144.27	144.27	92.9		50.8			43.2
24									
25	168.66	241.81	231.65	137		60.8	46		31.1
26	93.47	148.34	119.89	63		44	44		
27	81.28	42.67	62.99	37.6		24.3	25.4		
28									
29	227.58	237.74	156.46		499	156	77		
30						76.1	51.6		
31						3169	490		

Shot	12_N_S_TL	12_O_S_TL	12_O_S_FL	6_S_FC	6_S_TC	6_S_FL	AS_20_R	AS_20_V	AS_20_T
1									
2	1.18								
3	2.9								
4	1.63								
5	1.13	0.77							
6	6.6	8.7	11.5	9.1	23	10.5			
7	0.63	0.54	0.68						
8	2.4		2.04			1.59			
9	1.59	1.4	1.54		1.31				
10									
11	26	17.2	14.1	12.7	39	14			
12		21	23.4	19.6	26.7	31			
13	1.18	0.91	1.36						
14	1.09								
15		26.1	23.7	12.8	30.5	32.4			
16	13.3	13.3	10.1	8.4		15.6			
17	14.4		5.17	13.6		5.98			
18		3.45	2.72	1.45		3.08			
19		4.08	3.63			2.04			
20		19.9	22.7	13.1		22.2			
21		23.6	19.5	29.5		51.7			
22		18.1	17.7	22.7		30.8	57.91	41.15	33.02
23	49.6			16.2	31.1	26.3	62.99	130.05	148.34
24									
25	50.8	37.6		38	53.5	59.9	178.82	211.33	79.25
26	32	28.8	36.7	20.5	28.8		87.38	95.5	67.06
27	18.8	22.2	17.7	14.3	18.8	15.6	41.15	34.04	39.62
28									
29	82			41.2	94.8		239.78	233.68	103.63
30	77.5			22.1	55.8				
31	3140			499	664				

Shot	Distance	Kg_delay	20_S_45	SR4_1_R	SR4_1_V	SR4_1_T	SR4_2_R	SR4_2_V	SR4_2_T
1	338	435							
2	1064	135							
3	381	435							
4	436	435							
5	869	588							
6	180	751							
7	933	218							
8	802	464							
9	847	539							
10	756	626							
11	146	639							
12	125	773							
13	920	301							
14	951	181							
15	131	689							
16	192	959							
17	387	465							
18	506	828							
19	552	600							
20	88	731							
21	88	964		228.6	88.9	165.1	188.72		241.30
22	116	884							
23	67	964		139.7	88.9	279.4			
24									
25	50	839	32.5	203.2	165.1	241.3	647.70	276.86	190.50
							368.30	125.73	228.60
26	74	872	21	88.9	76.2	152.4	665.48	812.80	736.60
27	158	668	9.97	63.5	25.4	101.6			
28									
29	20	839	68	584.2	444.5	254			
30	52	706	27.8	152.4	152.4	279.4			
31	14	743	2035	889	698.5				

Shot	B&K_R	B&K_V	B&K_T
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21	167.64		185.42
22	100.08		114.81
23	60.96		60.96
24			
25	520.70		191.26
	530.86	207.52	
26	982.98	3200.40	
27			
28			
29			
30			
31			

Key to Column Headings, Appendix B

Date.....31892.00000 is March 18, 1992

Hour_Min....1107.000 is 11:07 on 24-h clock

20_GV_V....Vertical vibration of 50.8-cm (20-in) pipe, mm/s

20_GV_R....Radial vibration of 50.8-cm (20-in) pipe, mm/s

6_GV_V.....Vertical vibration of 16.8-cm (6-in) pipe, mm/s

6_GV_R.....Radial vibration of 16.8-cm (6-in) pipe, mm/s

MB_R.....Radial ground vibration above 50.8-cm (20-in) pipe, mm/s

MB_V.....Vertical ground vibration above 50.8-cm (20-in) pipe, mm/s

MB_T.....Transverse ground vibration above 50.8-cm (20-in) pipe, mm/s

Alpha_S_R..Radial ground vibration above point midway between 50.8-cm (20-in) steel pipe and PVC water pipe, mm/s

Alpha_S_V..Vertical ground vibration above point midway between 50.8-cm (20-in) steel pipe and PVC water pipe, mm/s

Alpha_S_T..Transverse ground vibration above point midway between 50.8-cm (20-in) steel pipe and PVC water pipe, mm/s

PVC_TL.....Top longitudinal strain of PVC pipeline, μmm/mm

PVC_FL.....Front longitudinal strain of PVC pipeline, μmm/mm

20_S_TL....Top longitudinal strain of 50.8-cm (20-in) steel pipe μmm/mm

20_S_TC....Top circumferential strain of 50.8-cm (20-in) steel pipe μmm/mm

20_S_FL....Front longitudinal strain of 50.8-cm (20-in) steel pipe μmm/mm

20_S_FC....Front circumferential strain of 50.8-cm (20-in) steel pipe μmm/mm

12_N_S_TL..Top longitudinal strain of new 32.4-cm (12-in) steel pipe μmm/mm

12_O_S_TL..Top longitudinal strain of old 32.4-cm (12-in) steel pipe μmm/mm

12_O_S_FL..Front longitudinal strain of old 32.4-cm (12-in) steel pipe μmm/mm

6_S_FC.....Front circumferential strain of 16.8-cm (6-in) steel pipe μmm/mm

6_S_TC.....Top circumferential strain of 16.8-cm (6-in) steel pipe μmm/mm

6_S_FL.....Front longitudinal strain of 16.8-cm (6-in) steel pipe μmm/mm

AS_20_R....Alpha-Seis monitoring of radial vibration of 50.8-cm (20-in) pipe, mm/s

AS_20_V....Alpha-Seis monitoring of vertical vibration of 50.8-cm (20-in) pipe, mm/s

AS_20_T....Alpha-Seis monitoring of transverse vibration of 50.8-cm (20-in) pipe, mm/

Distance...Vector distance from top of closest blasthole to 16.8-cm (6-in) pipeline,

Kg-delay...Maximum charge weight per 8-ms delay

20_S_45....Top 45° angle strain of 50.8-cm (20-in) steel pipe, μmm/mm

SR4_1_R....Strong-motion monitoring of radial vibration above 16.8-cm (6-in) pipe, mm/s

SR4_1_V....Strong-motion monitoring of vertical vibration 16.8-cm (6-in) pipe, mm/s

SR4_1_T....Strong-motion monitoring of transverse vibration 16.8-cm (6-in) pipe, mm/s

SR4_2_R....Strong-motion monitoring of radial vibration above and between two 32.4-cm (12-in) pipes

SR4_2_V....Strong-motion monitoring of vertical vibration above and between two 32.4-cm (12-in) pipes

SR4_2_T....Strong-motion monitoring of transverse vibration above and between two 32.4-cm (12-in) pipes

B&K_R.....Radial ground vibration above 50.8-cm (20-in) pipe, mm/s

B&K_V.....Vertical ground vibration above 50.8-cm (20-in) pipe, mm/s

B&K_T.....Transverse ground vibration above 50.8-cm (20-in) pipe, mm/s

APPENDIX C.—SURVEY DATA[1] FOR FIVE PIPELINES

Date	East upright North	East upright East	East upright Elev	Center upright North	Center upright East	Center upright Elev	West upright North	West upright East	West upright Elev
				16.8-cm STEEL					
4-8.....	0.628	0.470	0.696	0.771	0.498	0.559	0.789	0.274	0.144
5-7.....	0.619	0.470	0.682	0.776	0.480	0.562	0.791	0.271	0.144
6-11....	0.622	0.480	0.682	0.777	0.491	0.559	0.779	0.281	0.142
8-5.....	0.614	0.469	0.685	0.794	0.496	0.546	0.824	0.293	0.114
9-14....	0.618	0.484	0.675	0.779	0.479	0.535	0.791	0.286	0.105
9-18....	0.603	0.476	0.671	0.780	0.517	0.540	0.797	0.315	0.113
10-24..	0.618	0.472	0.583	0.804	0.538	0.458	0.817	0.300	0.065
10-26..				2.959	-2.385	0.273	0.839	0.474	0.113
				32.2-cm STEEL (USED)					
4-8.....	0.672	0.416	0.714	0.071	0.939	0.299	0.396	0.223	0.988
5-7.....	0.660	0.404	0.702	0.054	0.945	0.315	0.383	0.221	0.988
6-11....	0.648	0.428	0.692	0.047	0.946	0.306	0.377	0.232	0.982
7-5.....	0.673	0.432	0.691	0.055	0.952	0.296	0.411	0.223	0.962
9-14....	0.659	0.439	0.675	0.038	0.947	0.281	0.400	0.225	0.948
9-18....	0.658	0.446	0.674	0.045	0.974	0.284	0.393	0.235	0.952
10-24..	0.688	0.445	0.579	0.065	0.964	0.194	0.421	0.249	0.910
10-26..	0.841	-0.207	0.392	0.820	-2.736	0.455	0.405	0.674	0.892
				32.2-cm STEEL (NEW)					
4-8.....	0.741	0.459	0.656	0.771	0.970	0.608	0.271	0.362	0.589
5-7.....	0.723	0.431	0.647	0.757	0.968	0.609	0.276	0.367	0.597
6-11....	0.741	0.425	0.643	0.761	0.978	0.594	0.277	0.377	0.600
7-5.....	0.740	0.429	0.648	0.781	0.980	0.585	0.314	0.346	0.585
9-14....	0.731	0.430	0.638	0.749	0.979	0.571	0.284	0.372	0.569
9-18....	0.738	0.432	0.639	0.765	0.004	0.570	0.285	0.391	0.559
10-24..	0.775	0.413	0.540	0.805	0.008	0.473	0.318	0.394	0.506
10-26..				0.922	-3.849	2.859	0.287	0.585	0.553
				50.8-cm STEEL					
4-8.....	0.102	0.291	0.049	0.220	0.261	0.423	0.470	0.756	0.637
5-7.....	0.108	0.314	0.047	0.220	0.276	0.430	0.462	0.754	0.643
6-11....	0.131	0.299	0.032	0.223	0.285	0.426	0.471	0.763	0.641
7-5.....	0.116	0.275	0.031	0.231	0.269	0.419	0.497	0.752	0.611
9-14....	0.130	0.313	0.017	0.220	0.274	0.403	0.477	0.716	0.594
9-18....	0.129	0.309	0.014	0.220	0.283	0.394	0.481	0.755	0.598
10-24..	0.171	0.297	-0.092	0.271	0.302	0.299	0.518	0.766	0.540
10-26..	0.105	2.252	-1.685	-1.561	-5.930	0.487	0.577	0.831	0.573
				21.9-cm PVC					
5-7.....	0.436	0.353	0.251	0.794	0.218	0.999	0.633	0.690	0.068
6-11....	0.364	0.356	0.245	0.794	0.176	0.989	0.650	0.737	0.072
7-5.....	0.310	0.369	0.251	0.826	0.128	0.974	0.658	0.719	0.048
9-14....	0.268	0.328	0.237	0.808	0.146	0.962	0.626	0.737	0.029
9-18....	0.246	0.301	0.236	0.812	0.165	0.967	0.633	0.744	0.032
10-24..	0.403	0.276	0.143	0.866	0.146	0.873	0.627	0.762	-0.037
10-26..	0.242	1.11	0.125	-0.112	-2.823	0.933			

[1]As measured by Amax Coal Co.; relative elevations in feet.

PATHFINDER CHART FOR CALCULATING BLASTING STRESS ON STEEL PIPELINES

PATHFINDER CHART provides step by step directions on how to convert complex shot-pipeline configurations to one of two basic analysis modes. Once this is done, the user simply solves one of two equations to find the blasting stress.

PATHFINDER CHART equations were developed by Southwest Research Institute of San Antonio, TX for the American Gas Association. PATHFINDER is based on results published in the American Gas Association report, "Pipeline Response to Buried Explosive Detonations", by E. D. Esparza, P. S. Westine and A. B. Wenzel, Aug.1981, (No L51406). Users are advised to read the AGA report prior to applying PATHFINDER CHART methods.

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EQUATIONS & NOTES

PATHFINDER CHART CARD 1
MODES OF ANALYSIS AND PRECAUTIONS

NOTE: Users of this PATHFINDER CHART are assumed to be knowledgeable in the use and general effects of explosives detonated near underground structures. It is also assumed that the user has read and understood American Gas Association report L51406, "Pipeline Response To Buried Explosive Detonations, Volumes I & II".

POINT SOURCE is the first mode. A point source can be thought of as a spherical charge placed in a single hole buried to a depth equal to that of the pipe's center. Equation A is used to determine blasting stress on a steel pipeline from such a charge. Equation A is also used for more complex shots by substituting equivalent values for the variables. Equivalent values can be determined easily by using the remaining **PATHFINDER CHART** cards.

LINE SOURCE is the second mode. A line source can be thought of as a continuous line of charge buried at the same depth of a pipeline's center and running parallel to the steel pipeline. Equation B is used for multiple-holed shots which cannot be simplified to the point source mode. Equivalent values are given for each variable on the remaining **PATHFINDER CHART** cards.

EQU. A
(Point Source)

$$\sigma = C \; E \left(\frac{(n\,W)}{(E\,h\,F)^{.5} \; (R)^{2.5}} \right)^{0.77}$$

EQU. B
(Line Source)

$$\sigma = C \; E \left(\frac{(1.4\,n)\,(W/L)}{(E\,h)^{.5} \; (R)^{1.5}} \right)^{0.77}$$

where, consistently using either English or Metric units:

- σ = blasting stress (PSI or KPa)
- C = 4.44 for English units; C = 2.5 for Metric units
- E = Young's modulus of elasticity (PSI or KPa)
- W = equivalent charge weight (LB or KG)
- h = wall thickness (IN or CM)
- R = equivalent distance between pipe and shot as measured along a line perpendicular to the pipeline (FT or M)
- L = equivalent length of explosive line (FT or M)
- F = correction factor (= 1 unless specified otherwise)
- n = equivalent energy release, as given on the next card

Equation A assumes that "R" is greater than 2 pipe diameters and was developed using stress data exceeding 600 PSI (4.2 MPa). Equation B was developed using stress data over 1828 PSI (12.6 MPa).

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EQUATIONS & NOTES

PATHFINDER CHART CARD 2
EQUIVALENT ENERGY RELEASE TABLE

EXPLOSIVE	AVE. SPEC.ENERGY (million ft-lbf/lbm)	n
HBX-1	1.30	.86
TNT	1.49	.98
AN Low Density Dynamite	1.50	.99
ANFO (94/6)	1.52	1.00
NG Dynamite	1.59 - 1.70	1.05 - 1.12
Pentolite (50/50)	1.68	1.11
Comp B (60/40), Comp C-4	1.70	1.12
RDX	1.76	1.16

"n" is based on the specific energy of the explosive relative to that of ANFO. See explosives supplier to verify specific energy.

PRECAUTIONS & GENERAL GUIDELINES
Most shot patterns in the field will differ from those given here. Analysts must use their own judgement and bear sole responsibility in any use, misuse or modification of the methods. When in doubt, choose the most conservative assumption. A few rough guidelines are given below.

- Single holes with a short column of explosives can be approximated as single hole charges. Use the correction factor for depth based on the lowest point in the column.
- 'Line Sources' and 'Grid Sources' are assumed to be a group of identical, single hole charges detonated simultaneously. Decks, holes or groups of holes are assumed to detonate simultaneously if the actual delay intervals between the detonation of the decks, holes or groups of holes are less than 25 milliseconds.
- When blasting occurs near looped pipelines (two of more parallel pipelines), the pipeline(s) farthest from the shot may experience greater blasting stress than the closest pipeline. Assume a standoff distance for the more distant pipeline equal to that of the closest pipeline.
- The PATHFINDER CHART equations determine only the blasting stress on a steel pipeline. Blasting stress must be combined with other pipeline stresses, i.e. thermal, internal pressurization, etc., to determine the total stress.
- The user should use a safety factor. In determining the safety factor, consider that Equations A and B have a standard deviation of 34%. Using statistics, 95% of all blasting stresses should be within those values calculated plus or minus two standard deviations.
- For any line or grid source, always check to see if the charge nearest the pipeline would produce a greater stress than that calculated using PATHFINDER CHART methods. Use the most conservative calculation.

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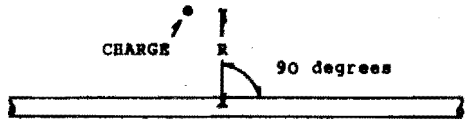
POINT

PATHFINDER CHART CARD 3
Point Charge



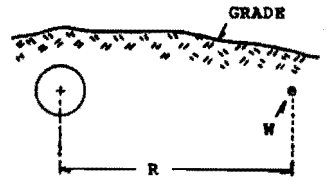
CASE/EQUATION VALUES	EQUIVALENT DIAGRAM

1) Charge depth equal to depth of pipe center, use:

EQU. A

where:

W = charge weight
R = perpendicular distance between charge and pipe

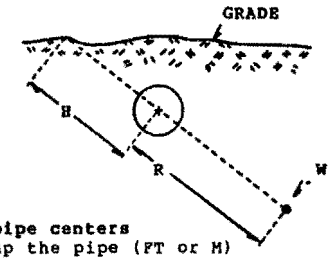


2) Charge is much deeper than pipe center or pipe is located near a depression, cliff, or hill as shown below right, use:

EQU. A

where:

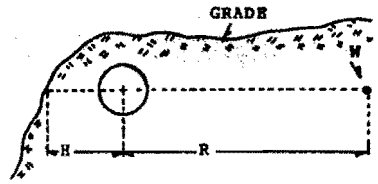
W = charge weight
R = distance between charge & pipe centers
H = thickness of soil backing up the pipe (FT or M)



If $R \leq 4H$ then: $F = 1$
If $R > 4H$ then:

$$F = \frac{(H)}{(R)} + \frac{C2 \ (\rho p \ h)}{(\rho s \ R)}$$

ρp = pipe material density (LB-SQ.SEC/FT or KG/CU.M)
ρs = mass density of soil (LB-SQ.SEC/FT or KG/CU.M)
C2 = 0.833 for English Units
C2 = 0.010 for Metric Units



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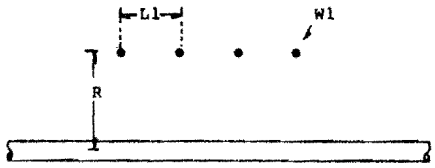
LINE (PARALLEL)

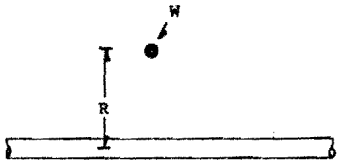
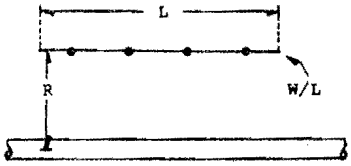
PATHFINDER CHART CARD 4

Parallel Line Charge



L = (N1)(L1)

If R > L, use method (a). If R ≤ L, use method (b).

CASE/EQUATION VALUES	EQUIVALENT DIAGRAM
(a) Line charge parallel to pipeline and R > L use: EQU. A where: N1 = no. of charges in line W1 = weight of each charge W = (N1)(W1) R = R	
(b) Line charge parallel to pipeline and R ≤ L use: EQU. B where: N1 = no. of charges in line W1 = weight of each charge L = (N1)(L1) W = (N1)(W1) W/L = (W1)/(L1) R = R	

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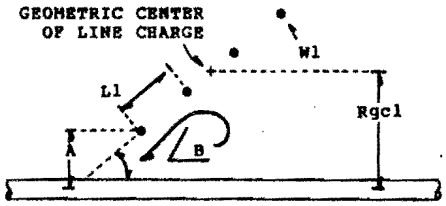
LINE (ANGLED)

PATHFINDER CHART CARD 5
Angled Line Charge



L = (N1)(L1)

"Rref" is calculated to determine which mode to use.
Rref = Rgcl/cosB: If Rref > L, use (a). If Rref ≤ L, use (b).

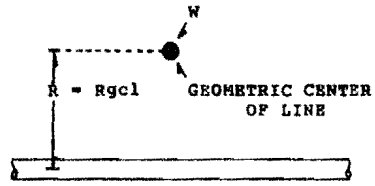
CASE/EQUATION VALUES	EQUIVALENT DIAGRAM

(a) Line charge angled to pipeline and Rref > L use:

EQU. A

where:

N1 = no. of charges in line
W1 = weight of each charge
W = (N1)(W1)
R = Rgcl = A + [((N1-1) L1 SinB) / 2]



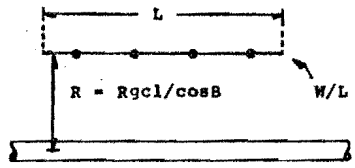
(b) Line charge angled to pipeline and Rref ≤ L use:

EQU. B

where:

N1 = no. of charges in line
W1 = weight of each charge
A = distance to nearest charge
L = (N1)(L1)
W = (N1)(W1)
B = angle which line charge forms with pipeline
W/L = (W1)/(L1)

$$R = Rgcl/\cos B = \left[\frac{A + [\ ((N1-1)\ L1\ \sin B\ )\ /\ 2\ ]}{\cos B}\right]$$



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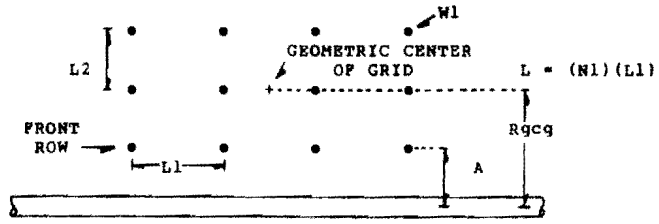
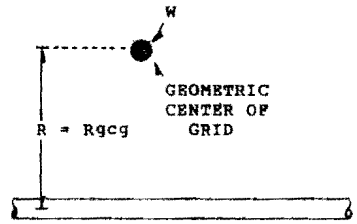
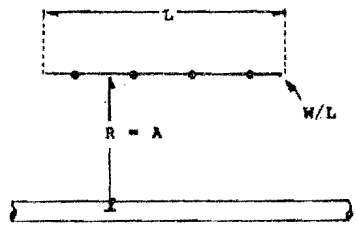
GRID
(PARALLEL)

PATHFINDER CHART CARD 6
Parallel Grid



"Rref" is calculated to determine which mode to use.
Rref = A: If Rref > 1.5L, use (a). If Rref ≤ 1.5L, use (b).

CASE/EQUATION VALUES	EQUIVALENT DIAGRAM
(a) Grid charge parallel to pipeline and Rref > 1.5L use: EQU. A	
where: N1 = no. of charges in front row; N2 = no. of rows; W1 = weight of each charge; W = (N1)(N2)(W1); $R = Rgcg = A + \frac{(N2-1)L2}{2}$	
(b) Grid parallel to to pipeline and Rref ≤ 1.5L use: EQU. B	
where: L1 = spacing of charges in front row; L2 = spacing of rows; W1 = weight of each charge; N1 = no. of charges in front row; L = (N1)(L1); A = distance to nearest charge; W/L = W1/L1; R = A	

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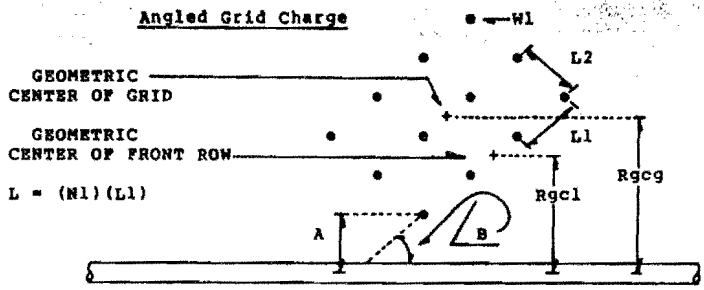
GRID (ANGLED)

PATHFINDER CHART CARD 7

Angled Grid Charge



"Rref" is calculated to determine which mode to use.
Rref= Rgcl/cosB: If Rref > 1.5L, use (a). If Rref ≤ 1.5L, use (b).

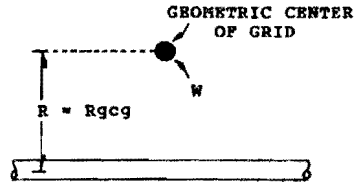
CASE/EQUATION VALUES	EQUIVALENT DIAGRAM

(a) Grid charge angled to pipeline and Rref > 1.5L use:

EQU. A

where:

A = dist. to nearest charge
N1 = no. of charges in front row
N2 = no. of equally spaced rows
W1 = weight of each charge
W = (N1)(N2)(W1)
R = Rgcg = A + [[(N1-1)(L1)(sinB) + (N2-1)(L2)(cosB)] / 2]

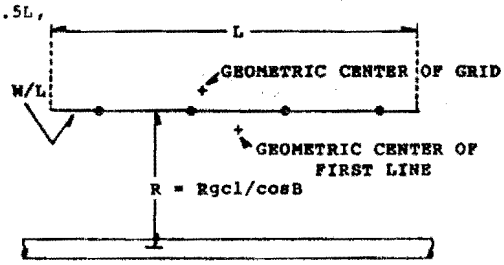


(b) Grid charge angled to pipeline and Rref ≤ 1.5L, use:

EQU. B

where:

A = distance to nearest charge
L1 = charge spacing
N1 = no. of charges in front row
N2 = no. of equally spaced rows
W1 = weight of each charge
W/L = (W1)/(L1)
R = Rgcl/cosB = [A + [((N1-1) L1 SinB) / 2]] / cosB



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TECHNICAL REPORT

REG. NO.:

DATE: 2/19/85

BLASTING AND PIPELINES

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Gerald Murray, P.E.
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1984 KENTUCKY BLASTING CONFERENCE

ABSTRACT

On-site diagnostic testing is the only assured way for the explosive user to conclude that blast effects are safe to fluid transmission pipelines, or water and sewer lines. The current regulatory limitations based on ground particle velocity have no bases and correspond to residential criteria.

This paper reviews reports for the American Gas Association and other studies, including in-house reports that show particle velocity is not the limiting criteria, but pipe stress is. Pipe stress-particle velocity can be related but only by field testing.

INTRODUCTION

The problem of blasting adjacent to pipelines carrying everything from water to natural gas has troubled many, both the explosive user, the pipelines owner and those dependent on the pipelines availability. Pipelines are encountered in rural and urban areas, likewise explosives are used in widespread areas, so one is assured that at times the explosive user and pipeline operator will be in contact. Each will have to understand the concern of the other party and the effects on performance and how they can co-exist in a safe manner.

The construction industry, mainly those involved in utility projects encounter water, sewage, gas and other services buried underground and transported or protected by pipe or conduit. When explosives are employed, extreme care is used or one excavates by hand or mechanical methods. In the majority of cases, ground displacement rather than vibration levels are a major concern and cautious blasting procedures need to be followed to assure any or all standards of safety are met.

Quarries and other surface mining operations outside of coal, follow the recommendations of consultants, regulations of various local or state agencies, or agreements between the interested parties. Since the distance between the pipeline and the mining is relatively large, the limitation is in terms of vibration and induced stresses rather than the physical displacement of ground which occurs in close-in blasting.

Blasting, in the operation of surface coal mines is regulated by federal standards outlined in General Performance Standards (Part 715, Sec. 19 - Use of Explosives) of the U.S. Department of the Interior, Office of Surface Mining (OSM). In 715.19,(e) Blasting Procedures, it states under paragraph (vii)(B):

. "Except where lesser distances are approved by the regulatory authority (based upon a pre-blasting survey or other appropriate investigations) blasting shall not be conducted within-

  500 feet of facilities including, but not limited to disposal wells, petroleum or gas-storage facilities, fluid-transmission pipelines, gas or oil-collector lines, or water and sewage lines; and"

A vibration criteria has not been set, therefore in Subchapter K - Permanent Program Performance Standards 816.67,(d) - Ground Vibration - (1) General, states:

. "All structures in the vicinity of the blasting area, not listed in paragraph (d)(2)(i) of this section, such as water towers, pipelines and other utilities, tunnels, dams, impoundments, and underground mines, shall be protected from

damage by establishment of a maximum allowable limit on the ground vibration, submitted by the operator in the blasting plan and approved by the regulatory authority."

The majority of the explosive using industry when confronted with a potential problem of blast vibrations has used standards that were developed for the protection of residential structures. Present conditions though have made both the blasting industry and the pipeline owner desire a method based on relating maximum pipe stress to particle velocity and charge weights.

INSTRUMENTATION

To carry on an investigation of pipeline response one needs to use a ground motion seismograph that records a full time history. In addition, strain gauges should be used along with a recorder to determine the actual stresses on the pipeline, if this is determined to be necessary.

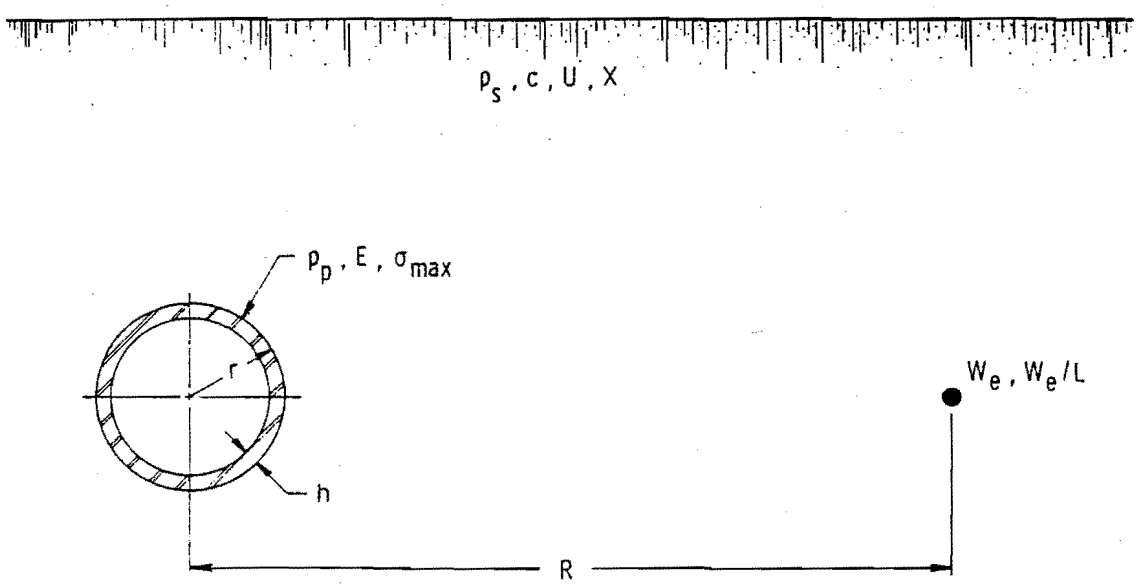
In choosing a seismograph, it is important that the instrument records the entire waveform since it is a far more versatile method of recording because information pertaining to frequency, duration and amplitude can be obtained. Peak recording instruments provide only peak amplitude and contain no information about duration of frequency. Film or magnetic analog or digital waveform recorders are currently available and one should choose from any of the various types manufactured today.

For strain measurements one could use either weldable or adhesive (bondable) type strain gauges, depending on the weather conditions and temperature. The majority of pipes need to be cleaned and the surface prepared for the placement of the gauges. Once the gauges are placed on a pipe, a protective coating or barrier is laid over the gauges to keep out moisture and dirt to ensure that the gauges function.

To actually record the strains, one needs to use a recorder, film or tape with signal conditioning modules. Like waveform seismographs, many recorders presently on the market are available, one that we have used is a Honeywell Model 1858, fiber-optic cathode-ray tube, 18 channel paper recorder. Along with the recorder, plug-in modules for signal amplification and conditioning are required.

Using figures from Reference #6, one can see the layout of how a test was done by Westline and the circuit diagram for the instrumentation used.

Figure #1 is general review and definition of the pipe response problem. Some of the nomenclature is different from what is normally used for the more common terms, but the items are pertinent to the problem.



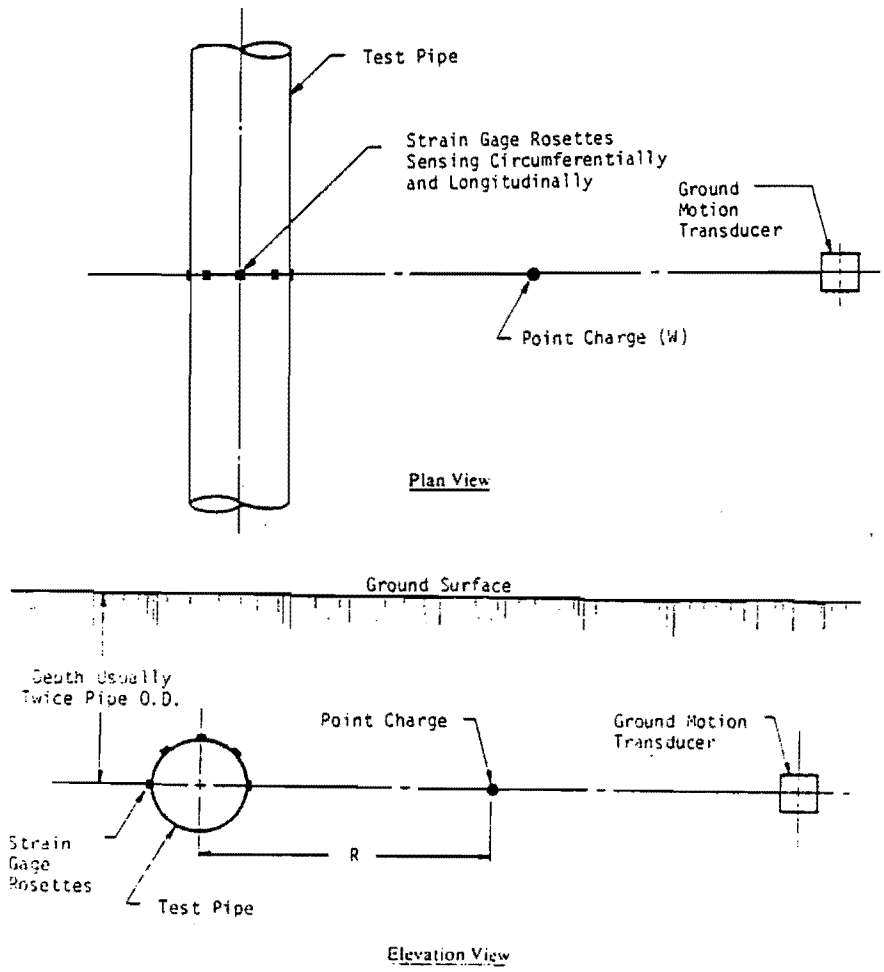
Definition of Pipe Response Problem

FIGURE 1

where:
- r = pipe radius
- h = wall thickness (t)
- ρp = mass density
- E = modulus of elasticity
- σmax = stresses
- R = distance (D) between pipe & explosion
- We = explosive, point source
- We/L = explosive, line source
- ρs = soil mass density
- c = P-wave propagation velocity
- U = particle velocity (v)
- X = particle displacement (A)

Figure 2 is a typical experimental layout for an explosive point source test by SWRI. Per SWRI, the experiments whether model of full-scale, were set up the same way.

> "With the exception of the one set of tests in which the charge was buried deeper, all point sources were buried at about the same depth as the centerline of the pipe opposite a location on the pipe that had been strain-gaged. On the other side of the charge, several ground motion transducers at different stand-off distances were buried to the same depth as the pipe, and oriented to sense horizontal radial ground motions. To measure the response of the tested pipes, strain gages were epoxy-bonded at a minimum of three and a maximum of five different stations along the upper-half-circumference of each pipe. Two-element strain gage rosettes were used to sense both hoop and axial strains at each station."

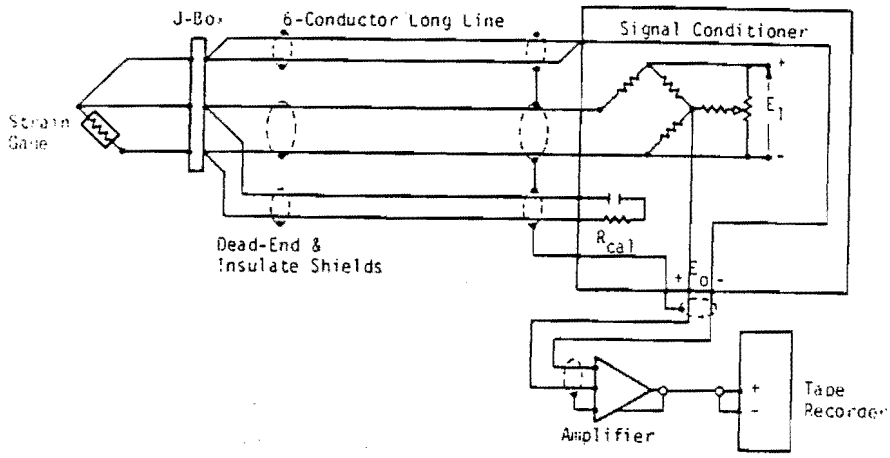


Typical Experimental Layout for Point Source Test

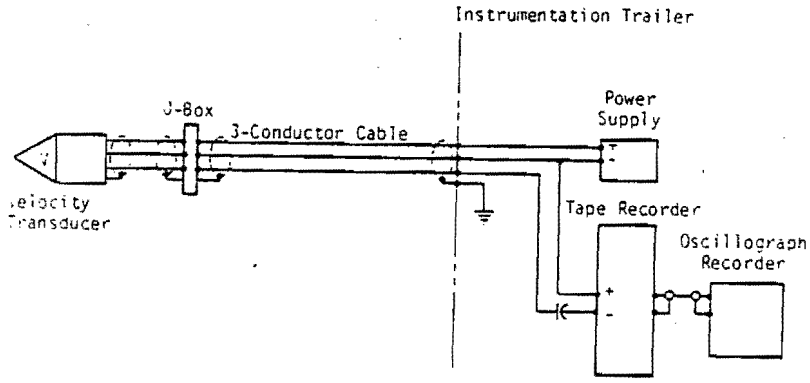
FIGURE 2

Figures 3 & 4 are circuit diagrams of the pipe strain gages and the velocity transducer (seismograph). SWRI states in their report on the gage installation:

> "Regardless of whether bondable or weldable gages were being used, each strain element was connected as a single active arm three-wire hook-up and remote electrical calibration connections as shown in Figure 3. B&F Model 1-700SG signal conditioner units provided bridge completion and balance, excitation voltage to the bridge, and a two-point electrical calibration. For each bridge, 14-15 VDC was used as the excitation voltage, making the bridge sensitivity about 7.5-8.0 microvolts/microinch/inch (μ V/Mϵ). Peak strains as low as 6 inch/inch ($\mu\epsilon$) were recorded for which the peak voltage prior to amplification was 0.045 millivolts.



Circuit Diagram for Pipe Strain Gages



Circuit Diagram for Soil Velocity Transducer

FIGURES 3 & 4

THE PROBLEM

Pipelines are totally restrained structures and can be damaged due to axial deformation, bending and buckling. Stretching and bending produce stresses in the longitudinal axis but the major concern is local buckling-hoop deformation which is due to perpendicular wave interaction on the pipe's long axis and circumferential stresses that are imposed overtime. Seismic waves that cause loads on a long buried structure are extremely complex. For example, in motion due to an earthquake, one to find its effects would need to use a 3-dimensional dynamic analysis of the pipeline and surrounding soil, including the effects of the soil-structure interaction.

Many criteria have been advanced to limit the amount of vibration allowable and still insure that no damage be done to structures such as homes but little has been done pertaining to engineered structures such as pipelines. Some general considerations that are needed are what the potential effects that near explosive detonation can have on a pipe.

The first, and potentially severe, effect would be abrupt displacement in a zone of rock breakage. The second effect would be ground failure due to the seismic motion. This could include a broad definition of ground failure such as liquefaction and gross settlement. Transient, recoverable deformation of the ground during seismic shaking constitutes the third effect on buried pipes. Transient loads and deformations are induced in buried components by two phases of shaking. The first, and most important phase in our case, is related to seismic waves in the surrounding soil or rock and the second phase is related to deformations of structural connections.

The first phase is the transient deformation imposed by seismic waves traveling through the rock and soil surrounding the pipe. Such deformations include longitudinal tension, compression, and bending in a pipe resulting when ground motion at two points along the propagation path of the seismic waves are out-of-phase. In the case of large diameter pipes, deformations of and/or lateral earth pressures acting on the cross section of the structural element may also require consideration in the design. The

overall complexity of the mechanism makes it difficult to predict the wave type that causes the peak ground motions and corresponding strain levels at a given location. In general, shear (S) and compression (P) waves are predominant in near distances, whereas the Rayleigh and Love surface waves are predominant in the far distances. Based on the complexities of the vibration wave, conservative procedures have been used to assure that the total stresses of strains remain within basic designed allowables.

If the explosive detonations would be some thirty feet from the existing pipeline, there is no danger from abrupt displacement. The reason is that if the nominal bore hole (drill hole) diameter is three inches, the approximate maximum that rock would be damaged is six times the bore hole diameter in feet, where damage is micro-cracking rather than physical displacement. This relates to:

Max Extent of cracking=6X(diameter)
= 6x3=18 feet

Also, damage due to liquefaction would only occur if the pipe is underlain or surrounded by saturated cohesionless soils. In addition, settlement would occur if pore water pressures in saturated soils are generated in soils during blasting and then dissipate afterwards. If there are very thin soils present neither case would apply. The basic concern is due to transient loads on the pipeline that are developed in hard rock at shallow depths, at near distances.

In reference #2, some general equations are given relating ground motion to strains and the assumptions that they're based on are:

1. Compressional, shear or surface waves are propagated in one direction without interference from other waves.

2. Changes in wave shape are ignored.

3. The relative motion of the buried motion of the pipeline is the same as the surrounding soil except at the elbows or tees or if the friction force between pipe and soil is exceeded; the buried structure is assumed flexible.

With the above assumptions, the instantaneous axial and bending strains in a section of pipe are given by:

$$\varepsilon a = V/C \qquad (1)$$

$$\varepsilon b = Ra/C^2 \qquad (2)$$

where:

εa = Axial strain

εb = Bending strain

V = Particle velocity

a = Particle acceleration

c = Apparent wave velocity

R = Radius of pipe

Empirical Stress Analysis

During the past five years, the Southwest Research Institute conducted an experimental study to determine the effects of explosive detonations on nearby pipelines. The work resulted in the following practical empirical equations for relating maximum induced stress to the explosive parameters:

$$\sigma max = 0.253\, \sigma^{1.304} \qquad (3)$$

$$\sigma = 46.53\, W(E/t)^{.5}/(D)^{2.5} \qquad (4)$$

where:

σmax = maximum pipe stress, psi
σ = stress constant, psi
W = Explosive weight, pounds
E = Modulus of elasticity of pipe, psi
t = Wall thickness of pipe, inches
D = Standoff distance, feet

Allowable Pipe Stress

The assumed allowable pipe bending stress is the difference in the allowable stress a-cording to the American Petroleum Institute (API) specification and pipeline location (Design factor) minus the

calculated longitudinal pressure stress divided by two:

$$S_A = 0.75 \times SMYS \times F \qquad (5)$$

$$S_L = P(d-2t)^2/d^2-(d-2t)^2 \qquad (6)$$

$$S_B = (S_A-S_L)/2 \qquad (7)$$

Factor of Safety = 2

Where: S_A = Allowable Stress (psi)

S_L = Longitudinal Pressure Stress (psi)

d = Pipe diameter, nominal outside (inches)
t = Pipe wall thickness (inches)

P = Maximum operating pressure (psi)

F = Design Factor (from 1 to 0.4)

S_B = Allowable bending stress (psi)

Scaled-Distance Criteria

The continuing research effort confirms that a relatively simple and useful criterion exists for relating the particle velocity of ground vibrations to explosive weight and distance. The general propagation equation is a log-normal function:

$$V = K(D/W^n)^X \qquad (8)$$

Where: V = Maximum particle velocity (in/sec)
D = Shot-to-pipe distance
W = Weight of explosive per delay
n - Scaling factor
k&X = Site characteristic parameters

Equation (8) is useful for predicting the level of ground vibrations to be expected at specific locations once the site parameters ($k\&_X$) have been determined. Previous experience on monitoring blasting in rock shows the relationship

$$V = 40.4\ (D/W^{.5})^{-1.206} \qquad (9)$$

Equation (9) is not true for all cases but one we developed from monitoring shots in medium hard

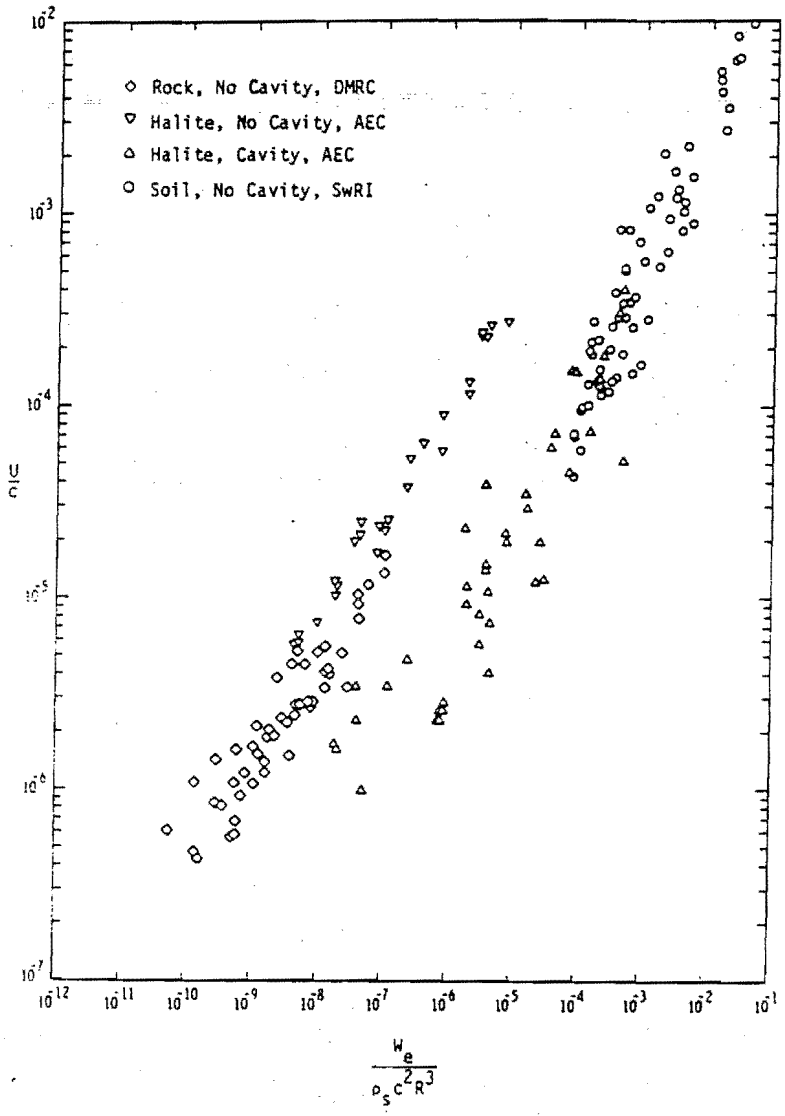
rocks in three different locations. Each site will give different variables for the propagation equation.

In Pipeline Response, etc., by Westline, a number of figures or curves were shown in their chapter on Ground Motion Relationships. Two curves, Figures 5 & 6 relating particle velocity to a scaled distance show blasts in different materials, coupled and uncoupled. Coupling occurs when the explosive is in contact with the rock or soil, poor coupling is when an air gap or cavity is between the explosive and transmitting media.

Figure 5, Particle Velocity in Rock and Soil No Coupling, shows data from the SWRI test site (shots of one pound or less in soil) and tests for the AEC (Atomic Energy Commission) in the salt domes of the deep South which were shots of 200 to 1,000 pounds. Also data from USBM Bulletin 656 was used, which is velocities obtained from quarry shots.

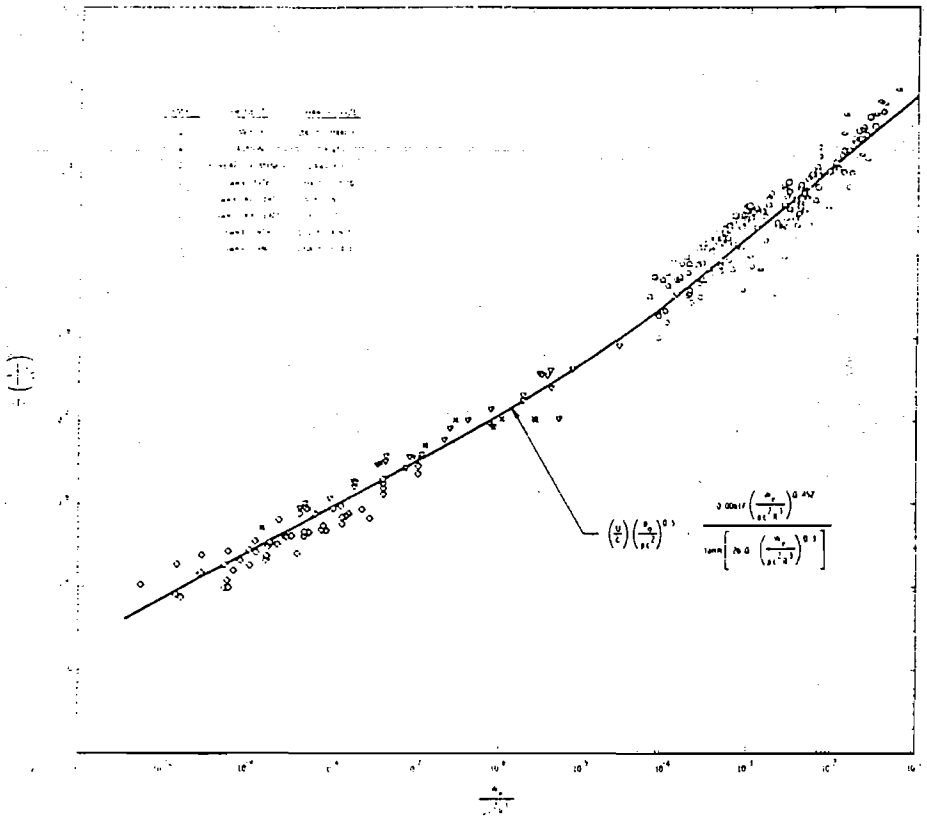
Figure 6, Coupled Radial Particle Velocity in Rock and Soil, in AEC data, SWRI data in soil and soft rock along with USBM quarry tests. The plot has the addition of an impedance term to the scaled velocity (U/C, which is radial ground particle velocity in ft. /sec., over rock or soil sound, P-wave, velocity in ft./sec.).

The two curves shown are based on empirical equations that are different from the common Scaled Distance relationship that predicts ground motion. The equation for the curve in Figure 6 is not log linear, and covers more orders of magnitude with a coupling term. Its discussion is beyond the scope of this paper, but it does show that type of blasts with site locations have effects on expected particle velocities.



Particle Velocity in Rock and Soil No Coupling

FIGURE 5



Coupled Radial Particle Velocity in Rock and Soil

FIGURE 6

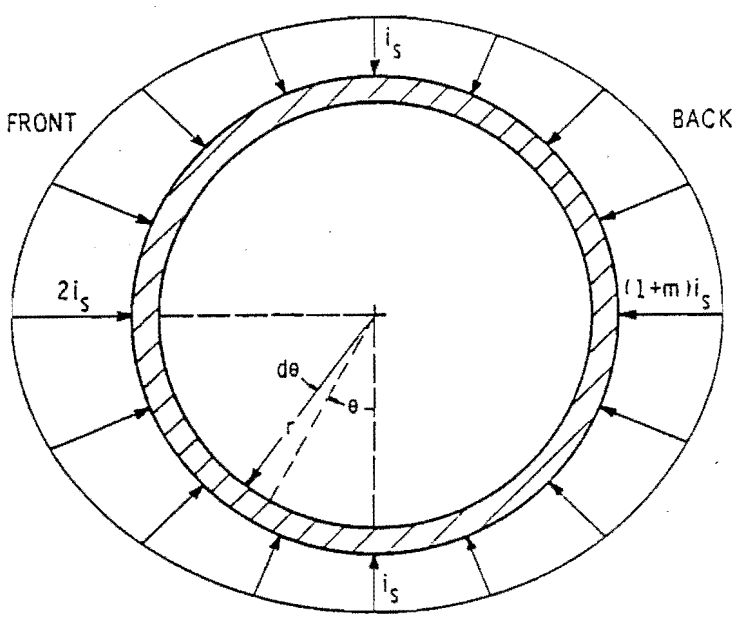
PIPE STRESSES

The ground motion from conventional blasting imparts a transient loading to a buried pipe which is the form of an impulse imparting kinetic energy. The kinetic energy is dissipated by changing to strain energy in both circumferential and longitudinal directions. The work by SWRI considered only elastic analysis of strain since yielding of a pipeline is considered unacceptable.

The impulse (i_s) is a function of soil density, ground seismic velocity and the particle displacement. Figure 7 shows a pipe loaded by an assumed distribution of applied impulse (SWRI). At the top and bottom of the pipe, the applied impulse will be i_s. A lower limit at the front of the pipe for the impulse will equal at least $2i_s$. Between the top and front edge of the pipe, some distribution will exist which is not known. The back side will also be loaded by the shock wave diffracting around the pipe, however, no one knows the exact magnitude. This was solved by assuming that the applied specific impulse equals $(1+m)i_s$ at the back side where m is less than 1.

$$i = i_s \left(1 + \frac{2\theta}{\pi}\right) \quad \text{for} \quad 0 < \theta < \frac{\pi}{2}$$

$$i = i_s \left(1 - \frac{2m\theta}{\pi}\right) \quad \text{for} \quad 0 > \theta > -\frac{\pi}{2}$$



Assumed Distribution of Impulse Imparted to a Pipe

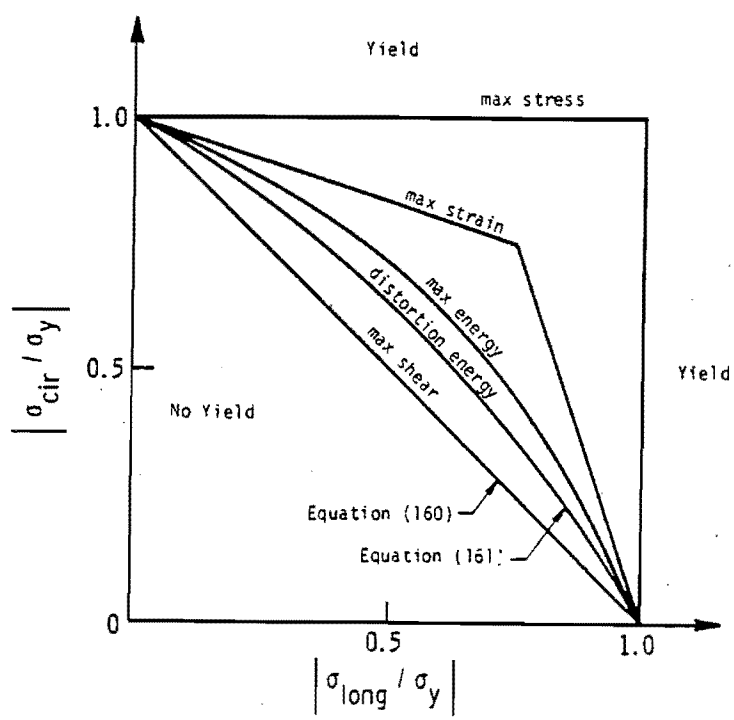
FIGURE 7

The studies done by researchers has shown that kinetic energy and strain energy are functions of pipe diameter. In the case of larger diameter pipes, more kinetic energy is imparted to the pipe as its diameter increases, but more strain energy can also be stored in pipes with larger diameters.

Stress is related to other variables, such as charge weight, pipe modulus of elasticity, pipe wall thickness and distance from shotpoint to the pipeline. Stress is most sensitive to distance and least sensitive to the pipe properties. The stress to blasting is only one of the stress parameters needed to determine if a buried pipe will yield, other loads cause a pipe to be stressed. These additional stresses are important and should be considered and includes:

1) Internal pipe pressurization
2) Thermal movements
3) Overburden thickness
4) Residual stresses

Once the resultant longitudinal and circumferential stresses have been obtained, a criteria for determining yield is needed. Figure 8 is the plot for the five theories of pipe yielding.



Simplified Yield Theories

FIGURE 8

The five theories are:

1) Maximum stress
2) Maximum strain
3) Maximum shear
4) Maximum energy
5) Distortion energy

All the lines in Figure 8 are envelopes and depending on the theory used, no yield occurs if one stays within a given envelope. From the plot, one can see that maximum shear is the most conservative criteria.

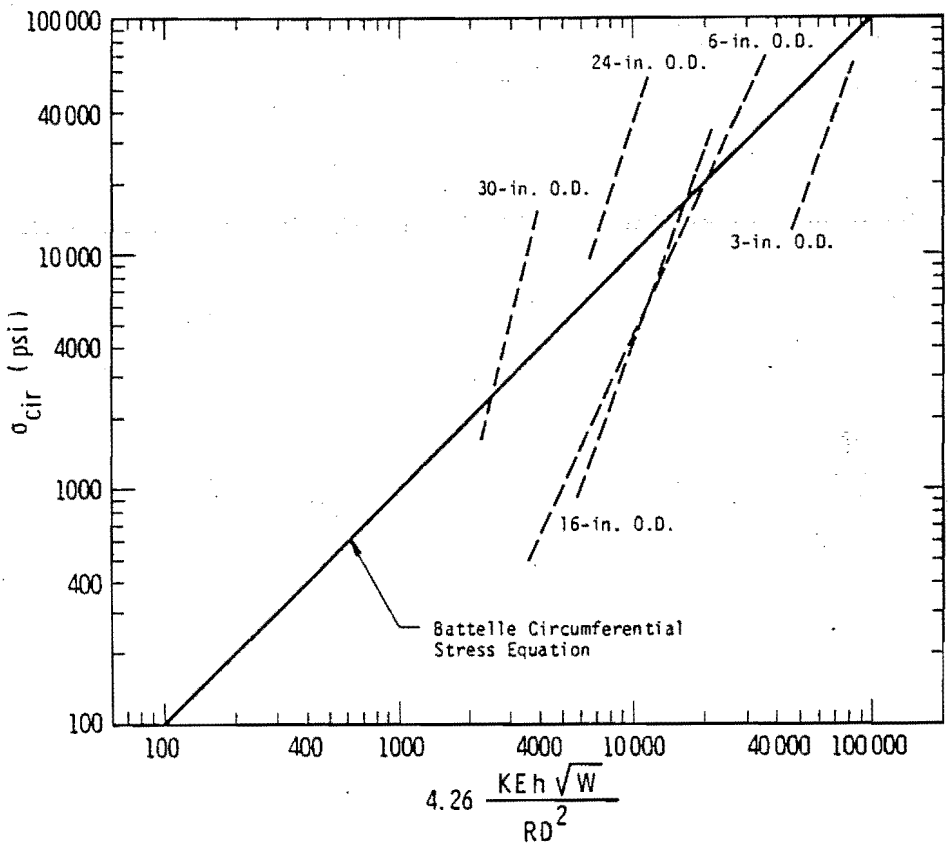
The SWRI report as is the Battelle Memorial Institute report (1964), both done for the AGA do not use a velocity criteria. The SWRI report states:

> "The velocity criteria are valid for buildings, <u>but not at all for buried pipes</u>. If one computes the radial soil particle velocity for many of our experiments, the unstressed pipe has very acceptable stress levels for particle velocities greater than 2.0 in./sec. These velocity criteria are in state laws because no data on pipelines existed, and no one had any concept of what else could be easily used."

The criterion derived by McClure, et al. (Ref. #7) assumes a quasi-static analysis and "permits no diffraction of the shock front around the pipe".

Figure #9 from the SWRI report shows a plot of their data versus the Battelle circumferential stress equation, stating that the equation is not proper since:

- The Battelle "Equation is not valid for standoff distances less than 100 ft. Nevertheless, this comparison is made because users have ignored the author's (McClure) qualifying statement and have used the equation at standoff distances smaller than 100 ft."



Battelle Circumferential Stress Formula Compared to Measured Pipe Stresses from Nearby Point Source Tests

FIGURE 9

What has been used in the past was the longitudinal bending stress equation at distances within 100 ft., for blasting in rock. Two assumptions made by McClure to predict longitudinal stresses are:

- The pipe is a long elastic beam on an elastic foundation.
- The displacement profile is the same as that produced by a concentrated load.

The major problem with any set of equations is that they have limitations and one can significantly under-predict pipe stresses. On-site diagnostic measurements to monitor blasting effects using low charge weights at the proposed or greater distances for the actual operation is the best alternative.

CASE BACKGROUND

The following is an actual case on how one can use the methods discussed for developing a program for predicting safe stresses on a 34.0 inch diameter pipeline that supplies the major portion of potable water to a city in the western U.S.

The water department wanted to place a parallel line within 35 ft. to the existing line and if it was possible to excavate the proposed trench for the new line by drilling and blasting. It would be the most cost effective method and a cost saving of some $1,000,000.00 dollars was projected if the use of explosives could be authorized. To assure the safety of the existing pipeline and the concerns of the water department, a relationship between actual ground motion and pipeline stress needed to be developed.

The existing line is some 15 to 20 years old and its thickness varies by some 1/16th of an inch and is constructed by welded steel sections. The pipe data presented by the owner was:

. Pipe Diameter, nominal	34.0 inches
. Pipe Wall thickness	0.31 inches
. Spec. Min. Yield Strength	42,000 psi
. Max. Oper. Pressure	386 psi
. Pipe Modulus	29×10^6 psi
. Design Factor*	0.5

*The Design Factor (F) is a safety factor that reduces the allowable stress (equation 5) and was selected so the allowable stress would be conservative. The Design Factor could be one or the other:

- For ideal flow, F = 1.0
- Undeveloped areas, F = 0.8
- Rural areas, F = 0.6
- Near populated areas F = 0.5
- Urban areas F = 0.4

Pipeline Effects:

The following calculations show an example of predicting the value of stress and particle velocity due to the detonation of 5 lbs. of explosive at a

distance of 20 ft.

$$\sigma max = 0.253^{1.304} \quad (3)$$

$$\sigma = 46.53W(E/t)^{.5}/D^{2.5} \quad (4)$$

where $E = 29 \times 10^6$
$t = 0.31$

$\sigma = 1,253$ psi

$\sigma max = 2,772$ (maximum stress)

Calculated Particle Velocity

$$V = 40.4\ (D/W^{.5})^{-1.206} \quad (9)$$

$V = 2.88$ in./sec.

Calculated Allowable Stress

Using the pipe data presented above and equations 5 thru 7, the projected allowable bending stress is:

. $S_A = (0.75)(42,000)(0.5)$ (5)

$= 15,750$ psi

. $S_L = 386(34-0.625)^2/34^2-(34-0.625)^2$ (6)

$= 10,210.6$ psi

. $S_B = (15,750-10,210.6)/2$ (7)

$= 2,770$ psi

Therefore, the allowable bending stress of the pipe is 2,770 psi while it is operating at 386 psi.

TEST PROCEDURES

To achieve an empirical formula to determine a safe blasting technique for this site, the following relationships were calculated:

. Scaled distance to generated ground particle velocity.

. Scaled distance to generated dynamic stress in the pipe.

. Ground particle velocity to generated dynamic stress in the pipe.

Using the theoretical relationship between stress and particle velocity, some ten different shots with various configurations were detonated. To calculate the relationship, transient measurements were made of pipe strain and particle velocity.

The test program consisted of the following, using the same explosive and borehole diameter:

. SHOTS #1 THRU #6, SINGLE HOLE
  - 2 lbs @26 ft.
  - 3 lbs @30 ft.
  - 4 lbs @34 ft.
  - 5 lbs @26 ft.
  - 6 lbs @30 ft.
  - 7 lbs @34 ft.

. SHOT #7, 3 HOLES, 1 HOLE/DELAY
  - 5 lbs @30 ft.

. SHOT #8, 6 HOLES, 2 HOLES/DELAY
  - 8 lbs @28 ft.

. SHOT #9, 10 HOLES, 3 HOLES/DELAY
  - 15 lbs @30 ft.

. SHOT #10, 8 HOLES, 3 HOLES/DELAY
  - 19.5 lbs @30 ft.

Particle Velocity:

For determination of the ground particle velocities three - three plane transducers were used. Two were placed on the ground next to the pipeline and one was directly in line to the shot. The other was located 50 feet behind the pipe to determine propagation of the wave-form in the rock and behavior of the ground particle velocity with increasing distances from the blast holes.

Strain Gage Measurements:

In order to determine dynamic stress on the pipeline induced by rock blasting adjacent to it, strain gage rosettes were used. Two sites on the pipeline approximately 30 feet from each other were

used for strain gage placement. At each site, two rosettes were placed. One of them was mounted on the top of the pipe and the other one on the side, approximately 90 degrees from the first one. The purpose of this type of installation was to study the maximum elastic change in stresses both circumferential and longitudinal and the propagation of elastic changes along the pipe.

ANALYSIS OF DATA

Digitization of Recorded Data:

All of the data signals were recorded on paper, sensitive to light along with fiducial and time base reference signals. This data was digitized on the 9111A Graphics Table Hewlett-Packard model and plotted by Hewlett-Packard Model 7470B Graphics Plotter. The coordinates of the points are electrically determined by a digitizer. All of the record points depend upon the nature of the recording. On the average, approximately 100 points per record were detected. The data points are converted to equal time intervals of .01 second for further analysis.

Method of Analysis:

The method which is used to analyze ground particle velocity waveforms is called "steady-state sinusoidal analysis". This method assumes that the ground motion is a sinusoidal, and zero-to-peak trace is the amplitude of the wave for each peak. The length between two successive peak is the period of the wave.

For computation of stress-time history, the strain waveforms were digitized into the computer. After they converted to time equal data, each datapoints were inserted in the equation 10 and 11 in order to calculate stress-time records in longitudinal and circumferential direction.

$$\sigma \text{ circ.} = \frac{E}{(1 - v^2)} (\text{ circ.} + \text{ long}) \qquad (10)$$

$$\sigma \text{ long.} = \frac{E}{(1 - v^2)} (\text{ long} = \text{ circ.}) \qquad (11)$$

Where: E = Modulus of Elasticity (29×10^6 psi)

v = Poisson's ratio (0.3)

circ = Measured circumferential strain(in/in)

long = Measured longitudinal strain (in/in)

The stresses computed with these equations were the surface biaxial stresses at the location on which the strain gages were mounted. The algebraic signs for the strain were taken into account, as is the time phase for dynamic or transient strains.

The available energy transmitted in the ground had a determining effect on both particle velocity and stress. Underloaded blast holes when detonated develop much higher levels of vibration and slightly lower stresses, since the majority of the explosive force is dissipated as waste energy and not in breaking the surrounding rock. As the efficiency of the explosive energy increases the waste effects lessen and greater forces were imposed on the rock.

The generated values of stress were more closely related to the Scaled Distance (SD) than is particle velocity when one considers both extremes being under or/and overloaded blasts. Also after the initial series of test blasts, the energy generated by the blast had available non-virgin rock to move into, which increased the efficiency of the available explosive energy. These blasts compare favorably with production trench blasting where one would have free faces.

Examples of the Time Histories in a digitized format are shown in the following figures.

Figure #10 is the waveform from the ground motion at 37 feet from the detonation of 19.5 lbs. per delay interval.

Time History

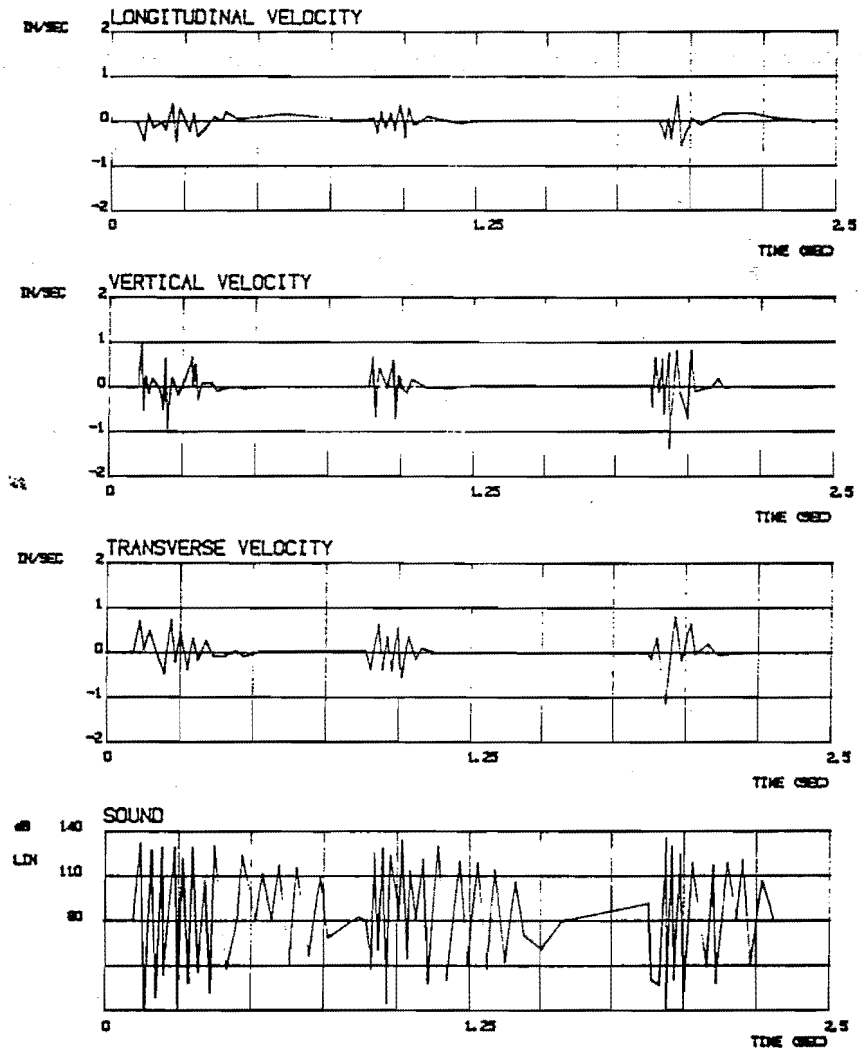


FIGURE 10

From the traces per plane one can see that the blaster used long delays, 3/4 and 1.0 second intervals between the series of holes shot. The additional trace is air overpressure, which was not used in the determination of the pipe response.

The Trace Diagram, Figure 11, relates the frequency-hertz or cycles per second to the particle velocity per trace for the time histories in Figure 10.

Trace Diagram

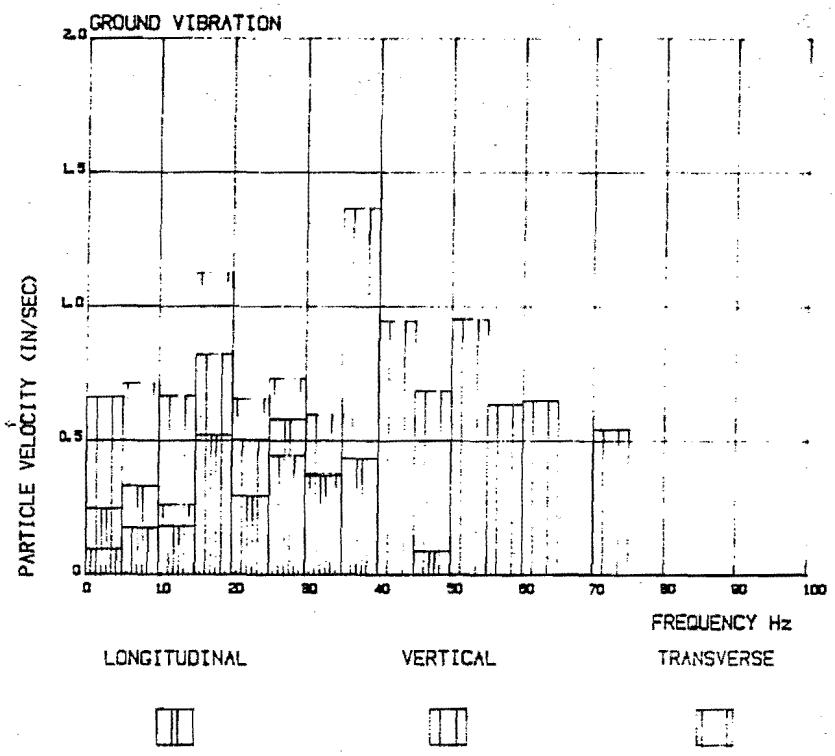


FIGURE 11

The strain and resulting stress-time history waveforms for the same detonation at the rosette site on the pipe closest to the blast siste is shown on Figure 12.

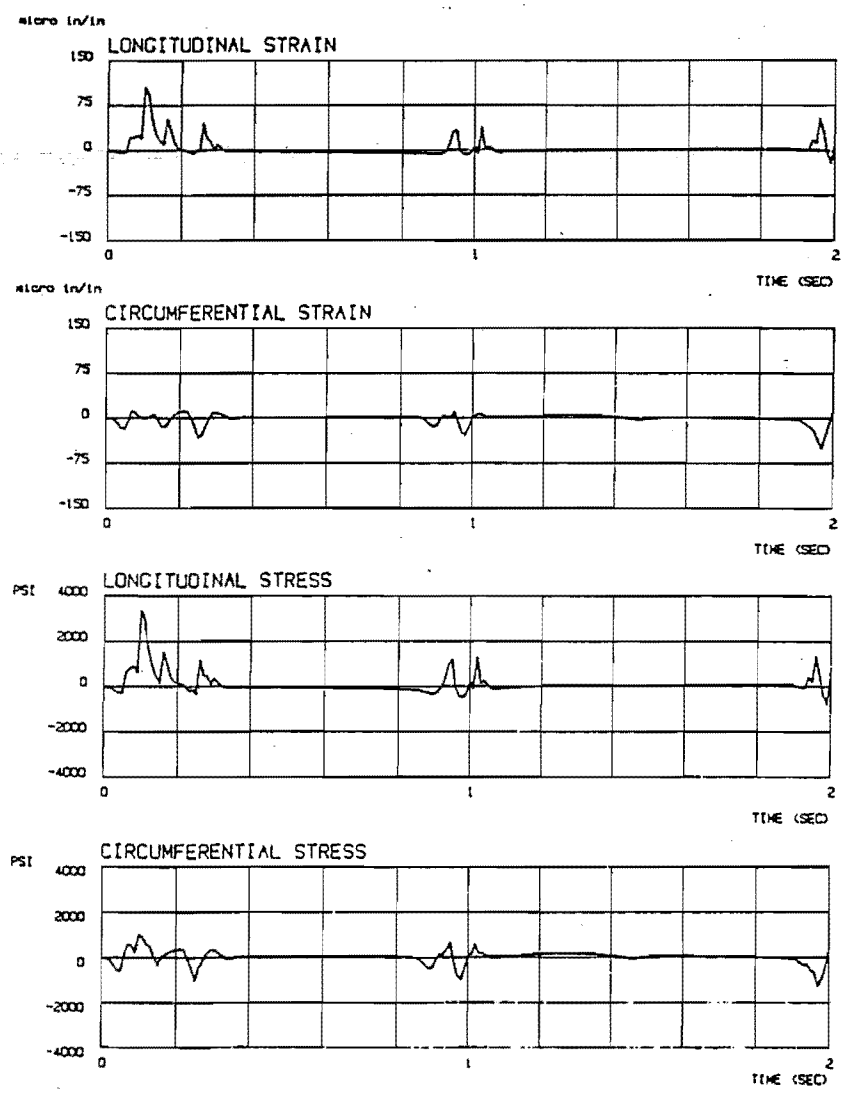


FIGURE 12

RESULTS

Ground Motion Relationships:

An empirical equation was developed for predicting the maximum ground velocity when buried explosive charges are detonated in rock. This equation shows relationship between scaled distance and particle velocity. The equation is the result of statistical analysis of over 20 waveforms and found to be:

$$V = 39.002 \times (SD)^{-1.17} \qquad (12)$$

Prediction of Stress in the Pipe:

In order to develop an empirical formula to calculate circumferential and longitudinal stresses, statistical analysis was performed on 34 calculated stress waveforms with respect to the scaled distance at each shot which caused the stress. According to these computations, the prediction formula for stresses are:

$$\text{circ.} = 29233 \times (SD)^{-1.51} \qquad (13)$$

$$\text{long.} = 74381 \times (SD)^{-1.88} \qquad (14)$$

Where: circ. = Circumferential stress (psi)

long. = Longitudinal stress (psi)

SD = Scaled Distance

The accumulations of this data together is:

$$\text{Stress} = 46622.7 \times SD^{-1.7} \qquad (15)$$

The ground motions impart a transient loading to the buried pipe. Basically, this load takes the form of an impulse, imparting kinetic energy to the pipe which is dissipated by changing to strain energy and produced some stress on the pipe.

The relationship between stress and scaled distance, equation 15, is shown in Figure 13.

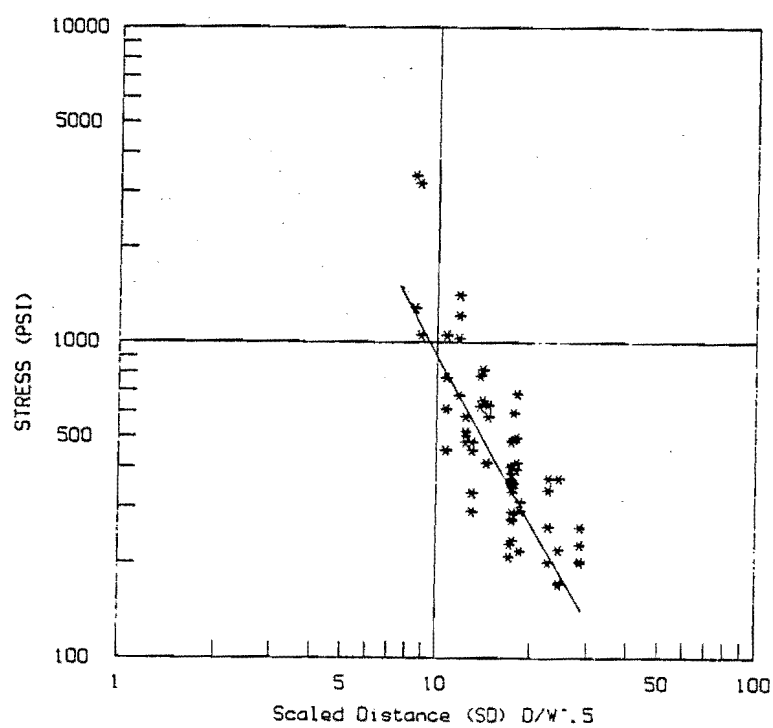


FIGURE 13

Likewise the relationship between equation 12 and equation 15, particle velocity to stress is depicted in Figure 14.

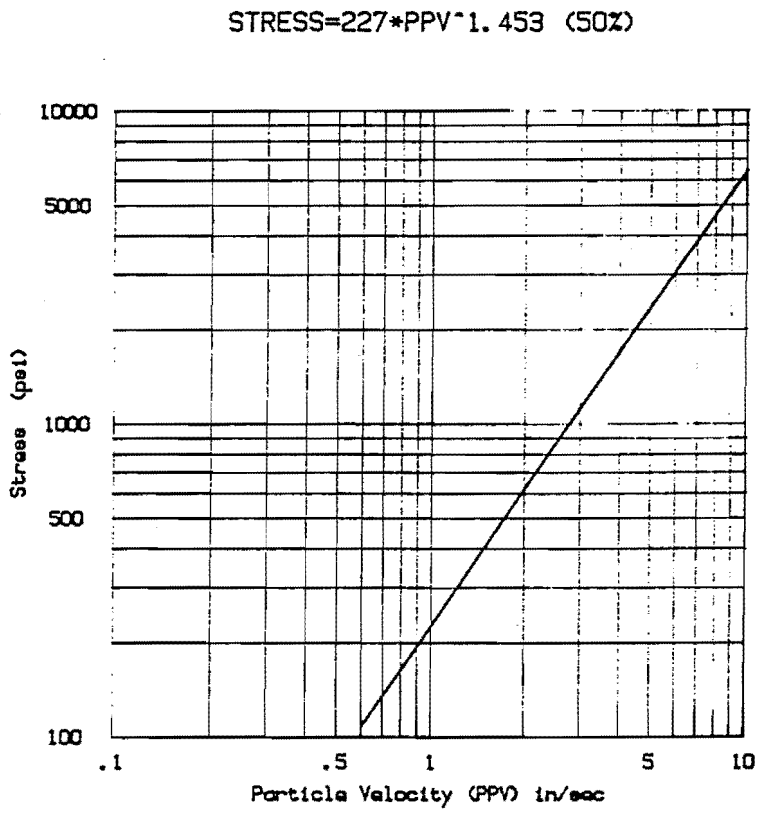


FIGURE 14

The tests confirmed that explosives could be used in a safe manner, the stresses were all within the allowable external transient stresses for the pipe calculated from its physical properties.

Those points that were out of line with the majority of the data, scatter as seen in Figure 14, were due to a number of variables with the major cause being specific site conditions and blasting procedures. A number of the test shots were either over or under loaded to achieve data that would spproximate what one would expect in actual blasting situations.

In the particular case discussed, it was determined that the optimum stress on the pipe without internal pressure approached 15,000 psi, but since the line is used and water remained in the line during blasting, the acceptable allowable limit was determined to be 2,770 psi, with a not to exceed 5,500 psi in any case. The limit of 2,770 psi in this case was equal to a ground particle velocity of approximately 5.5 inches per second.

CONCLUSIONS

Due to the varying nature of rock and the type of explosive available to those blasting, along with other variables such as drill hole diameter and pattern, etc., it is impossible to write a series of equations without field testing to design the best blasting procedure and accepting limits to protect any pipeline. There are guidelines available though and one is a nomograph that SWRI presented in their 1981 report to the AGA.

The nomograph shown on the following page represents the logarithms of the equation:

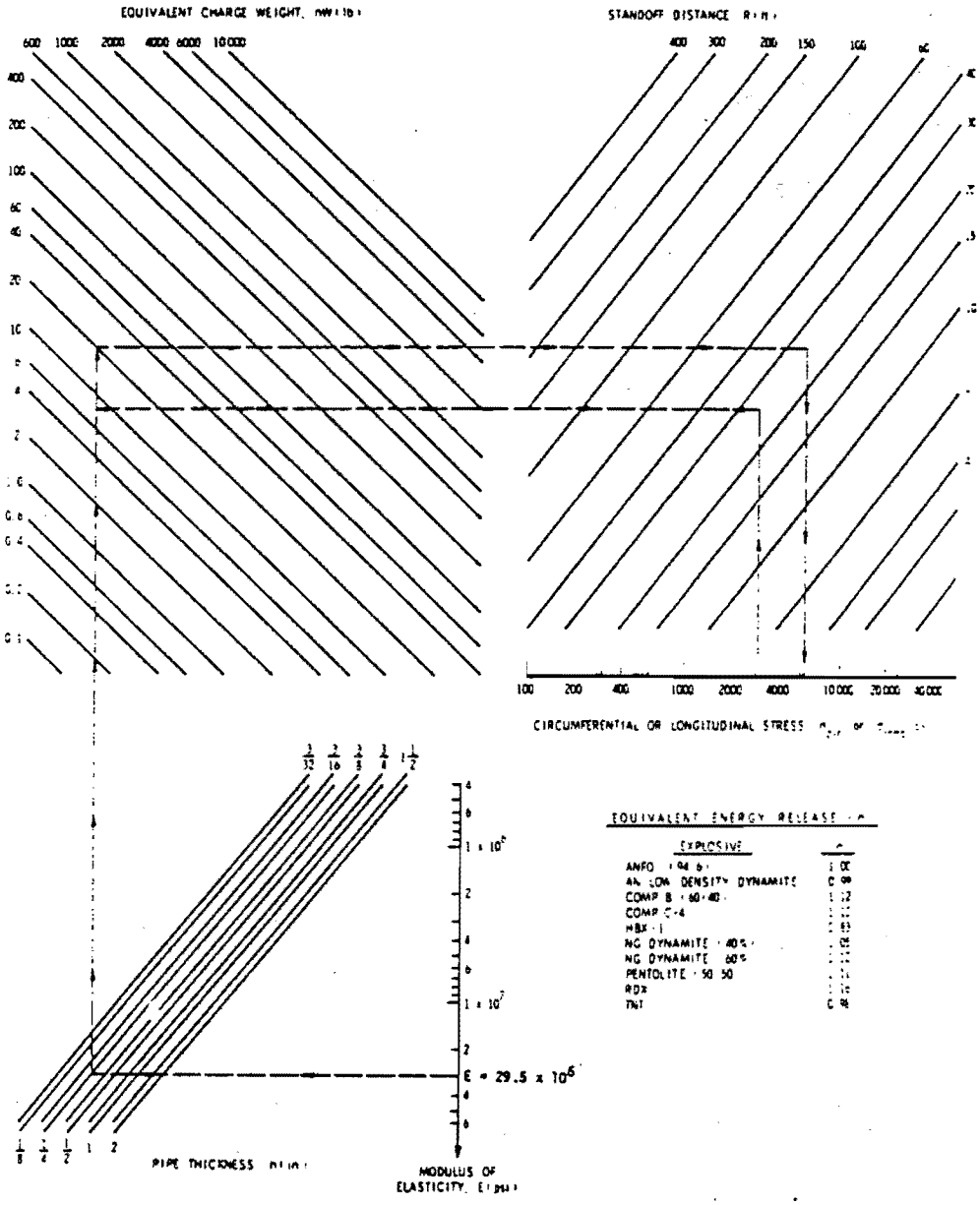
$$\sigma/E = 4.44(nW/(Et)^{0.5}D^{2.5})^{0.77}$$

Where: σ = stress (psi)
E = modulus of elasticity (psi)
n = equivalent energy release
W = charge weight
t = pipe wall thickness (in)
D = distance (ft)

The factor "n" was derived by SWRI by relating energy release per unit weight (We). Average energy release values for some commercial explosives per SWRI are as follows:

Explosive	We
ANFO(94/6)	1.52×10^6
ANL.D.Dyn.	1.50×10^6
N.G.40% Dyn.	1.59×10^6
N.G.60% Dyn.	1.70×10^6

Using the energy release of ANFO(94/6) as the base, all explosive energies were normalized to determine the value of n. Thus, for ANFO(94/6), n equals 1.00.



Pipe Stress Nomograph for Point Sources

The above list per equivalent energy (n) is:

Explosive	n
ANFO(94/6)	1.00
ANL.D.Dyn.	0.99
N.G.40% Dyn.	1.05
N.G.60% Dyn.	1.12

The illustration on the nomograph is for the following parameter:

$E = 29.5 \times 10^6$ psi
t = 0.25 in (h on the nomograph)
nW = 20 lb.
D = 25 ft (R on the nomograph)

The maximum pipe stresses read were approximately 6,000 psi. Likewise if the limiting stress is 3,000 psi at a distance of 25 feet for the same pipe parameters, the allowable equivalent charge weight (nW) would be 8 pounds.

One breakdown that SWRI made that was not addressed in this paper is a differentiation of blast-induced pipe stresses from five explosive configurations, these being explosive geometries:

- point source
- parallel line source
- angled-line source
- parallel grid source
- angled-grid source

Per SWRI "the first two geometries, prediction equations were derived using theoretical and experimental analyses---. For the other three, more complex geometries, the concept used was to simplify the explosive geometry in such a way as to be able to represent it as an equivalent parallel line or point source." In addition, SWRI did not consider maximum charge weight per delay interval. A point source was one charge, while a line was a series of point charges in a single row parallel to the pipeline, detonated at one instant of time. Therefore, the nomograph shown is for a "point source" assuming a charge per unit time at one specific location within a shot pattern.

Also, SWRI detonated explosives in soil, without the availability of a free face or unbroken rock to "absorb" the energy released from the explosives.

The concern expressed when blasting near any pipeline is real, but reference #3, when discussing earthquake ground shaking effects stated:

> "Modern pipelines are fabricated from ductile steel with full penetration butt welds at joints. Such pipelines possess good inherent ductility. There does not appear to be any case of a buried petroleum transmission pipeline ever having ruptured from the effects of ground shaking. Although less certain, there also does not appear to be any case of an above ground section of pipeline rupturing from the inertial effects of ground shaking. For buried pipelines, however, ruptures or severe distortions of the pipeline are most often associated with relative motion arising from fault movements, landslides, liquefaction, loss of support, or differential motion at abrupt interfaces between rock and soil. Also, breaks have occurred at piping connections to tankage and other structures where there have been large relative responses between the soil-restrained buried piping and the less-restrained structure or tank."

For any situation, where major concern has been expressed, on-site diagnostic measurements are a necessity and should include strain gage measurements along with ground particle velocity readings.

When blasting next to a pipeline that is of concern, one should remember:

1. "Explosives function best when there is a free face approximately parallel to the explosive column at the time of detonation."

2. "There should be adequate space into which the broken rock can move and expand."

As stated in U.S.B.M. Information Circular 8925 - "Excessive confinement of explosives is the leading cause of poor blasting results such as backbreak, ground vibrations, air blast, unbroken toe, flyrock, and poor fragmentation."

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TECHNICAL REPORT

REG. NO.:

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RELATIONSHIPS BETWEEN PIPE STRESS, GROUND PARTICLE VELOCITY AND SCALE FACTORS IN BLASTING DOLOMITE

By Dennis Allen Clark

2nd Conference - 1976
Society of Explosive Engineers

ABSTRACT

An increase in construction and quarry operations has necessitated blasting activities in areas once considered rural and in the close proximity of transmission pipelines.

A method to determine the maximum allowable bending stress by the formulas outlined by the Battelle Memorial Institute report of October, 1962, and the assumed stress comparison with actual measured data is presented.

A direct relationship between pipe stress and ground particle velocity is shown, and a method to predict stress by relating stress to charge weight and distance from the shot point is discussed.

INTRODUCTION

The rapid growth of urban areas in locations that were only farm land just a few years ago, has increased the necessity of relating ground particle velocity to stress when blasting activities occur in the vicinity of high pressure transmission pipe lines. Blasting operations in the Upper Midwest has been encountering the need to take into consideration the close proximity of pipe lines more than any previous time.

There is an inherent danger when blasts occur near high pressure pipelines, more so than blasting near other types of man-made structures. When failure

occurs to structures and water or sewage pipelines, normally only physical damage is thr result. Failure to a high pressure line will most likely result in the loss of human life. Since the blaster and his associates are the closest to such activities, if they value their life, they must take care to preserve it by understanding or at least have a fear of the energy available to them in the form of commercial explosives. The resulting transcient seismic ground motion has a potential to cause damage and must be controlled to the best of our abilities.

The relationships which will be presented here are applicable in different rock and soil types but the specific data and case histories relate only to blasting in dolomite similar to that located in the metropolitan Chicago area.

Our firm has experienced an increase in the concern on the part of both the pipeline operator and the quarry-construction industry to arrive at a satisfactory solution when blasting is to take place close to a pipeline, since neither party wants to seem uncooperative and disruptive to a necessary industry.

In the early 1970's work was undertaken by the American Gas Association Pipeline Research Committee to establish limits for charge size (pounds per delay) and distance from a blast to high-pressure gas transmission lines. The primary research found that there had been no case of pipeline failure due to blasting activities when prudent measures were taken by the blaster. Only when explosives were detonated directly adjacent to a pipeline were failures recorded.

Even though this be true, there always is concern for the safety of human life and installations when blasting occurs and questions arise which must be answered to assure those who question safe blasting procedures out of ignorance. Those persons who operate natural gas utilities or transmission pipelines, (along with the explosive user) are not always aware of the information available to them to understand the relationship between excessive pipe stress and ground vibration from blasting; therefore the method outlined here will insure job safety.

Even though the assumed pipe stresses are conservative, it will be shown that actual measurements are required due to the variables in the formulas.

BASIC CONSIDERATIONS REGARDING VIBRATION

We normally report the level of vibrations in terms which are functions of amplitude and frequency, be it either ground particle velocity or energy ratio. An assumption is made that the motion is sinusoidal and thereby the amplitude can be related to pressure, the critical radius (radius surrounding a bore hole in which the rock is fragmented) the rocks' modulus of elasticity and the distance from the blast.

Amplitude can be represented as:

$$A = a^2 P_o / kr$$

a = Critical radius
P_o = Pressure
k = Modulus of elasticity
r = Distance from blast

Frequency of the vibration is a relationship of sound velocity and critical radius, written as:

$$f = C/a$$

C = Sound velocity of the medium
a = Critical radius

A shot fired in limestone gives use to higher frequencies than in shale or soils and also since the modulus of elasticity of limestone is greater, the resulting wave amplitude would be less than that in shale or soil.

A high sound velocity rock produces higher frequencies therefore than a low-velocity medium and high frequencies which are present in low velocity rock or soils, attenuate rapidly with increasing distance.

The vibration waves' potential for damage decreases with increasing time and distance but the rate at which the wave is damped decreases as r/a increases.

The geologic environment is the most variable parameter, since its presence gives rise to the departure from the ideally elastic and infinite medium. Geology will control to some degree the frequency, amplitude, and other quantities characterizing the ground motion from a blast.

The prime concern is the measurement or determination of the maximum value of the ground motion, regardless of the direction of wave travel or type. Depending upon the distance the pipe is from the blast, the direct, refracted, and reflected waves will arrive at varying times and the direct wave since it travels the shortest distance will normally carry the most energy but will not necessarily produce the maximum movement at the pipe.

Of the many criteria that has been advanced to limit the amount of vibration allowable to man-made structures, Particle Velocity is presently the most common. Particle Velocity is equal to 2 fA.

The United States Bureau of Mines and other experimenters have equated the amplitude of ground motion to the square root of the explosive weight divided by the distance from the shot point, times a constant relating to: 1. Average overburden, 2. Deep overburden and 3. Rock.

$$A = KW^{\frac{1}{2}}/r$$

K = Site constant
W = Weight of the explosive
r = Distance from blast

The constant, according to Morris (2), is 0.03 for rock; 0.4 for soil.

The scale factor is the inverse relationship of the amplitude by which a single regression line can be drawn to represent vibration from a wide range of charge sizes when plotted on log-log paper versus the resulting maximum ground particle velocity.

$$SF = r/W^{\frac{1}{2}}$$

There will be scattering of data but this only indicates the uncertainties when using emperical formulas to express the magnitude of ground motion as a function of charge weight and distance.

ASSUMING ALLOWABLE PIPE BENDING STRESS

To be able to predict if the stress produced in a pipeline by nearby blasting activities is sufficient to cause failure one must assume.

1. Soil displacements can be adequately predicated by the equations described in the previous section.

2. The pipeline is subject to movement equal to those of the surrounding soil.

These two assumptions result in a very conservative predicted stress.

Two types of pipe stress will be discussed.

1. Longitudinal Bending Stress

2. Circumferential Bending Stress

For blast in rock, which we are mainly concerned with, longitudinal stresses are predominant, while circumferential stresses effect pipelines in blasts detonated in soils or thick overburden.

1. Longitudinal Bending Stress

   Two assumptions made to predict longitudinal stresses are:

   a. The pipe is a long elastic beam on an elastic foundation.

   b. The displacement profile is the same as that produced by a concentrated load.

   Longitudinal Stress = $S_L = (KDW^{\frac{1}{2}}/2r)(kE/I)^{\frac{1}{2}}$

   K = Site factor
   D = Pipe diameter, nominal outside
   W = Single charge weight (lbs/Delay)
   r = Distance from blast
   k = Soil Modulus
   E = Pipe Modulus
   I = Moment of Inertia of the pipe:
   $0.0491 \quad D^4-(D-2t)^4$
   t = Pipe wall thickness

2. Circumferential Bending Stress

   Here the stresses imposed by the soil displacement are expected to be such that the bending causes the pipe to be deflected out-of-round.

While it is normally assumed that the soil would provide side support for the pipe walls, the assumption made in the prediction equation is that the "side support is small in comparison to the magnitude of the applied load." In addition, the pipeline is assumed to be unpressurized.

Circumferential Stress = $S_c = 4.26(KEtW^{\frac{1}{2}}/rD^2)$

K = Site factor
E = Pipe Modulus
t = Pipe wall thickness
W = Single charge weight (lbs/Delay)
r = Distance from Blast
D = Pipe diameter, nominal outside

The above function is critical in soil and is not recommended for distances less than 100 feet.

In calculating the stresses from the equation presented, the results will vary to a large extent upon the choice of the site factors and soil constants as well as the ranges of the other variables over which the relations apply.

DETERMINATION OF ALLOWABLE PIPE STRESS

The assumed allowable pipe bending stress is the difference in the allowable stress according to the American Petroleum Institute (API) specifications and the pipeline location (Design Factor) minus the calculated longitudinal pressure stress divided by two.

The following pipe data is needed to calculate allowable pipe stress.

Pipe Diameter, nominal outside	D - inches
Pipe wall thickness	t - inches
Specified Minimum Yield Strength(SMYS)..	S - psi
Maximum Operating Pressure(MOP).....	P - psi
Design Factor(A/.72;B/.60;C/.50;D/.40)..	F

This data can be supplied to you by the gas transmission company or local utility which operates the pipeline.

To solve for allowable pipe stress.

$S_A = 0.75 \times S \times F$
$S_L = P \times (D-2t)^2 / D^2-(D-2t)^2$
S_B = Allowable Pipe Bending Stress
$S_B = (S_A-S_L)/2$

CASE HISTORIES

The following two cases are examples of data gathered from field work on an installation of a sewer line and the proposed expansion of a quarry.

Case 1

A 48 inch sewer line was to be installed, crossing two high pressure gas lines, and the transmission company wanted insurance that failure would not occur as the blasting operation approached the pipes.

A. Pipe Data

1. 30 inch Main Line Loop

Pipe Diameter..... D = 30 inches
Pipe Wall Thickness ..... t = 0.344 in.
SMYS..... S = 52,000 psi
MOP ..... P = 850 psi
Design Factor..... F = 0.6

Allowable Pipe Stress

$S_A = 0.75 \times 52{,}000 \times 0.6 = 23{,}400$ psi

$S_L = 850 \times (30-.688)^2/30^2 - (30-.688)^2$
$= 17{,}897$ psi
$S_B = (23{,}400 - 17{,}897)/2 = 2{,}751.5$ psi

2. 22 inch Main Line

Pipe Diameter ..... D = 22 inches
Pipe Wall Thickness ..... t = 0.25 in.
SMYS..... S = 52,000 psi
MOP..... P = 850 psi
Design Factor ..... F = 0.6

Allowable Pipe Stress

$S_A = 0.75 \times 52{,}000 \times 0.6 = 23{,}400$ psi

$S_L = 850 \times (22-0.50)^2/22^2-(22-0.50)^2$
$= 18{,}065$ psi

$S_B = (23{,}400-18{,}065)/2 = 2{,}667.5$ psi

The pipeline company requested that the allowable pipe stress for both pipes be held to 2,500 psi.

The pipeline company required both pipes to be monitored by strain gauge methods and seismic particle velocities measurements were taken to correlate, particle velocity, bending stress and the distance to the shot point and pounds per delay interval (Scale Factor).

A curve of the scale factor versus particle velocity was maintained for each shot and changes in loading procedures were made as the blasting approached the pipes (Figure #1).

The maximum pounds per delay interval varied from 25.0 to 2.7 pounds per delay interval as the blasting proceeded from 100 to 5 feet of the pipelines.

The maximum particle velocities reached a high of 9.85 inches per second and the bending stress 1,785 psi.

The formula for assuming longitudinal bending stress was projected for both the 30 and 22 inch pipeline.

The site factor K was 0.03 since blasting was in dolomite while the soil modulus was projected to be 20,000 pounds per square inch. This factor had been selected since the soil was a sandy clay which was water saturated. The water table in the area was quite high and the pipelines intersected the sewer line in a low lying area.

Figure #2 shows the assumed bending stresses for both diameter pipes, and its relationship to the measured bending stress.

Figure #3 plots the actual maximum particle velocity versus the bending stress recorded by the strain gauges.

The limiting bending stress (2,500 psi) was never recorded but the last blast which was five feet from the 22 inch diameter pipe did have a measured particle velocity of 9.85 inches per second. The strain gauge recorder malfunctioned due to water shorting out the electrical connections. A projected stress though from Figure #3 is 3,300 psi which is above the 2,500 psi allowed but below the 5,335 psi calculated bending stress.

Case 2

A pipeline company has an easement through the property owned by a stone company which operates a quarry on the property. The stone company plans to expand their operation and approach the easement.

Particle velocity measurements had been made at nearby residents and a knowledge of the blasting procedures used was available. The quarry owner wanted to keep the same drill pattern, hole size, and pounds per delay, therefore, the distance he could approach pipeline depended on the pipes' characteristics.

The pipeline company was approached and a plot with their easement, and pipe data was supplied to us for evaluation.

The pipe characteristics were

Pipe Diameter ..... D = 34 inches
Pipe Wall Thickness ..... f = 0.281 in.
SMYS ..... S = 52,000 psi
MOP ..... P = 770 psi
Design Factor ..... F = 0.6
Pipe Modulus ..... E = 30×10^6 psi

Allowable pipe bending stress was assumed to be

$$S_A = 0.75 \times 52{,}000 \times 0.6 = 23{,}400 \text{ psi}$$

$$S_L = 770 \times (34-0.562)^2 / 34^2 - (34-0.562)^2$$
$$= 22{,}716 \text{ psi}$$
$$S_B = (23{,}400 - 22{,}716)/2 = 342 \text{ psi}$$

The pipeline companies' plot showed that the soil types that the pipe was buried in was sandy loam. The soil constant k, was assumed to be 2,000 psi.

The maximum pounds per delay used at the quarry was 200 pounds.

Solving for the distance of the shot point to the pipeline in the formula

$$342 \text{ psi} = (KDW^{\frac{1}{2}}/2r)(kE/I)^{\frac{1}{2}}$$

The distance was found to be 82 feet, with a scale factor of SF = 5.8.

The scale factor versus particle velocity curve of previous blasts showed that a maximum particle velocity of 3.2 inches per second could be expected when the pipe stress approached the limiting criteria.

Both the quarry and the pipeline company accepted the assumptions, but plan to undertake strain gauge test once the pipeline is approached to within 100 feet.

CONCLUSION

The predictions which are made regarding the potential for damage to pipelines by blasting is sufficient to give the blaster and the pipeline operator a guide but the assumption must be used with the upmost care.

The best protection for both parties will be for strain gauge test to be made along with particle velocity measurements to assure the pipelines integrity and personnel safety at the point when the particle velocity is equal to one half assumed allowable bending stress.

The potential for failure is great, when one is working with explosives around high pressure pipelines and the transcient nature of the seismic ground waves should not be allowed to influence one to disregard this hazard by thinking that since the external pressure lasts only a second or two, nothing will happen.

For operations which are planned for start-ups in the future, and a pipeline is in the area, strain gauge test made on the pipe along with particle velocity measurements of single hole blast at varying distances from the pipeline would be the best check on the estimate of pipe stress, decay of soil displacement with distance and the relationship between charge weight, bending stress and particle velocity.

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TABLE 1

SEISMIC VELOCITIES IN SUBSURFACE MATERIALS

Soil Type	Velocity ft/sec Minimum	Maximum
Top soil :		
Light dry	600	900
Moist foamy silty	1,000	1,300
Clayey	1,300	2,000
Semiconsolidated sandy clay	1,250	2,150
Wet Loam		2,500
Clay, dense wet	3,000	5,900
Rubble or gravel	1,970	2,600
Cemented sand	2,800	3,200
Sand clay	3,200	3,800
Cemented sand clay	3,800	4,200
Water-saturated sand		4,600
Sand	4,600	8,400
Clay, clayey sandstone		5,900
Loose rock talus	1,250	2,500
Weather-fractured :		
Rock	1,500	10,000
Shale	7,000	11,000
Sandstone	4,250	9,000
Granite, slightly seamed		10,500
Limestone, massive	16,400	20,200

TABLE 2

SUMMARY OF SOIL FACTORS

Site Factor (K)	
Deep overburden	0.40
Rock	0.03

Soil Constant (k), psi	Minimum	Maximum
Top soil :		
Light dry	262	590
Moist, loamy silty	812	1,370
Clayey	1,420	3,370
Semiconsolidated sandy clay	1,510	4,150
Wet loam		5,600
Clay, dense wet	8,850	34,100
Rubble or gravel	6,400	11,100
Cemented sand	9,700	12,600
Sand clay	10,000	13,900
Cemented sand clay	17,800	21,700
Water-saturated sand		22,500
Sand	26,200	87,000
Clay, clayey sandstone		45,000
Loose rock talus	1,750	7,000
Weather-fracture		
Rock	3,100	140,000
Shale	63,000	156,000
Sandstone	23,500	160,000
Granite, slightly seamed		160,000
Limestone massive	390,000	590,000

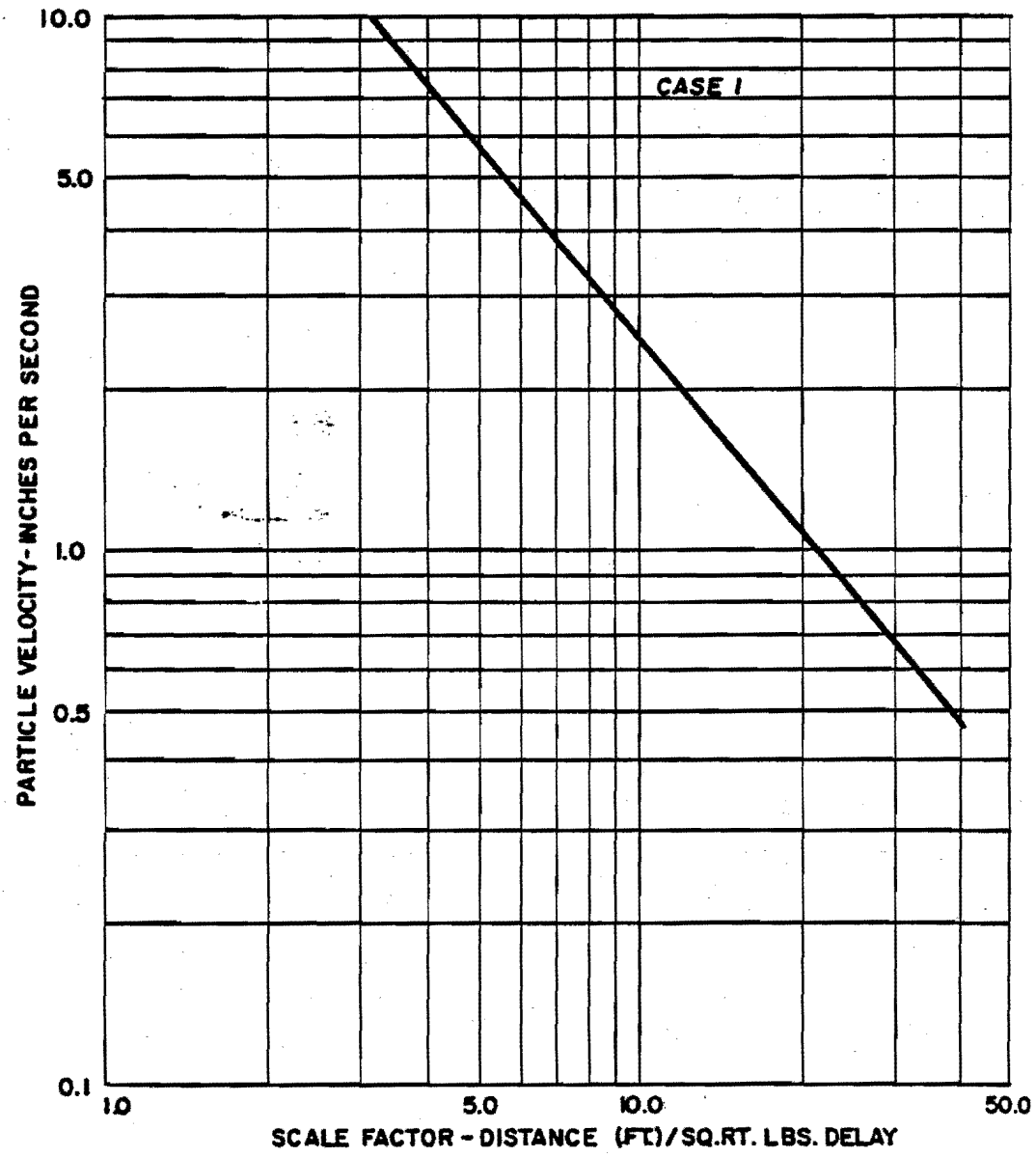
10.0
5.0
1.0
0.5
0.1
PARTICLE VELOCITY-INCHES PER SECOND
CASE I
1.0
5.0
10.0
50.0
SCALE FACTOR - DISTANCE (FT.)/SQ.RT. LBS. DELAY

FIGURE-1

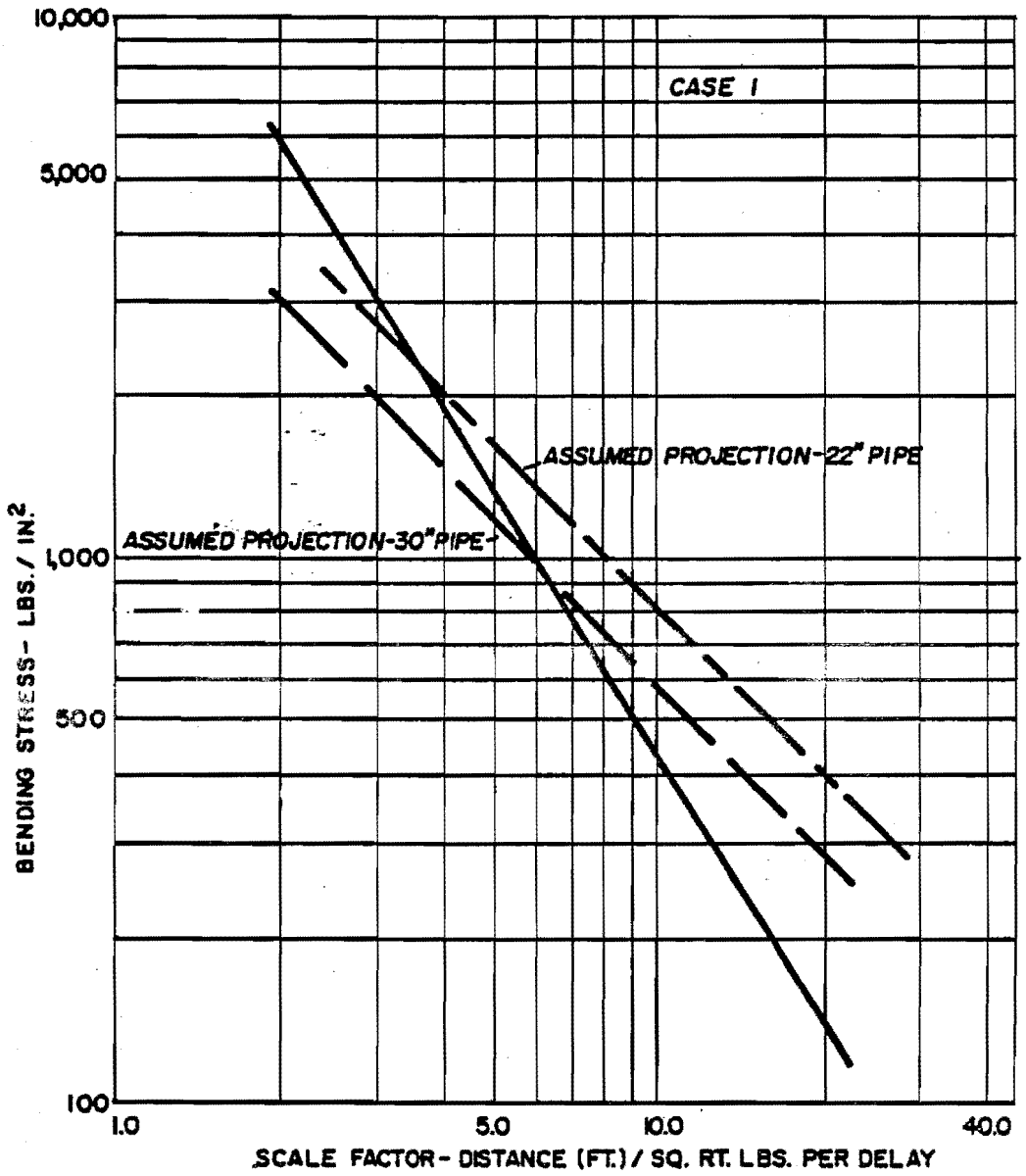
10,000
5,000
1,000
500
100
BENDING STRESS - LBS. / IN.²
CASE I
ASSUMED PROJECTION-22" PIPE
ASSUMED PROJECTION-30" PIPE
1.0
5.0
10.0
40.0
SCALE FACTOR - DISTANCE (FT.) / SQ. RT. LBS. PER DELAY

FIGURE-2

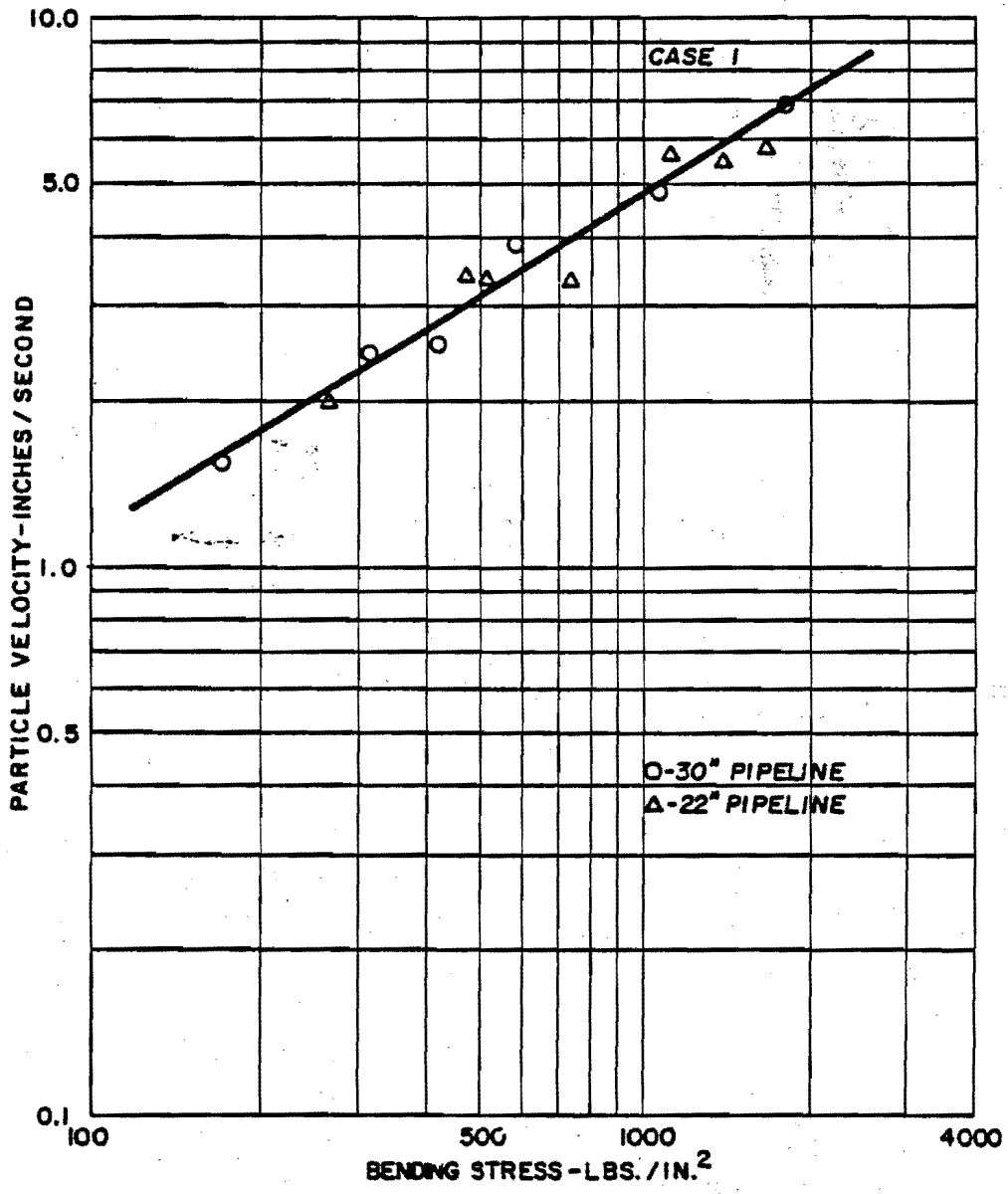
CASE I
O-30" PIPELINE
Δ-22" PIPELINE
PARTICLE VELOCITY-INCHES / SECOND
10.0
5.0
1.0
0.5
0.1
100
500
1000
4000
BENDING STRESS-LBS./IN.²

FIGURE- 3

Response of Pressurized Pipelines to Production-Size Mine Blasting

by

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ABSTRACT

The mining industry occasionally blasts near pressurized transmission pipelines and has requested guidance on safe vibration levels and setback distances. The Bureau of Mines and the Indiana Department of Natural Resources cooperated with AMAX Coal Company on a study of coal mine overburden blasting. Five buried and pressurized 250-ft pipeline sections were specifically installed on the Minnehaha Mine highwall near Sullivan, IN for testing to failure. Four welded steel pipes ranging from 6- to 20-in diameter and one 8-in PVC water supply pipe were monitored for vibration, strain, and internal pressure for a period of 6 months while production blasting advanced up to the pipeline field. In contrast to previous studies of small-scale blasting representing construction activities, these tests involved overburden blasts of up to 2100 lb per delay in 12-1/4-in diameter holes.

Initial analyses found low strains and calculated stresses from even large blasts, a result consistent with previous tests of small-scale blasting. Ground vibrations of 5 in/s produced worst case (circumferential) strain levels about 25 pct of those resulting from pipeline pressurization and calculated stresses of only about 10-18 pct of the ultimate tensile strength. No pressurization failures occurred at the vibration amplitudes reached, over 20 in/s. These results suggest that buried pipelines are relatively resistant to blast vibrations.

Illustrations and tables follow text

INTRODUCTION

The Bureau of Mines participated in a study of blasting impacts on transmission pipelines in a cooperative effort between AMAX Coal Company, Division of Reclamation of the Indiana Department of Natural Resources (IDNR), Vibronics, Inc., New Mexico Tech, and Ohio Valley Pipeline, Inc. AMAX has concerns about blasting near active pressurized transmission pipelines at the Minnehaha Mine, near Sullivan, IN as well as at other mines. They approached the Bureau and other cooperators in the fall of 1991 about the feasibility of conducting such a study, involving a variety of test pipelines subjected to full-scale overburden blasts at one of their surface coal mines.

The Bureau's role was to install and operate monitoring equipment for measuring strain and vibration and interpret the results of those measurements. Other cooperators had responsibilities for pipeline installation (Ohio Valley Pipeline), supplemental vibration monitoring and continuous monitoring of internal pressures (Vibronics), and analysis, interpretation, and monitoring support (IDNR and New Mexico Tech). AMAX provided the site, costs of pipeline installation, security fence and other facility improvements, and shot coordination.

This project provided an opportunity to study a problem previously identified as of widespread concern. Numerous requests for advice on blasting near pipelines have been received by the Bureau over the years, many related to mine or quarry operations. In a research planning document first prepared in March 1989, the Bureau identified blasting near pipelines as a key research need. Although some work has been done in the 1970's and 80's on blasting near pipelines, none to the authors' knowledge, involved large-scale production mine blasting.

Involved parties met for initial planning in November 1991. Installation and monitoring began in March 1992 allowing time to procure needed supplies, equipment, pipelines sections, etc., and also insuring reasonable weather for the difficult installation phases. Monitoring locations were chosen so that the first vibrations would be as high as 2 in/s (5 cm/s). Five total mining cycles of roughly 30 days each were expected to bring the blasting adjacent to the pipelines. Eight months actually would be required for the study.

This report describes the results up to and including the penultimate cycle of mining approaching the pipeline field. One additional pass is expected, which will likely include some blasts that will be within the inelastic zone of permanent ground deformation. The authors expect to prepare a more comprehensive report on this study. However, the high interest in this work and its significance justified its earliest reporting.

BACKGROUND

Some previous work on vibration impacts on transmission pipelines exists. An examination of earthquake-induced pipeline responses concluded that buried pipelines move with the ground and not differentially. The most serious concern was for locations where the soil-rock characteristics abruptly change (Ref. 1). The Corps of Engineers conducted a test of pipeline responses to a concentrated 10-ton blast (Ref. 2). One end of a 6-in diameter, 220-ft long, pressurized pipeline was located only 79 ft from ground zero. Despite that end being in the crater and ejecta zone and experiencing some permanent displacement, no visible breaks occurred. Internal pressure had dropped from 500 to 400 psi, but no leaks could be seen. Peak dynamic strains, all measured longitudinally, were 1100-1400 μin/in and estimated total strains, including those from pressurization, would be about 1550. The authors of the Corps' report estimated yield stresses and strains of 60,000 lb/in^2 and 2,000 μin/in, respectively, and reported measured radial vibration of 168 in/s.

The most extensive studies of blasting and pipelines were conducted by the Southwest Research Institute (SwRI) for the Pipeline Research Committee (PRC) of the American Gas Association (Ref. 3-5). Their concerns were of both mining and close-in construction blasting with small charges. In their initial studies, they examined vibration propagation in soil and developed equations and nomographs predicting stresses from pipeline characteristics, distances and charge weights. These tests were done both at laboratory scale an on two operating mainline systems of 24- and 30-in diameter. Even though the pipelines were full size, stand-off distances and charge weights were small, being 6-13 ft and 5-15 lbs/delay for the 24-in pipeline and 9-15 ft and 3-5 lbs for the 30-in. Such small distances were placing the pipelines close or possibly within the permanent or plastic ground strain zones.

The Enron Gas Pipeline Group developed a standard based on this SwRI research (Ref. 6). They applied the prediction equations with maximum dynamic stress criteria of 1000 lb/in^2 for arc-welded and 500 lb/in^2 for acetylene-welded or mechanically jointed pipelines. A follow-up study by SwRI for PRC examined blasting in rock (Ref. 5). Again concern was for small charges, up to 20 lbs/delay. Measured strains were less than those from the previously found for the experiments in soil. Strains were very low except for a few measurements made so close as to likely be in the inelastic deformation zone (as close as 16 blast-hole diameters). Although the authors of this report are unsure how comparable the previous SwRI studies are to full-scale mining blasts, they anticipate some comparisons in the more comprehensive report to follow.

Dowding's text (Ref. 7) includes prediction equations for pipeline stresses and strains showing worst cases for low propagation media. They address strains from bending and stretching and stresses based on ground displacements.

PROCEDURES

Pipelines

Five 250-ft-long sections of transmission pipeline, with properties described in table 1, were installed on the AMAX Coal Company's Minnehaha Mine highwall for testing to destruction. They were all parallel to each other with 10-ft spacings and also to the highwall at an initial distance of about 500 ft as shown in figure 1. The location, in increasing distance from the highwall, are as listed in table 1. Ohio Valley Pipeline welded and installed the pipelines, using their standard procedures, after the Bureau attached longitudinal and circumferential strain gages and sensors for vibrations in the center area of the pipelines. All pipelines had longitudinal strain gages on tops and fronts and the 6- and 20-in had circumferential as well. Vibration transducers were also placed on tops and fronts of the 6- and 20-in pipes. Other vibration sensors were placed on the surface above the buried 20-in pipeline. Following installations and the placement of 3-ft of soil cover, the pipelines were internally pressurized (Figs. 2-3). Pressures gradually crept up in steel pipelines to 950-1230 lb/in^2 as the ground warmed up from early spring to summer. It dropped in the PVC to 40 lb/in^2 in the following months consistent with reports that such o-ring-jointed water pipes leak continuously. Note: Figure 1 does not show blasts 26 through 30, done too late to be included.

Mine

The Minnehaha Mine is a surface coal mine, blasting overburden by casting and also a thick parting using hole diameters of 12-1/4 and 10-5/8-in, respectively. Charge weights per delay are as high as 2,100 lbs. The highwall, including the pipeline field area, has about 7 ft of clayey soil over-lying about 40 ft of shale.

Monitoring

Strains and ground and pipeline vibrations measured by the authors from selected parting blasts and all nearly overburden blasts are presented in table 2. In addition, Vibronics Inc. continuously monitored both surface and underground vibrations at several locations as well as pipeline pressures. AMAX and the IDNR also had blasting monitors in the area for purposes unrelated to the pipeline study.

In front of the pipeline, AMAX had installed both coaxial and fiberoptic phone cables, and also had a vertical well off the east end of the 6-in pipeline. The well, of about 120-ft depth, was instrumented for pressure by Vibronics. It was tested for cement bond log on three occasions: prior to blasting, after 4 in/s and after 9 in/s. No significant bond loss was noted. The phone lines were tested by Indiana Bell and will be reported separately.

RESULTS

Between the Bureau and Vibronics, about 34 data channels were used for each blast. A comprehensive future report will list all measurements; however, only highlights are presented in this paper. Table 3 lists the highest measured ground vibrations, pipeline vibration responses and strains for each blast. Figure 4 shows a set of vibration and strain records from blast No. 25. Note that strains resemble vibration records, cycling nearly symmetrically about the zero line. Therefore, tension and compression amplitudes were about equal.

Vibrations

Vibration amplitudes on the buried pipelines were less than corresponding R and V components measured on the ground directly above (shallow burial). This consistent and significant reduction of about 40 pct at a depth of only 3-4 ft was surprising, however, it is entirely in agreement with other studies including Bureau of Mines RI 8969 (Ref. 8), which examined the effects of vibration monitoring on basement walls and floors. Figure 5 summarizes the surface radial vibration component and corresponding horizontal response of the 20-in pipeline. Vertical vibrations behaved similarly.

Vibration frequencies of some blasts were low for the relatively small distances. As shown in figure 4, the radial component of shot No. 25 is about 5.6 Hz. This is possibly a site phenomenon caused by the thick clay layer over the shale.

Strains

Figures 6 through 10 show a variety of comparisons of measured strains and surface ground vibrations. These are obviously not the only correlations possible out of 34 total independent channels and, in some opinions, not the best choices. The SwRI authors calculated stresses from blasting parameters (explosive type, amount, distance, etc.) and believe that particle velocities will not consistently be related to strains (and stresses). The Fig. 6-10 plots suggests that rough correlations with velocities or at least maximum envelopes covering all the highest measurements are possible. Alternatives could be direct pipeline vibration response, conversions of velocities to displacements, computations of stress and strain propagation equations, etc. The authors anticipate future examinations of alternatives.

Strains are relatively high for the PVC pipeline by contrast with the steel, consistent with its lower stiffness. If the pipelines were all fully coupled and moving with the ground, this difference should not exist. This problem will be examined in more detail in the follow-up comprehensive report. Generally, similar measurements on the steel pipelines gave similar amplitudes (e.g, front longitudinal strain of a 12-in agreeing roughly with other front longitudinal measurements). Circumferential strains were often, although not always, the highest, particularly when measured on top compared to on the side.

Compared to previous studies, strains were relatively low for given particle velocities. The large blasts involved in this study produced high particle velocities at relatively large distance. Hence, the pipelines experienced high vibration amplitudes at distances beyond the inelastic zone. In addition, charges are in blastholes, being vertical columns which are long compared to the closest blast to pipeline separations. By contrast, the previous studies involved close-in "point" sources. Interesting is the apparent limiting effect of pipeline responses. Circumferential strains, in particular, do not continue to increase in proportion to increasing surface particle velocity. This could be from lack of total coupling with the ground.

Another possibility is that the spatially extended charge with its relatively long detonation time impacts the pipeline less than a point source type blast. The hypothesis requires further analysis.

Stresses

Stresses were calculated for each blast using maximum circumferential and longitudinal strains (table 4). As with previous SwRI studies by Esparza, these were assumed to be principle plane strains, and represent a type of worst case (as in pseudo vector sum compared to true vector sum). Esparza's values of Young's modulus (29.5×10^6) and Poisson's Ratio (0.3) were used (Ref. 5). Stress values calculated from these tests are based on pseudo sums of longitudinal and circumferential. An initial examination of time-correlated strain components found that peaks did not occur at the same time. Phase is also important in calculating the stresses corresponding to given strain states. If the two component are opposite (one tensile and one comprehensive at any instant), the calculated stresses are actually less than would correspond to either uniaxial strain.

Circumferential or hoop stresses from internal pressurization can be easily calculated from the thin-walled cylinder equation;

$$\text{Stress } (\text{lb/in}^2) = PD/2t$$

where P is pressure, lb/in^2; D is inside diameter and t is wall thickness, both in inches. Table 5 lists pipeline specifications and hoop stresses produced by internal pressurization. As the table shows, the pressurization-induced circumferential or hoop stresses are close to 72 pct of yield strengths (and would be exact if D was set to outside diameter). The PVC is also an exception for reasons unknown to the authors. Also in table 5 are both stresses and strains equivalent to 18 pct of yield strength. This 18 pct level is used by some transmission companies as an informal guideline for transient environmental effects such as traffic over a pipeline beneath a highway.

The minimum biaxial strain values in table 5 (last column) were calculated from the stress-strain equation in table 4 based on the worst-case assumption that the two strain components peak at the same time and are the same peak amplitude. They are minimums in that they are the lowest (most restrictive) values that correspond to the 18 pct of SMYS stress.

Settlement

A small amount of settlement was found by laser transit surveys conducted to show dimensional changes. Between May 7 and August 5 (90 days), all 5 pipelines settled by amounts of 0.011 to .025 ft (.34-.76cm). Another survey on September 14 (40 days) found additional settlement of 0.011 to .016 ft (.34-.49cm). Strains from the small amount of differential settlement are very small.

ANALYSIS

The last mining cycle brought the production blasting within 48 ft of the closest pipeline (blast 29). There was little backbreak and no apparent permanent ground displacement at this minimum distance of 44 hole diameters. Vibration levels were 25 in/s for this blast on the ground surface and 9.2 to 10.8 on the two instrumented pipelines with no loss of pipe integrity (pressure drops). Figures 6 through 10 show measured strains, are composites of two types of blasts, different azimuthal directions and 5 pipelines of two different materials. It is not surprising that considerable scatter exists in the summary figures, although a pipe-by-pipe analysis is better. This will be shown in the follow-up comprehensive report. Also in common with other studies, there were problems with use of strain gages and electronics in an unfriendly environment and for an extended period. Generally, circumferential strains were higher than longitudinal by a rough factor of two and PVC strains higher than steel again by about the same factor. Further analysis is anticipated.

Blasting Criteria for Steel Pipelines

Criteria are needed for blasting near pipelines that will insure that damage will not occur and yet be reasonable with regards to resource recovery and other requirements for blasting. The exact definition of "damage: is yet to be established but certainly includes any failures leading to pressure or product less and any plastic deformation. The Enron Standard (ref. 6) specifies allowable stresses of 1,000 lb/in^2 for electrically-welded pipelines and 500 lb/in^2 for gas-welded or mechanically joined steel pipes. As table 4 shows, these stresses have already been greatly exceeded. Mentioned previously, was one guideline which allows 18 pct of yield strength for transient environ-mental excitation caused by highway traffic. If this 18 pct guide were adopted for blasting, then stresses and strains listed in table 5 would apply. It is not unreasonable to allow such a criterion for blasting as it is unlikely that a pipeline would simultaneously be subjected to traffic stress and high-level blast vibration. For analysis of dynamic stresses being added to static (from pressurization), only circumferential are probably the most critical because of longitudinal constraint. Not only are blast-produced circumferential strains larger, but they must be added to those resulting from pressurization. Longitudinal strains are from the transient sources alone plus a relatively small component composed of Poisson's factor and some possible static bending.

An initial estimate of a safe level criterion is possible from the particle velocity strain comparisons from figures 6 and 8, and extrapolating particle velocities corresponding to 150 to 239 μin/in from table 5, the strains corresponding to 18 pct of minimum yield strength. Minimum peak particle corresponding to class B, x42 and x56 pipelines are then 5, 6 and 8 in/s, respectively, for vertical vibrations and slightly higher for radial.

It is important to consider if this approach is conservative. The 18 pct criteria allowed for traffic still includes a safety factor, the Specified Minimum Yield Strength (SMYS) itself has a safety factor in that it is a "minimum", and the blast data are well contained by the maximum value envelopes. Strains are calculated as worst-case biaxial. Furthermore, the low frequency (and potentially higher strain-producing vibration) found here (5.6 Hz) is about as low as could be expected for such close-in blasting (ref. 9). On the other hand, the pipeline may not yet be fully coupled after only 6 months in the ground. The soil over the pipelines was softer than nearby undisturbed ground even after six months.

Blasting Criteria for PVC Pipeline

Unlike the steel pipeline, the specified maximum pressure produces far less hoop stress than 72 pct of SMYS (table 5). It is likely that there is some other limiting factor, such as the couplings. The strain corresponding to the maximum operating pressure of 160 lb/in^2 is 4800 μin/in, contrasting strongly with the yield failure strain of 17,500 μin/in. Again, a rough estimate of particle velocity is possible from the strain figures and a doubling for circumferential strain, which was not monitored on the PVC. (In retrospect, it would have been better to forgo some longitudinal gages for additional circumferential ones). Assuming a strain equal to 5 pct of that produced by pressurization, or 1.35 pct that of yield, and the worst case maximum strain envelope (from fig. 7), the corresponding peak particle velocity would be about 10 in/s. Because of the lack of actual circumferential strains this level should be further reduced until more data are available. Possibly, users of PVC pipe have an environmental criterion similar to the 18 pct SMYS suggested for steel.

CONCLUSIONS

This paper describes a study of full-scale blasting near pressurization pipelines and contains an preliminary analysis of results. The authors expect provide an additional comprehensive report (BuMines RI, likely) with all measurements, additional analyses, and comparisons with other analytical studies and predictions. In the interim, it is suggested that 5 in/s be permitted for large surface mine blasts at Class B or better steel pipelines. Also those of Class 6 or better PVC. It is suggested that this criterion not be applied at construction sites if experience has shown that higher particle velocities are tolerable. Also, in the interim, no adjustment is needed for pipeline age assuming the protective coating is intact and unless the pipeline is known to be at higher risk from previous damage or other cause.

ACKNOWLEDGEMENTS

The authors wish to thank AMAX and particularly John Brown for planning and sponsoring this study. John Wiegand of Vibronics provided invaluable field assistance with his own monitoring program and shared his data generously. Willard Pierce of the Indiana Department of Natural Resources, Division of Reclamation assisted in the planning and execution as well as monitoring activities from the regulatory standpoint. Ohio Valley Pipeline installed the test sections and Texas Gas Transmission Company provided useful suggestions, sections of pipes and test results. Suggestions were also received from Dr. Catherine Aimone of New Mexico Tech as well as citizens of Indiana.

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Table 1.--Pipeline Information for Study

Outside diameter, in	Wall thickness, in	Fill material	Initial pressure, lb/in^2 test start	Age and material
6-5/8	.188	Gas	900	New, steel, x42
12-3/4	.250	Gas	900	Used, steel, Class B
12-3/4	.250	Gas	900	New, steel, x42
20	.261	Water	900	Used, steel, x56
8-5/8	.332[1]	Water	90	Used, PVC

[1]Lowest permitted value.

Table 2.--Blasts monitored for pipeline response

Number	Date	Time	Charge weight, lbs		Distance, ft[1]	Scaled Distance		Type of blast
			Total	Per delay		Square root	Cube root	
1	3-18	11:10	20,199	960	1110	35.8	113	Parting
2	3-20	11:12	24,618	297	3490	203	524	Overburden
3	3-20	13:43	24,114	960	1250	40.3	127	Parting
4	3-20	13:53	21,696	960	1430	46.2	145	Parting
5	4-2	17:16	35,172	1,296	2850	79.2	262	Parting
6	4-2	17:40	67,344	1,656	590	14.5	50.0	Overburden
7	4-2	18:40	22,491	480	3060	140	392	Parting
8	4-29	11:25	31,251	1,023	2630	82.2	262	Parting
9	4-29	19:18	29,898	1,188	2780	80.7	263	Parting
10	6-2	11:23	49,565	1,380	2480	66.8	223	Parting
11	6-2	17:23	53,788	1,408	480	12.8	42.9	Overburden
12	6-5	11:17	60,680	1,704	410	9.93	34.2	Overburden
13	6-5	11:25	16,311	664	3020	117	209	Parting
14	6-5	14:09	17,799	398	3120	156	425	Parting
15	6-5	17:20	64,292	1,520	430	11.0	37.5	Overburden
16	6-10	09:25	72,682	2,114	630	13.7	49.2	Overburden
17	8-3	14:13	22,945	1,025	1270	39.7	126	Parting
18	8-5	11:13	32,638	1,826	1660	38.8	136	Parting
19	8-6	14:55	38,018	1,322	1810	49.8	165	Parting
20	8-6	17:10	66,961	1,612	290	7.22	24.8	Overburden
21	8-6	18:04	66,934	2,126	288	6.24	22.5	Overburden
22	8-7	18:19	69,977	1,949	380	8.61	30.5	Overburden
23	9-16	11:09	70,894	2,126	220	4.77	17.2	Overburden
24	9-18	missed	--	--	--	--	--	Parting
25	9-18	10:57	67,298	1,850	165	3.84	13.5	Overburden
26	9-19	14:25						Overburden
27	9-21	12:05						Overburden
28	10-21	missed	--	--	--	--	--	Overburden
29	10-23	11:20			48			Overburden
30	10-24	15:57			169			Overburden

[1]Distance is from closest blasthole to center of 6-in pipeline, which is closest to the highwall. Shot data from 9-19-on was unavailable in time for this report.

Table 3.--Vibrations and highest strains measured on any pipe.

Shot no.	Ground vibrations, in/s		Strains, μ in/in		
	Surface	On pipeline	Circumferential steel	Longitudinal steel	Longitudinal, PVC
1	0.52	.37	5.3	4.3	6.9
2	.15	.07	2.8	.73	2.5
3	.42	.21	2.2	2.9	3.0
4	.36	.25	8.0	1.6	7.0
5	.36	.15	3.6	1.1	2.0
6	2.64	1.20	NA	12.5	17.6
7	.20	NA	2.5	.68	1.0
8	.31	NA	10.0	2.9	4.8
9	.27	NA	6.3	1.8	3.6
10	.21	NA	NA	NA	NA
11	3.68	NA	66.4	24.2	35.0
12	4.76	NA	51.3	31.0	47.3
13	.13	.09	1.8	1.4	2.0
14	.15	.06	NA	1.1	2.5
15	3.47	1.89	NA	32.4	38.5
16	2.64	1.41	8.4	15.6	23.5
17	.68	NA	4.2	6.0	10.1
18	.67	NA	2.7	3.5	9.6
19	.65	.27	10.7	4.8	15.9
20	5.36	3.42	45.4	31.1	97.5
21	6.56	4.02	NA	51.7	102.5
22	4.96	1.41	13.1	30.8	76.2
23	8.10	4.78	43.2	50.8	92.9
24	NA	NA	NA	NA	NA
25	9.52	8.32	46.4	55.3	137
26	5.84	3.76	39.0	40.0	63.0
27	3.20	1.62	25.4	24.3	37.6
28	NA	NA	NA	NA	NA
29	25.5	10.8	48.6	68.4	223
30	20.9	8.76	43.1	45.3	NA

NA Not Available

Table 4.--Peak strain and calculated stresses on pipelines

Shot no.[1]	Measured peak strains, μ in/in		Calculated peak stresses, lb/in^2	
	Longitudinal	Circumferential	Longitudinal	Circumferential
		20-in Pipeline		
1	4.30	5.30	191	214
2	.73	2.81	51	98
3	2.20	2.20	93	93
4	1.54	7.98	127	274
5	.60	3.62	55	123
7	.45	2.50	39	85
8	2.94	10.0	105	353
9	1.77	6.25	118	220
11	24.2	66.4	1430	2390
12	26.5	51.3	1360	1920
13	1.00	1.77	50	67
16	15.4	8.40	580	422
17	4.49	4.22	186	180
18	3.36	2.72	135	121
19	4.76	10.7	258	393
20	31.1	45.4	1450	1770
25	55.3	43.1	2210	1930
26	88	87	3700	3670
27	112	112	4560	4670
29	191	191	9930	8610
30	34	34	1790	1540
		6-in Pipeline		
8	1.59	2.08	72	83
11	14.0	39.0	833	1400
12	31.0	26.7	1260	1170
25	38.8	46.4	1710	1880
27	69	63	2850	2710

[1] Only shots listed are those with both longitudinal and circumferential strains. All stresses are pseudo two-dimensional maximums, based on peak strains, regardless of time of occurence.

$$\sigma_1 = \frac{E}{1 - \nu^2}(\epsilon_1 + \nu\epsilon_2)$$

$$\sigma_2 = \frac{E}{1 - \nu^2}(\epsilon_2 + \nu\epsilon_1)$$

Table 5.--Pipeline Characteristics

Pipeline, nominal diam.	SMYS[1]	MAOP[2]	Tangential stress from pressurization[3]	72 pct of SMYS	18 pct of SMYS	Minimum biaxial μstrain at 18 pct SMYS[5]
6 used	42,000	560	9,309	30,240	7,560	179
12 used	35,000[4]	989	24,231	25,200	6,300	150
12 new	42,000	1186	29,057	30,240	7,560	179
20 used	56,000[4]	1048	36,315	37,440	10,080	239
8 PVC	7,000	160	1,918	5,040	--	--

[1]SMYS = Specified minimum yield strength, lb/in^2.
[2]MAOP = Maximum allowable operating pressure, lb/in^2.
[3]Circumferential stress based on PD/2t where P is internal pressure (MAOP), D is inside diameter and t is wall thickness. If D is the outside diameter, the pressurization-induced stresses are exactally equal to the 72 pct of SMYS for the 12 and 20-in pipelines.
[4]Tested by MQS Services and found to be 34,800 and 55,000 for the 12- and 20-in, respectively.
[5]Strains computed by assuming simultaneous peak and equal stresses as worst possible case, using formulas in table 4.

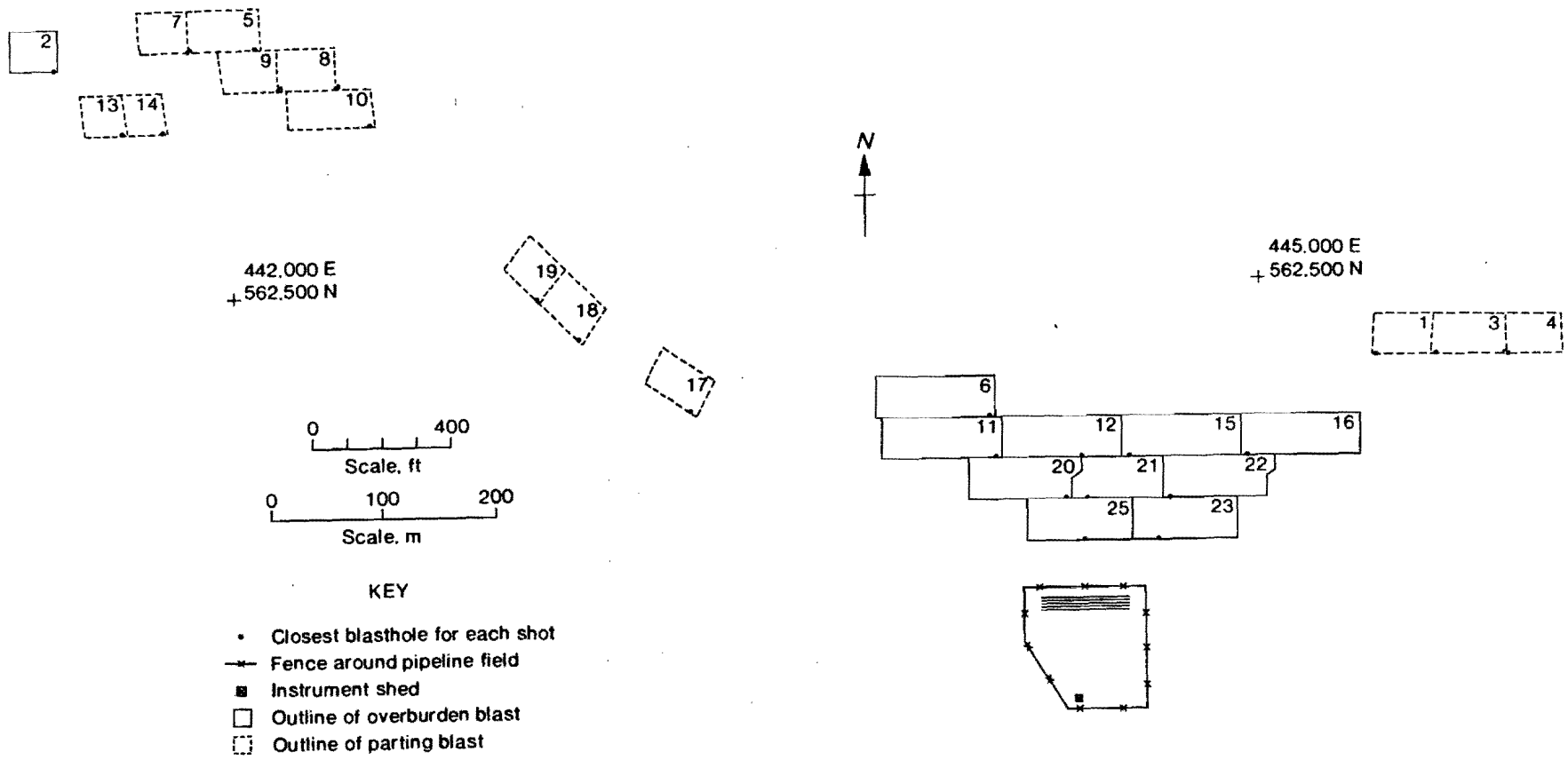

Figure 1.- Minnehaha mine pipeline test area and production blasts monitored

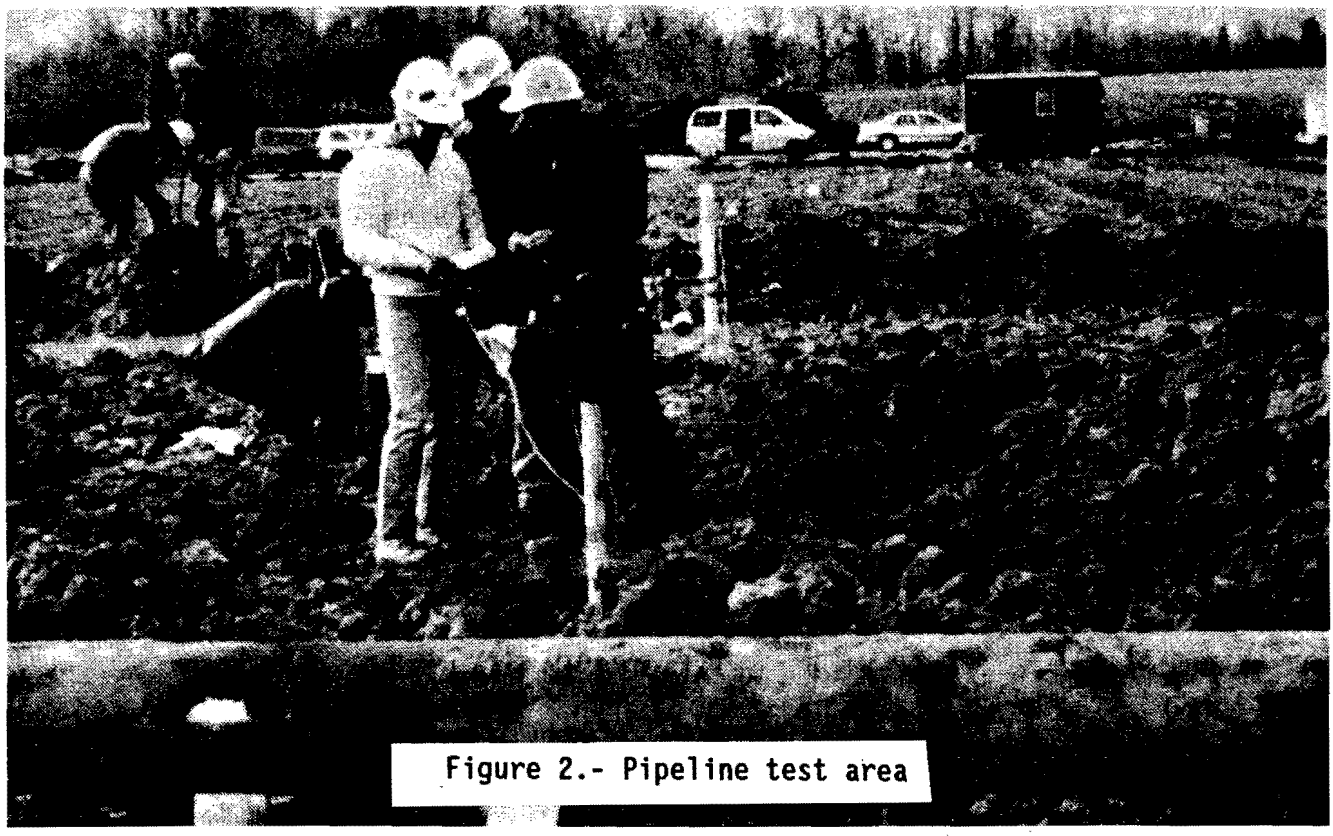

Figure 2.- Pipeline test area

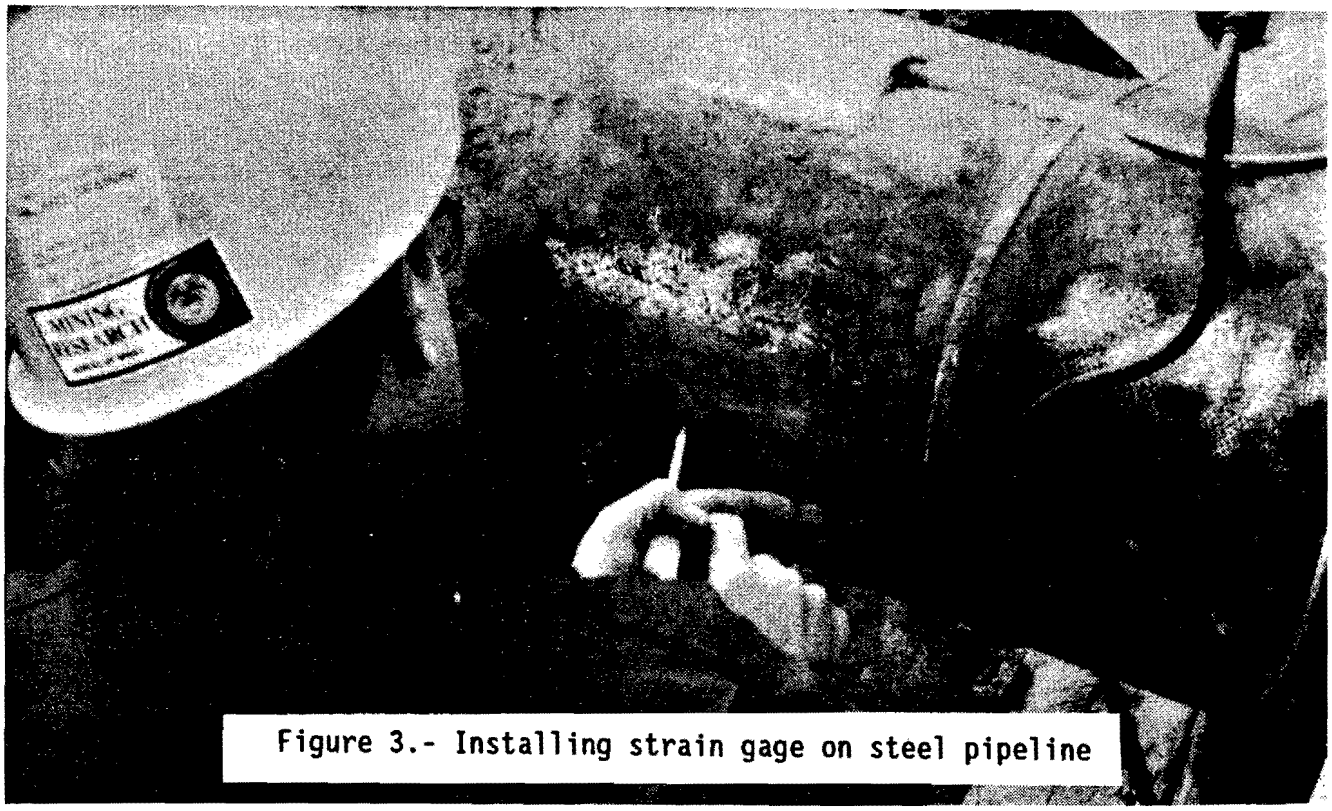

Figure 3.- Installing strain gage on steel pipeline

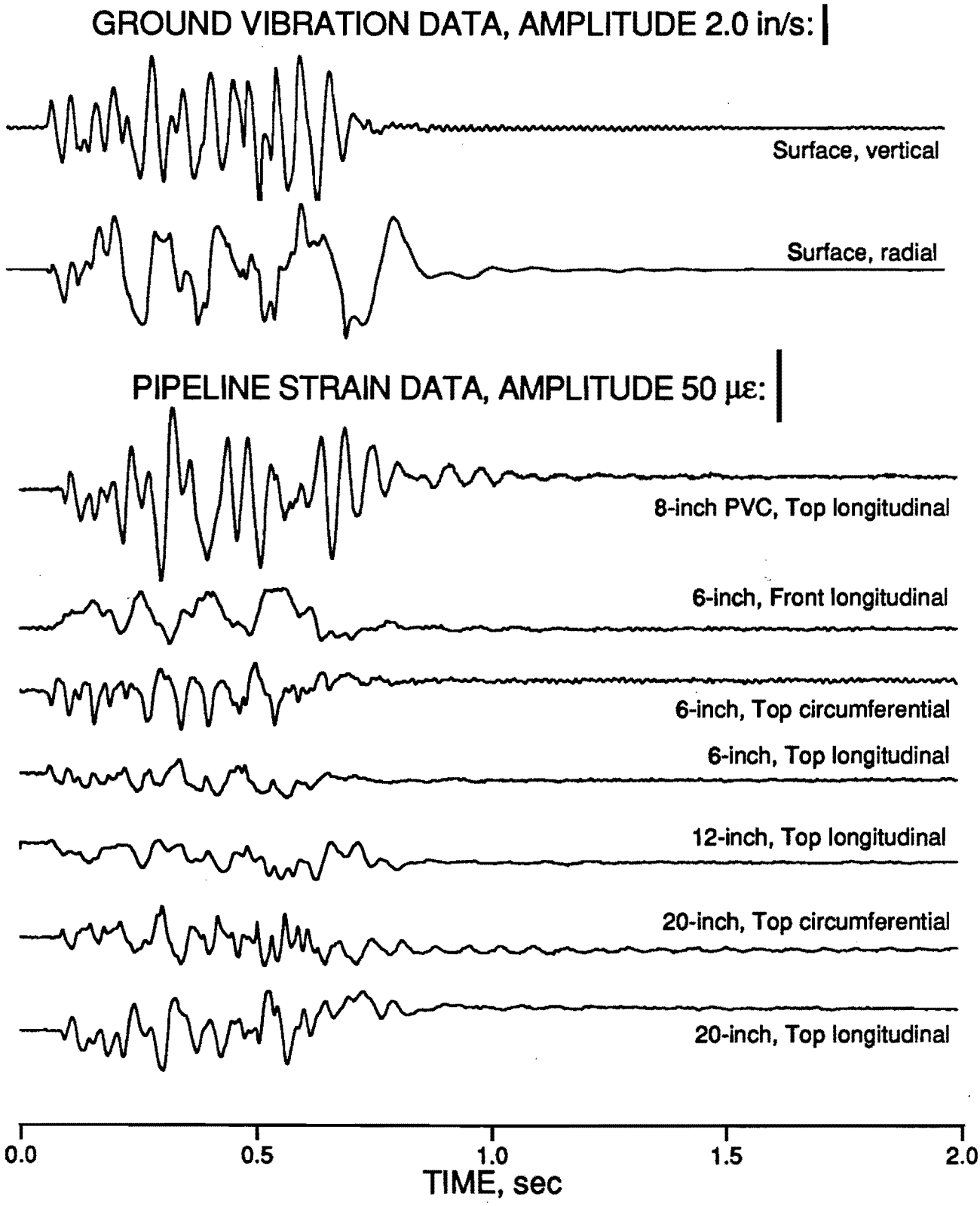

Figure 4.- Vibrations and strain time histories for blast No. 25

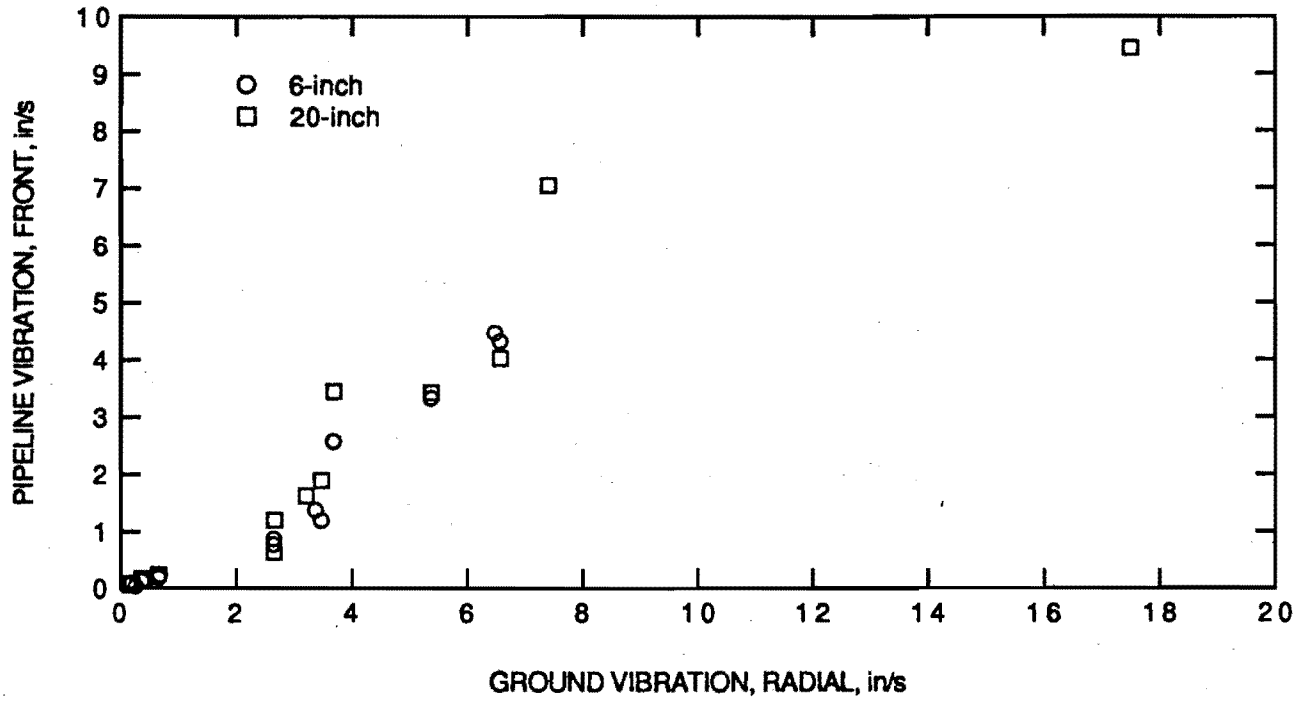

Figure 5.- Ground and pipeline vibrations

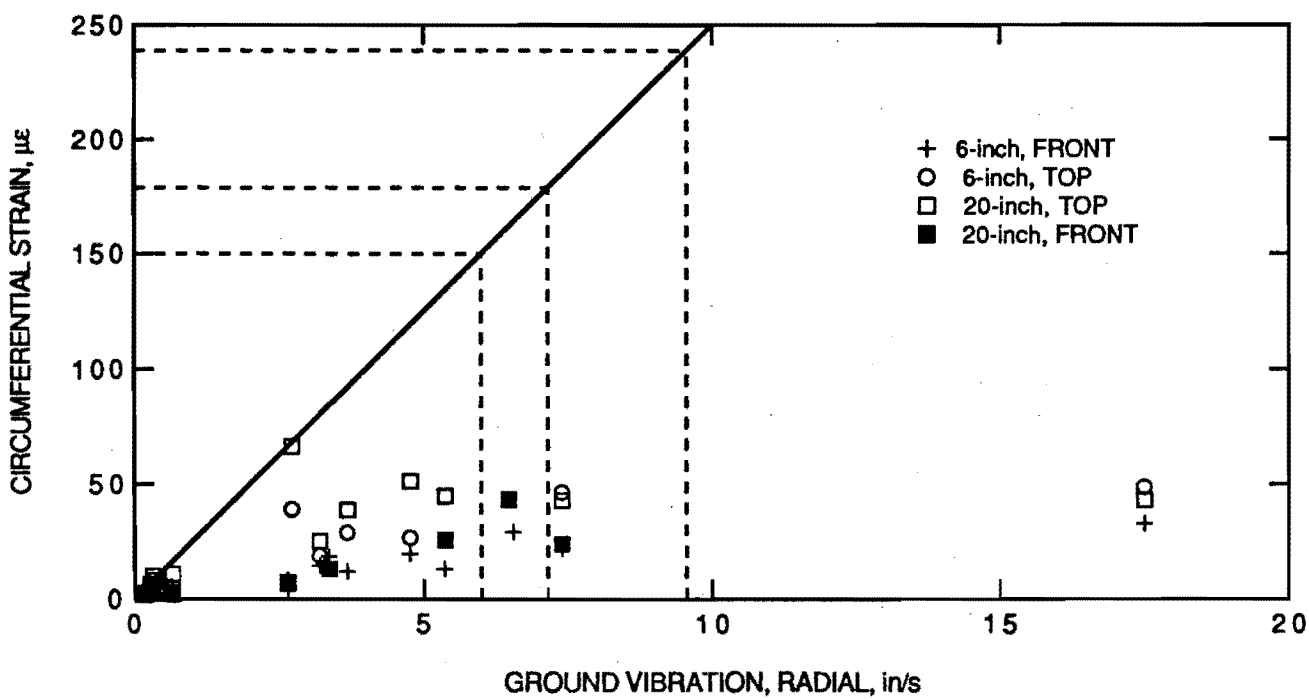

Figure 6.- Circumferential strain and surface radial vibration

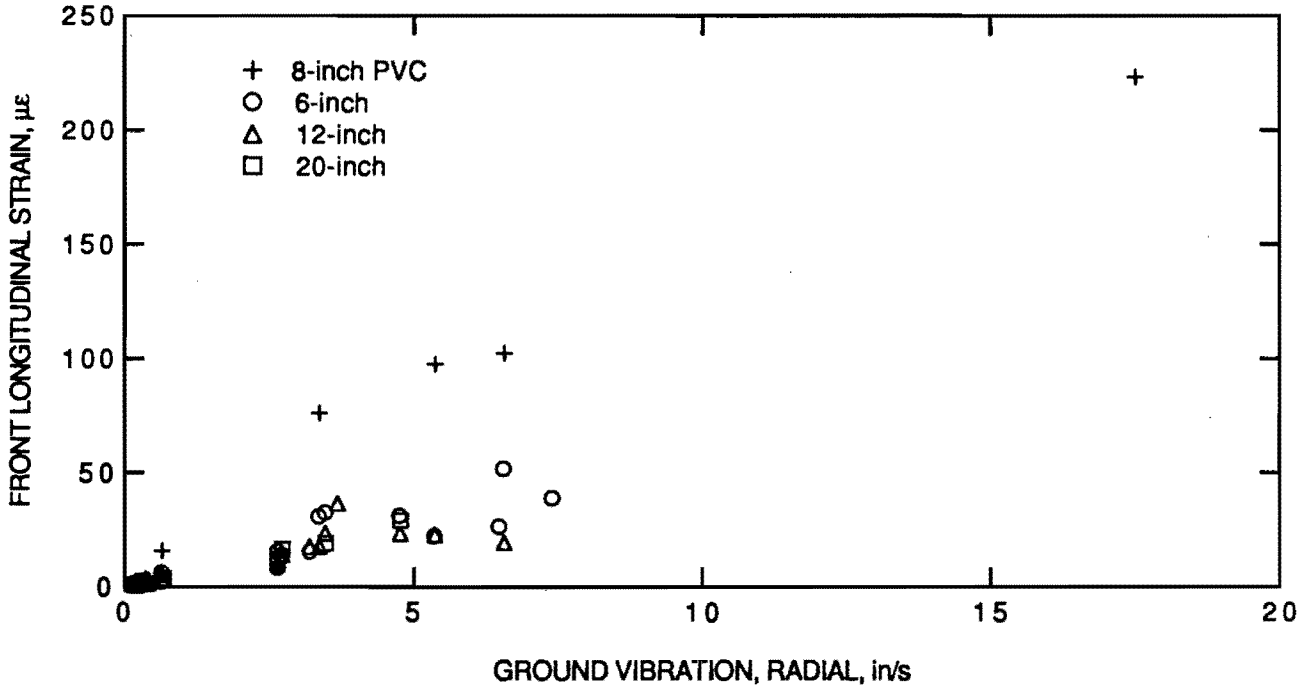

Figure 7.- Longitudinal strain and surface radial vibration

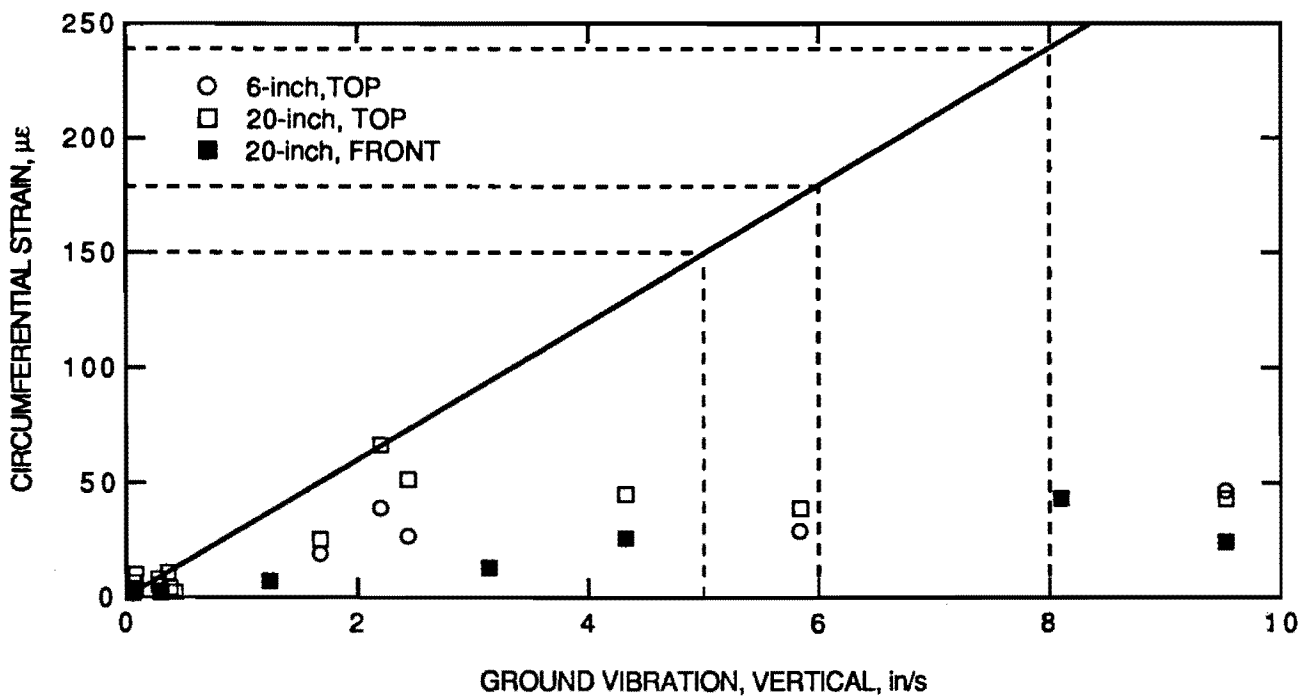

Figure 8.- Circumferential strain and surface vertical vibration

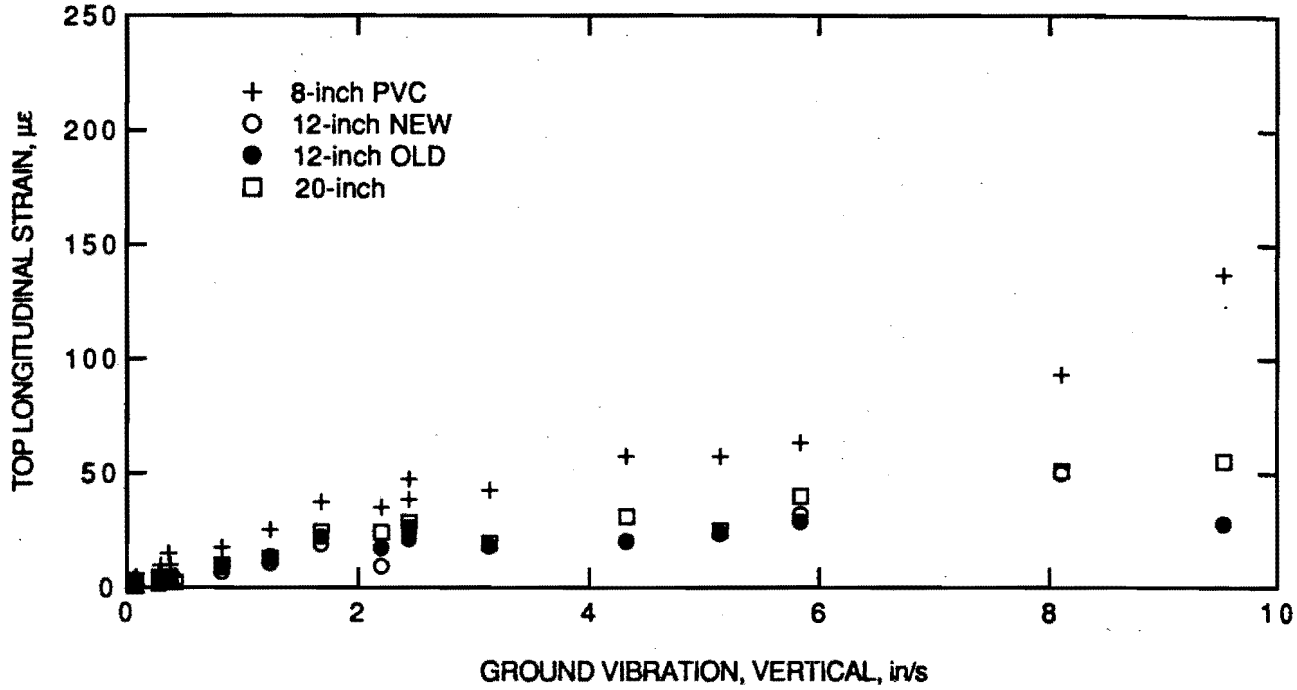

Figure 9.- Longitudinal strain and surface vertical vibration

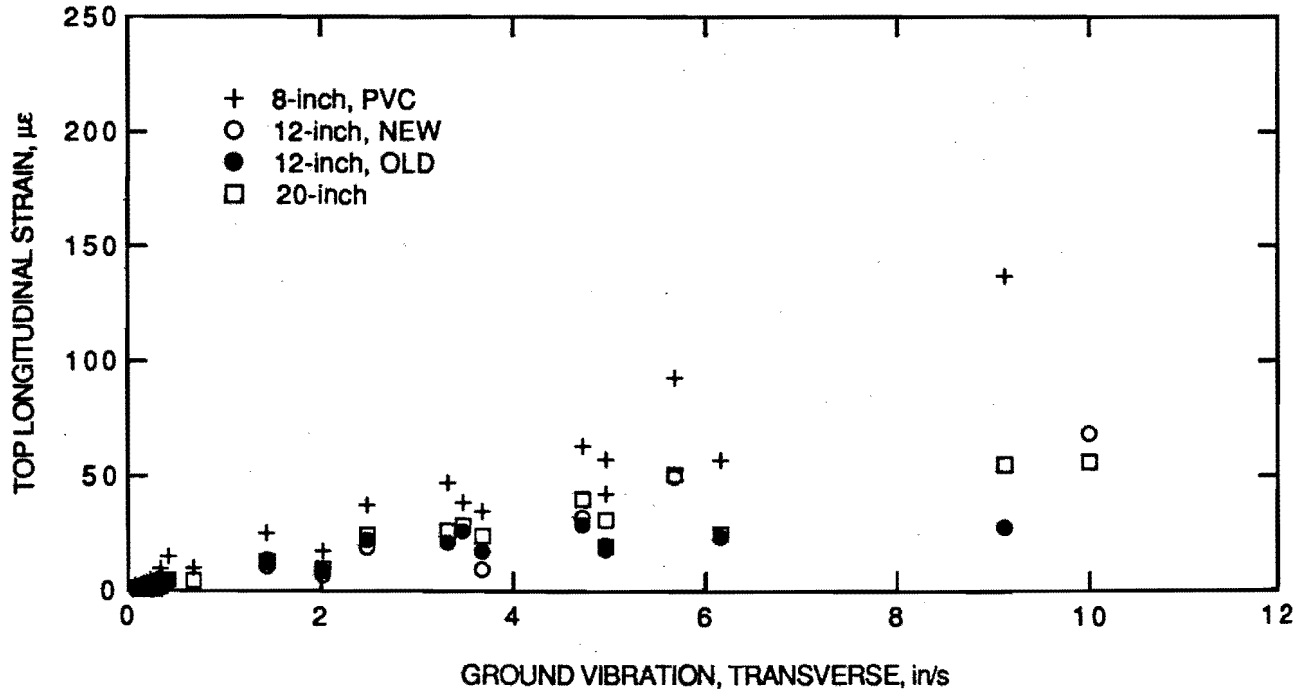

Figure 10.- Longitudinal strain and surface transverse vibration