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EXPLOSIVES RESEARCH CENTER

INITIATION OF DETONATION BY LOW AMPLITUDE SHOCKS

Quarterly Report
August 1, 1963 to October 31, 1963

BUREAU OF MINES, PITTSBURGH, PA.

UNITED STATES
DEPARTMENT OF
THE INTERIOR

INITIATION OF DETONATION BY LOW AMPLITUDE SHOCKS

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INITIATION OF DETONATION BY LOW AMPLITUDE SHOCKS

INTRODUCTION

This is a quarterly report concerning studies on the initiation and growth of detonations in propellants and explosives. Current emphasis is placed on reactions that result from low amplitude shock wave stimuli in liquid explosives; the resultant decomposition is usually a low-velocity detonation.

The nature of the low-velocity detonation regime in liquid explosives has been a matter of conjecture for many years and, until recently, the question of stability of such reactions had not been resolved. Taylor[1/], for example, quotes low-velocity detonation rates for nitroglycerin (NG) ranging from 890 m/sec to 2530 m/sec, depending on the diameter of the explosive column and the strength of the initiation source. However, since these values represent rates averaged over column lengths considerably greater than the column diameter, little could be concluded regarding the stability of such reactions. Evidence presented in an earlier report of this series[2/] indicated that stable low-velocity detonations in nitroglycerin-ethylene glycol dinitrate (NG-EGDN) could be attained under certain environmental conditions. These preliminary results have now been verified in an extended photographic study of the effects of confining wall material and thickness on the stability of low-velocity detonation in NG-EGDN.

[1/] Taylor, J. Detonation in Condensed Explosives. Oxford at the Clarendon Press, London, England, 1952.

[2/] Bureau of Mines Quarterly Progress Report, "Initiation of Detonation by Low Amplitude Shocks", ARPA Order 44-63, Department of Defense, February 1, 1963 to April 30, 1963.

EXPERIMENTAL STUDIES

NG-EGDN in Cylindrical Tubes

The basic charge arrangement used in these studies is shown in figure 1 and consists of a cylindrical tube 16 inches long, having an inside diameter of nominally 1 inch. The shock source consisted of a 1 in. long x 1-5/8 in. diameter tetryl charge coupled with a Lucite shock attenuator of the same diameter and having a length of 4.0 inches. This source is capable of delivering a peak pressure of 2.4 kilobars to the NG-EGDN and has proven adequate for the initiation of a low-velocity reaction under most circumstances. The tube materials investigated were: lead, Lucite, aluminum, and steel with wall thicknesses of 1/16 in, 1/8 in, and 1/4 inch.

In these experiments a streak camera was used to observe the progress of the detonation along the entire length of the charge. In the case of the transparent Lucite containers, the detonation could be viewed directly. For the case of the opaque container, the progress of the reaction was viewed through 1/4-inch diameter ports spaced at 1 inch intervals along the length of the tube as indicated in figure 1. The ports were sealed by a strip of transparent tape cemented to the interior of the tube to minimize the effect of surface discontinuities.

Typical streak camera records illustrating both stable and unstable low-order detonations are presented in figures 2, 3, 4, and 5. Figure 2 shows the results obtained with a 1/4-inch wall Lucite container. It will be noted that after the first 10 to 15 cm of travel the detonation stabilizes and traverses the remainder of the column at a uniform rate. The results obtained with a 1/16-wall Lucite container are shown in figure 3 and illustrate an unstable detonation. While the initiation phase of the reaction resembles that obtained with the 1/4-inch wall container, the reaction in the 1/16-inch wall tube progresses in a pulsating fashion and appears to be dying out as it approaches the end of the container. Similar results are presented in figures 4 and 5 for the metal containers. Figure 4 shows a stable low-order detonation obtained in a 1/4-inch wall steel container. An unstable detonation, as indicated by the step-like appearance of the trace shown in figure 5, was obtained with a 1/4-inch thick lead tube.

The individual test results obtained in this series of experiments are presented in table 1 in terms of the type of reaction observed. Detonation rates are also included for the cases where stable detonations took place.

It will be noted that both the sonic velocity of the wall material relative to the NG-EGDN as well as the tube wall thickness appear to be the decisive factors in controlling the stability of the detonations. In particular, for the case of lead tubes where the sound velocity is less than that of the liquid, unstable reactions were observed for all wall thicknesses studied. For Lucite, which has a sound velocity somewhat in excess of that of NG-EGDN, unstable reactions were observed in the 1/16-inch wall tubes whereas stable detonations occurred in the 1/8 inch and 1/4-inch wall containers. Essentially the same results were obtained for the 1/16 inch and 1/4-inch thick wall trials in aluminum. On the other hand, for steel containers, reasonably stable detonations were observed for all three wall thicknesses. It will also be noted that for the stable low-velocity detonations the rates are invariably in excess of the sonic velocity of the explosive. This suggests that the subsonic detonation rates reported in the literature represent unstable reactions.

TABLE 1. - Results of low-velocity stability studies with NG-EGDN

Wall Thickness (in)	Result	Detonation Rate (m/sec)
	Lead Tubes;[*] $c_o = 1190$	
1/16	Unstable L.V.D.	-
1/16	do. do.	-
1/16	do. do.	-
1/8	Unstable L.V.D.	-
1/4	Unstable L.V.D.	-
1/4	do. do.	-
	Lucite Tubes; $c_o = 1840$	
1/16	Unstable L.V.D.	-
1/8	Stable L.V.D.	2140
1/4	do. do.	1700
1/4	do. do.	2040
	Steel Tubes; $c_o = 5200$	
1/16	Stable L.V.D.	1950
1/16	do. do.	1970
1/8	do. do.	1880
1/4	do. do.	2120
1/4	do. do.	2100
	Aluminum Tubes; $c_o = 5000$	
1/16	Unstable L.V.D.	-
1/16	do. do.	-
1/4	Stable L.V.D.	2060
1/4	do. do.	2010

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[*] Thin rod sound velocities.

Discussion

It has been postulated that cavitation plays an important role in the initiation and propagation of a low-velocity detonation in liquid explosive systems. Indeed, photographic studies in both cylindrical tubes and cubical containers have shown that severe cavitation precedes the onset of violent chemical reactions. During the initiation phase of a low-velocity detonation, the rarefaction leading to cavitation can enter the liquid along the axis of the system in the direction of the initial shock input or can originate at the laterally expanding container walls. However, for the case of a steady-state detonation in the cylindrical geometry, the source of the rarefaction leading to cavitation is somewhat more difficult to envision. This is due in part to the fact that the region of cavitation must maintain a fixed position ahead of the compressive shocks generated in the reaction zone.

A simple physical model of the steady-state low-velocity detonation under current consideration is depicted in figure 6. Referring to the figure and assuming an observer moving with the reaction, the following events take place:

(1) The undisturbed liquid in Section "AA" moving along the particle paths "uu" is first compressed by the shock waves delivered to the fluid by the precursor wall shocks located at "BB".

(2) The compressed fluid then moves into an expanded region, beginning at "CC", where the wall begins to move outward due to the pressures generated in the reaction zone.

(3) The liquid continues to expand and eventually cavitates in the region of "DD".

(4) The cavities grow until they encounter the pressure

field in the liquid near the reaction zone. This point is labeled "EE" in the figure.

(5) On entering the pressure field at "EE", the cavities collapse generating the high pressures necessary to cause chemical reaction.

The combined effect of a multitude of microscopic reaction centers can then be visualized as the reaction zone. The important feature of this model, of course, is the hypothesis that a low pressure region exists behind the precursor wall shock and ahead of the pressure field due to the reaction zone. This can only occur if the initial expansion of the container wall takes place at a point appreciably ahead of the reaction zone. A preliminary experiment has been carried out and the results indicate that such is the case.

The experimental setup is shown in figure 7 and consists of a cylindrical Lucite column 16 inches long, having a 1-inch inside diameter and a wall thickness of 1/8 inch. The tube was filled with NG-EGDN and initiated by a shock derived from a 1-5/8-inch diameter x 1-inch long tetryl donor and a 4-inch Lucite attenuator of the same diameter. In order to detect wall motion, a steel straightedge was aligned along the axis of the tube and placed .015 inch from the tube side wall which was painted black to provide a well-defined slit parallel to the tube axis.

A framing camera sequence is presented in figure 8. A close examination of the slit closure shows that the tube wall begins to expand at a point ahead of the reaction zone. This is perhaps better illustrated in figure 9 which is an enlargement of frame #21 of the sequence. The tube expansion appears to begin at a point approximately 5 cm ahead of the reaction zone; a cavity field appears to originate in this same region. It is not intended that this single trial be offered as sole support of the proposed model but the experiment does offer strong evidence that the gross features of the mechanism are correct. Additional experiments are underway in an attempt to gain added support for this hypothesis.

Studies on Water in Tubes of Various Materials

As a control experiment relative to the work previously reported on NG-EGDN in tubes (to determine the effect of tube wall characteristics on the transmission of shocks), the following series of experiments was performed: Tubes of 1-inch inside diameter, 1/4-inch wall thickness, and of varying lengths were filled with water (not degassed) and subjected to a shock delivered by a 1-5/8 inch diameter x 1-inch long tetryl pellet through a 1-5/8 inch diameter x 2-inch long Lucite attenuator coupled to the bottom of the tube. An expendable pressure gage was inserted in the tube on the axis, a distance L from the attenuator. Tube materials used included aluminum, lead, and Lucite. The pressure records obtained show a number of peaks; however, the first peak was selected to plot time of arrival and pressure vs distance L in figures 10 and 11 respectively.

The time-of-arrival plots for aluminum and Lucite show a discontinuity where the waves propagated from the walls overtake those propagated directly through the liquid. The velocities indicated for these waves in Lucite and aluminum are 2.8 and 5.8 mm/μsec respectively and are in approximate agreement with the longitudinal wave velocities for these materials[3/]. The value of 1.8 mm/μsec for lead may correspond either to the velocity of a slightly over-driven shock in water or the longitudinal wave velocity in lead. Some of the pressures obtained fall below the

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[3/] American Institute of Physics Handbook, Second Edition, McGraw-Hill Book Company, Inc., 1963, p. 3-88.

range of calibration of the gage and its response in this region is such that extrapolation is not feasible. For this reason, the Lucite curve is truncated beyond L = 7 cm.

The above results clearly show that waves of appreciable magnitude may be propagated into the liquid with a phase velocity considerably higher than the velocity of a shock propagated through the liquid, thus affording support for the cavitation hypothesis given in the preceding section.

Studies on TMETN in Cylindrical Tubes

Because it was considered desirable to explore the effect of the physical properties of the explosive on the low-order detonation process, it was decided that at least two other liquid explosives should be studied in the arrangement used for NG-EGDN -- one of higher viscosity and lower vapor pressure, the other of lower viscosity and higher vapor pressure. The explosive chosen to exemplify the first set of properties was trimethylolethane trinitrate (TMETN)[**].

Initially, only a small amount of material was on hand and a set of survey experiments was run to serve as a basis for later work. The qualitative results may be stated briefly:

(1) In addition to a high- and low-order detonation, TMETN exhibits a fast deflagration as evidenced by negligible damage to the container; however, noticeable blast effects to the surroundings are observed which cannot be attributed solely to the donor charge.

(2) With the same attenuator, a low-order detonation, a deflagration, or total failure to react may re-

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[**] This substance is known to exhibit high-order detonation but no attempt was made to study this phenomenon.

sult depending on tube material.

(3) The length of the acceptor can determine whether a deflagration or detonation will ensue.

(4) The pressure developed in the low-order detonation is strongly dependent on the wall material.

When additional TMETN became available, a series of trials similar in scope to that done with NG-EGDN was begun; this study is still in progress. Preliminary results indicate that with tube materials of other than steel of 1/4-inch or 1/8-inch wall thickness, the pressure developed is too small to produce an interpretable record using the greatest sensitivity available with the present pressure gage, although the pressures ultimately produced are adequate to completely fragment the detonation tube.

NM-TNM Studies

The other liquid explosive system studied was a mixture of nitromethane (NM) and tetranitromethane (TNM). This system was chosen because of its high vapor pressure and low viscosity and also because of interest in both components--NM because of instances of alleged accidental detonation involving very large quantities; TNM because of its alleged role as a sensitizer in certain systems. Also, a series of mixtures can be formulated covering a wide range of oxygen balance since NM is extremely oxygen poor and TNM extremely oxygen rich.

The mixtures used to date are described in table 2 (pure NM is included for convenience) according to their composition, nominal products, fuel utilization, apparent detonation rate D, approximate detonation pressure P, and sensitivity expressed as the length L of 1-5/8-inch diameter Lucite attenuator, used with a 1-5/8-inch diameter x 1-inch long tetryl donor, which will result

TABLE 2. - Composition and properties of NM-TNM mixtures

% TNM (by wt)	TNM/NM (moles)	Products[1]				Fuel utilization[2]	D (mm/µsec)	P (kilobars)	Attenuator length (in)
		CO_2	CO	H_2O	H_2				
44.5[3]	.250	.33	0	.40	0	1.00	2.05	25.5	5.5
18.7[4]	.0714	0	.33	.46	0	.71	2.2	7.5	4.5
10.0	.0345	0	.33	.40	.08	.64	2.2	7.7	2.25
5.0	.0170	0	.33	.37	.125	.60	1.8	5.2	2.25
0	0	0	.33	.33	.17	.57	(high-order detonation)		0.3

1/ Nominal products: oxygen is assumed to be used in the formation of CO first, then H_2O, then CO_2. The numbers given do not sum to unity; the balance is, of course, nitrogen.

2/ Defined as $\frac{2\,[O]}{4\,[C] + [H]}$ where [ ] represents the number of moles of the element indicated.

3/ Balanced to $CO_2 + H_2O$.

4/ Balanced to $CO + H_2O$.

in failure to detonate at all in about 50 percent of the trials.

The results given are only for containers of 1 inch id, 1/4-inch wall thickness, about 6 inches long. The 5-percent mixture was also tried in aluminum and Lucite containers of the same dimensions but no clear-cut evidence of detonation was found even with attenuators as short as 1 inch. It should be noted that the results are based on a limited number of shots in each case; hence, the above data should not be considered definitive.

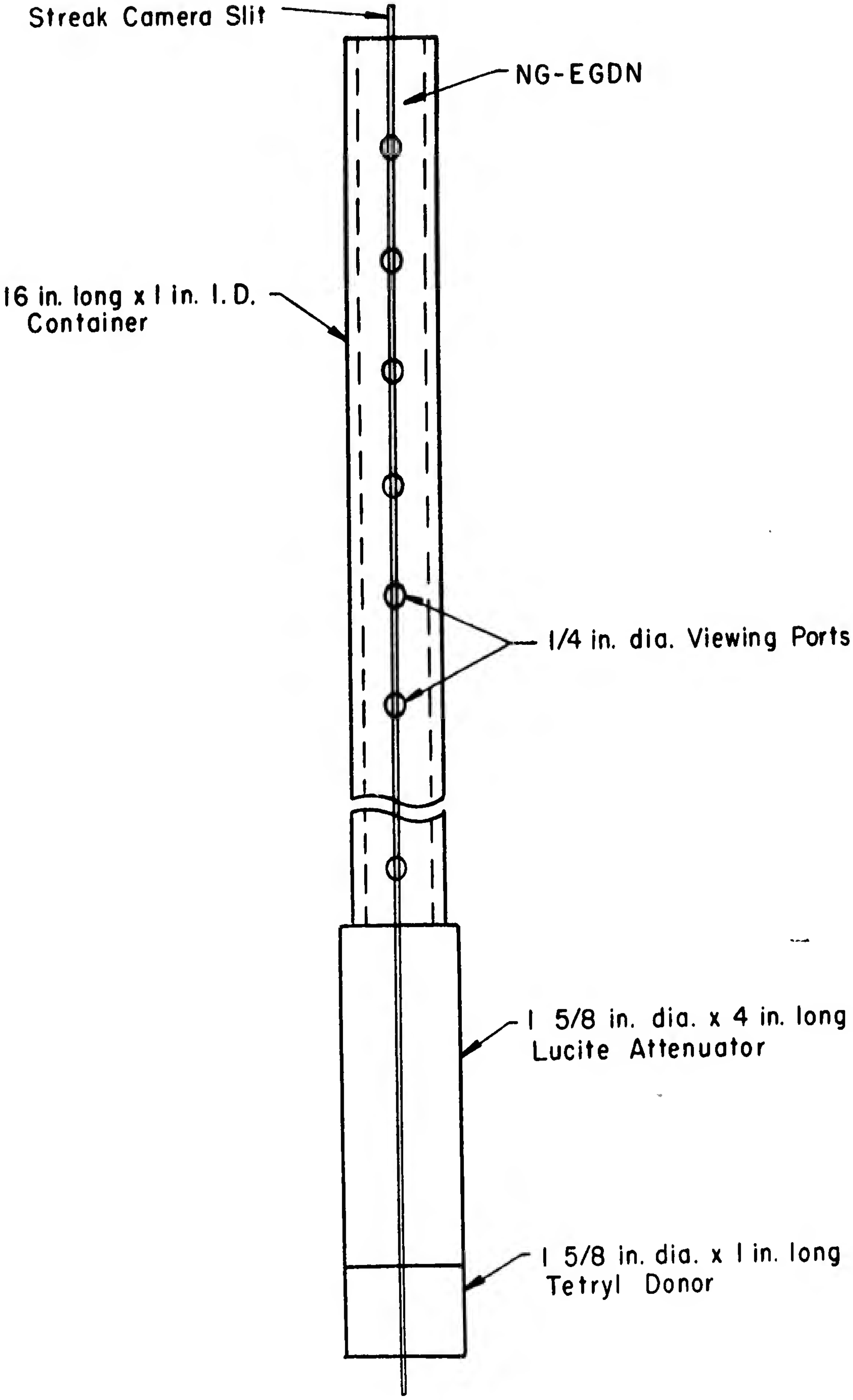

FIGURE 1. - Experimental setup used in stability studies with opaque containers.

FIGURE 2. - Streak camera record of low-velocity detonation of NG-EGDN in 1/4-inch wall Lucite tube showing stable propagation.

FIGURE 3. - Streak camera record of low-velocity detonation of NG-EGDN in 1/16-inch wall Lucite tube showing unstable propagation.

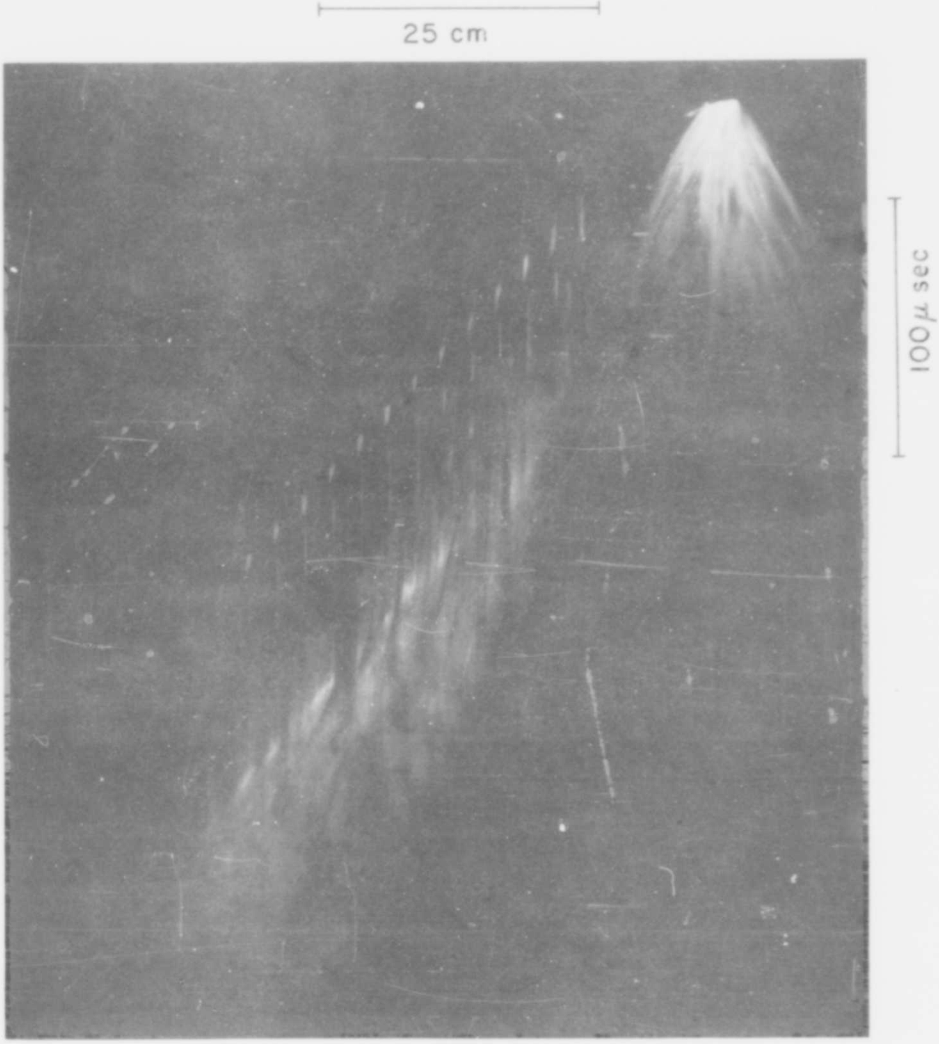

FIGURE 4. - Streak camera record of low-velocity detonation of NG-EGDN in 1/4-inch wall steel tube (with perforations on slit) showing stable propagation.

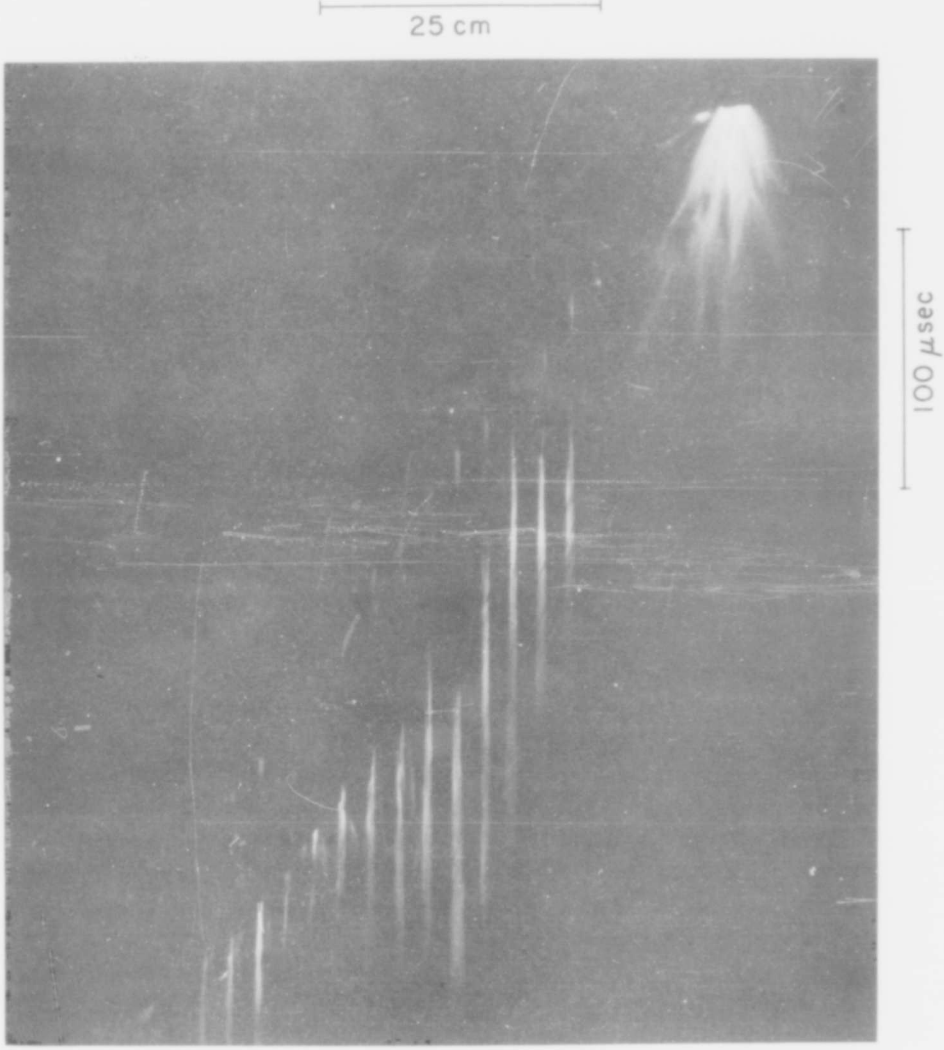

FIGURE 5. - Streak camera record of low-velocity detonation of NG-EGDN in 1/4-inch wall lead tube (with perforations on slit) showing unstable propagation.

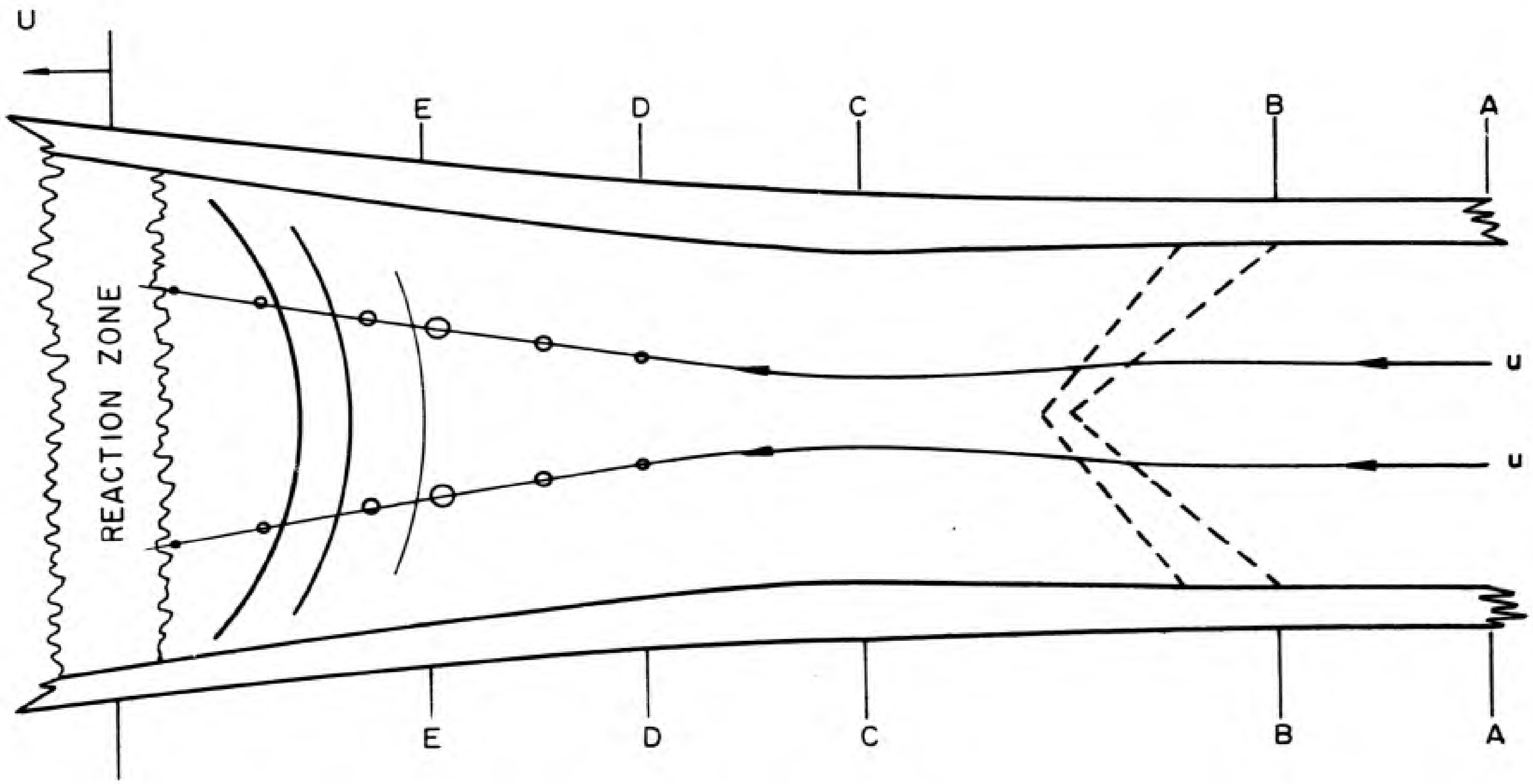

FIGURE 6. - Pictorial representation of a steady-state low-order detonation in a confined liquid explosive.

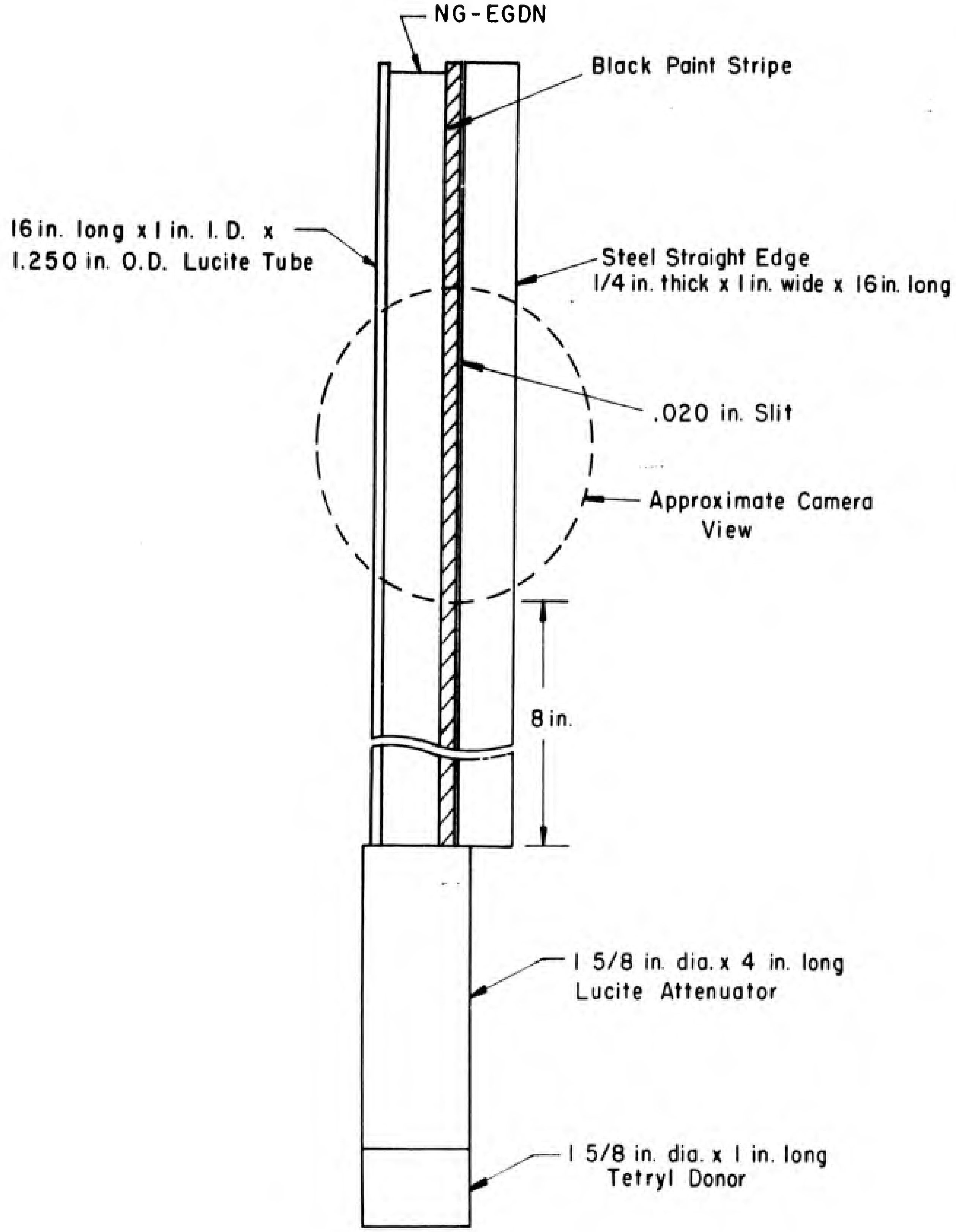

FIGURE 7. - Experimental arrangement used to estimate point of initial tube expansion relative to detonation front.

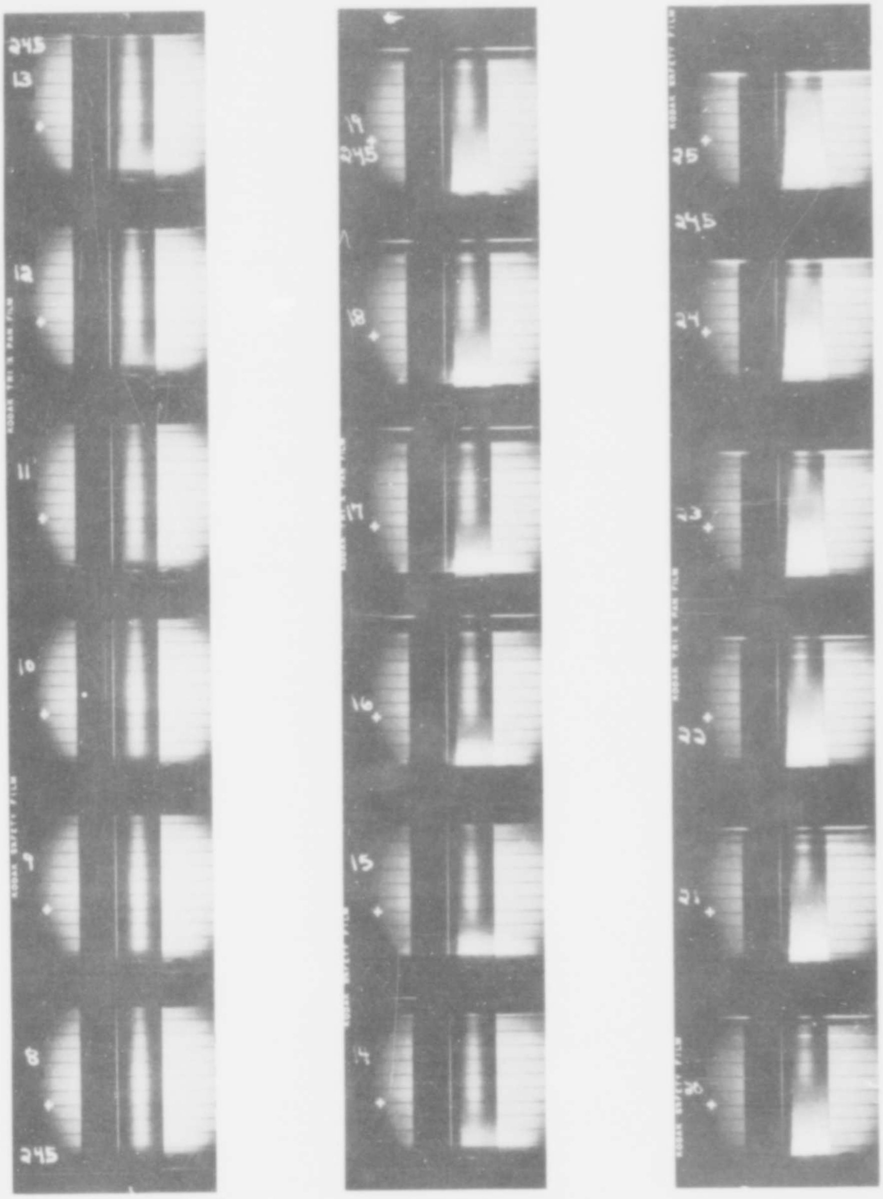

FIGURE 8. - A framing sequence showing tube expansion ahead of a low-order detonation front.

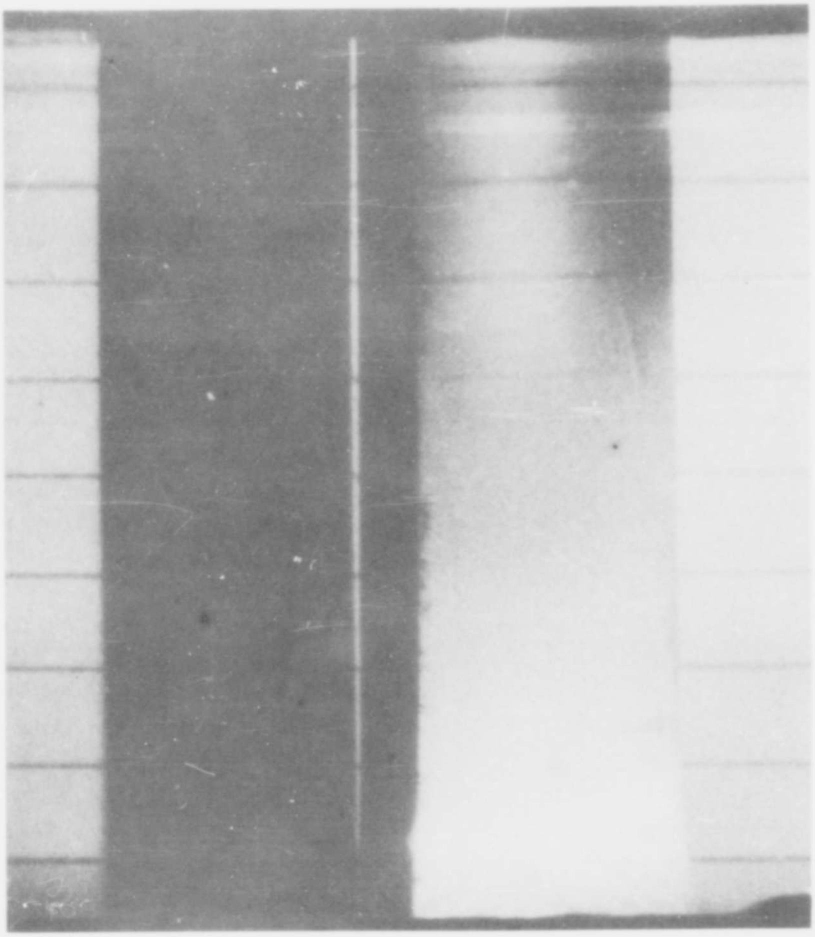

FIGURE 9. - An enlargement of frame 21 of figure 8.

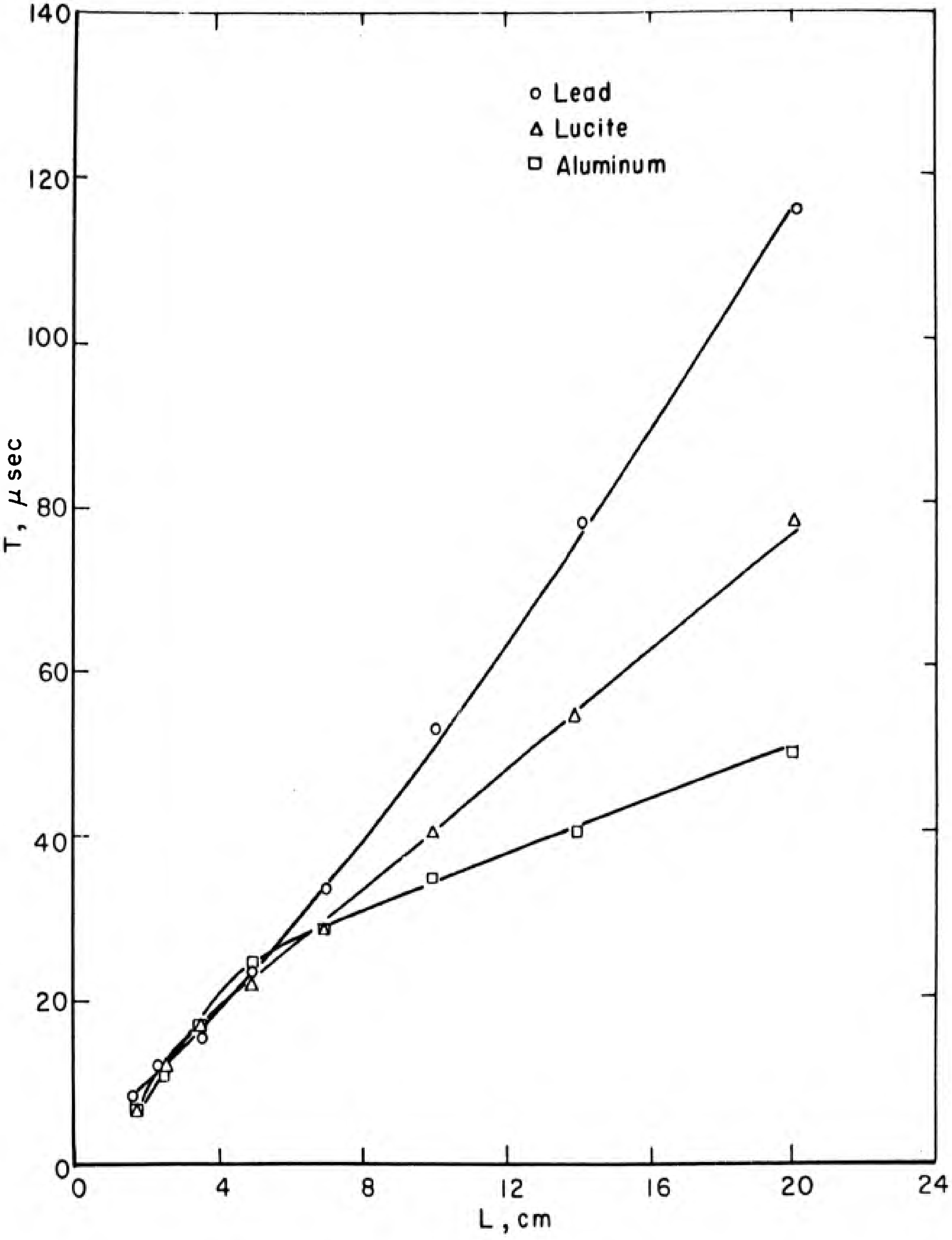

FIGURE 10. - Time vs distance from the attenuator interface for water in 1-inch id 1/4-inch wall tubes.

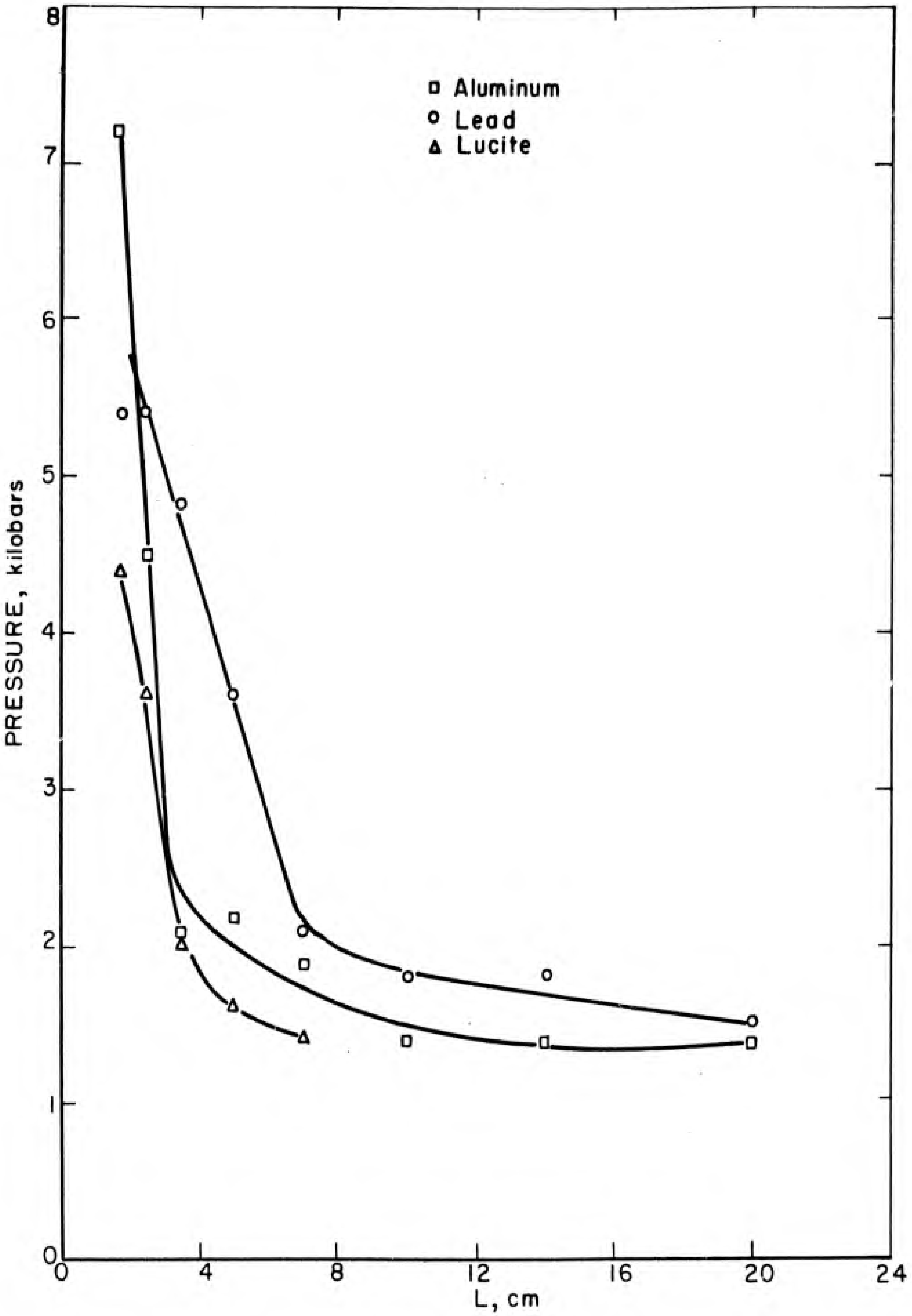

FIGURE 11. - Pressure vs distance from the attenuator interface for water in 1-inch id 1/4-inch wall tubes.

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