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TRANSIENT STUDIES OF DETONATION WAVES

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A new theoretical model for the self sustenance of transverse waves which qualitatively explains these observations will be presented.

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The smoked foil technique is being used to study the transient behavior of transverse wave systems on propagating detonations that encounter either compositional or tube area changes.

A technique has been developed which allows the measurement of the strength of individual transverse waves at each intersection with a wave of the other family from the observed deflection of the wave trajectories at the intersections.

We have observed positive decay of transverse waves in situations where the waves are forced to be too close together and we have observed that the production of new waves when necessary is complex.

A new theoretical model for the self sustenance of transverse waves which qualitatively explains these observations will be presented.

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Introduction

In recent years the smoked foil technique(1) has been used to obtain a considerable amount of information concerning the structure of propagating detonation waves(2-6). In particular, by using this technique it has been observed that the regularity of the structure as well as its characteristic size and the strength of the transverse waves in the structure are dependent upon the initial composition of the mixture and the initial pressure at which the mixture is detonated. Specifically, with proper mixtures in straight rectangular tubes one can observe quite regular structure. When the structure is observed to be extremely regular the detonation is called an equilibrium configuration detonation. These equilibrium configuration detonations have the property that their structure is exactly repeatable at equal time intervals or at equal intervals of distance down the length of the tube(7). In a development which is parallel to these experimental observations there has also been a considerable theoretical effort in an attempt to explain the nature of the structure and its origin(7-9). However, this effort has been hampered by the fact that, to date, the only quantitative observations have been of structure which is already well established. There have been no observations of the processes which occur when structure relaxes from one form to another or when the structure is formed initially on the detonation front. Therefore, at the present time there is a considerable need for the observation of transient behavior of detonation waves so that one may gain insight into the mechanisms by which the structure originates or maintains itself.

In this paper we will report on the observation of two types of transient behaviors produced by perturbing equilibrium configuration detonations. In one set of investigations the detonation's structure was perturbed by placing a two dimensional obstruction in the detonation tube so that the area of the tube was altered with time as the detonation propagated over the obstruction. In the other type of transient study the detonation was forced to propagate from a gas mixture of one composition into a gas of another composition so that the characteristic preferred spacing and structural regularity of the mixture could be changed as the detonation propagated over the compositional interface.

Experimental

In all cases the detonations which were to be perturbed were equilibrium configuration rectangular mode detonations propagating in a stoichiometric hydrogen-oxygen mixture diluted with at least 50 mole percent of the inert monotomic gases helium or argon or mixtures thereof. Gas mixtures were prepared from prepurified gases obtained from high pressure tanks. No further purification was used. Mixtures were prepared by partial pressure and stored for at least three hours before being used for an experiment.

All studies were performed in rectangular section tubes of 3 1/4 x 1 1/2" internal dimensions at pressures such that the detonation was not marginal. Even though the propagation velocities of these detonations were not measured it is well known that under these conditions the detonation velocity will be only slightly below CJ. All observations were made with the use of smoked foil records. No other datawere taken. It is well known that such records faithfully record the presence of all transverse waves of reasonable amplitude and therefore yield data on spacing and reproducability of the transverse wave pattern.

The studies which used obstructions in the tube were performed in a horizontal detonation tube which had an 18" x 3 1/4" smoked foil mounted on one of its walls. The tube had a 20' straight section rectangular pipe before the test section to insure that the detonation would have a well established equilibrium configuration before being perturbed by the obstruction. The obstructions were two dimensional diamond shaped wedges whose walls were perpendicular to the smoked foil wall of the tube. Three diamond wedges were used. They were asymmetric wedges which were 1 3/4" wide at their widest point and had tip angles of 20° and 70°, 30° and 60° and 40° and 50° respectively. The majority of the data was taken with a 20°/70° wedge. The wedge models could be mounted along and symmetric to the tube center line and could also be rotated so as to be placed asymmetrically within the tube. Since the wedge always contacted the smoked foil its position is accurately recorded on every smoked foil record.

For the studies in which the detonation passed from one mixture into another with different properties, a vertical detonation tube was constructed. This tube allowed for density separation of two gas mixtures and caused the concentration gradients at the separation interface to be parallel to the tube walls and therefore to the propagation direction of the detonation. This means that the detonation encountered a minimum amount of lateral perturbation as it propagated over the concentration interface.

The sliding valve which accomplished this type of interface formation is shown in Fig. 1. In the filling position there are three separate ports to allow the operator to fill the lower tube section, the valve section and the upper tube section separately and with different gaseous mixtures. In practice the upper section and the valve body were filled with one mixture and the lower section was filled with a different mixture. After adjusting pressures to be nearly equal the three sections were connected externally to exactly equalize the pressure. The valve was then placed in the firing position and an easily detonatable gas of proper density to avoid stirring was added at the spark ignition end of the detonation tube. This was necesarry to ignite the test mixtures in our apparatus. The addition of this gas mixture after opening the valve caused the diffusion interface to be displaced 10-12 inches below its original position. The tube was fired from one to ten minutes after this operation. This allowed density layering and diffusion to produce a concentration gradient which was exactly parallel to the direction of propagation of the detonation so that the detonation experienced a minimum of lateral perturbation as it passed over the concentration interface. As can be seen from Fig. 1 the valve is so constructed that when it is in the firing position there are no holes or external crevices over 0.001" wide to perturb the detonation structure as it passes through the valve. This valve is sealed from the surrounding atmosphere by sliding "O-Ring" seals but contains no inner seals. However, the leakage rate across the valve is very slight and leakage is minimized by filling both the bore and the two sides of the valve at the same rate while simultaneously monitoring the filling pressure using two external pressure gauges. The valve is preceeded by 17" of rectangular section tube which contains a 2' x 3 1/4" smoked foil holder positioned about 4" ahead of the valve. Following the valve is 5 1/4' of rectangular tubing that contains a 5" x 3 1/4" smoked foil holder to record the behavior of the detonation after it passes into the new mixture.

Analysis

It has been shown by Strehlow and Biller$^{(10)}$ that the entrance angle of a symmetric intersection may be used to determine the average strength of the two transverse wave systems which are intersecting at that point. Furthermore, they found that the calculated strength was very insensitive to the Mach number of the incident shock just prior to the intersection.

It has now been discovered that the strengths of the two intersecting waves may be measured individually by determining both the entrance angle ϕ and the deflection angles ψ_1 and ψ_2 for the triple point paths that are involved in the intersection$^{(11)}$. Consider the asymmetric intersection shown in Fig. 2. The problem is to determine ψ_1 and ψ_2 for fixed ϕ and M_I as a function of S_1 and S_2, the strengths of the incident Mach stems. Here, strength, S, is defined as the dimensionless pressure rise across the reflected shock at the triple point, $(P_3-P_2)/P_2$. For fixed $\phi, \beta_1 = 180°-\phi-\beta_2$, therefore for fixed ϕ and M_I there is a unique relationship between S_1 and S_2, the initial strengths of the two intersecting transverse waves. Thus, the calculation proceeds as follows. For the specific gas composition under consideration enthalpy is a function of temperature only, H(T). This enthalpy function is obtained from the JANAF tables$^{(12)}$ and is used to solve normal shock relations for each shock of the Mach stem and to iterate on all Mach stem properties given β and M_I for that Mach stem. Therefore, values of M_I and ϕ are chosen and a value of β_2 is assumed. This allows a complete calculation of the shock gemoetries and all flow properties before the intersection has occurred. Now, irrespective of the amount of asymmetry of the collision process, the two initial Mach stem shocks retain both their identity and orientation throughout the collision process. Therefore, shock MS_1 is identical to shock I_3 and shock MS_2 is identical to shock

I_4. That is $M_{MS1} = M_{I3}$, $M_{MS2} = M_{I4}$ and the orientation of these two shocks relative to a fixed frame of reference remains unchanged. The next step is to use this information to calculate the Mach number and orientation of the new Mach stem shock $MS_4 = MS_3$. In this calculation β_3 and β_4 are varied in a systematic manner until the Mach number and orientation of MS_3 and MS_4 are identical. Using this information the orientation of the two new triple point trajectories are calculated by determining, from the known shock velocities, the location of the intersection of shocks I_3 and MS_3 and I_4 and MS_4 for some fixed time after the intersection of $MS_1 = I_3$ and $MS_2 = I_4$ at point 0. This information is then used to determine ψ_1 and ψ_2, the two deflection angles. This calculation is similar to that discussed by Oppenheim et al(13) recently.

The results of this calculation are shown in Figs. 3-7 for a stoichiometric hydrogen-oxygen mixture diluted with various amounts of argon. Figure 3 shows a plot of ψ_1 versus ψ_2 at fixed ϕ for a 70% argon dilution mixture where $M_I = 4.12 = 0.83\ M_{CJ}$. This plot shows that the three angles are interdependent since ψ_1 and ψ_2 are related to each other for fixed ϕ. Thus, in reality only two angles of any one intersection need be measured to determine the third. In practice we always measured the three angles and then checked the accuracy of our measurement by determining if, for the measured ϕ, ψ_1 and ψ_2 agreed with the graph. If the agreement was poorer than one or two degrees we would either read the smoked foil again or slightly adjust the values of ψ_1 and ψ_2 until they agreed at a fixed ϕ. The reason for fixing ϕ is that it is by far the most accurately measured angle on the record. This is because the triple point trajectories just prior to an intersection are usually quite straight while after an intersection they are usually quite curved. Figure 4 is a plot of S_1 and S_2 versus ψ_1 and ψ_2 for a number of values of ϕ. After adjusting ψ_1 and ψ_2 values using Figure 3, Figure 4 is used to determine S_1 and S_2. Figure 5 illustrates the effect of argon dilution in the stoichiometric hydrogen-oxygen system on the calculated values of ψ_1 and ψ_2 for $\phi = 80°$ and $M_I = 0.83\ M_{CJ}$. Figure 6 shows the variation of ψ with S for a fixed value of ϕ and various dilutions. Figure 7 shows the effect of variations in the incident Mach number on the ψ_1, ψ_2 relation for fixed values of ϕ. We note from Fig. 7 that the Mach number has only a slight effect on the values of ψ_1 and ψ_2 for any fixed ϕ and gas composition and therefore that the measurement of strengths from ϕ, ψ_1 and ψ_2 measurements is not very sensitive to an error in M_I. Since we know that M_I is approximately equal to $0.83\ M_{CJ}$ at the apex of the intersection in ordinary propagating detonation, this value was used to reduce all the data reported in this paper.

Results

A. The Equilibrium Configuration Detonation

As was mentioned in the introduction, stoichiometric hydrogen-oxygen mixtures that contain more than 50% of an inert monotomic gas such as argon or helium propagate in rectangular tubes as equilibrium configuration detonations, that is, as detonations that have a structure which is exactly repeatable down the length of the tube. Wall and side wall smoked foil records of such a detonation are shown in Fig. 8. Notice that the two orthogonal waves in this system are decoupled from each other because they "walk" relative to each other as the detonation propagates down the tube. Thus, they are related to the two orthogonal acoustic modes of the hot gas column that exists downstream of the front in a truly independent manner and their spacing is only incidentally controlled by some characteristic chemical length of the detonatable gas.

This behavior is further illustrated in Fig. 9. Here the mode number that is observed at any one pressure is plotted versus pressure for equilibrium configuration detonations. We note from this figure that at certain pressures both the n and n + 1 modes are observed in the tube (where n is an integer). These results refer to independent firings of the detonation tube and reflect the fact that we see either a 6th or 7th mode (for example) on successive firings over a certain short pressure range. Notice also that one may draw a curve through all the data ranges, thus indicating that there is a specific pressure at which a certain mode number is preferred over all other mode numbers. However in between the pressure levels for neighboring preferred mode numbers the detonation front does adapt itself so that it always exhibits a specific mode number in the tube. Figure 9 also shows that even mode numbers appear to be perferred, at least for mode numbers of 8 or above.

B. Wedge Studies(14)

When one wall of the initial portion of a wedge is placed parallel to the tube wall as shown in Fig. 10 we find that the transverse wave structure will quickly adapt itself to the new spacing. This is not unexpected because as we have seen above there is an overlapping range of mode number available at any one pressure. Therefore, in general no matter how many waves are captured by the entrance opening they will quickly equilibrate among themselves to form a spacing that is an integer divided into the newly available wall spacing.

Some measurements were made on the transverse wave that was produced when the lead shock of the detonation uncovered the leading apex of the wedge. A smoked foil illustrating this process is shown in Fig. 11. A number of measurements are compared to calculated Mach stem angles in Fig. 12. Notice that the measured angles for in situ detonations all lie somewhat above the theoretical values while those measured using artificial ramp produced Mach stems all lie somewhat below but nearer to the theoretical predictions. The reason for this systematic discrepancy in the case of in situ detonations has not been answered as yet. It will be discussed again later in relation to some other measurements of trajectory angles.

From the wedge experiments we also discovered that passing the detonation through a converging channel caused the transverse wave strength to decay very rapidly. This is illustrated by the smoked foil of Fig. 13 and graphically in Fig. 14. In Fig. 13 we note that the refraction of the transverse waves at their intersection decreases markedly as the detonation passes through the convergent section. In Fig. 14 the measured strengths for two transverse waves propagating into the convergent channel are compared to a theoretical calculation of the expected decrease assuming that the detonation is a converging cylindrical detonation and that the rise in overall pressure level associated with convergence will cause the dimensionless pressure level or strength of the transverse waves to be decreased. As can be seen from the graph, the experimentally observed rate of decay is extremely rapid when compared to the theoretically predicted rate of decay. It is, indeed, so rapid that by the time the detonation reaches the nozzle throat all transverse waves have been completely damped out and no longer occur on the front It thus appears that White's 18° nozzle produces laminar detonations downstream of the "throat" simply because the passage of the detonation through the convergent section ahead of the "throat" damps the waves completely before the detonation itself reaches the "throat".

Figure 15 shows the behavior of the detonation after it passed through the "throats" of the obstruction for a symmetrically placed obstruction. At first all transverse waves were suppressed by the obstruction but then two new strong transverse waves were produced by the intersection of the two expanding cylindrical shock waves as they met at the trailing apex of the obstruction. These two transverse waves dominated the flow for a few cycles. However, during this length of time new transverse waves start to appear and eventually the entire detonation tube is again filled with transverse structure of approximately the same size as that of the incident equilibrium configuration detonation. This process of reforming the structure inherent to this particular detonation takes place over a distance equivalent to 20-30 original cell lengths. It is expected that considerably further downstream the detonation will again become a truly equilibrium configuration detonation.

C. Compositional Interface Studies(11)

A number of different runs were made using the vertical tube with a density layered compositional interface. Conditions for a few typical runs are summarized in Table I.

In the first two runs of Table I the number of transverse waves had to decrease by two in the major tube dimension and one in the minor dimension if the detonation were again to become an equilibrium configuration detonation. Only the first of these runs was analyzed completely to observe quantitatively the behavior of the transverse waves but the mechanism of wave disappearance was the same for all cases in which a wave must disappear. The smoked foil record of run number 1 is shown in Figure 16. Notice that the first wave to disappear stops writing about forty inches downstream of the interface while the second wave disappears at forty-nine inches.

We assumed in our treatment that at each intersection the waves pass through each other. This appears to be a reasonable assumption because, for the interaction of a strong wave and a weak wave, both the strong and weak waves retain approximately their same strength if one assumes that they pass through each other. If, on the other hand, one were to assume that each wave reversed its propagation direction at the intersection, its new strength would be quite dependent upon the strength of the intersecting wave. Therefore we chose the numbering system shown in Figure 17 and reduced the record of Figure 16 by measuring the strength of each wave at each intersection.

Two representative strength versus distance plots are shown in Figures 18 and 19. Figure 18 is typical for a wave that did not fail throughout the record. Notice that the strength of this wave varies from about 0.3 to 0.7 with an average strength of about 0.5. Figure 19 illustrates typical behavior for a wave that failed. Notice that over the majority of the record the strength of this wave also varies from about 0.35 to 0.7 with an average strength of about 0.5 and that this behavior continues until about four intersections before the point of failure. However, from that point on the failure is rather catastrophic. This behavior has been observed repeatedly and indicates that it is essentially impossible to determine which of the waves is going to fail from strength measurements until a few intersections before final disappearance.

However, there is a criterion which determines which waves are to fail and which are to continue propagating. In Figure 20 we have plotted the x,y coordinates of each wave by unfolding the wave at each wall intersection. One thing which Figure 20 illustrates is that the extreme regularity of pattern that exists ahead of the compositional interface gradually deteriorates as the detonation propagates into a mixture which has a larger inherent wave spacing. In other words the spacing between neighboring waves starts to fluctuate once the detonation enters the new mixture. We always observed that this fluctuation eventually would cause one wave or another to follow closely its preceeding wave in the system. It was this following wave which then failed rapidly. Thus, we could tell which waves were about to fail by studying the spacing of the waves. Furthermore, in these experiments the failure was always rapid once it began. Waves were never observed to disappear by merging with one another.

In experiments 3 and 4 the detonation passed into a mixture which could support more transverse waves than were on the front at the time when it entered the mixture. Smoked foil records from these two experiments are reproduced as Figures 21 and 22. An enlargement of the interesting transition region of experiment 3 is shown in Figure 23.

In experiment 3 the detonation propagates for approximately fourteen inches from the valve before any apparent changes occur. This is the approximate location of the compositional interface. At this point new waves start to appear and at the twenty-four inch mark are well developed. It is interesting to note that at the twenty-four inch mark each of the old waves has essentially formed two new waves which are propagating quite closely to each other. Then as the detonation continues to propagate, this new asymmetric wave system becomes more symmetric but still retains two waves for each original wave. Thus a detonation which should have an equilibrium configuration containing a 3 x 6 mode number actually has a 4 x 8 mode number at the end our test section. We know that the detonation cannot continue to accommodate a 4 x 8 mode number for really long propagation distances because we always found that this mixture at this pressure had a 3 x 6 mode number when it was propagated as an incident detonation in our tube. In experiment 4 the detonation was propagated into a mixture whose properties differ only slightly from those of the incident detonation. In this case distinct changes in structure first occur about 10-12 inches from the valve location and approximately at the location of the diffusional interface. However, these changes do not precipitate the formation of new waves in the system but instead lead to a wave system which has a distinctly different structure from the incident wave system. About twenty-four inches from the interface the wave pattern has stabilized and is a 2 x 4 wave system in which the orthogonal waves are strongly coupled. This is evident from the fact that the minor mode waves always appears on the smoked foil very near and in exactly the same position relative to the intersection of the major mode waves.

In some experiments performed with a 63% dilution in the final mixture the transition of experiment 3 was observed at 150 torr initial pressure while the orthogonal mode locking of experiment 4 was observed at 140 torr initial pressure.

The smoked foil record for run 5 is shown in Figure 24. In this run a detonation with fully developed transverse structure was propagated into a completely inert mixture. Notice that the transverse waves retain their identity and ability to write on a smoked foil for fully thirty inches of travel beyond the diffusional interface (which is located 10-12 inches below the valve location). The decay of strength of one wave is plotted in Figure 25 on a log strength versus distance scale to determine quantitatively the rate of decay.It was found that on the average the logarithmic rate of decay was about 7% per cell length. This is a considerably slower decay rate than that which was observed when the waves decayed in a reactive system. Figure 24 also shows that when a detonation passed into an inert gas the frontal structure retained its regularity as it decayed.

Discussion

Two comments are appropriate in light of the observations mentioned above. Firstly, we have observed that in general the strength of an intersection measured by only determining the entrance half angle measured to a wall are on the average somewhat larger than the strengths of the transverse waves as measured by the new ϕ, ψ_1, ψ_2 technique. We also noted in Figure 12 that the strength of the transverse wave as measured from an angle relative to the ramp surface was also somewhat larger than one would predict from theory. We feel that these two observations are probably not significant but simply arise because a systematic measurement error occurs when one attempts to measure the angle between a smoke track trajectory and a wall.

The second comment concerns the observation that when small transverse wave spacing is produced it forces a decay of the transverse wave system which is much more rapid than that which is observed if the waves are allowed to decay in a completely inert medium.

It is highly probable that this observation can be explained adequately by some recent theoretical and experimental work performed by Professor Barthel of this department$^{(15)}$. He observed in controlled experiments with artifically produced Mach stems that trajectories in reactive mixtures were first identical to trajectories in equivalent unreactive mixtures but after some time deviated systematically from these trajectories such that they always appeared farther from the ramp. He has theorized that this behavior is due to the fact that the initial explosion of the gas treated by the newly formed Mach stem shock sends a pressure pulse to the triple point, thus causing it to be strengthened. The delay of its effect is explained as due to the normal explosion delay time plus the time it takes the signal to travel from the explosion to the triple point.

He then further applies this concept to the behavior of the Mach stem in a propagating equilibrium configuration detonation. He arrives at the conclusion that this reinforcing pulse must intersect the Mach stem which forms a cell boundary before the next intersection occurs if it is to cause the transverse wave to be reinforced and therefore self sustaining. The reason for this is that all transverse waves should, if left alone, loose amplitude until they disappear. Therefore, if there is no reinforcing mechanism the waves would not exist. Thus, there must be some mechanism by which a finite amplitude transverse wave is reinforced between each collision with the next oppositely facing transverse wave. The mechanism that Barthel has postulated produces just such a result. It contains an inherent delay after the previous intersection: therefore, it could control the cell size. It also allows one to surmise that if the next intersection occurs too soon after the previous one for that specific system, the amplitude of the following intersecting wave should be positively decayed. This is because the pressure pulse now reaches the new triple point from the incident shock side and not from the Mach stem shock side as previously. Therefore, waves that are following too close should be rapidly attenuated by the arrival of the explosion pulse from the previous intersection. While this theory has not as yet been reduced to a completely quantitative form it nevertheless very adequately explains the decay behavior that we have observed in both our transient experiments. Furthermore, it explains why upon propagation into a completely inert gas the decay of the transverse wave is observed to be much slower than the decay that is observed in a reactive situation.

Conclusions

The study of the transient behavior of detonation structure has the potential of giving new insights into the mechanisms which control the structural properties of the detonation wave.

In these experiments we have discovered that spacing which is smaller than the preferred transverse wave spacing for specific incident conditions causes a very rapid decay of a specific transverse wave. The inert experiments show that the natural rate of decay is much slower. Barthel's new theory for self sustenance of the transverse waves agrees with these observations.

In experiments with rectangular mode equilibrium configuration detonations we have learned that transverse wave spacing can accommodate itself over a reasonably large range when the detonation is propagating as a low mode number detonation. This view is further supported by the observation that the 4 x 8 detonation of experiment 3 did not relax to a 3 x 6 detonation after 3-4 feet of travel even though it eventually must relax to such a 3 x 6 detonation in our tube at these initial conditions.

In our experiments where strength was measured we found oscillating strengths of the transverse waves with quite a spread in strength from intersection to intersection. Both the average strength and the variation in strength that we observed is approximately that found by Strehlow and Biller(10). It appears from Barthel's theory that one should expect this type of behavior because the strength of the wave at the next intersection is dependent upon a "kick" that it receives from the previous intersection plus a general decay due to aerodynamic effects. The question as to why transverse wave strength averages about the same for many different systems has still not been answered but it appears to be definitely tied to the aerodynamics of the attenuation process.

Finally, we have observed a complex process for the formation of new waves in which each original wave of the system spontaneously forms two new waves. It appears from the record that this formation process may have a three dimensional nature because the waves originate in a region where the orthogonal minor mode waves are interacting with the major mode waves. However, this conclusion is tentative and will have to wait for further studies.

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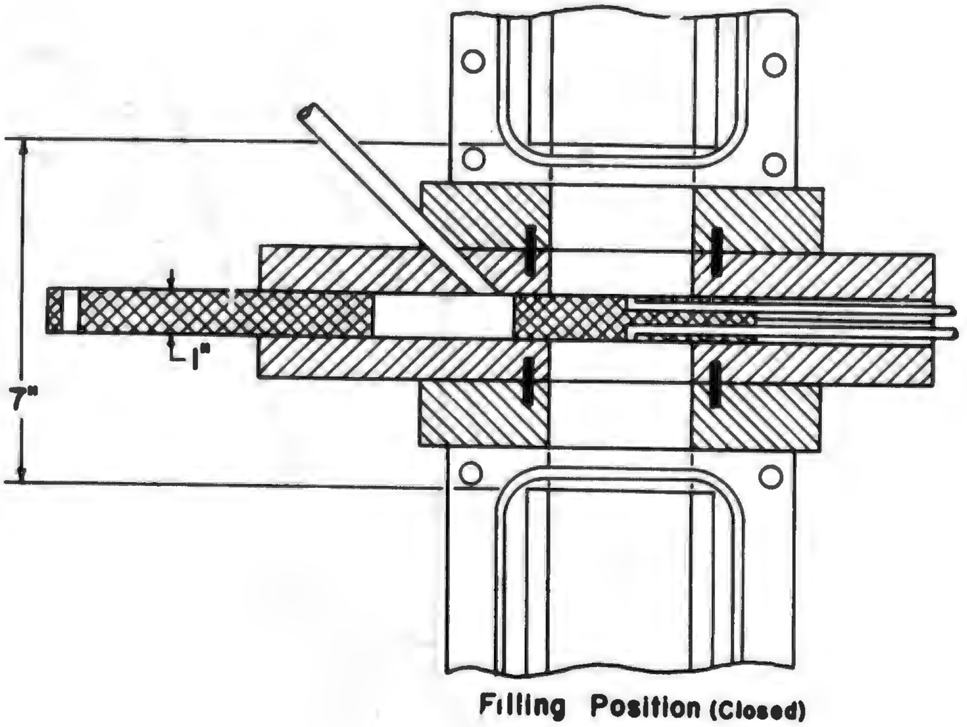
Table I

Transient Composition Studies

All Mixtures are Stoichiometric ($2H_2 + O_2$) diluted with Either He or Argon

Exp. No.	Initial Pressure Torr	Initial Mixture (upper chamber)				Final Mixture (lower chamber)			
		% of Dilutent	Equilibrium Mode No.	CJ Velocity m/sec	CJ Mach Number	% of Dilutent	Equilibrium* Mode No.	CJ Velocity m/sec.	CJ Mach Number
1	65	50% Ar	3 x 6	1842.3	4.852	70% Ar	2 x 4	1634.3	4.659
2	75	50% Ar	3 x 7	1847.5	4.865	70% Ar	2 x 5	1638.2	4.670
3	140	70% He	2 x 4	3674.6	4.719	60% He	3 x 6	3522.7	4.844
4	140	70% He	2 x 4	3674.6	4.719	65% He	3 x 5	3600.5	4.789
5	140	70% He	2 x 4	3674.6	4.719	30% Ar + 70% He	None		

* These equilibrium mode numbers were observed when an incident detonation was fired into these mixtures at these pressures.



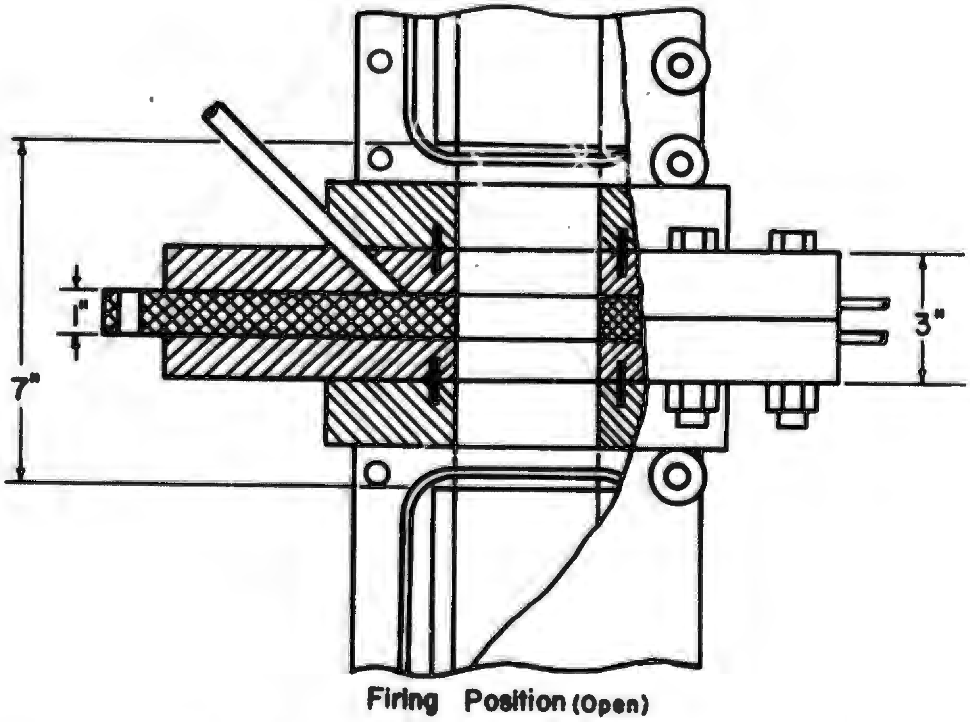


Figure 1. Schematic diagram of the sliding valve assembly showing both the filling (closed) and firing (open) positions.

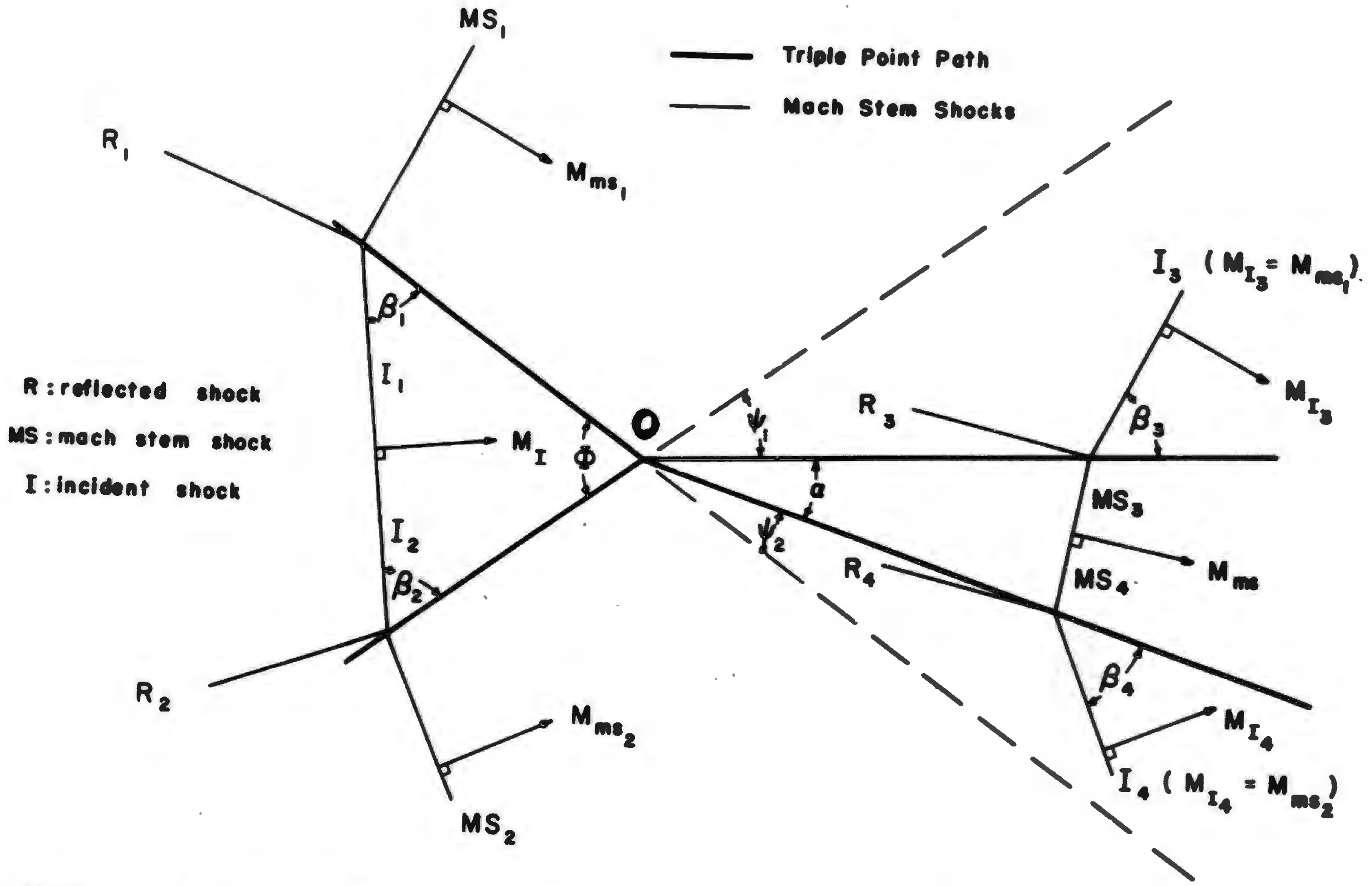


Figure 2. An asymmetric intersection of two Mach stems. Diagram shown Mach stem structure for two times: just prior to and just after the intersection.

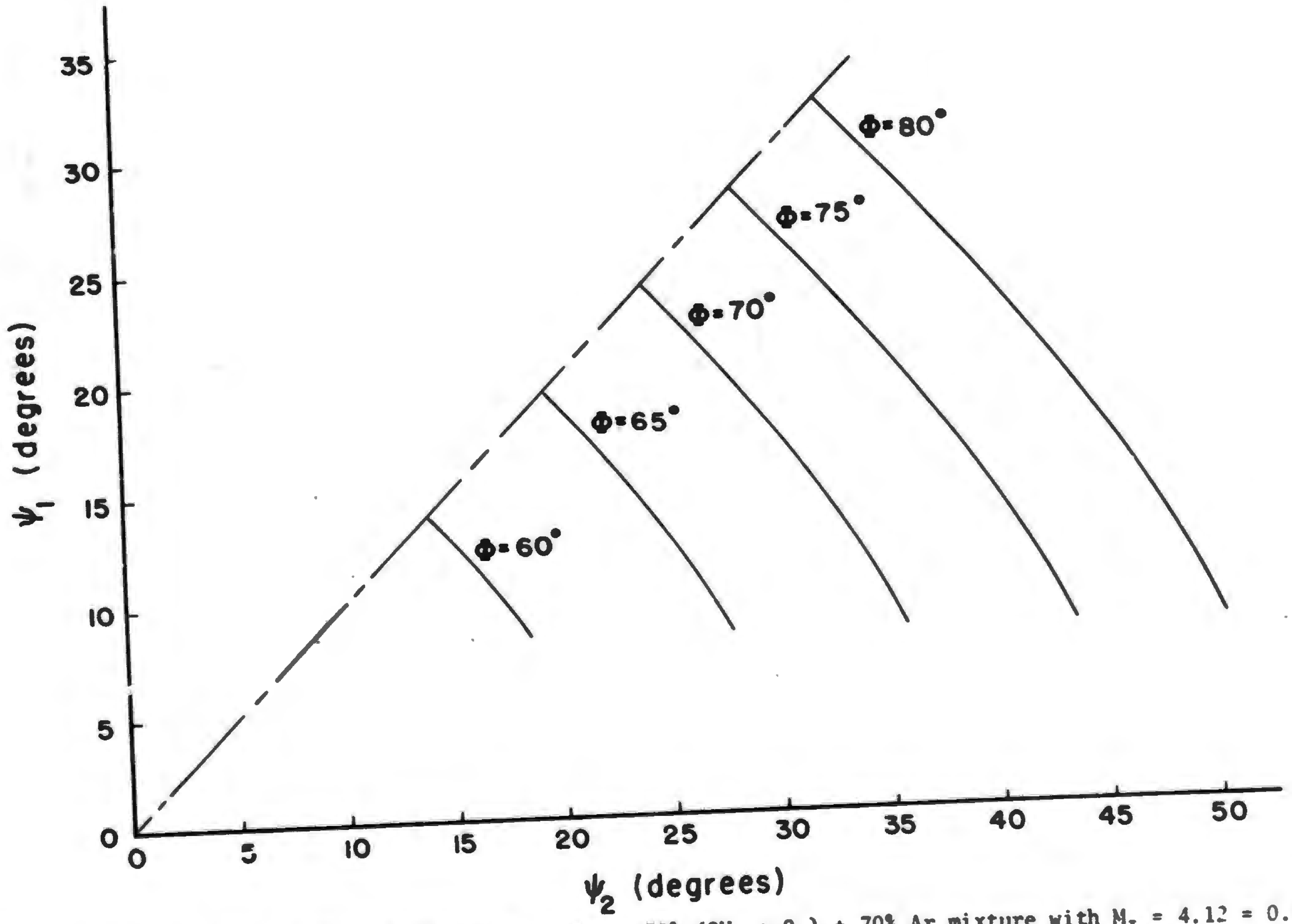


Figure 3. ψ_1 versus ψ_2 for a number of values of ϕ for a 30% $(2H_2 + O_2)$ + 70% Ar mixture with $M_I = 4.12 = 0.83\ M_{CJ}$.

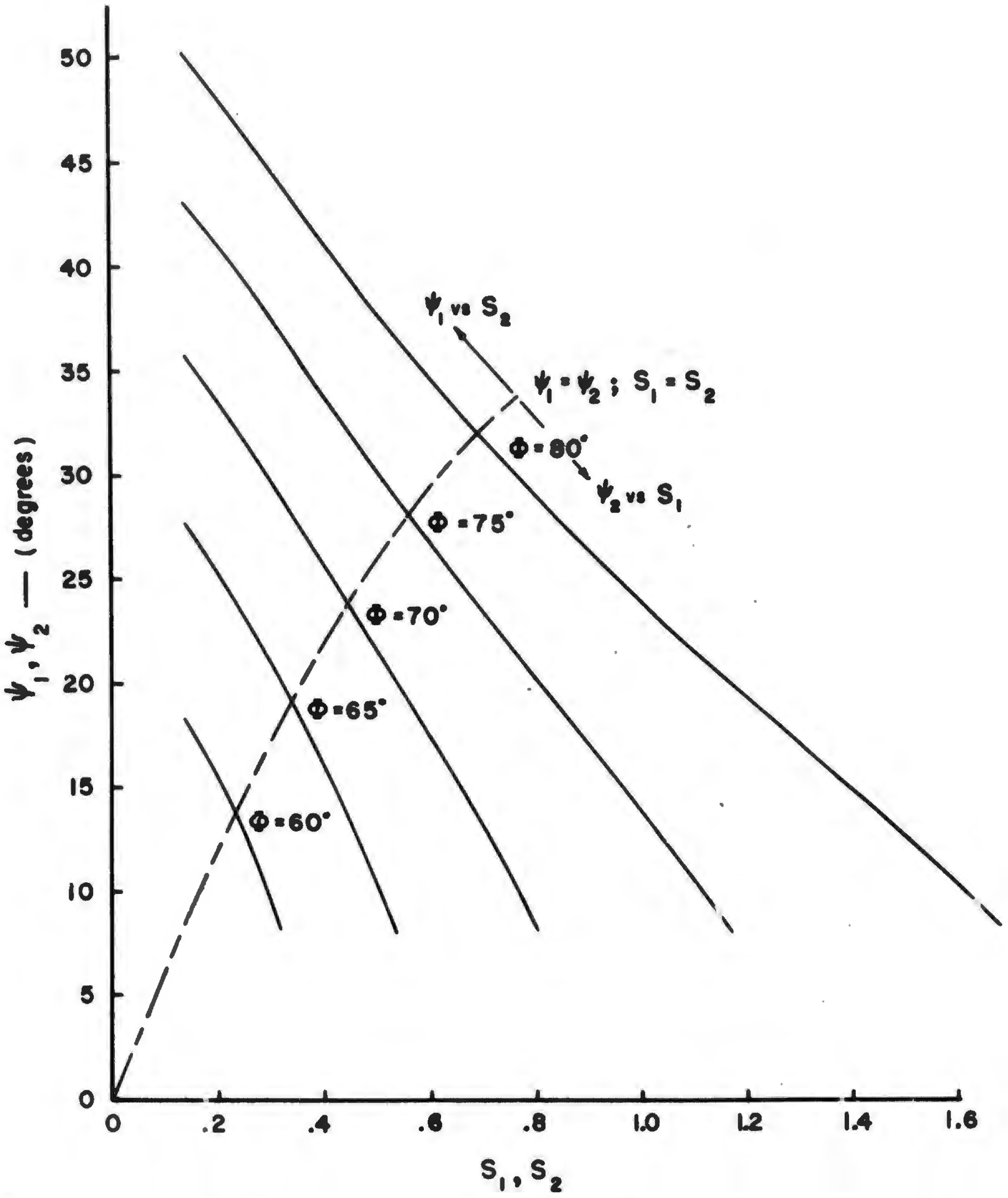


Figure 4. Strength S versus the angle ψ for a number of values of ϕ for a 30% ($2H_2 + O_2$) + 70% Ar mixture with $M_I = 4.12 = 0.83\ M_{CJ}$.

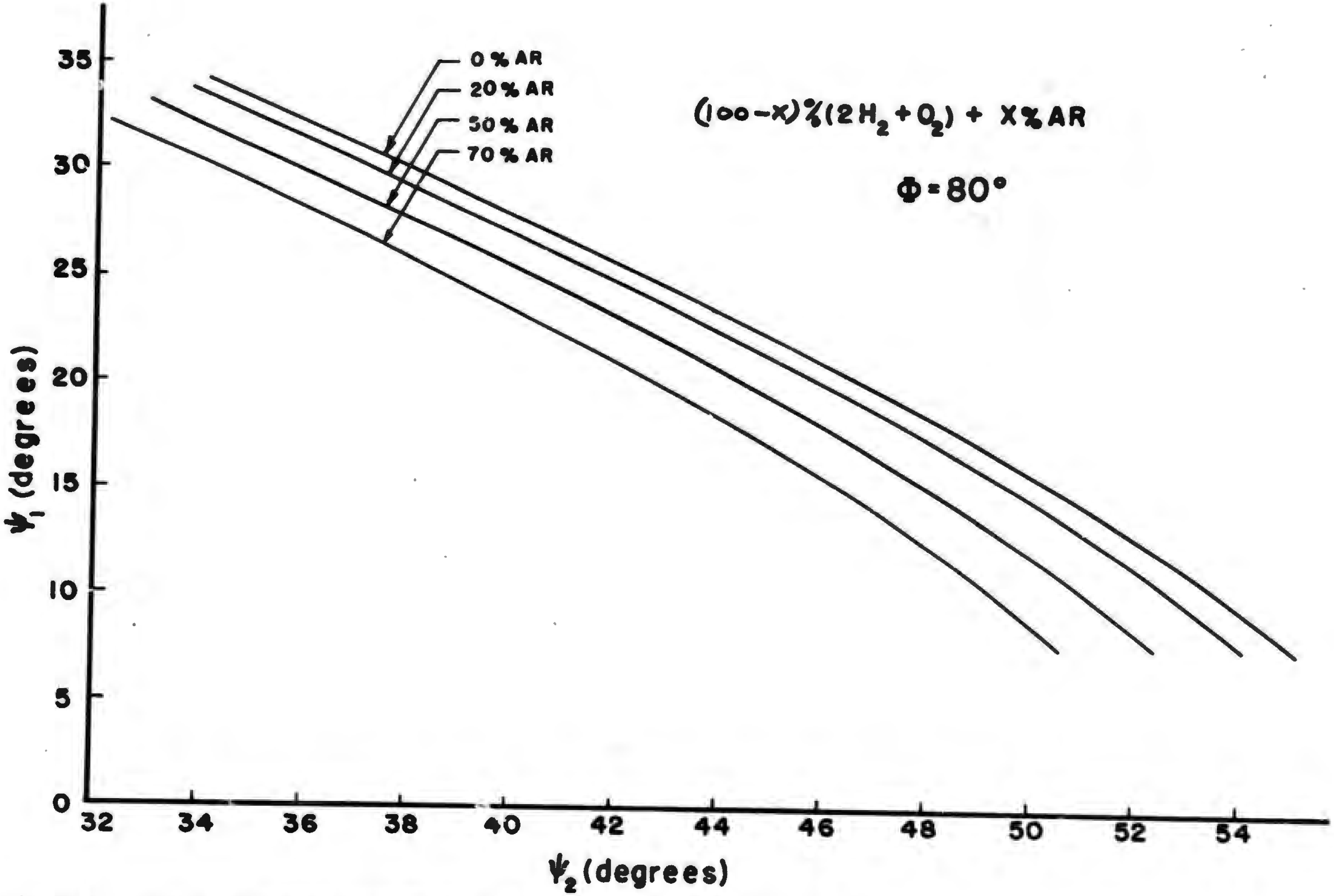


Figure 5. Effect of argon dilution on ψ_1 and ψ_2 for a stoichiometric $(2H_2 + O_2)$ mixture with fixed Φ and $M_I = 4.12$.

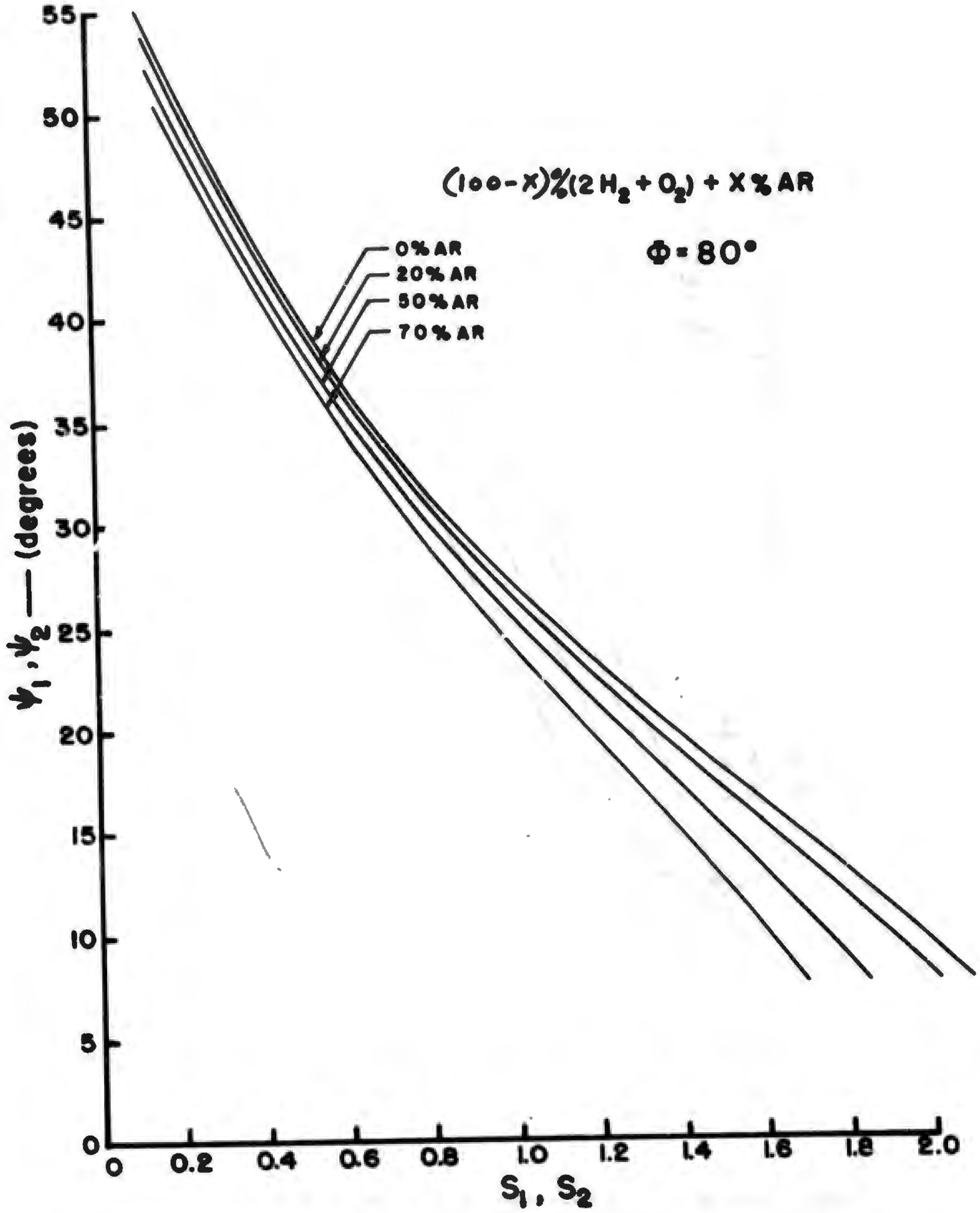


Figure 6. Effect of argon dilution on the dependence of strength S on ψ for stoichiometric ($2H_2 + O_2$) mixture with fixed ϕ and $M_I = 4.12$.

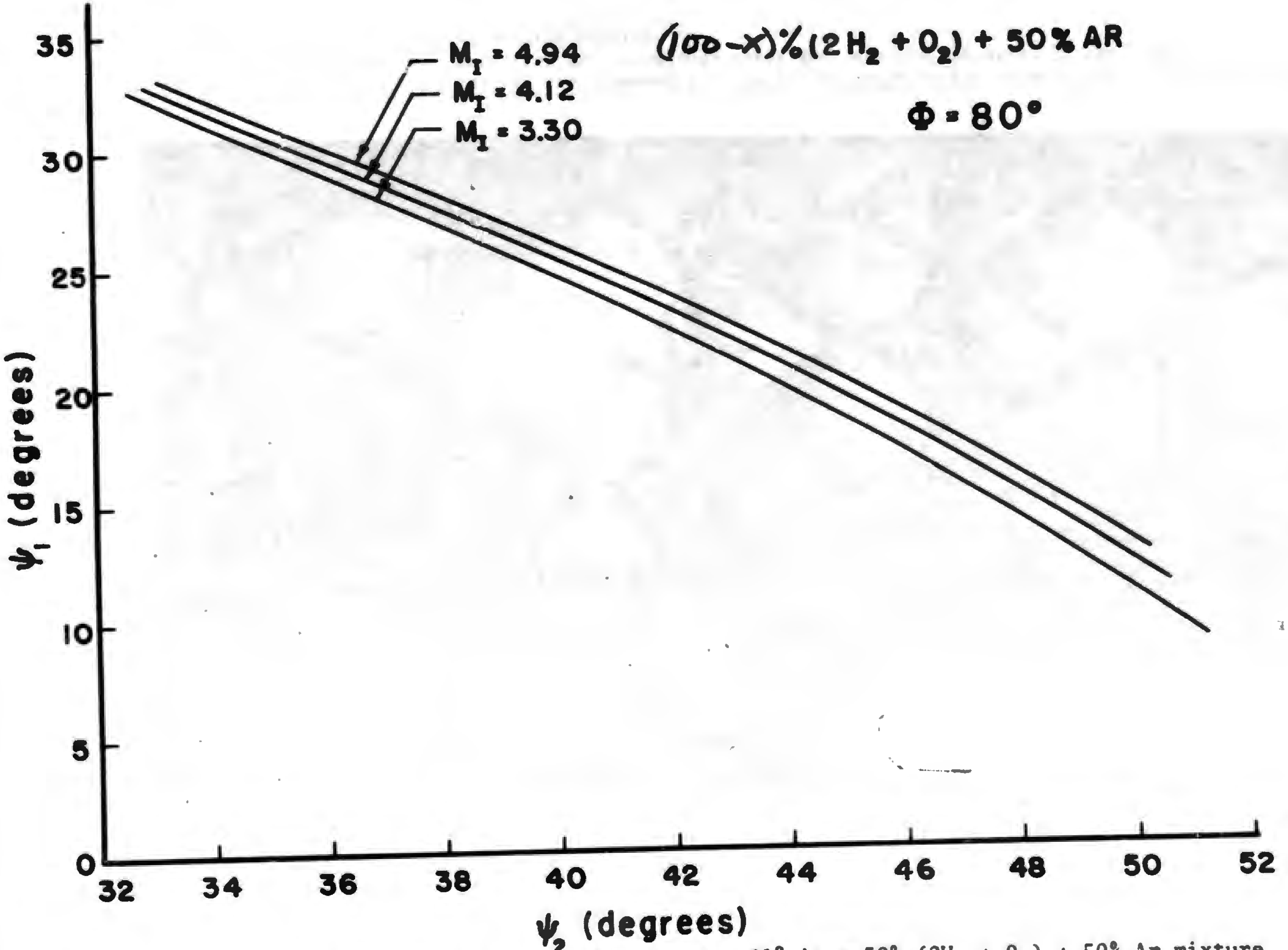


Figure 7. Effect of M_I on the ψ_1, ψ_2 relation for $\phi = 80°$ in a 50% $(2H_2 + O_2)$ + 50% Ar mixture.

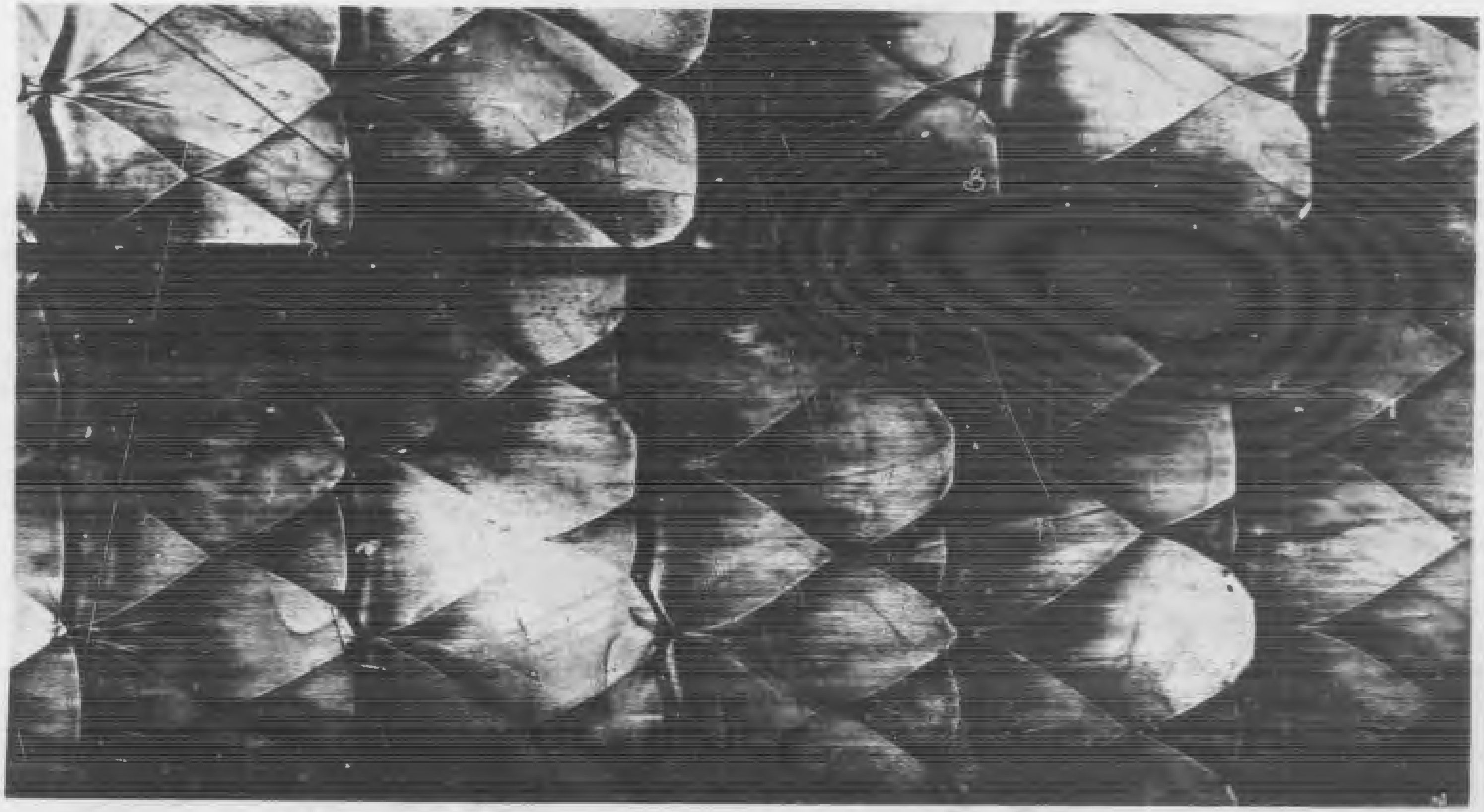


Figure 8. Side wall (1 1/2") and wall (3 1/4") smoked foil in proper juxtaposition showing the origin of slapping waves on the records. Note that the orthogonal waves are "walking" relative to each other. 50% ($2H_2 + O_2$)+ 50% Ar mixture at 65 torr initial pressure.

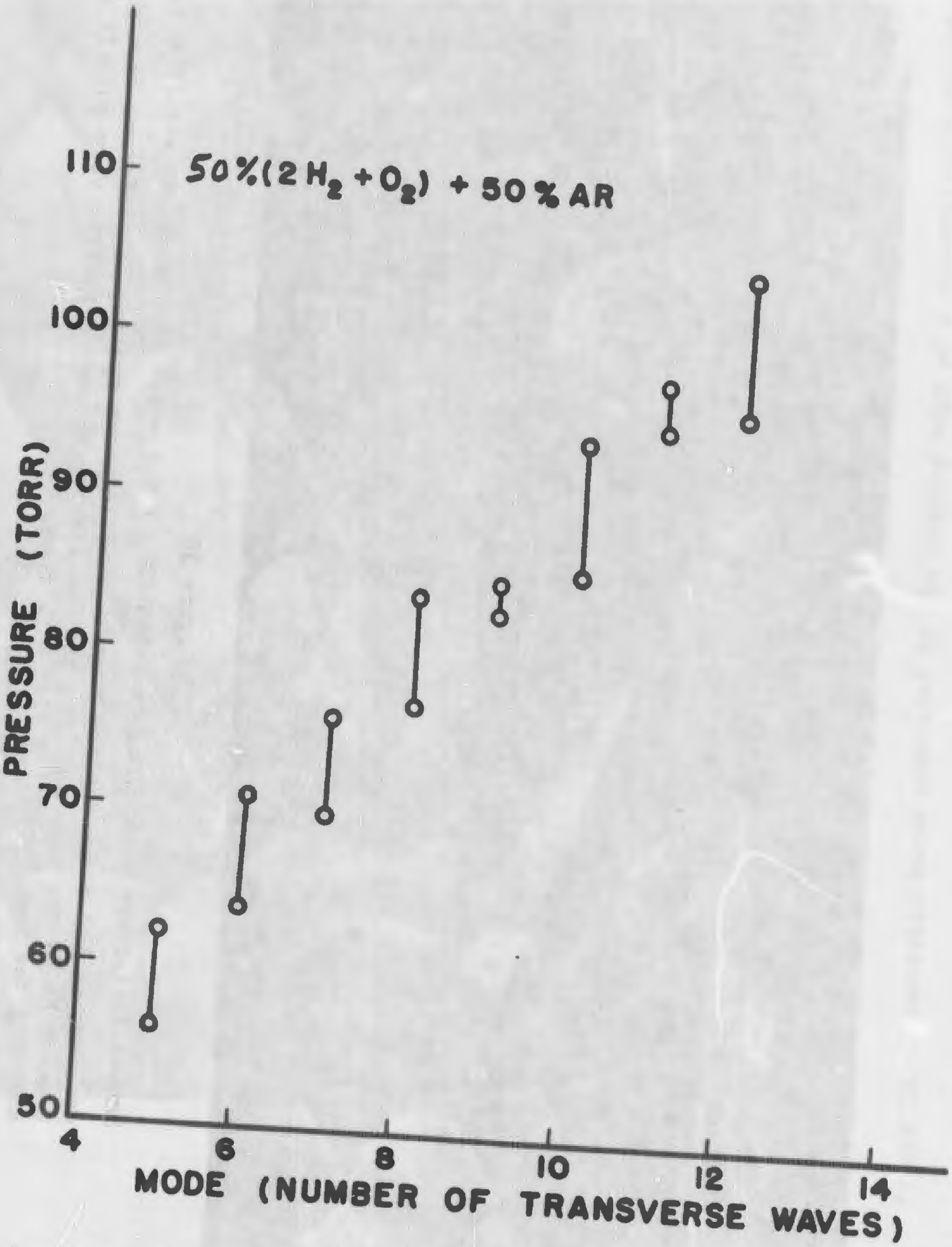


Figure 9. Mode number (number of transverse waves) observed in the 3 1/4 direction of a 3 1/4 x 1 1/2 inch rectangular detonation tube as a function of initial pressure.

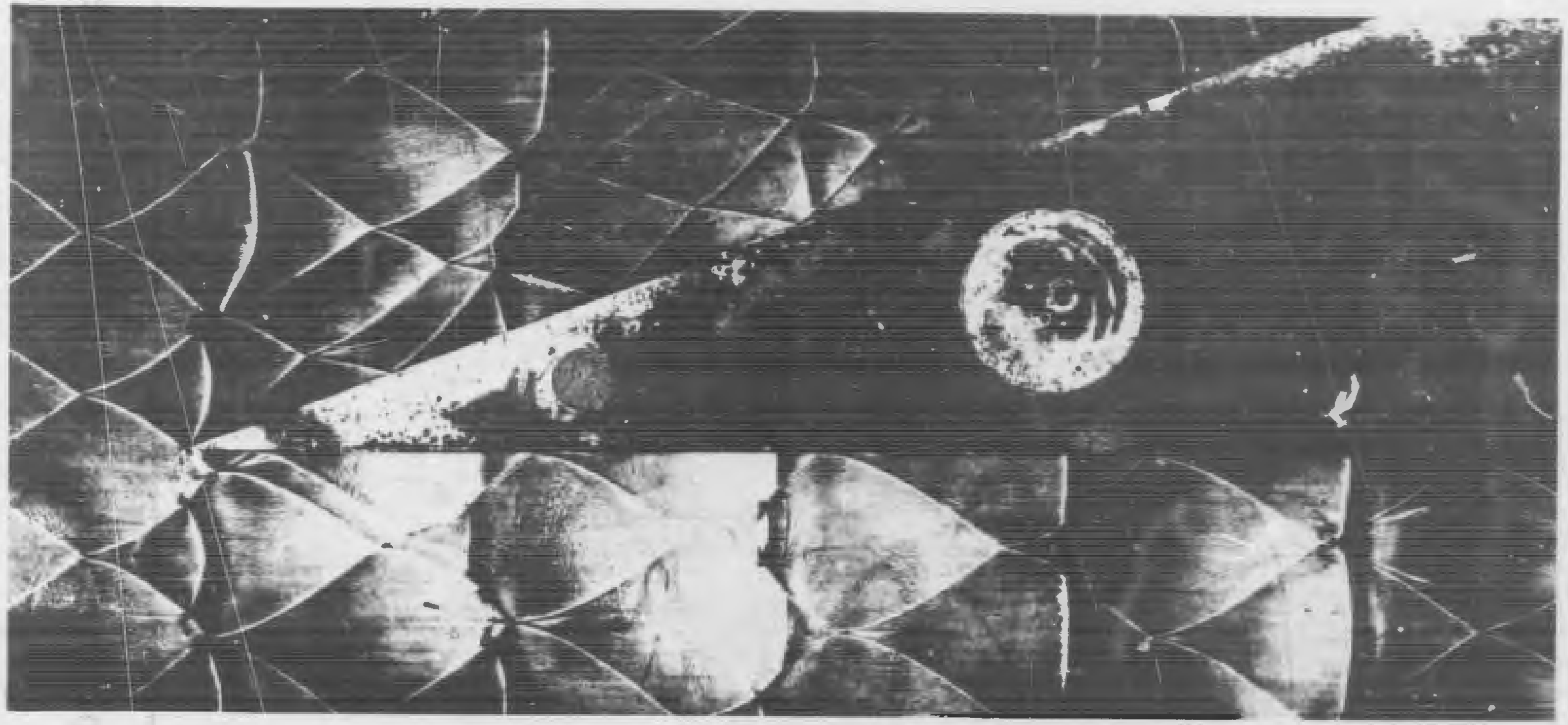


Figure 10

Smoked foil records obtained in a 50% ($2H_2 + O_2$) + 50% Ar mixture at air initial pressure of 100 torr. Notice that the initial wave spacing is different from the spacing below the ramp and that the new spacing becomes symmetric very quickly after entering the new channel. 3 1/4" wide tube.

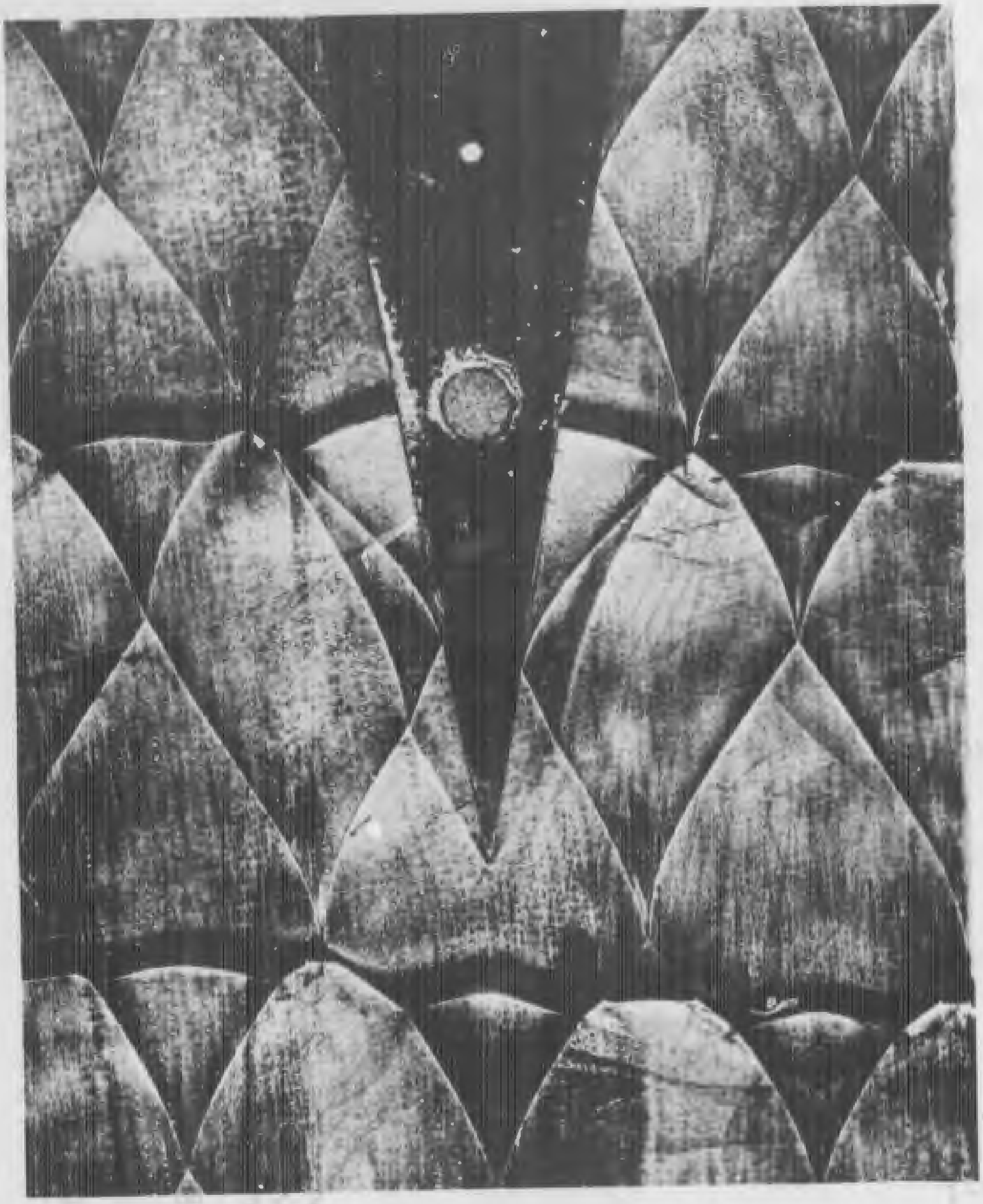


Figure 11. Transverse waves generated by the leading edge of a symmetrically placed wedge.

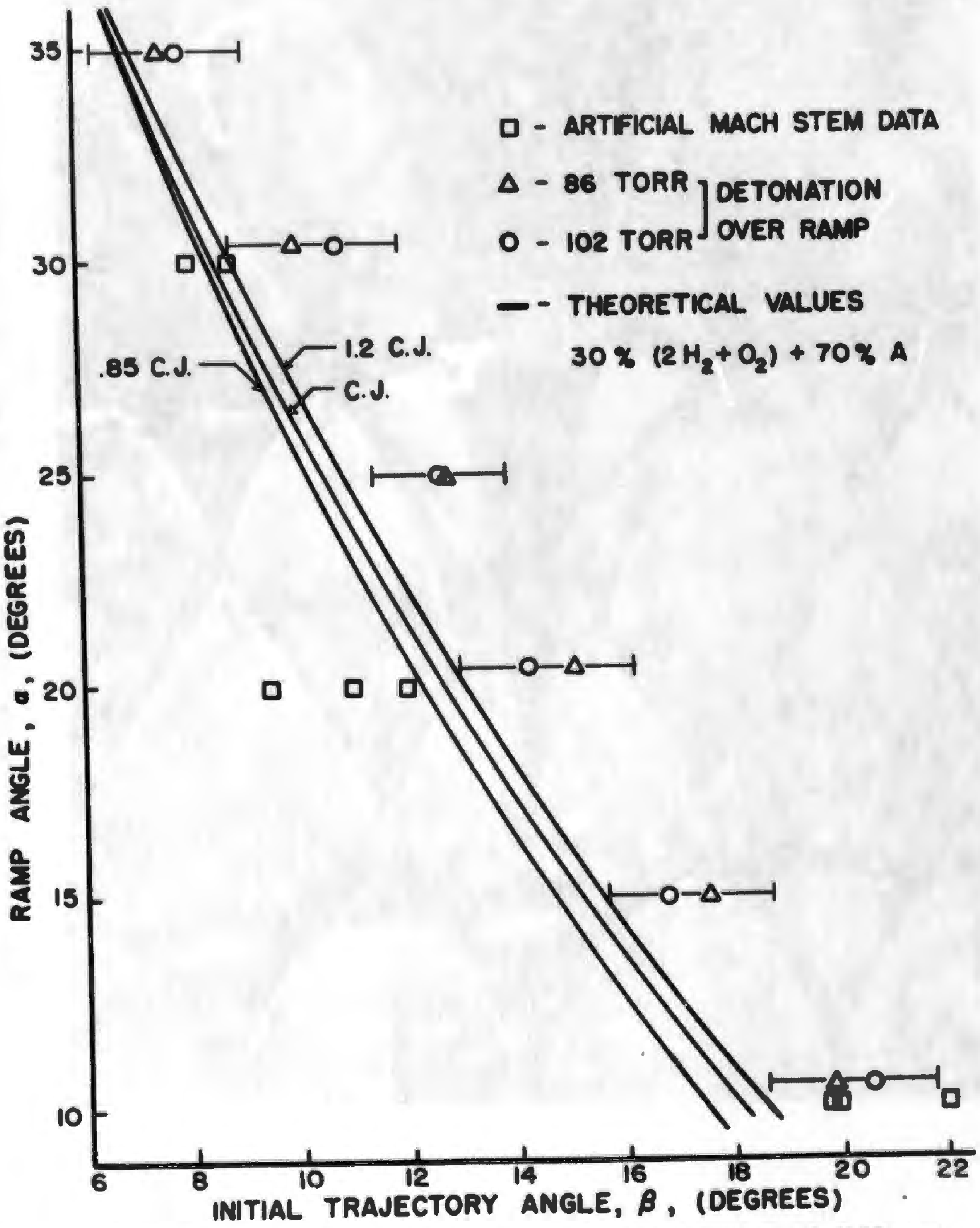


Figure 12. Effect of ramp angle on trajectory angle for a number of different ramp angles. Trajectory angle is defined as the angle between the ramp surface and Mach stem trajectory. These angles were all extrapolated to the tip by curve fitting the trajectory and determining the limit slope at the apex of the ramp.

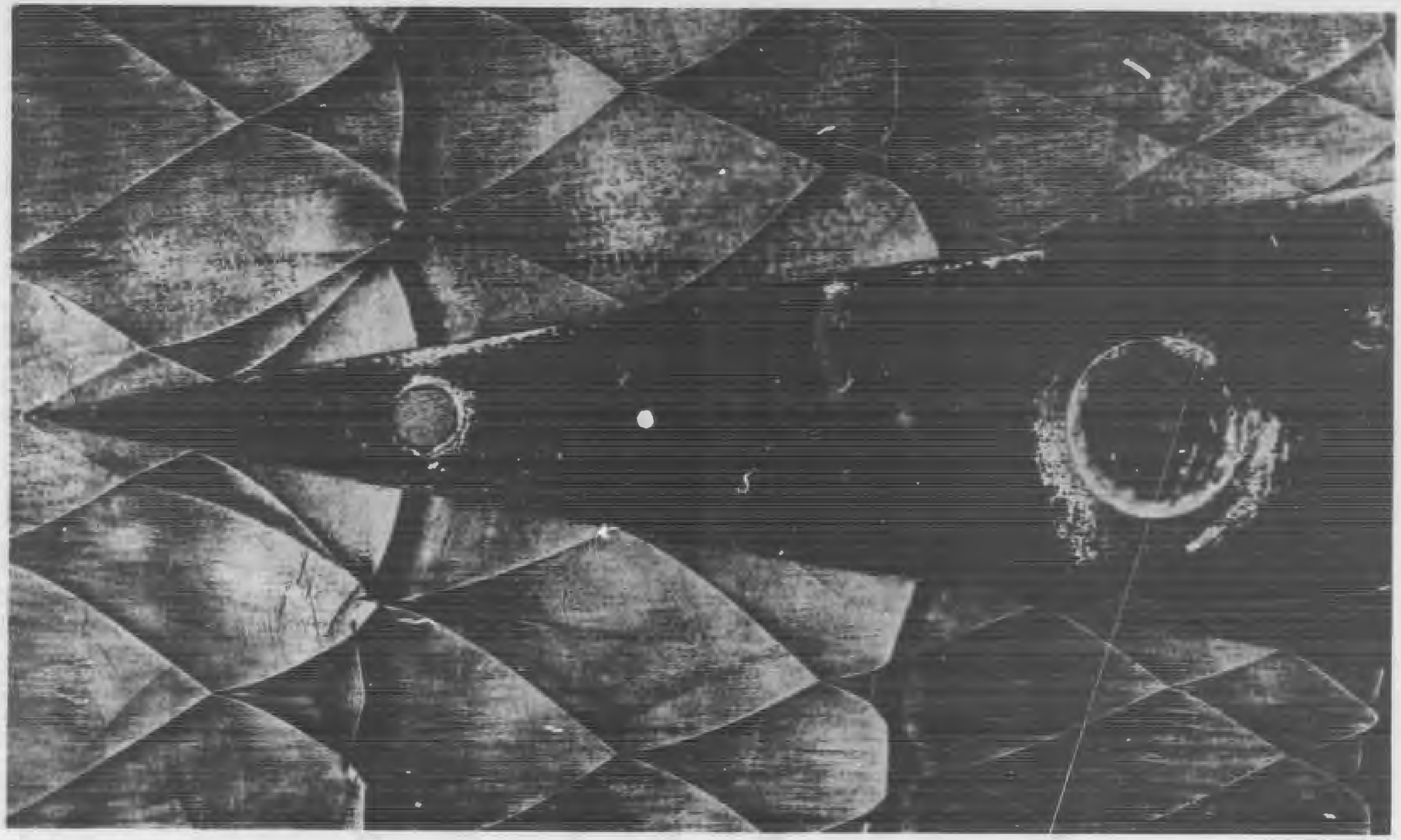


Figure 13

Smoked foil record in 50% $(2H_2 + O_2)$ + 50% Ar mixture at 50 torr initial pressure. Notice that the transverse waves get weaker as the detonation approaches the "throat".

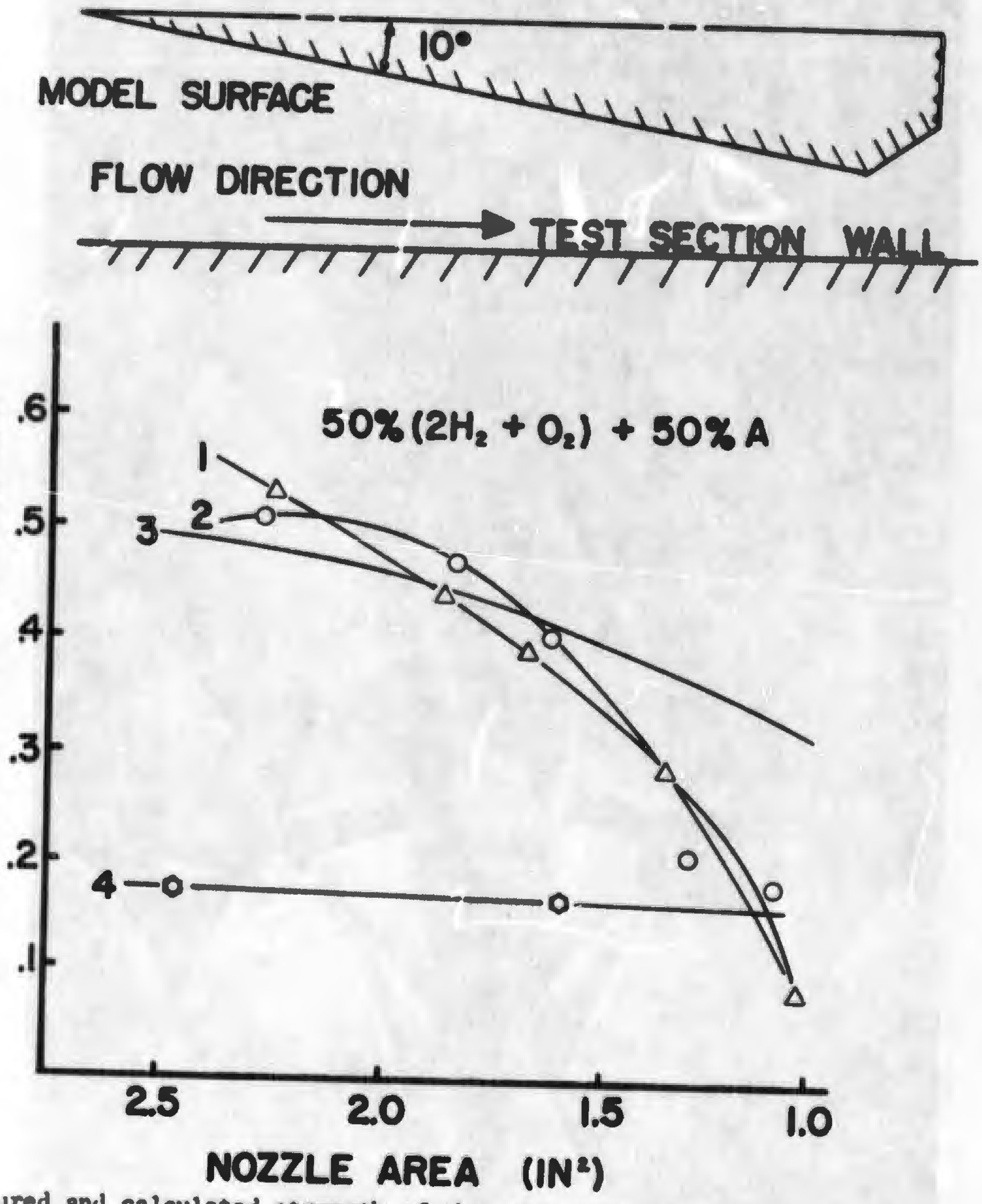
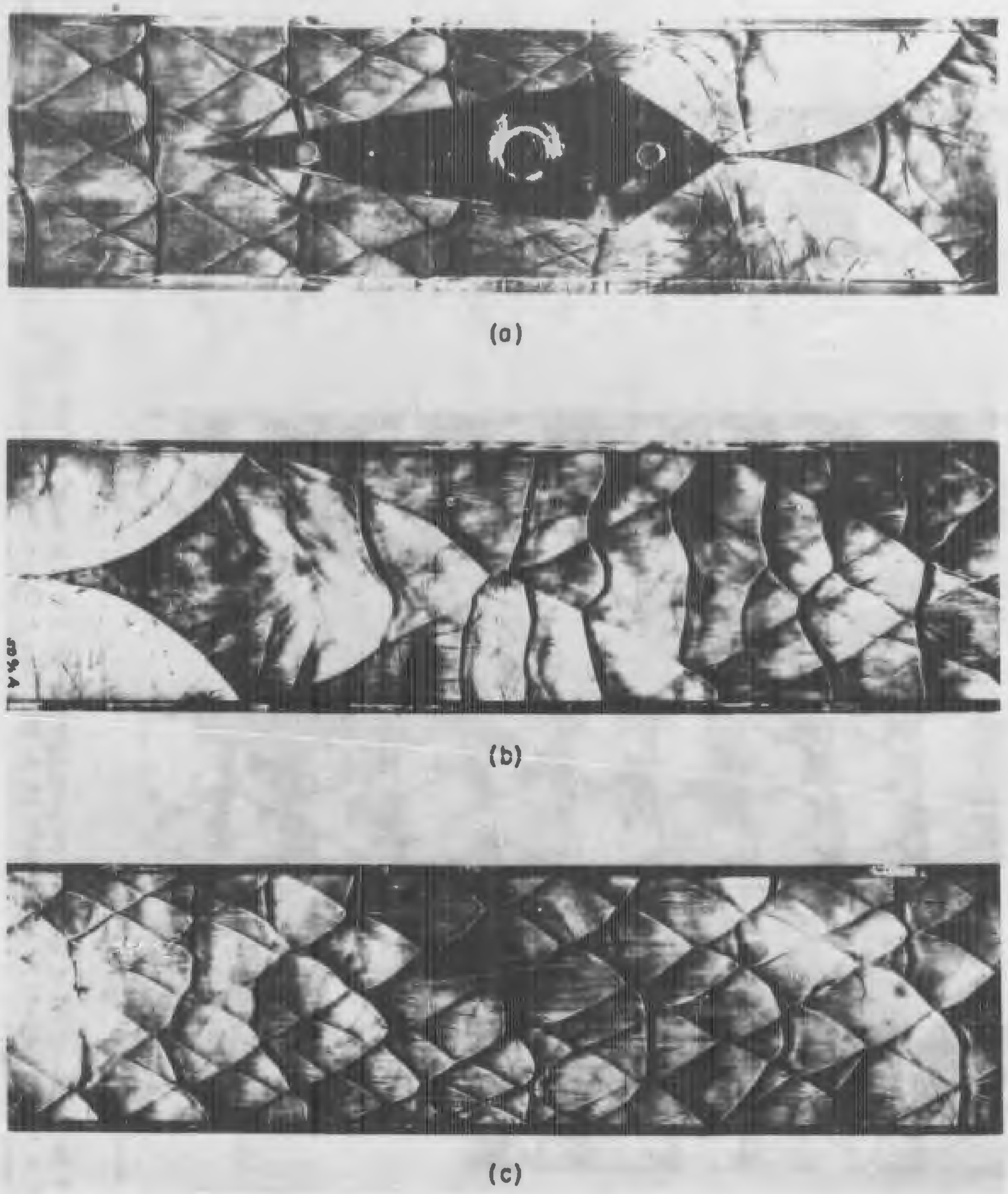


Figure 14. Measured and calculated strength of the transverse wave system as the detonation travels into the convergent section of a two dimensional nozzle. 1 and 2 experimental data for two different runs at 100 torr initial pressure. 3 calculated rate of decay assuming imploding cylindrical detonation. 4 strength of the transverse wave produced by the intersection of the lead shock with the ramp apex. This transverse wave quickly merged with one of the previously present waves in the experiment.



(a)

(b)

(c)

Figure 15. Smoked foil record of a detonation passing over the wedge model. Mixture of 50% ($2H_2 + O_2$) + 50% Ar at 55 torr initial pressure. Tube width 3 1/4".

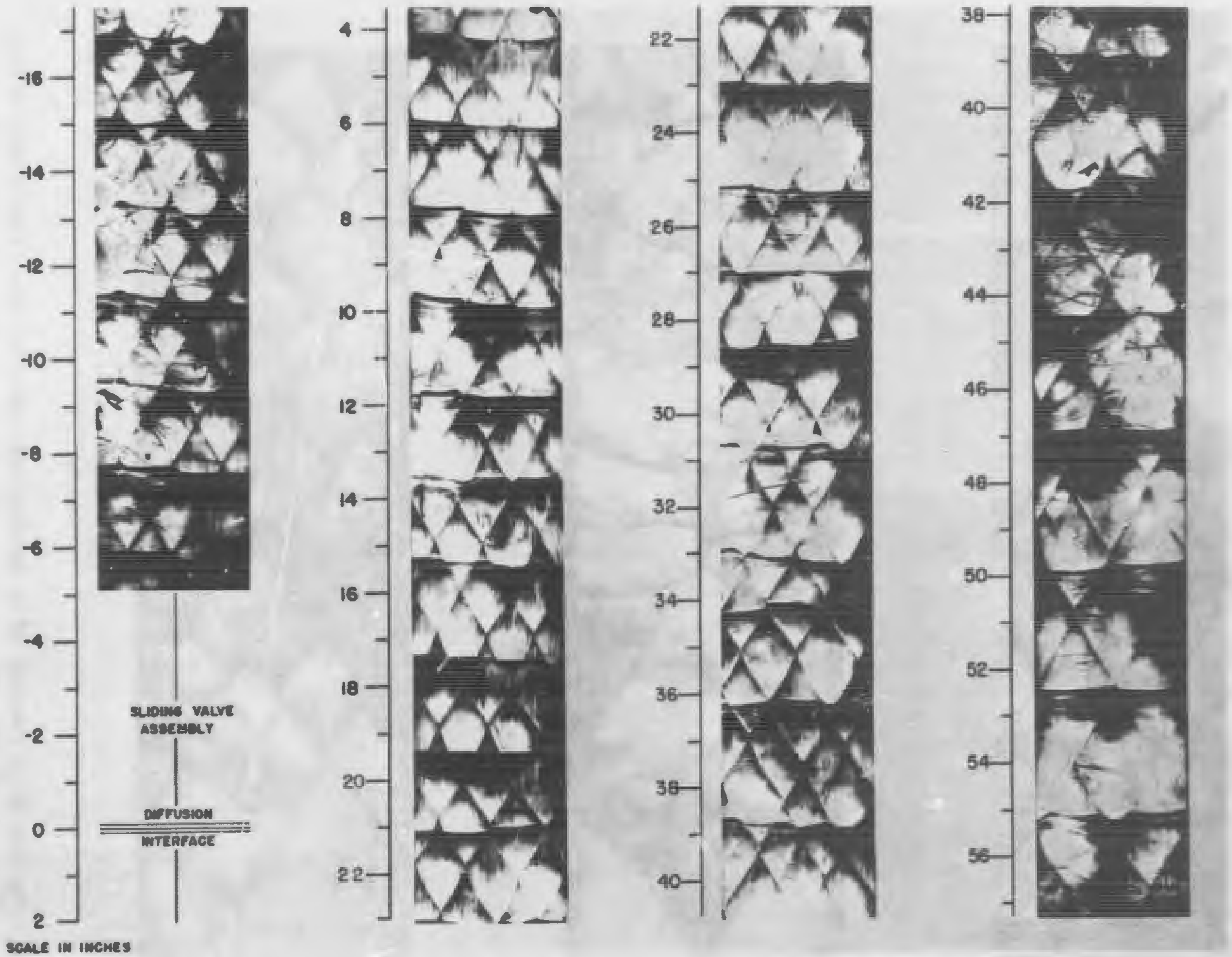


Figure 16. Smoked foil record of a detonation propagating in a 3 x 6 mode in 50% $(2H_2 + O_2)$ + 50% Ar mixture making a transition to a 2 x 4 mode in a 30% $(2H_2 + O_2)$ + 70% Ar mixture at 65 torr initial pressure. Experiment #1 Table I.

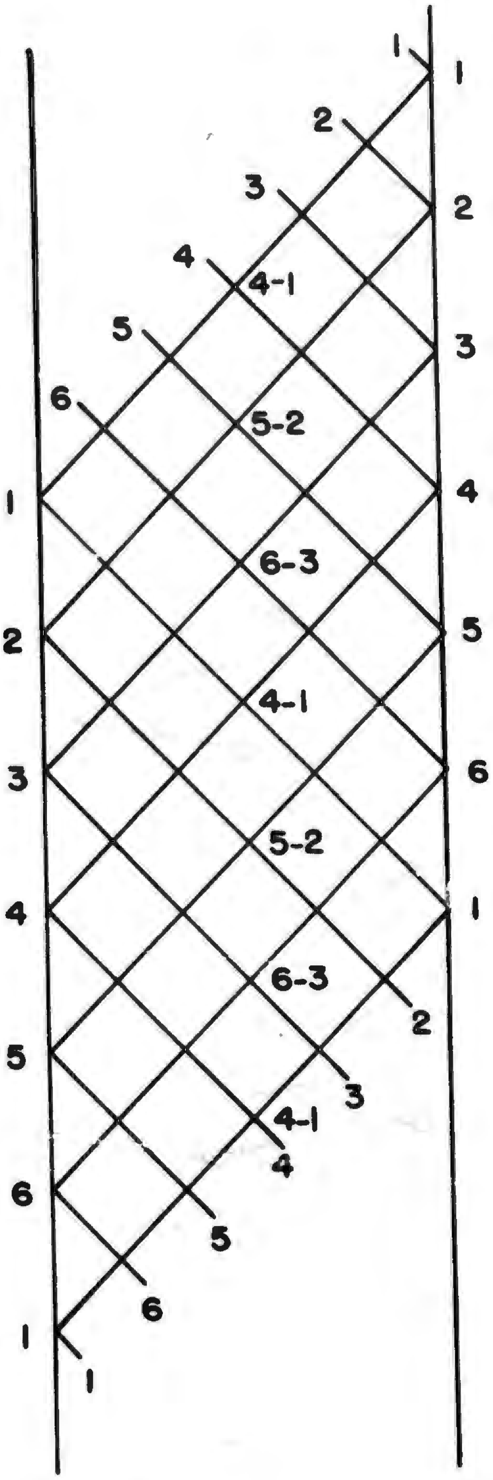


Figure 17. Numbering system for a 6th mode detonation.

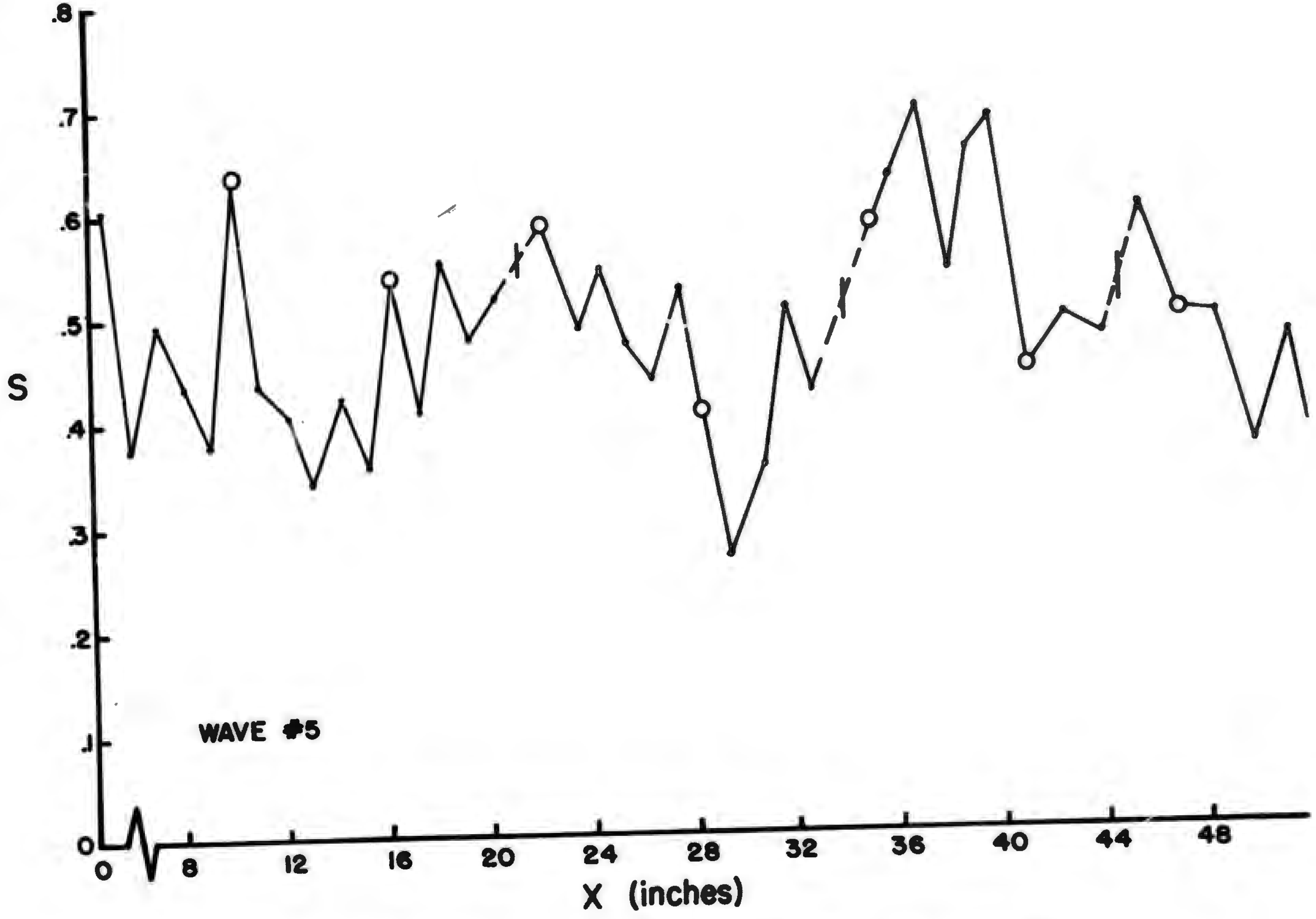


Figure 18. Strength versus distance for a wave which did not fail. Experiment #1 Table I.

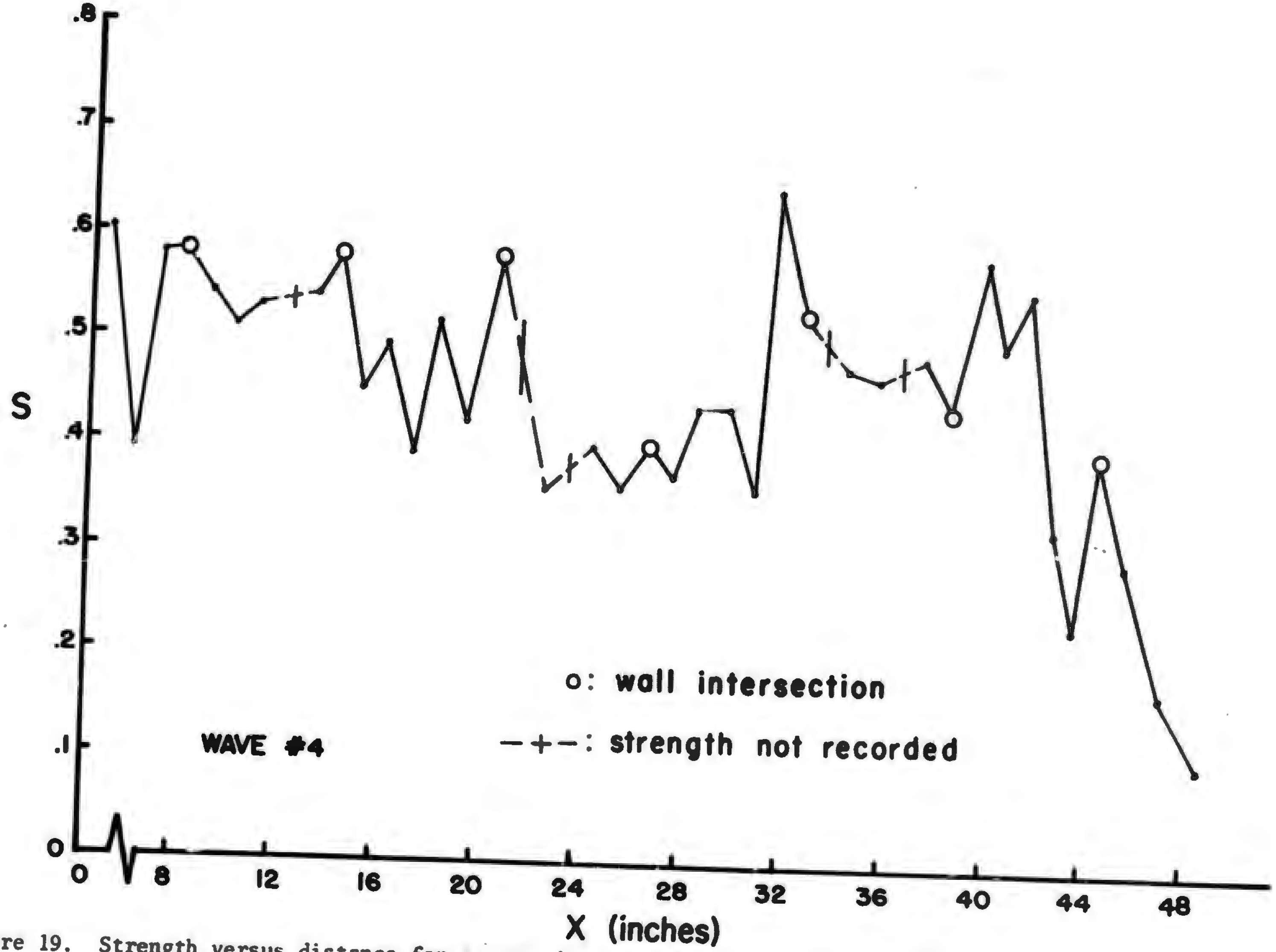


Figure 19. Strength versus distance for a wave which failed. Experiment #1 Table I.

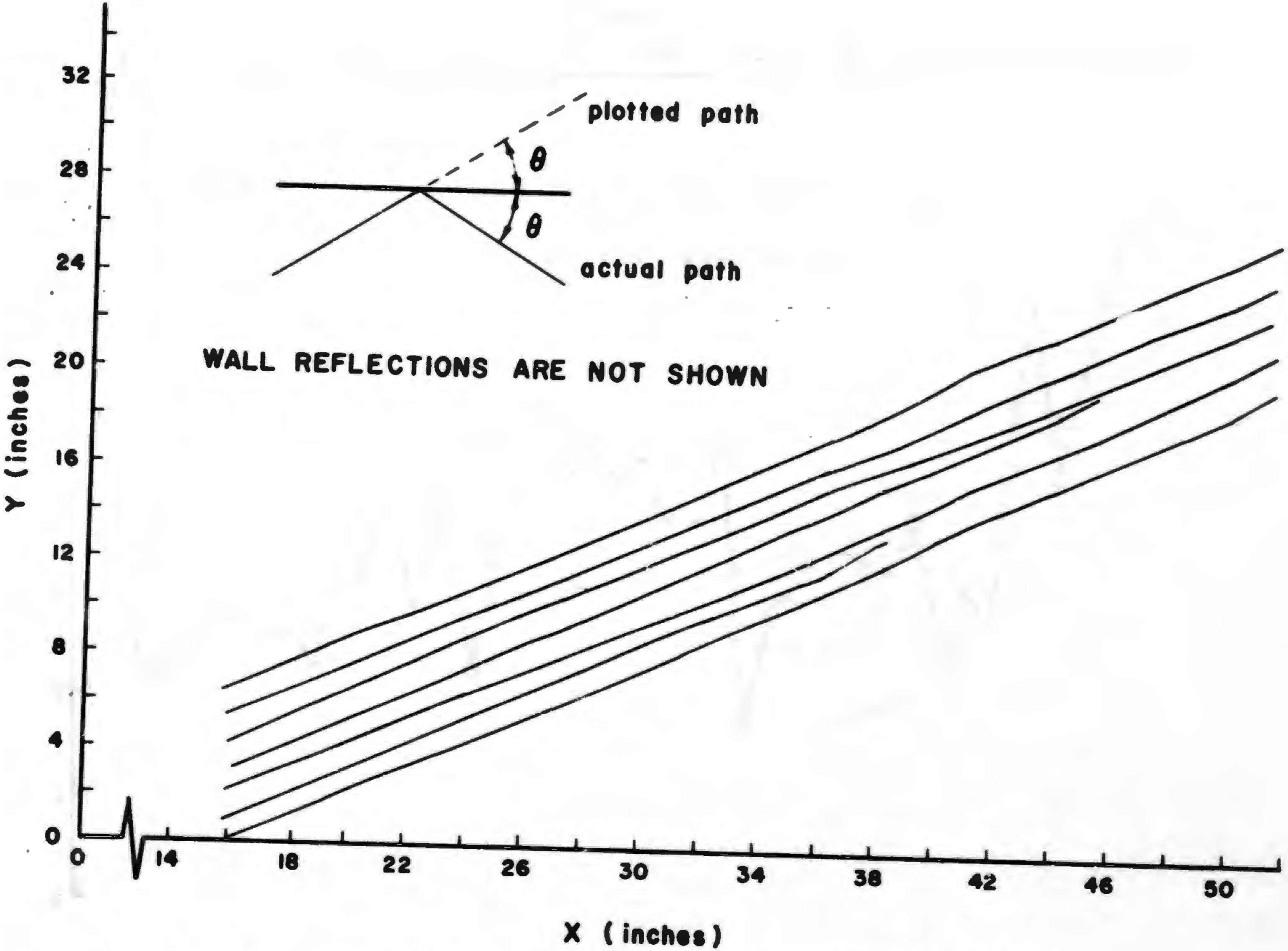


Figure 20. Trajectories of the 6 transverse waves in experiment #1 Table I.

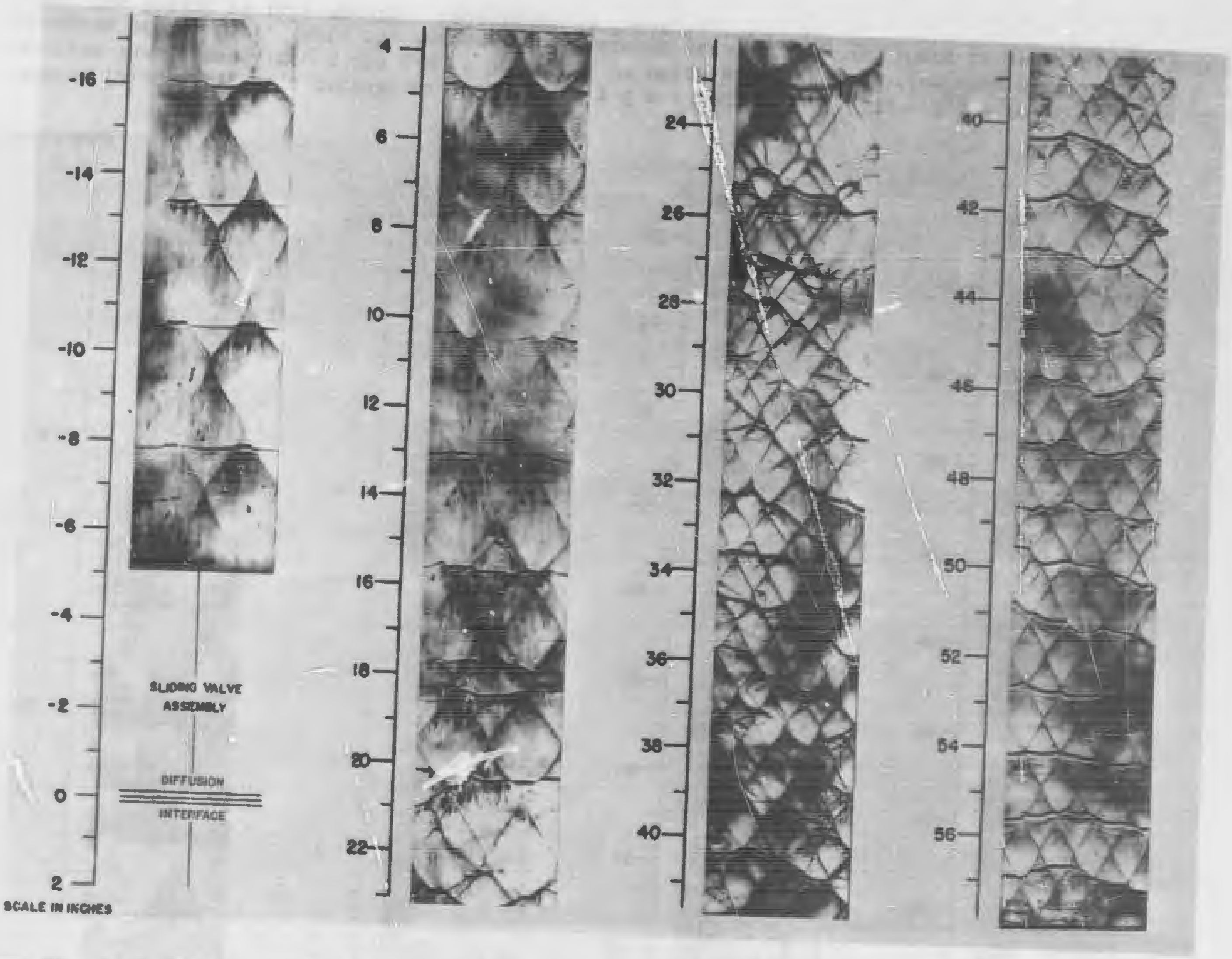


Figure 21. Smoked foil record of a detonation propagating in a 2 x 4 mode in a 30% $(2H_2 + O_2)$ + 70% He making a transition into a 4 x 8 mode in a 40% $(2H_2 + O_2)$ + 60% He mixture at an initial pressure of 140 torr. Experiment #3 Table I.

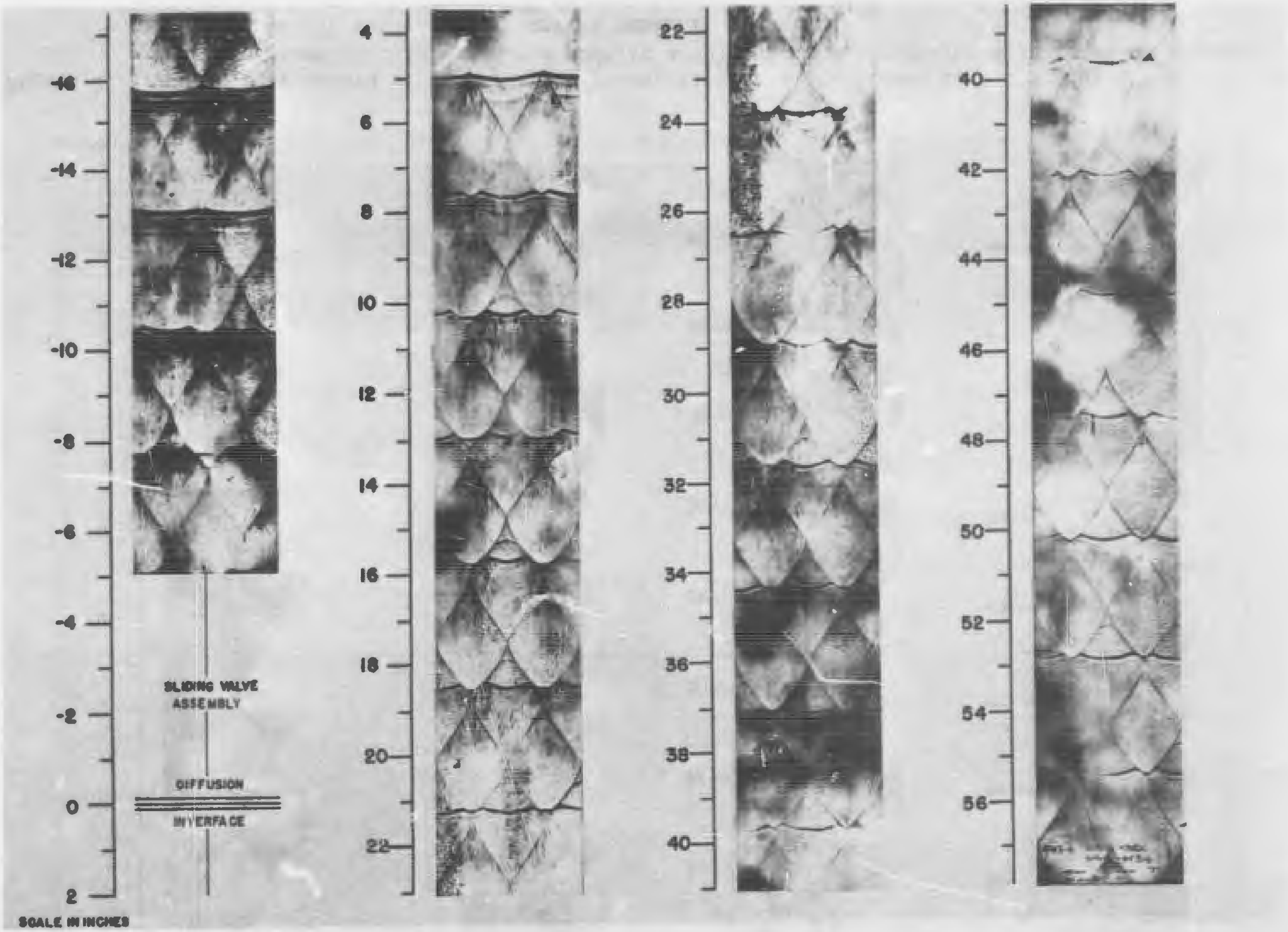


Figure 22. Smoked foil record of a detonation propagating a 2 x 4 mode in 30% ($2H_2$ + O_2) + 70% He mixture in the upper section that passed into a 35% ($2H_2$ + O_2) + 65% He which has an equilibrium mode number of 3 x 5 at the initial pressure of 140 torr. Note the changes in structural details although there is no change in mode number along the length of this record. Experiment #4 Table I.

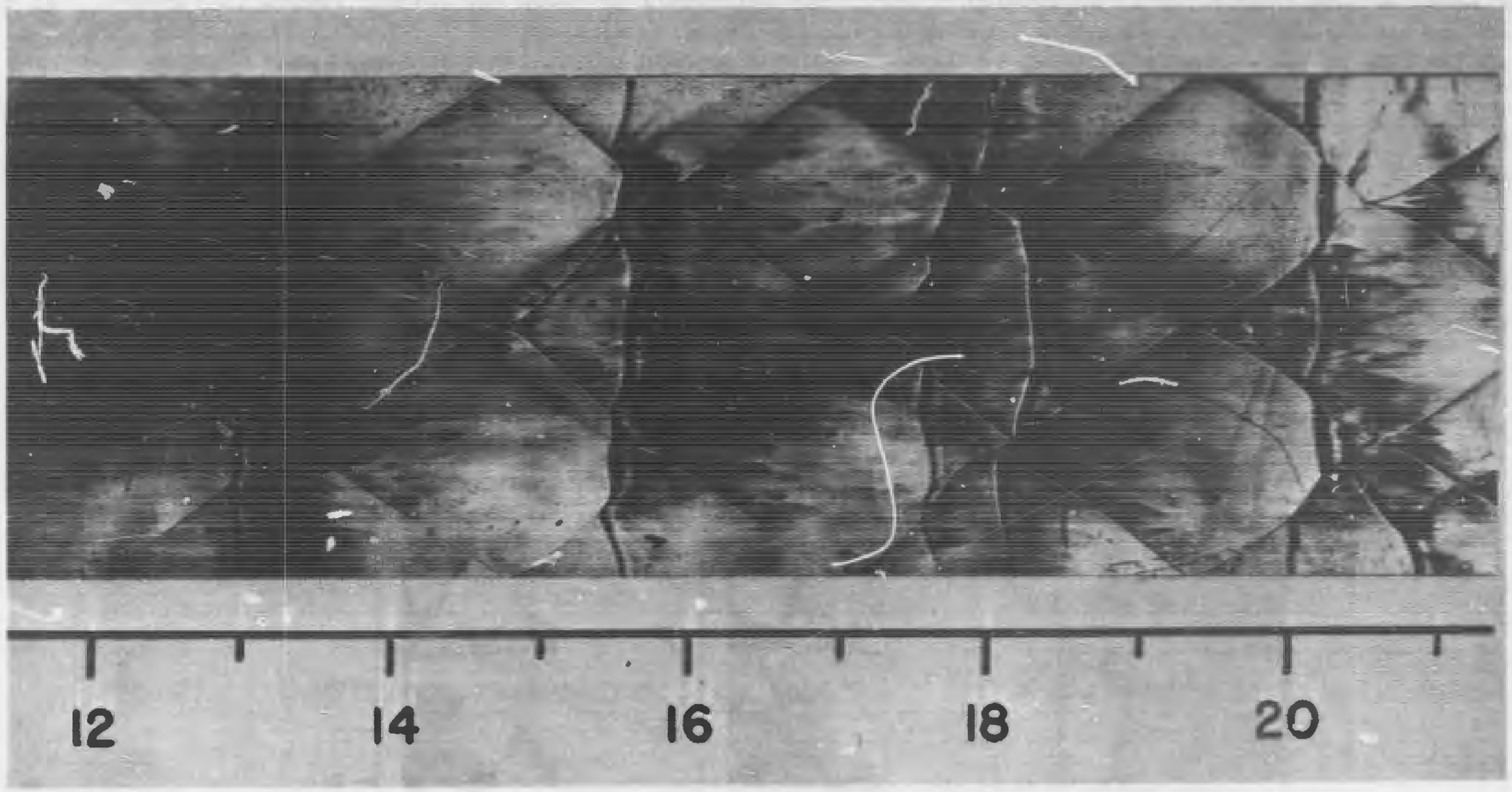


Figure 23. An enlargement of the interacting transition region of the record of Experiment #3 Table I. The entire record is shown in Figure 21.

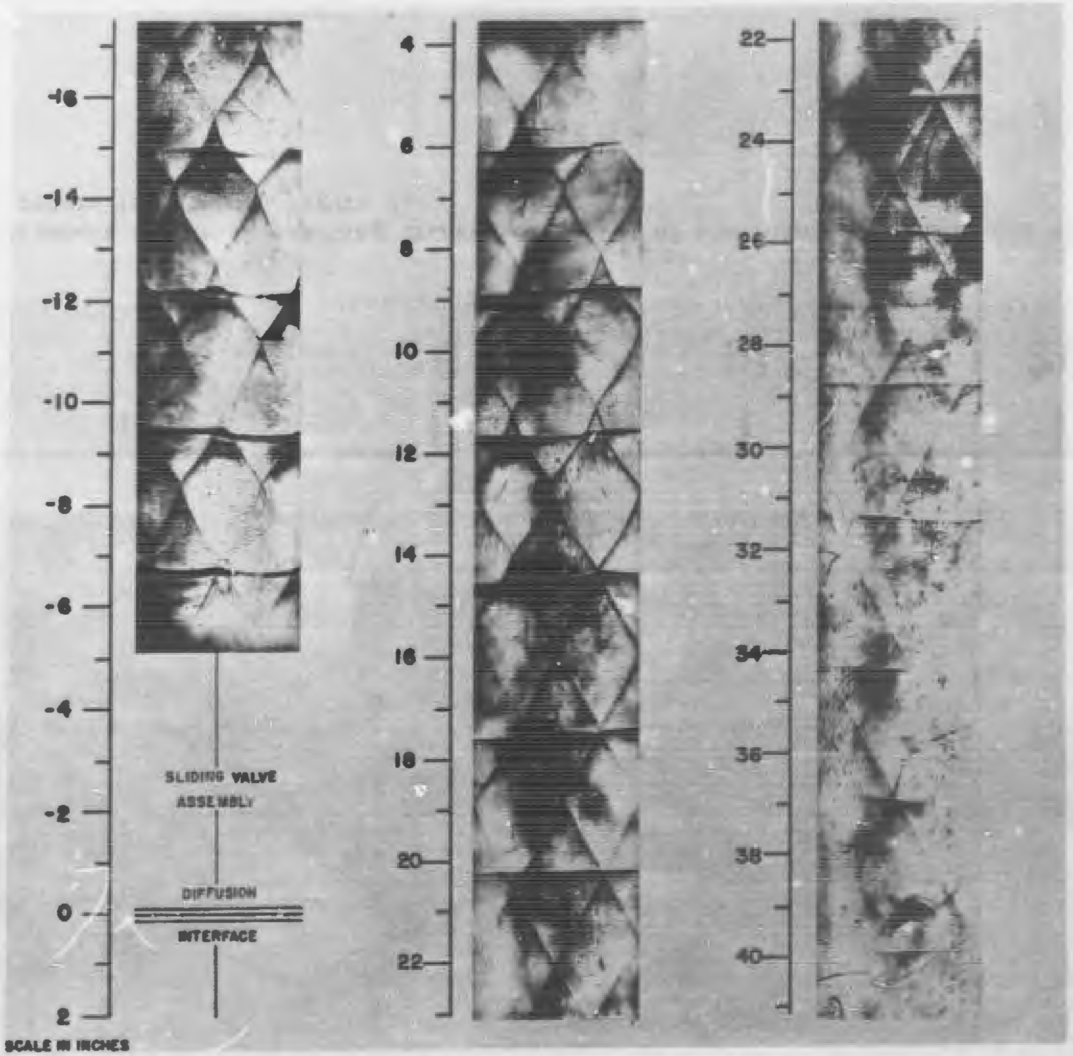


Figure 24. Smoked foil record showing the decay of transverse waves when a detonation is propagated into an inert gas. The initial detonation in a 2 x 4 mode detonation in a 30% ($2H_2$ + O_2) + 70% He mixture at an initial pressure of 140 torr. The gas mixture below the interface is a 30% Ar + 70% He mixture. Experiment #5 Table I.

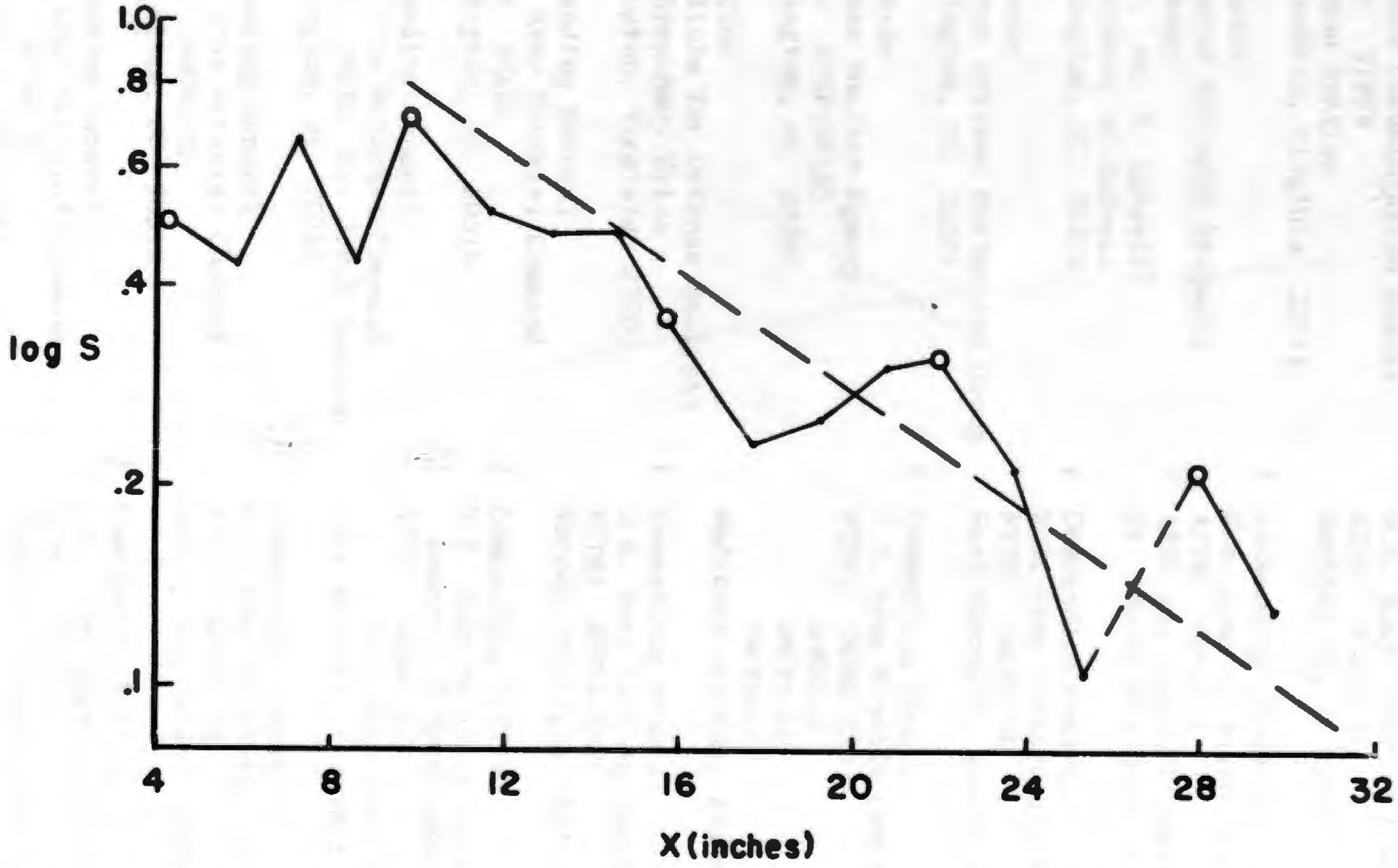


Figure 25. A plot of $\log_{10}$ S versus distance when S is the strength of a single wave in Experiment #5 Table I. Rate of decay is approximately 7%/cell length.