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SOUNDS FROM IMPLOSIONS OF STEEL CYLINDERS UNDER WATER

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ABSTRACT: Pressure pulses from steel cylindrical tanks imploding under hydrostatic pressure in the ocean are described. Several tanks were recovered after collapse for inspection so that the mode of collapse and resulting damage to the tanks could be correlated with the acoustic measurements. The imploding steel tanks generated acoustic signatures that differed significantly from those produced by underwater explosions and from those produced by underwater implosions of glass bottles. The observed negative onset of the implosion signatures from the steel tanks was apparently caused by the formation of an inward buckle. The subsequent pressure history depends upon the number and (CONT)

20. (CONT) relative size of the buckles that form. The final stage of the collapse was indicated by a positive pulse. Energy spectra of the tank implosion waveforms are discussed and compared with those from underwater explosion pulses and glass bottle implosion pulses.

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Sounds from Implosions of Steel Cylinders Under Water

The Naval Ordnance Laboratory's participation in the experiments described in this report, and the analysis reported here, were supported by Naval Ship Systems Command Task 16551/S1001.

The main experiments were conducted by a Naval Research Laboratory Group under Dr. Richard Swim. We appreciate his efforts and those of other members of the NRL group in making the Naval Ordnance Laboratory participation possible. Their efforts include provision of most of the tanks, photographs of the specimens, and most of the logistic support. We also appreciate the support rendered by the U. S. Naval Station at Roosevelt Roads, Puerto Rico.

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Captain, USN
Commander

I. KABIK
By direction

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I

INTRODUCTION

The implosion sounds of air-filled structures collapsing under hydrostatic pressure have, in the last decade, drawn considerable interest from the underwater acoustics community. Underwater implosions have provided safe, inexpensive sound sources for sound propagation studies (reference a) and have served as signaling devices. Urick (reference b) has described the pressure pulses emitted by glass bottles as they collapsed. More recent theory and experiments by Reader and Chertock (reference c) have shown that the pressure wave emitted by an imploding structure is negative while the interface is accelerating away from the water and positive while it is accelerating toward the water. This should be so whether the structure is glass walled, steel walled, or simply an air cavity.

But what effect do the type and thickness of the wall material have on the pressure emitted? Urick's results indicate that the number of oscillations might decrease as the amount of glass relative to the enclosed air volume increases. For example, consider a 4-oz. bottle that imploded at 7400 feet and that was presumably relatively thick-walled compared with a 1-gallon bottle that imploded at 1100 feet. The first produced a single pulse, but the second produced a train of diminishing oscillations. Faux and Niffenegger (reference d) indicate that the pressure waves emitted by some 10-inch diameter heavy walled glass spheres, when destroyed by explosion waves, produced a negative wave followed by a single positive pulse. The effect was obvious at 14500 and 22000 foot depths but not at 300, 6500 and 7200 foot depths. What if the material were ductile and confined the air even after collapse so that there was no free bubble of air? These questions, for small aluminum spheres, were addressed in reference (e). The records given in Appendix 1 of the reference show that, for most gage positions, the first phase of the collapse of the aluminum spheres was a long, low amplitude negative pressure wave which was followed by a short, more or less abrupt positive pulse.

The Naval Research Laboratory recently conducted an implosion experiment using steel cylindrical structures (tanks) that were either dropped or lowered into the ocean. The Naval Ordnance Laboratory recorded the acoustic signals emitted as the tanks collapsed. The purpose of this report is to show representative acoustic signals emitted by the imploding tanks and to correlate the measured acoustic signals with the mode of collapse and the resulting damage to the tanks. Energy-density spectra of selected acoustic signals will also be discussed.

II

EXPERIMENTAL ARRANGEMENTS

The implosion experiment was conducted in September 1972 near Puerto Rico. Twenty-four tanks (Table 1) containing air at atmospheric pressure were either dropped or lowered into the ocean. Each 3-compartment tank had axially aligned compartments separated by rigid bulkheads. The center compartment was longer than the other two which were of equal length.

The 13 tanks that were lowered were recovered after it was determined that something had happened (though collapse may not have been complete), and thus the tanks could be inspected to determine the extent of damage. Tourmaline gages were mounted within a few feet of these tanks for nearby external pressure measurements, and a pressure gage for measuring the pressure inside the center compartment was installed in an axial tube through one of the end compartments.

Several tanks were dropped in lieu of lowering. The free drops allowed more of the air-filled compartments to implode. One 3-compartment tank that was dropped had an internal pressure gage connected to the recorder by an expendable wire. None of the dropped tanks had external pressure gages mounted.

Hydrophones were suspended from the ship at depths of about 80 and 160 feet for recording the acoustic signals emitted from each collapsing tank. Signals from the hydrophones, tourmaline gages, and the internal pressure gage were recorded on magnetic tape recorders on the support ship. Calibration signals were also recorded. Adequate performance of the recording system was verified by recording signals from known (explosive) sources.

III

IMPLOSION WAVEFORMS CORRELATED WITH TANK DAMAGE

Most of Urick's air-filled glass bottle implosions generated an initial negative pulse followed by several diminishing pulsations from the oscillating gas bubble formed after breaking of the bottle. This oscillating bubble behavior is similar to that of an underwater explosion, though the explosion pulse begins with a large, positive shock wave. Figure 1 compares the pressure signal from one of Urick's glass bottle implosions with that from an explosion. In contrast, the acoustic signals generated by the imploding steel cylinders began with a negative excursion, as did the glass bottle implosion signals, and ended abruptly with a large positive pulse. Oscillations were sometimes present during the negative excursion.

Close inspection of these implosion waveforms and the recovered tanks has indicated that, in general, tanks of a given size (or type) were damaged in much the same way and generated pulses that were similar, i.e., the tanks were uniform and collapsed reproducibly. It is believed that all the tanks failed under hydrostatic pressure by first forming a longitudinal inward buckle. Further damage then proceeded in a manner determined by such factors as the length-diameter ratio of the compartment, wall thickness-radius ratio, mechanical properties of the material, and end structure. The differences in results from the various tanks are demonstrated in the discussion below.

A. 30-Inch Diameter, Single-Compartment Carbon-Steel Tanks

The 30-inch diameter tanks did not have strong, rigid ends and were not divided into compartments. They collapsed at about 130 feet depth, as determined by arrival time analysis of the acoustic signals. The pressure pulse emitted by one of the tanks and recorded from a hydrophone suspended from the support ship is shown in Figure 2. Each of the 30-inch tanks emitted a simple, relatively low frequency implosion pulse that began with a long duration negative excursion (at least 40 msec) and ended with a large positive pulse. The hump during the negative excursion may indicate a local stiffening during the collapse. The surface reflection arrives just after the large positive pulse in this figure. None of these tanks was recovered for damage inspection, but they were probably mashed or flattened out under hydrostatic pressure.

B. 26-Inch Diameter Carbon-Steel Tanks

The 26-inch diameter tanks emitted pulses similar to those of the 30-inch tanks. The upper trace of Figure 3 is the pressure pulse emitted by the center compartment of a 3-compartment 26-inch tank that collapsed at 570 feet. The pulse consists of a single 20 msec duration negative pulse followed by a large positive pulse of shorter duration. As with the 30-inch tank, there is a hump during the negative phase. The lower trace of Figure 3 is the internal pressure history of the center compartment of the tank. The arrival time difference between the gages has been subtracted to display simultaneity of occurrences. Internal pressure appears to oscillate during collapse of the compartment and then stabilizes to ambient hydrostatic pressure, indicating complete flooding of the center compartment.

A photograph of a recovered 26-inch tank whose center compartment emitted a signal much like that of the above discussion is shown in Figure 4. The cylindrical shell of the center compartment is torn away from the end plate at the welded joint, exposing the internal pressure gage mounted in the center of the bulkhead. Apparently only one buckle was formed in this long tank, and the longitudinal folding followed immediately. The forming of the buckle and the folding of the shell were probably a single, continuous event and together generated the relatively long duration negative pulse of Figure 3. The positive pulse occurred at the end of the folding process when the front surface impacted with the rear surface.

C. 14-Inch Diameter Carbon-Steel Tanks

Figure 5 is a photograph of a recovered 14-inch diameter tank in which the center compartment collapsed at about 600 ft depth. Several longitudinal buckles were formed. Note also that the cylindrical shell tore away from the bulkheads. The corresponding acoustic signal emitted by the buckling and collapse of this tank is shown in Figure 6. The upper signal was received at the gage mounted near the collapsing tank. The onset of the buckling process emits a negative pressure pulse; several oscillations make up the intermediate portion of the pulse as other buckles form. The large positive pulse is emitted at the end of the collapse process. The internal pressure of the center compartment is shown in the lower trace. It rises rapidly to a peak as the collapse stops, and there is an immediate decrease in pressure. Then the internal pressure quickly rises to ambient hydrostatic pressure (at about 80 msec) indicating complete flooding of the chamber.

Three of the 14-inch diameter tanks were dropped. Of these, one emitted three major collapse pulses in addition to several minor pulses (which will be discussed in detail in Section III F) following the first and second major collapses; one emitted only two major collapse pulses; and the third emitted only one collapse pulse. In the latter two cases either hydrostatic pressure was not great enough to cause complete collapse of the remaining compartments during the time the recorder was on or the damage to one compartment might have caused sufficient leaking into adjacent compartments to prevent their subsequent collapse.

D. 8-Inch Diameter Carbon-Steel Tanks

Two of the 8-inch diameter tanks presumably experienced almost simultaneous collapse of two compartments. A pressure pulse in which the time between compartment collapses is about 10 msec is shown in Figure 7. Although the waveform is slightly more complicated than those from the single compartment collapses, the positive pulse at the end of each collapse can be detected and is indicated by an arrow in the figure.

E. 8-Inch Diameter Stainless Steel Tanks

Two 8-inch stainless steel tanks of approximately the same length as the carbon-steel tanks were also tested; one was recovered and one was a free drop. The recovered tank did not leak but all the compartments were severely buckled into deep lobes. The other tank produced three compartment collapse noises and three additional noises, probably from second order damage to each compartment caused by additional pressure at great depths. Such damage after major collapse was possible because the compartments probably had not leaked and still contained air at relatively low pressure.

The pressure pulse emitted by a collapsing compartment of one of these stainless steel tanks is shown in Figure 8. From this waveform, recorded from a hydrophone, we infer that at least two buckles formed before the compartment collapsed completely. Note the relatively gradual decrease in pressure after the peak of the positive collapse pulse. This behavior was observed in collapse pulses from both of the 8-inch stainless steel tanks tested but was not observed in any of the pulses from the 8-inch carbon-steel tanks or in either the 14-inch or 26-inch carbon-steel tanks of the above paragraphs. This behavior can be attributed to the relatively greater ductility of the stainless steel which prevented leaking and hence left the unruptured tank intact and perhaps in a more resilient state than the ruptured, flooded carbon-steel tanks.

F. 16-Inch Diameter Carbon-Steel Tanks

Two 16-inch diameter tanks were lowered and one was dropped into the ocean. The latter was the only dropped tank equipped with an internal pressure gage. Although the tank sank to the ocean bottom and was not recovered for damage inspection, we have attempted to determine the damage process entirely on the evidence of the internal pressure measurements, external pressure measurements, and the photograph of one of the lowered 16-inch tanks. Figure 9 contains sketches of the entire 18-second pulse train measured with an external pressure gage and that measured with the internal pressure gage. Also shown are the records at the times of events A through G with an expanded time scale. Pressure scales on these seven plots are alike. Each signal consists of a pair of pulses, the direct arrival and the surface-reflected arrival about 65 msec later.

Signals A, D, and G have been identified as the three compartment collapse pulses. The waveforms of these signals are quite similar to that of the collapsing center compartment of the 14-inch steel tank (Figure 6). The several oscillations in signal A prior to the large positive pulse indicate the formation of several buckles in the cylindrical wall. Additional evidence that signal A is a compartment collapse pulse is found in the abrupt rise in the center compartment's internal pressure at the same time that signal A occurs on the external acoustic measurement. An expanded time plot of the internal pressure showed a rise and stabilization to ambient hydrostatic pressure like that shown in Figure 6.

Signals B, C, E, and F are small, non-collapse type pulses that must have been emitted from one or both of the end compartments. This type of small pulse occurred only after the earlier collapse of another compartment. Perhaps the first collapse put the end compartments in a condition where they became susceptible to some minor type of damage prior to reaching full collapse depth. One of the recovered 16-inch tanks with a collapsed center compartment (Figure 10) exhibited a slight depression in the shell of an end compartment. (Note the curved shell indicated by the arrow in Figure 10.) Pulses similar to signals B, C, E, and F had been recorded prior to recovering this tank.

Returning to the acoustic pressure measurement of Figure 9, we give the following account of the damage taking place as each of the 7 signals is emitted. Signal A has already been identified as the buckling and collapse of the center compartment. The depth at which this compartment collapsed is 566 feet. Since this compartment was flooded, as previously noted from the internal pressure measurement, no additional sounds are emitted from this compartment. All later signals can therefore be attributed to the end compartments. Consider, for example, signals B and C, small non-collapse signals from one or both of the end compartments. Their detailed traces indicate they did not lead to immediate collapse of any compartment. The corresponding damage must have been minor and perhaps similar to that illustrated in Figure 10.

As the tank sinks deeper, one of the end compartments collapses under increasing hydrostatic pressure and emits signal D. Soon signals E and F are emitted from the remaining end compartment but again do not lead to immediate collapse. Finally, after about 5 seconds, the last compartment buckles and collapses as indicated by signal G. No additional sounds were emitted from the totally collapsed and flooded tank.

Although the 16-inch tank discussed in this section was not recovered for inspection, the sequence of signals has provided us with a valuable exercise in determining the damage process based entirely on the interpretation of internal and external pressure measurements. This interpretation is, of course, strongly dependent upon information gained from studying the damage to, and corresponding signals emitted from, other tanks that were recovered during the experiment.

IV

ENERGY-DENSITY SPECTRA OF THE ACOUSTIC SIGNALS

The underwater explosion is a commonly used sound source whose near-field acoustic signature and corresponding energy-density spectrum are quite predictable (for example, references f, g, and h). For this reason, we will compare the energy-density spectra of the tank implosion signatures with underwater explosion spectra.

Figure 11 is a digitally computed energy spectrum for a 1.8-lb charge (at about 5000 ft range) which detonated at 865 ft. The explosion spectrum is characterized by a very regular pattern of peaks and nulls; peaks are located approximately at harmonics of the bubble fundamental frequency, which is the inverse of the first bubble period and is defined as the interval, T_1, shown in Figure 1. The maximum energy occurs at the bubble fundamental frequency, about 50 Hz in Figure 11. Note also that subsequent maxima are spaced at about 50 Hz intervals corresponding to harmonics of the bubble fundamental frequency.

Urick's glass bottle spectra also exhibited a null-peak pattern with an absolute maximum located at the frequency corresponding to the bubble oscillation interval, T_2, of Figure 1. The pattern, however, was not as regular as that of the explosion spectrum of Figure 11.

The steel tank implosion signatures were quite unlike those of the two above sound sources and likewise have quite different energy-density spectra. When oscillation occurs in the tank implosion pulse, it is an effect of the buckling process and is therefore not necessarily regular. Furthermore there is the dominating effect of the large positive pulse emitted at the end of the collapse. Figure 12 compares the energy-density spectra of implosion waveforms from each of the tank sizes tested, in order of increasing tank diameter. Resolution bandwidth for each of the spectra, except for the 30-inch tank, is 24 Hz--corresponding to an analyzed signal duration of about 82 milliseconds. For the longer duration signature of the 30-inch tank, the resolution bandwidth is 12 Hz. From a cursory look at these spectra, one notes that energy tends to be concentrated more at lower frequencies as tank diameter increases. While all of the spectra exhibit patterns of nulls and peaks, none has a regular pattern like that of the explosion spectrum or the glass bottle implosion spectra.

In Figure 12 curves A, B, and C are all from 8-inch tank implosion signatures: A is the spectrum of the pulse corresponding to the single-compartment collapse of a carbon-steel tank; B is the spectrum of the pulse (Figure 7) corresponding to the nearly simultaneous collapse of two compartments; C corresponds to the collapse pulse (Figure 8) of one of the stainless steel tanks. The single-compartment collapse spectrum, curve A, shows the greatest amount of energy in the

100 Hz to 300 Hz band with a minor peak at about 500 Hz. While there are several nulls and peaks within the 2000 Hz shown, the pattern is not at all regular. The spectrum of the nearly simultaneous collapse pulses, curve B, peaks at about 100 Hz, corresponding to the time interval between the two large positive compartment collapse pulses. The second harmonic is indicated by the peak at 200 Hz. This spectrum is comparable to an explosion spectrum in that it peaks at the first and second harmonics of the frequency corresponding to two prominent peaks in the pressure-time history. Yet, like the other tank implosion spectra, there is no regular pattern of peaks and nulls, though several fairly deep nulls are apparent. The spectrum, curve C, of the 8-inch stainless steel tank implosion pulse (Figure 8) is much like that of the carbon-steel tank of curve A.

The spectrum of the 14-inch tank (curve D) peaks at 90 Hz and 160 Hz. The 160 Hz peak corresponds to the fairly regular buckling pulses of Figure 6; the 90 Hz component can be attributed to the interval between the first buckling peak and the collapse peak.

Curves E and F are spectra of the center compartment collapse pulse and the first non-collapse pulse, respectively, emitted by the 16-inch tank of section IIIF (signals A and B, respectively, of Figure 9). The spectrum of the collapse pulse (curve E) is much like that corresponding to the 14-inch tank (curve D). The peak at about 40 Hz to 60 Hz corresponds to the period between the first buckling pulse and the large positive collapse pulse. The buckling process emits a somewhat regular oscillation at about 250 Hz, perhaps accounting for the approximately 250 Hz spacing of the 3 deep nulls between 400 Hz and 1000 Hz. The spectrum (curve F) of the non-collapse pulse is typical of the spectra of all such pulses that we recorded. It is quite irregular and has a greater proportion of energy at high frequencies than do the spectra from complete compartment collapse pulses.

Both the 26-inch and 30-inch tanks emitted low frequency signals with a single negative phase followed by the positive collapse pulse (Figures 2 and 3). Their spectra, curves G and H, fall off rapidly after the peak at low frequency. Curve H is the spectrum of both the direct and surface-reflected pulses since these were not separable.

Table 2, derived from the spectral analyses of the tank implosion signals, lists the frequency below which 90% of the signal energy is contained. These results indicate, as expected from an examination of the pressure records, that the tanks of smaller diameter were sound sources of generally higher frequency energy content than were the larger tanks.

V

SUMMARY

From this steel tank implosion experiment, we have gained a good understanding of the implosion waveforms generated by compartmentalized tanks of various sizes. The recovery of several of the damaged tanks and the availability of both external and internal pressure measurements has enabled us to correlate the acoustic signals with the mode of collapse and resulting tank damage.

In a comparison of the tank implosion signatures with the glass bottle signatures of reference (b), and with explosion signatures, differences in waveforms were observed. The negative onset of the glass bottle pulse is due to implosion, while the oscillatory portion of the wave is caused by the gas bubble as is the oscillatory portion of the explosion signature. For the steel chambers, the negative onset is caused by the formation of an inward buckle. The subsequent pressure-time history depends on the number and relative size of buckles that form. The end of the collapse is indicated by a relatively large positive pulse.

The first noise emitted by every tank can be attributed to the collapse of one or more compartments. The last noise from each of the free-fall, carbon-steel tanks could also be attributed to the collapse of a compartment. Thus, the small, non-collapse noises from the carbon-steel tanks occurred only after compartments were weakened by collapse of the first chamber and prior to the collapse (and probable flooding) of the last compartment. Similar small noises were emitted by some collapsed stainless steel compartments since they did not leak and contained, after collapse, air at low pressure relative to ambient hydrostatic pressure.

Spectral analysis results have shown that tanks of small diameter were higher frequency sound sources than the larger tanks. Energy-density spectra of the tank implosion waveforms were quite unlike the spectra of glass bottle implosion signatures and explosion signatures. The explosion spectrum exhibits a regular pattern of peaks at many multiples of the bubble fundamental frequency. The glass bottle implosion spectra were similar to that of an explosion but with less regularity in the peak-null pattern. None of the tank implosion spectra had a pattern of regular peaks and nulls.

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TABLE 1

TANK DESCRIPTIONS

Number of Tanks No. Lowered	Number of Tanks No. Dropped	Diameter (inches)	Overall Length (inches)	Number of Compartments	Ends or Bulkheads	Material
2	3	8	34	3	Rigid	Carbon-Steel
1	1	8	39	3	Rigid	Stainless Steel
2	3	14	60	3	Rigid	Carbon-Steel
2	1	16	48	3	Rigid	Carbon-Steel
2	1	26	172	3	Rigid	Carbon-Steel
0	2*	26	53	1	Rigid	Carbon-Steel
4	0	30	96	1	Semi-Elliptical	Carbon-Steel
Total 13	11					

* These two tanks were the end compartments salvaged from one of the 172-inch long tanks.

TABLE 2

IMPLOSION FREQUENCY VS TANK DIAMETER

Tank Diameter		Approximate Frequency Below which 90% of Implosion Signal Energy is Concentrated
8-inch	Single Compartment	415 Hz
8-inch	Stainless Steel	300 Hz
14-inch		200 Hz
16-inch		190 Hz
26-inch		100 Hz
30-inch		50 Hz

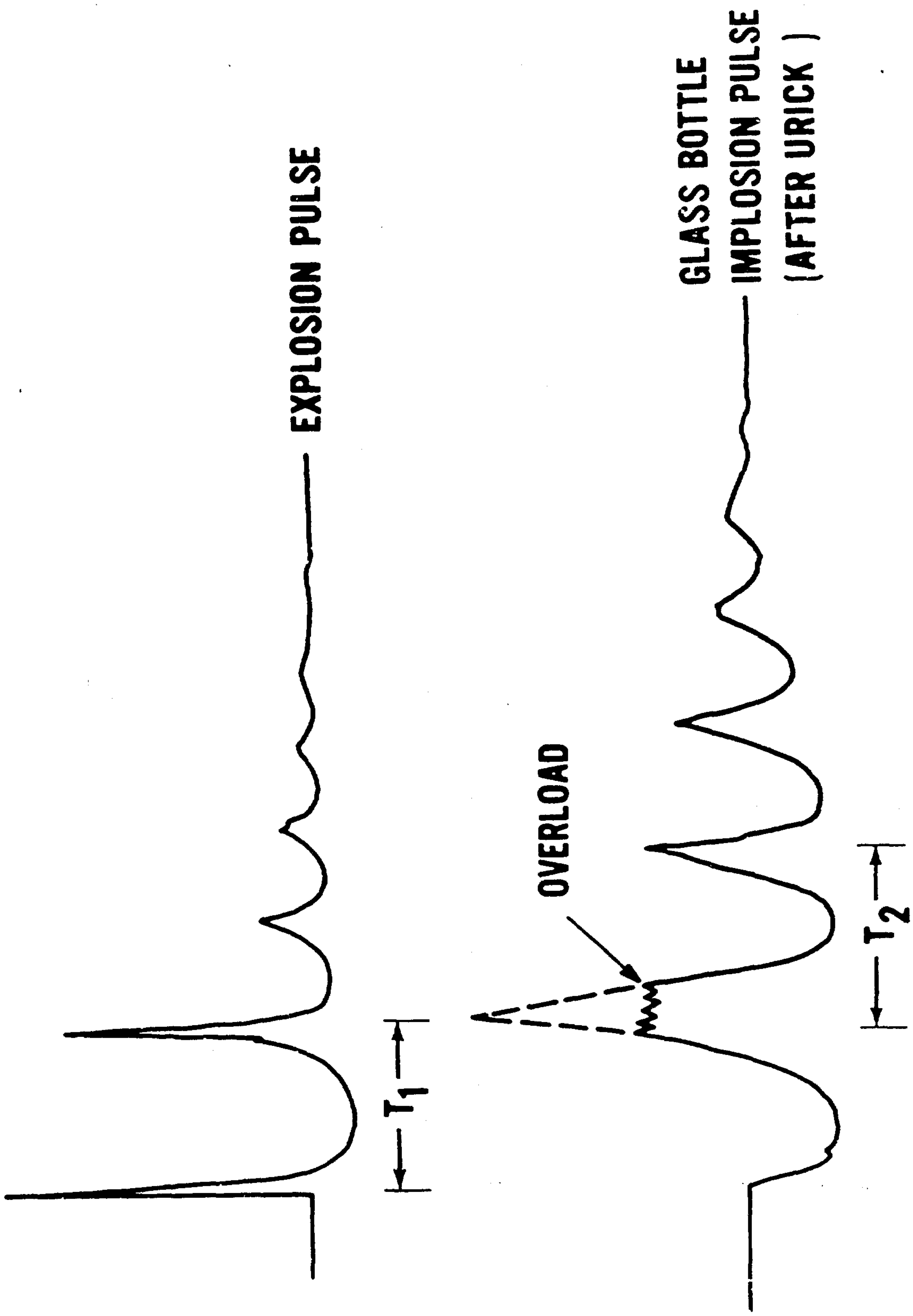

FIG. 1 COMPARISON OF EXPLOSION PULSE WITH GLASS BOTTLE IMPLOSION PULSE

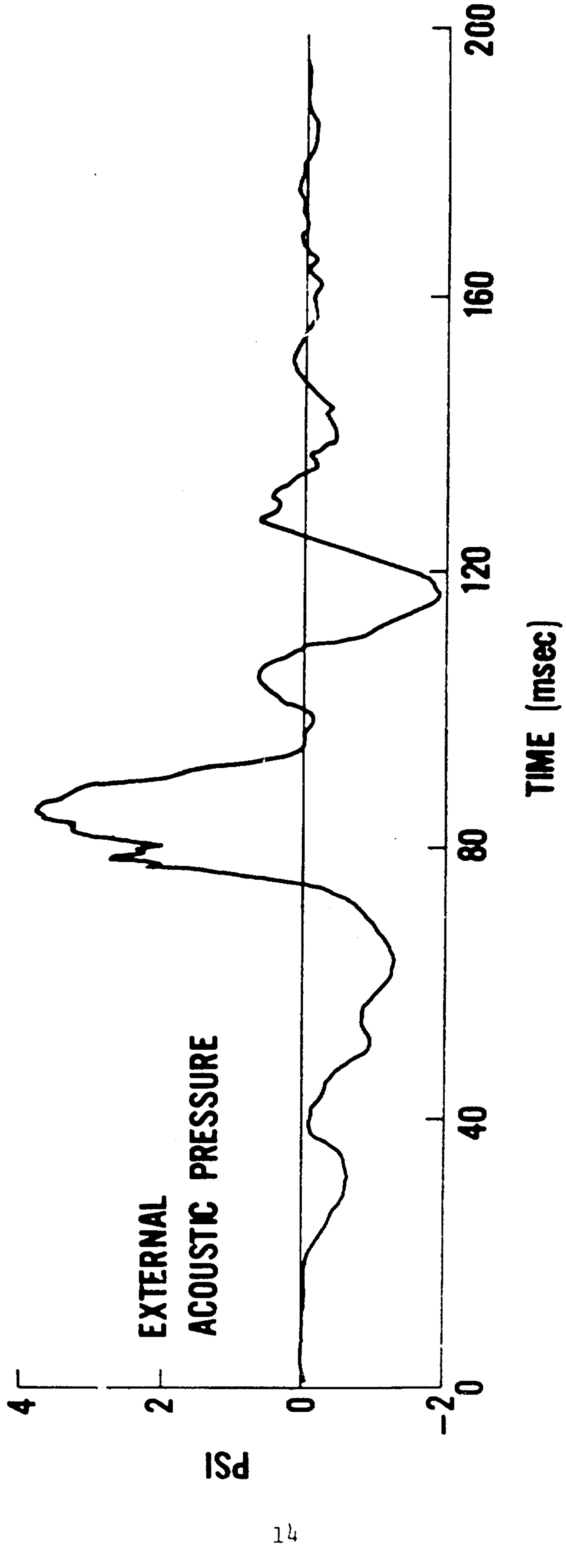

FIG. 2 IMPLOSION OF 30-INCH SINGLE-COMPARTMENT TANK

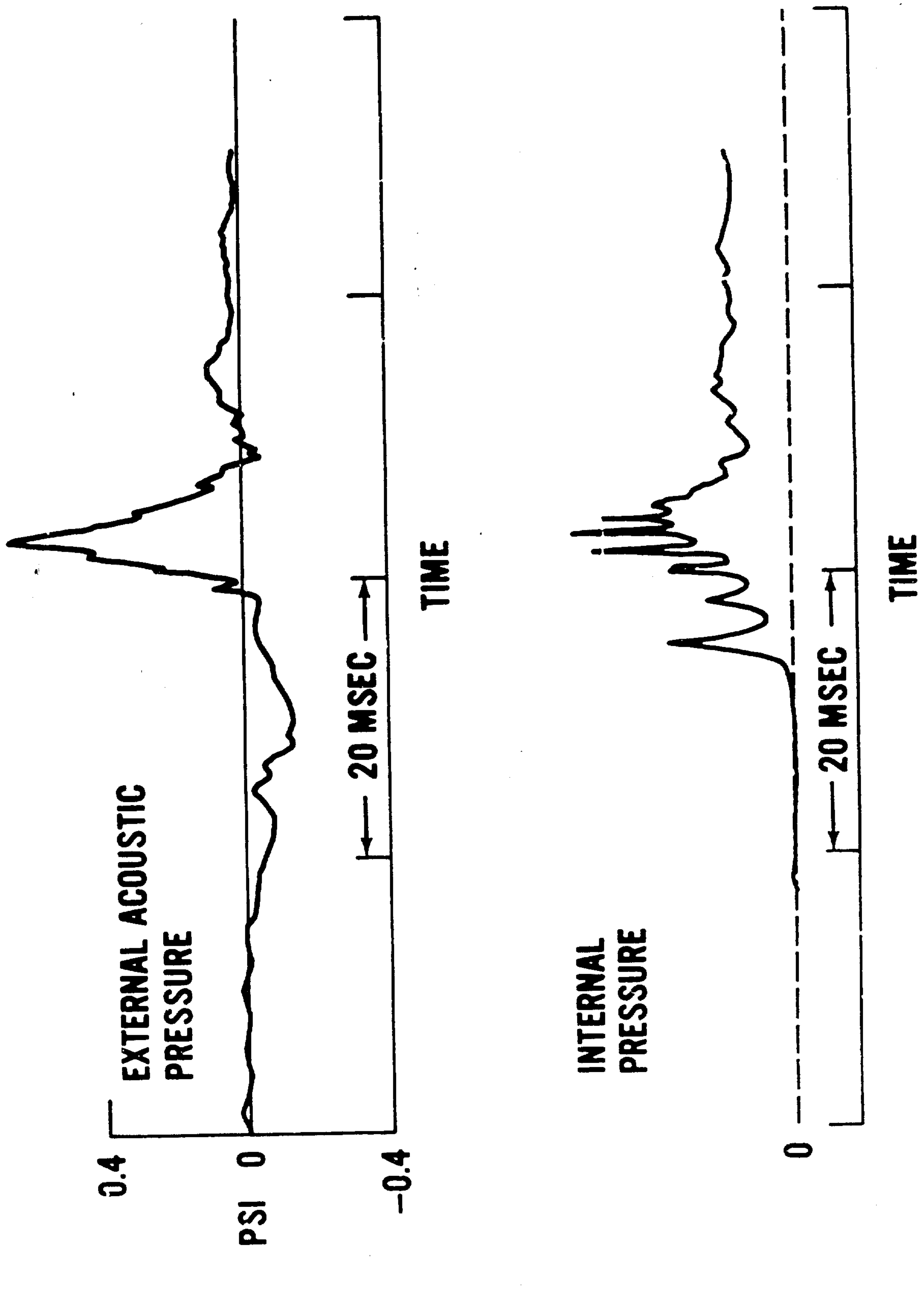

FIG. 3 IMPLOSION OF 26-INCH STEEL TANK

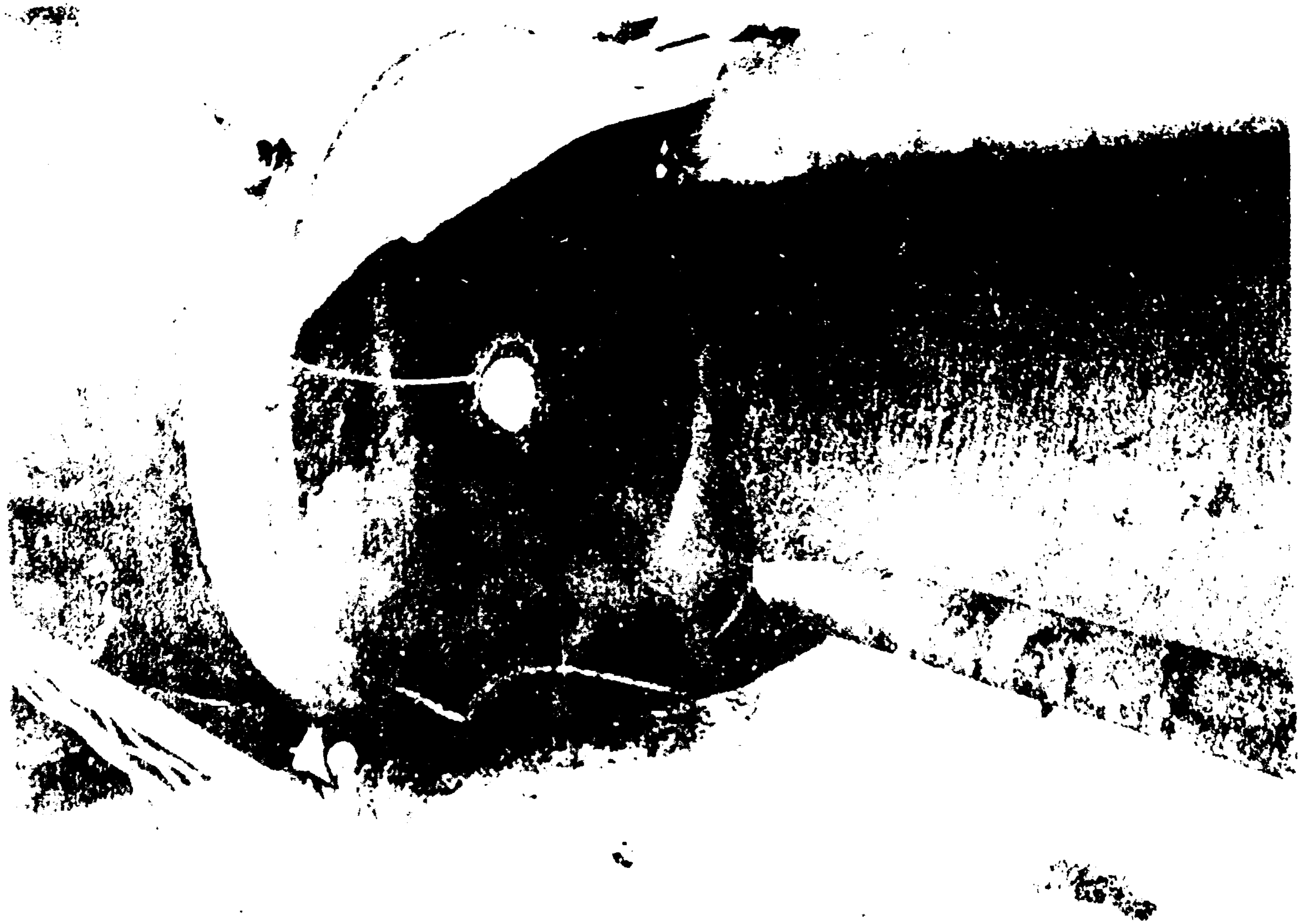

PHOTO BY NRL

FIG. 4 DAMAGE TO CENTER COMPARTMENT OF 26-INCH STEEL TANK

PHOTO BY NRL

FIG. 5 DAMAGE TO CENTER COMPARTMENT OF 14-INCH STEEL TANK

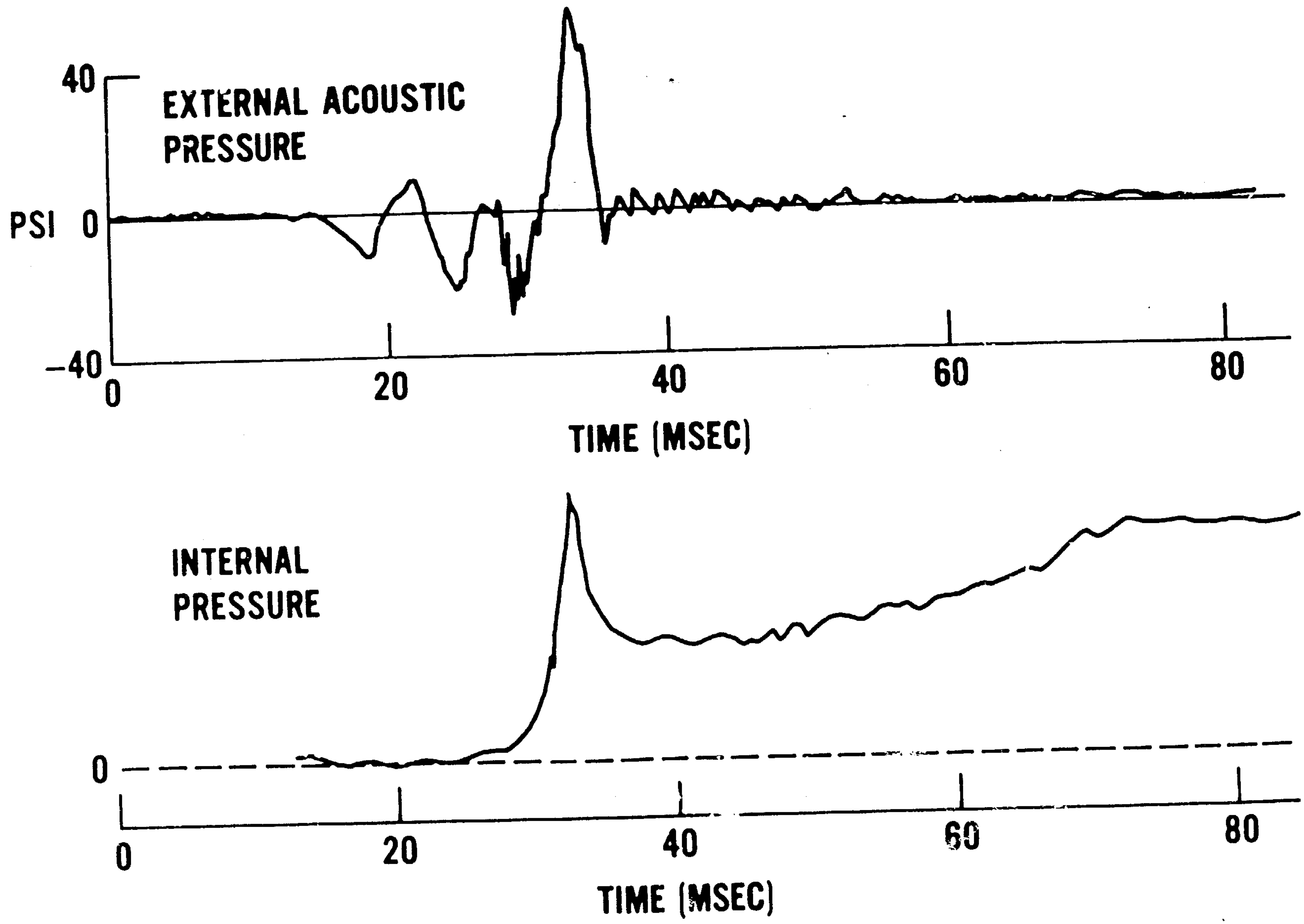

FIG. 6 IMPLOSION OF 14-INCH STEEL TANK

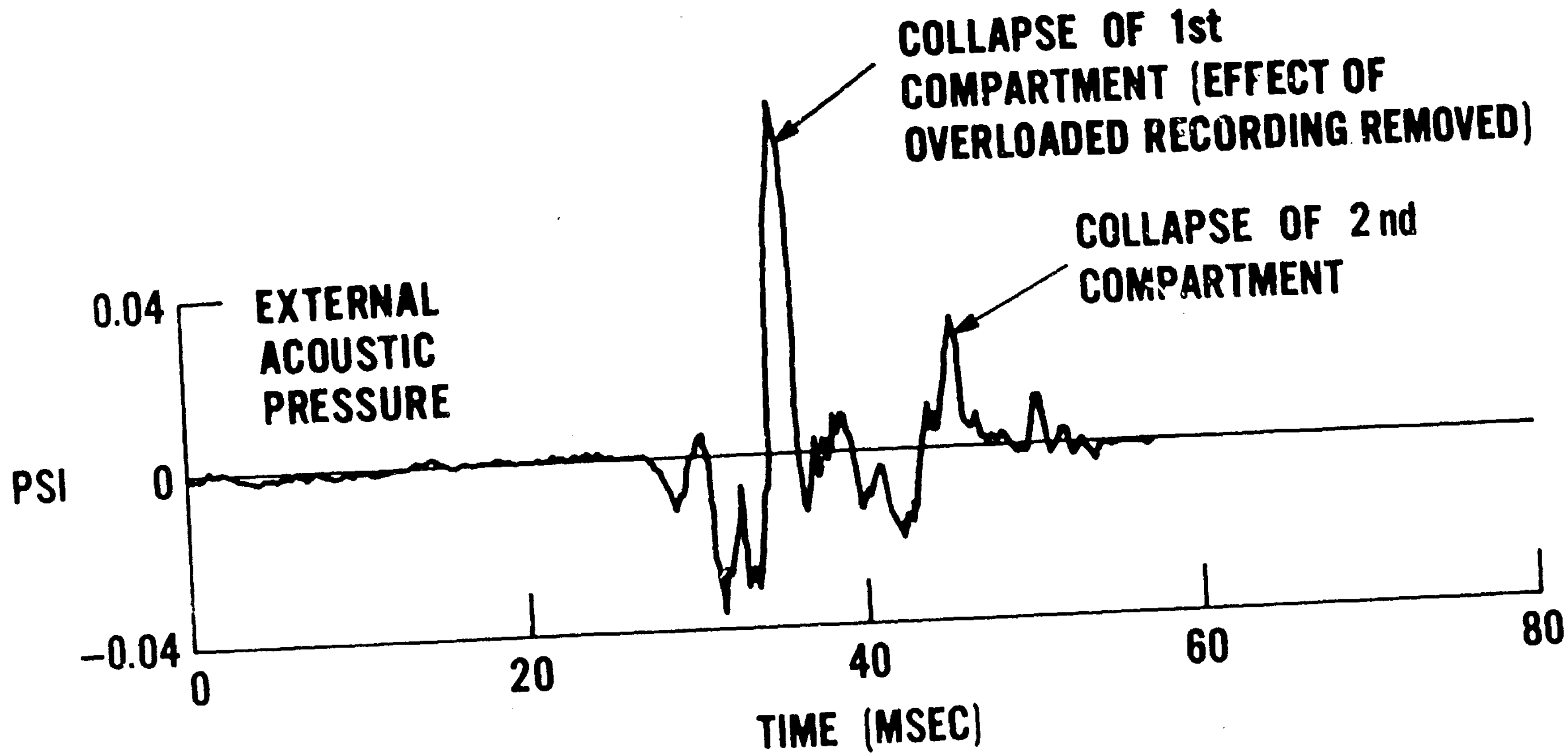

FIG. 7 ALMOST SIMULTANEOUS IMPLOSION OF TWO COMPARTMENTS OF AN 8-INCH STEEL TANK

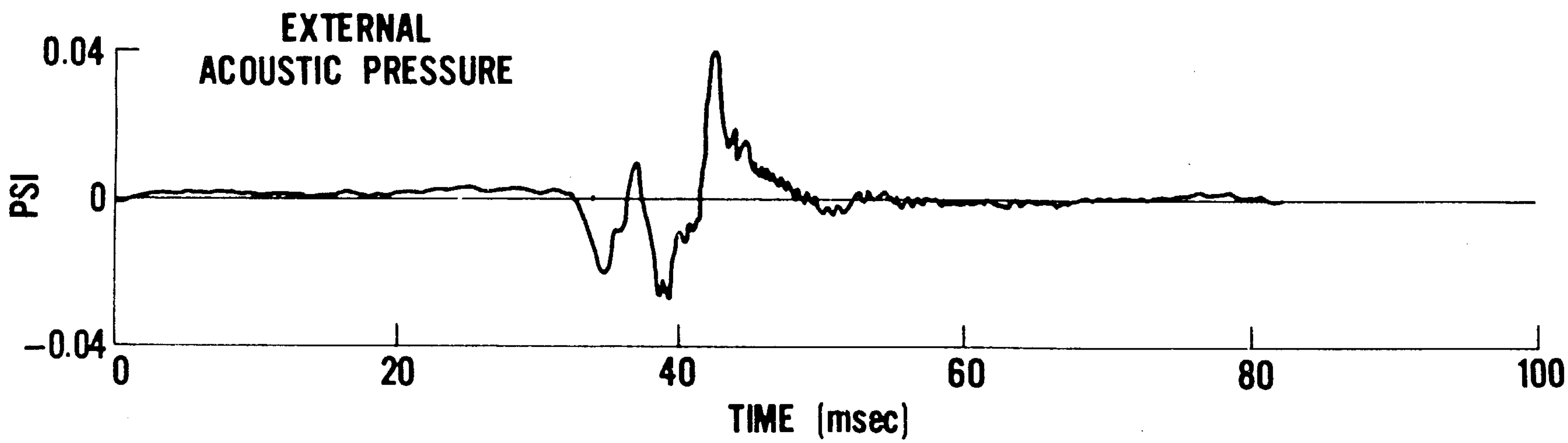

FIG. 8 IMPLOSION OF 8-INCH STAINLESS STEEL TANK

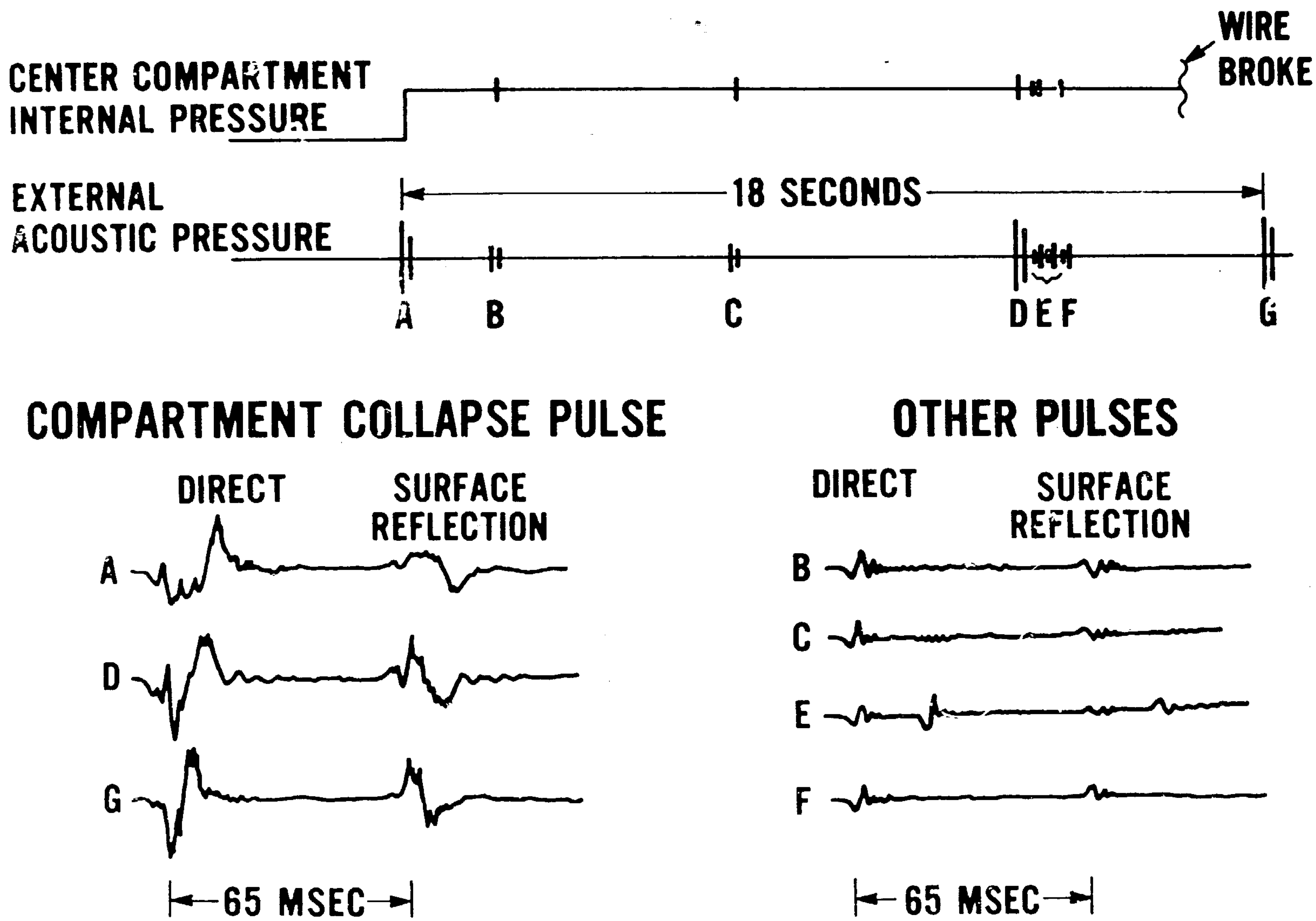

FIG. 9 IMPLOSION SEQUENCE OF ALL THREE COMPARTMENTS OF A 16-INCH STEEL TANK

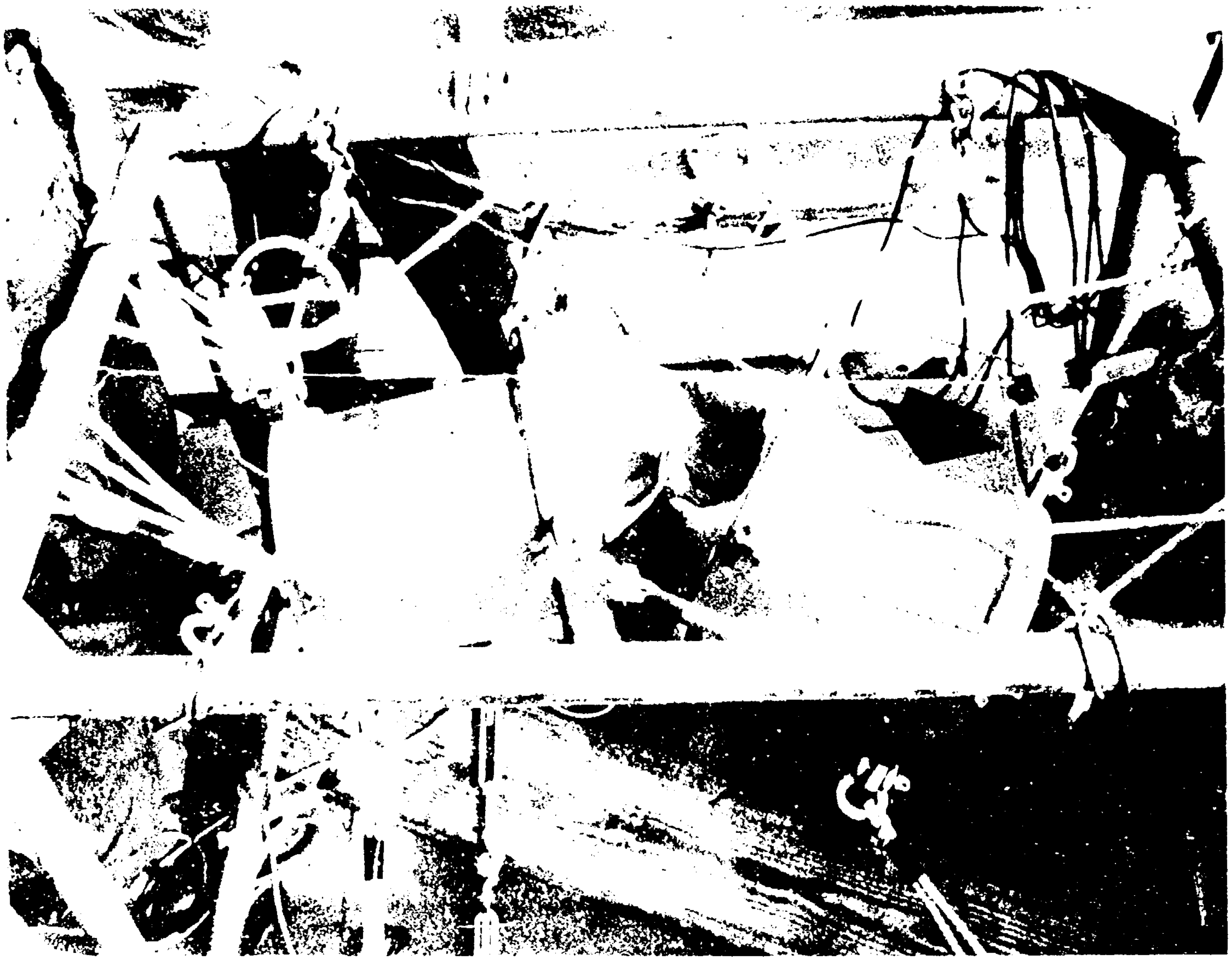

FIG. 10 MINOR DAMAGE TO RIGHT END COMPARTMENT FOLLOWING COLLAPSE OF CENTER COMPARTMENT (16-INCH STEEL TANK)

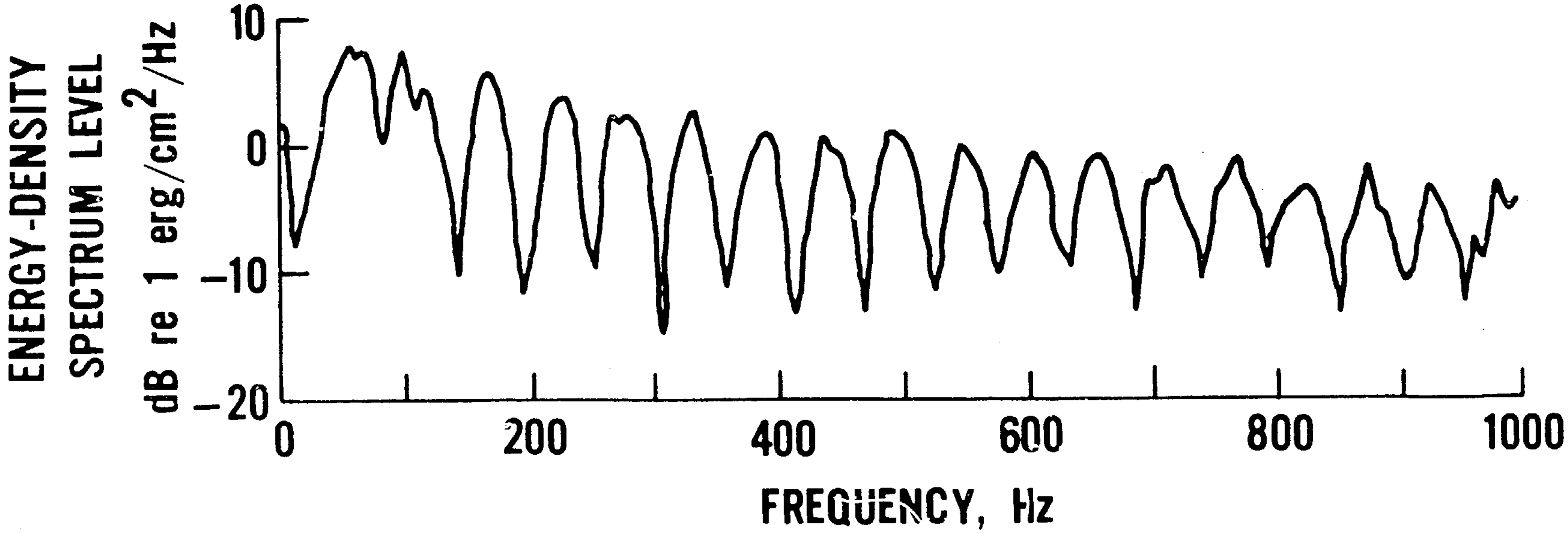

FIG. 11 DIGITALLY COMPUTED SPECTRUM FOR 1.8 LB SUS CHARGE; DEPTH OF DETONATION, 865 FT.

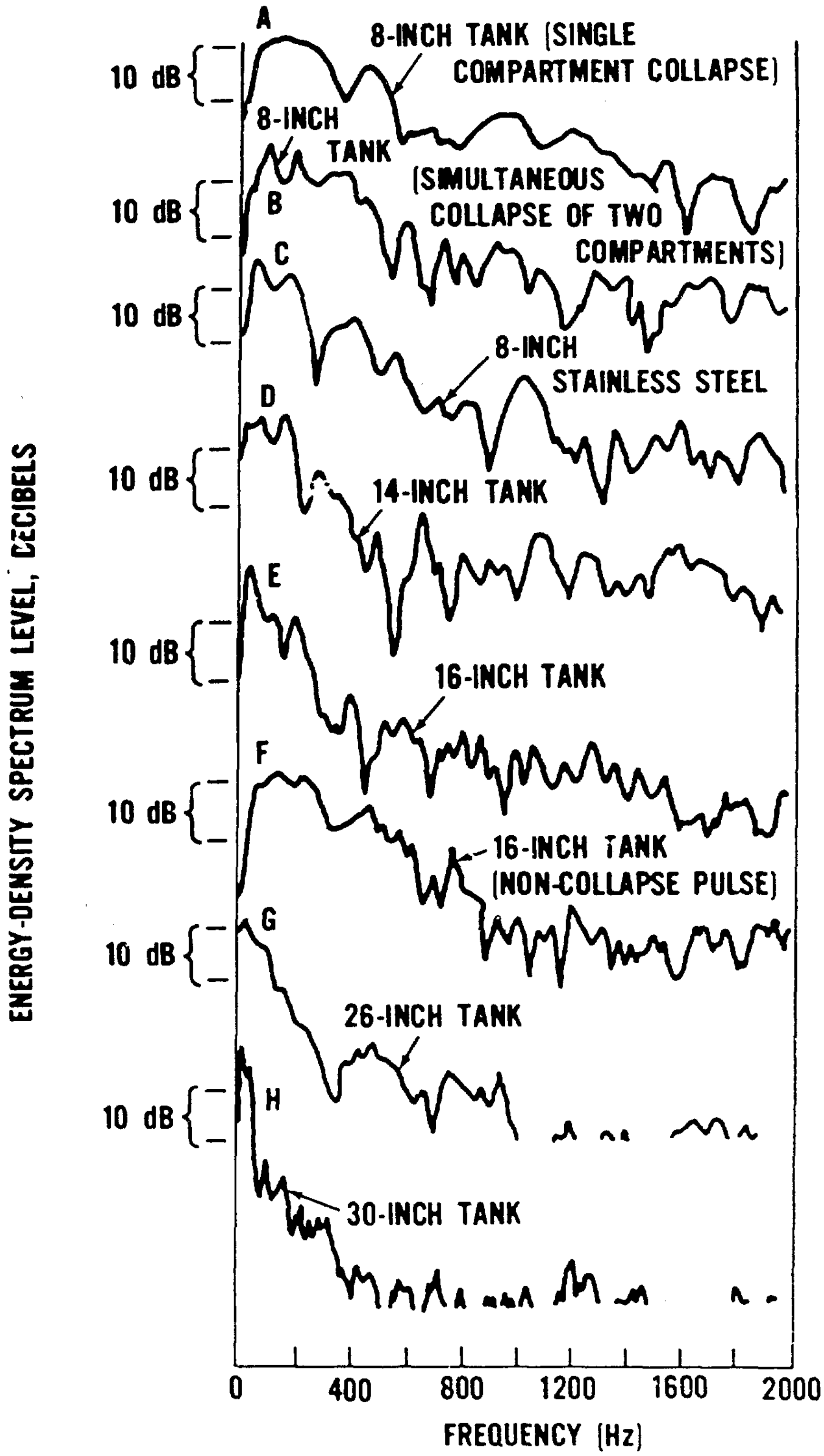

FIG. 12 ENERGY-DENSITY SPECTRA OF SIGNALS EMITTED BY COLLAPSING TANKS OF DIFFERENT SIZES