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FORMATION OF JETS IN PLANE SLABS

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ABSTRACT

A series of experiments done by Koski's section suggests a mechanism of jet formation depending essentially on the high interaction pressure of detonation waves combined with the interaction of the shocks passing through the slab, and the rarefaction which spreads from the free surface after the shock has reached it. It is likely that this mechanism of jet formation is responsible for the prominent jets observed in collapsing cylinders when four-point initiation is used. It is not yet clear whether the same mechanism applies to jets in multipoint initiation and lens initiation.

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FORMATION OF JETS IN PLANE SLABS

1. Experiments with two points of initiation

A plane steel slab of 1/4" thickness is placed underneath a Comp. B charge of 2-1/2" height (Fig. 1). The charge is initiated at two points, A and B, giving rise to two spherical detonation waves which meet along the interaction line I. By varying the distance between the points A and B the angle α is varied. The shape of the lower surface of the steel slab is photographed by flash photography at a fixed time interval after the detonation has reached the center M of the slab. In the experiments to be discussed the time interval was 12.3 microseconds (8 cm of primacord).

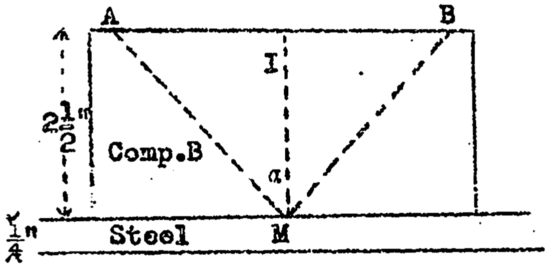
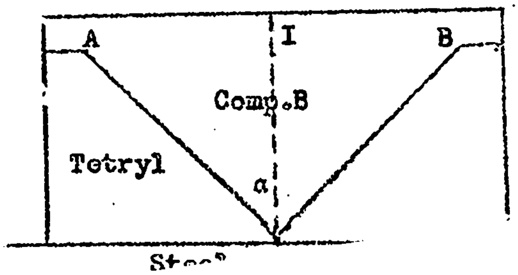


Fig. 1

A pronounced jet can be seen in most photographs directly under the interaction line for angles α between 20° and 80°. The jet length (i.e. distance of tip of jet from base of jet) is maximum when α is about 45°. The jet seems to vanish when α is about 20° or is somewhat above 80°.

2. Experiments with lenses

In the second set of experiments a lens system was used to produce two plane detonation fronts (Fig. 2). Initiation at the points A and B produces again two circular fronts in



Comp. B, interacting along the line l as in the previous experiments. However, in the tetryl the detonation fronts are plane. Variation of the angle α produces of course a variation of the angle at which the plane detonation fronts hit the steel surface.

It was found that with a lens system there was no jet if the angle α was chosen in such a way that the detonation front arrived at the steel plate first at a point under the interaction line, even though, with no lens system, pronounced jets would occur for this same angle α. Jets did occur if the lenses deviated in the opposite way, with the angle α chosen so that the detonation front arrived first under the points of initiation.

3. Evidence against interpreting the jets as Munroe jets

The experiment described under 2 suggests immediately that the jets might be Munroe jets, since they do appear if the detonation front, and therefore also the free surface of the slab, converges towards the center, and they do not occur if the free surface diverges from the center.

Evidence against this mechanism is given by X-ray photographs obtained by Tuck's section which show that there is no slug behind the jet, as there would be if the jet were of the Munroe type. On the contrary, there is a region of low density in the central region of the jet and behind the jet; this region eventually gives rise to spalling.

The interpretation as a Munroe jet is also untenable on theoretical grounds. It is possible to calculate the angle ϕ which the free surface makes after the initial acceleration with its original direction (Fig. 3). This angle is very small. The angle ψ, which can also be calculated, made by

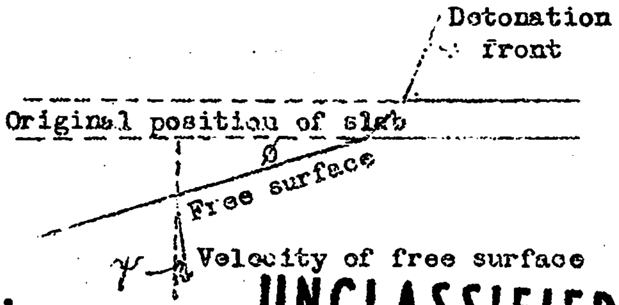


Fig. 3

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the velocity of the free surface with the normal to the original surface, is even smaller (about 1/2 ϕ). Values of ϕ and ψ are given in the following table for various angles α of the detonation front.

α	0°	10°	20°	30°	40°	45°	55°
ϕ	0°	2.2°	4.4°	6.1°	7.1°	7.4°	8.1°
ψ	0°	1.1°	1.8°	3.1°	3.5°	4.1°	4.7°

According to Taylor (BM-174), the velocity of the Munroe jet is given by[1]

$$u \cot (\pi/4 - \phi/2)$$

or, if ϕ is small,

$$u(1 + \phi)$$

where u is the velocity of the free surface and ϕ is expressed in radians. Thus for $\alpha = 10°$ the velocity of the jet is only 4 per cent higher than the velocity of the free surface. Even for 55° incidence we obtain a jet velocity only 14 per cent in excess of the velocity of the free surface. In the lens shots described above, the observed excess is far larger, and jets occurred for angles of incidence of only a few degrees. Clearly these can not be classified as Munroe jets.

4. The interaction pressure of the detonation waves

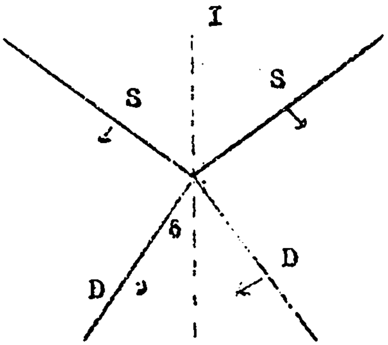

Fig.

If two detonation waves meet at an angle, they will reflect each other and give rise to two shocks following behind. The pressure behind the shocks is high and will be called

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[1] This is an overestimate, since Taylor assumes $\psi = \phi$ [redacted]

[redacted]

the interaction pressure (Fig. 4).

If the interaction angle δ is larger than 44.8°, the normal interaction shown in Fig. 4 is no longer possible. Instead we obtain a Mach interaction. The simplest Mach configuration is shown in Fig. 5. There is a central region of high pressure in which the detonation velocity is forced up from its normal value D to a higher value D'. This region ends at the "triple points" T where the detonation velocity and pressure return to their normal values; the regions of high and low pressures are separated by shocks S. The triple points T move slowly away from the center (along the dotted lines) and we call the angle ω between the direction of motion of the triple points and the center line the "Mach angle". For the interaction of shock waves this angle is known to be very small; we assume that it is small also for the interaction of detonation waves. In any case assuming ω to vanish leads to an underestimate of the interaction pressures.

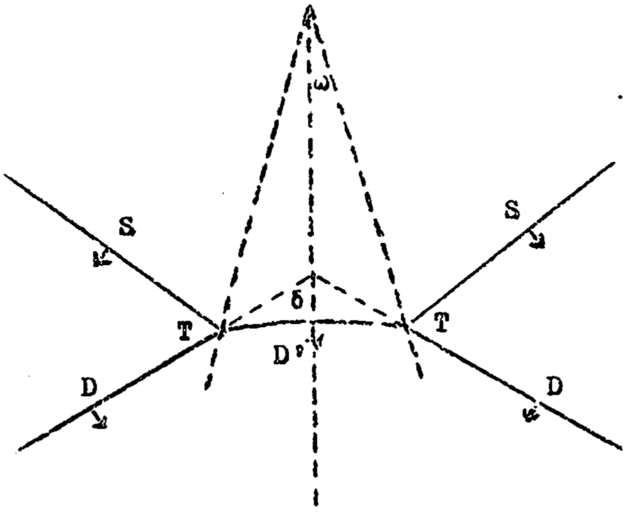

Fig. 5

Neglecting ω altogether the interaction pressure can be calculated. It varies slightly from the center to the triple point. The most outstanding features of this interaction pressure are that it is practically constant and equal to about 2.4 normal detonation pressures for normal interaction ($0 \leq \delta < 44.8^{\circ}$), and that it has a sharp maximum of 3.4 detonation pressures at the critical angle $\delta = 44.8^{\circ}$. The pressure is shown in Fig. 15, at the

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end of this report, as a function of $90^\circ - \delta$. In the case of interaction of detonation waves only one other Mach configuration is possible. This configuration has an additional shock preceding the Mach shock. This additional shock is fairly weak and follows closely the detonation front. The interaction pressure for this configuration is the same as for the first configuration in the center, but is lower at the triple point.

The sharp peak of the interaction pressure at α equals 45° agrees nicely with the fact that this value of α gives rise to the maximum jet length. However, there are two facts which show that the interaction pressure is not the whole explanation. The first fact is the constant interaction pressure for $0 < \delta < 44.8^\circ$, i.e., $90^\circ \geq \alpha > 45.2^\circ$, for which values nevertheless, the jet length decreases continuously with increasing α. The second and more conclusive bit of evidence is given by the lens shots mentioned above which show that the jet can be eliminated altogether without eliminating the interaction pressure.

5. The shock interaction in the slab

The clue to the missing link in the mechanism of jet formation is given by the lens shots. These show that jets appear or disappear according to whether the detonation fronts converge to or diverge from the center of the slab. The impulse is transmitted through the slab by means of shocks; clearly these shocks will also converge if the detonation fronts converge, and will diverge if the detonation fronts diverge (Fig. 6).

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In the first case the two shocks will collide and give rise to a shock interaction in the slab (Fig. 7). In this case the shocks S are each followed by a reflected shock R. Thus the free surface is accelerated in two steps first by the shocks S and then by the shocks R.

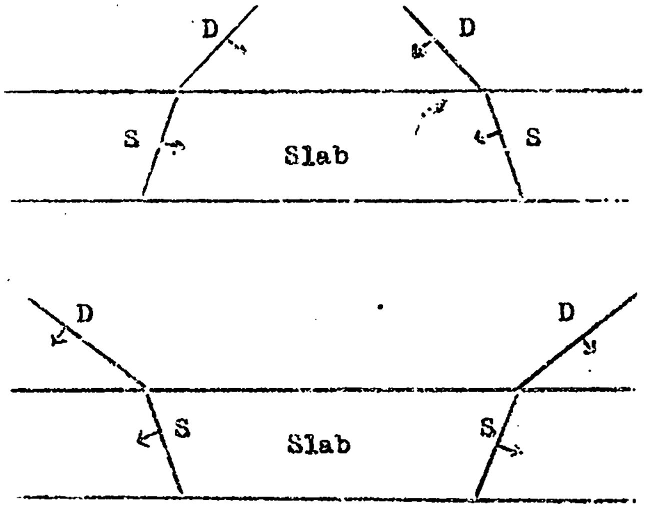

Fig. 6

The significance of these two steps is easily seen if we imagine what happens in the no-lens shots if the initiation point on the right were omitted. Then no shock S would come from the right and the shock S from the left would simply continue. No reflected shocks would occur and the second step in the acceleration would be missing. Thus the first step of acceleration corresponds simply to the acceleration given to the free surface by a spherically diverging detonation wave.

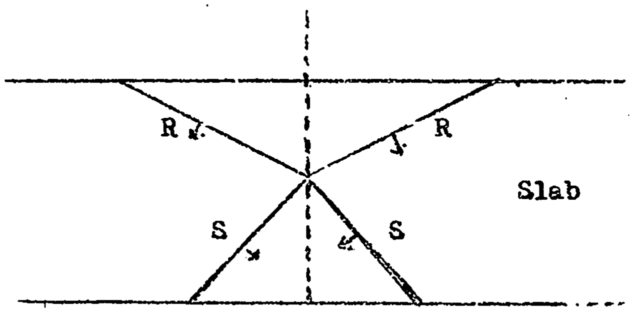

Fig. 7

However, if there are two detonation points the center region of the detonation front changes progressively into a plane front and this effect clearly spreads from the center outwards.

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If the reflected shocks R could maintain their strength they would of course accelerate eventually the whole free surface to the same velocity. However, several factors prevent this.

1) The shock S of course decreases in strength as it passes away from the upper surface and is constant at the free surface. The shock R, however, originates along the interaction line I (see Fig. 7) and decreases as it travels away from this line. Thus it is not constant along the free surface but strongest at the interaction line.

2) The shock R passes into a region which has already been accelerated by the shock S. After the shock S has reached the free surface a rarefaction wave passes back into the slab and the shock R runs into the rarefaction. This again reduces the shock strength. At the interaction line of course S and R arrive simultaneously and no rarefaction takes place in between. The further we go away from the interaction line the longer is the delay between S and R and the larger the rarified region. This is shown in Fig. 8, illustrating the moment when the two shocks S have just passed through the slab at the interaction line I. The reflected shocks R just start along the free surface and run into the rarefaction the head of which has reached the line H.

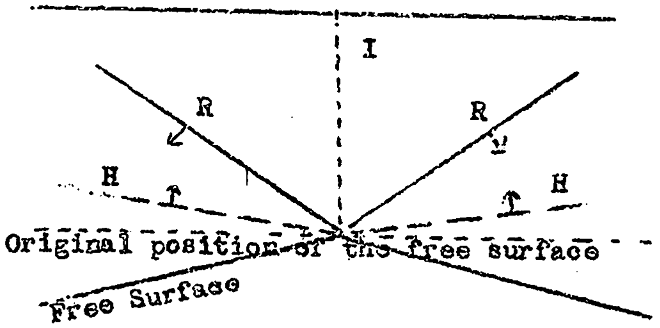

Fig. 8

3) The shock interaction is in a way a continuation of the interaction of detonation waves in the explosive. The high interaction pressure will influence the strength of the reflected shocks and this

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pressure has the same property as the pressure of the reflected shocks in so far as it decreases with the distance from the interaction line.

All these factors taken together should lead to a sharp decrease in the velocity of the free surface with the distance from the interaction and therefore to a jet with a sharp point.

Behind the jet there will be a strong rarefaction due to the acceleration given to the free surface by the combined strength of the shocks R and S. The heads of the two rarefactions (Fig. 9) have the effect of sucking more matter into the jet. This rarefaction is in agreement with Tuck's X-ray photographs.

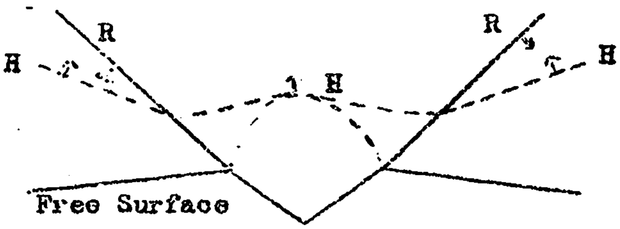

Fig. 9

The essential features leading to jet formation are:

1. Interaction pressure of detonation waves.

2. Interaction of shock waves in the slab giving rise to an acceleration of the free surface in two consecutive shocks with varying time interval.

3. Rarefaction starting from the free surface in the interval between the two shocks.

We have somewhat simplified the discussion of the shock interaction in the slab, by assuming that we are dealing with normal interaction. In actual fact, over most of the interesting region we are likely to have Mach interaction. However, since the Mach angle is very small this does not affect the argument essentially. On the other hand, we should not be

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surprised if the tip of the jet shows some fine structure, especially in the early stages. It is tempting for example to identify the three tips observed in some jets with the three regions of high pressure occurring in Mach interaction of shock waves in the center of the Mach region and behind the two triple points. But this is rather speculative and in any case does not contribute materially to our understanding of the jet formation.

6. Discussion of lens shots

The essential features of the lens shots with two converging detonation fronts are covered by the discussion given under 5. It remains to look somewhat more closely into the case of diverging detonation waves.

In order to simplify matters we disregard the reflection of shocks on all interfaces and between each other, since this does not alter the picture materially.

Fig. 10a shows the conditions in the explosive just before the detonation front D hits the slab, with the reflected shocks R behind the interaction in the fast explosive.

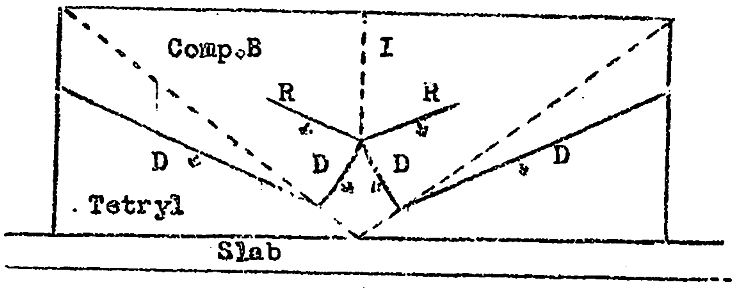

Fig. 10a

Fig. 10b shows the conditions just after the detonation front hits the center of the slab. Two shocks S have started to run away from the center and the shock R is running up behind them. The shock R must run faster than S, and since the center

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portion of either of them starts at the same moment at the same time the shock R will have reached the shock S over a finite region. (In fact, if the two explosives differ sufficiently the shock R might catch up with the detonation front in the slow explosive.)

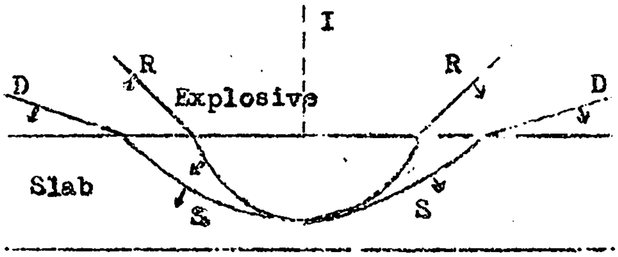

Fig. 10b

The shock R starts off with about 2-1/2 to 3-1/2 fast detonation pressures and the shock S with about 1.6 to 1.7 slow detonation pressures. (In the actual experiments one fast detonation pressure = 4.4 slow detonation pressures.) Hence the shock R has a good chance of catching up with S over a fairly wide region. Thus there is a finite region in which the first and second shock arrive simultaneously at the free surface and the pressure behind the shock will have a broad maximum instead of the sharp peak associated with the shock interaction. Hence we expect a broad bulge under the interaction line but not a jet.

7. The strength of the shock in the slab

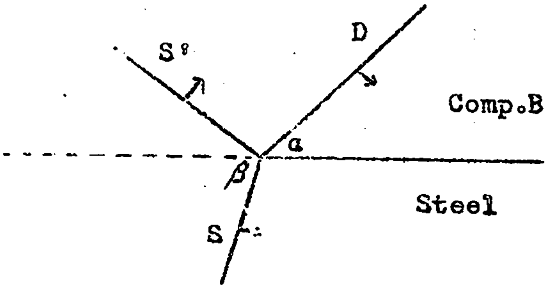

Fig. 11

The shock strength in the slab depends on the angle of incidence α (Fig. 11). For α below 60° the strength is nearly constant (1.6 to 1.7 detonation pressures). For α above 60°, Mach reflection of the detonation occurs (Fig. 12) and the shock pressure in the steel slab goes up to 1.94 detonation pressures. (Again we neglect the

[redacted]

Mach angle ω, so that this pressure is an underestimate.)

Mach reflection stops with a at 1° or 2° below 80°, and with a at about 1° above 80°, reflection stops altogether. Instead, the explosive gases begin to expand against the steel so that the shock pressure drops below the detonation pressure (to 0.71 detonation pressures). This gives rise to the graph shown at the end of this report. The attenuation of the shock in the slab has not been taken into account.

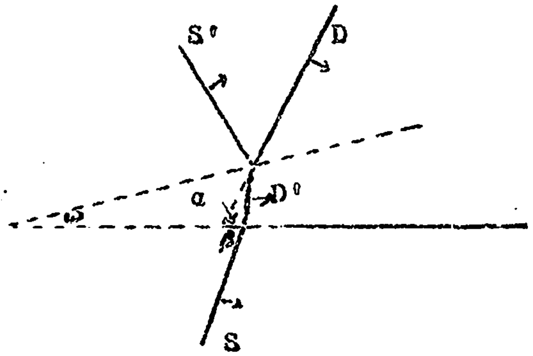

Fig. 12

The angle β which the shock makes with the original surface of the slab determines the interaction angle, $90^\circ - \beta$, of the two shocks in the steel slab. Values of the angle β are given in the following table.

a	0°	10°	20°	30°	40°	45°	55°	60°	70°	80°	90°
β	0°	7.10°	14.9°	20.9°	27.2°	30.1°	35.6°	39.4°	41.5°	41.5°	40.5°

8. <u>The shock interaction in the steel slab.</u>

For values of a up to 60° the shock strength is fairly constant and therefore also the shock velocity, which is about $5.55 \cdot 10^5$ cm/sec. Compared with the normal sound velocity of $4.64 \cdot 10^5$ the shock has a Mach number equal to 1.193. In these conditions Mach reflection should certainly occur for all angles β less than 30°.

[redacted]

Considering the values given above, Mach reflection of the shocks S will occur for values of α below 45°. The pressure at the center of the Mach region is easily calculated and is shown in Fig. 15.

For values of α above 60° the angle does not vary appreciably and therefore the pressure of the reflected shock should behave similarly to the pressure in the shock S, except that it is higher. There is not much point in calculating this pressure, since in this region there is no direct relation between the pressures and the jet length, as we shall see presently.

9. Discussion of slab shots with two detonation points

Let us consider now the experiments described under 1. Let α' be the angle of incidence of the detonation front on the slab (see Fig. 13) and δ the interaction angle of the two detonation fronts along the interaction line I. When the detonation front has just reached the center, then α' = α, δ = 90° - α. Hence, we have collected in the graph, Fig. 15, all the pressures described above and the jet length as functions of α and 90° - δ.

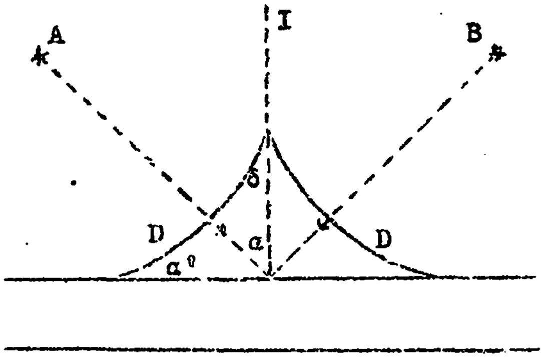

Fig. 13

The angle of incidence α' starts at α' = 0 when the detonation front just reaches the slab below the point of initiation. Thus in any given shot the history of the first shock in steel is given by following the curve of the shock pressure from left to right up to the angle α. At this point the interaction with the shock coming from the second detonation point begins and the pressure behind the reflected shock rises to the value given in the graph for the given value of α (Fig. 15, curve "Reflected Shock in Steel").

Similarly the interaction of the detonation waves starts with

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$\delta = 0$ and therefore the history of the interaction in the explosive is obtained by following the curve from right to left, to the given value of α.

Consider an angle α below 45°. In this case the past history of the interaction in the explosive is of little significance, since the high pressure at the peak of the Mach interaction is quickly eaten up by the sharp pressure drop behind the spherically diverging detonation front. The pressure of the shock in steel is in any case practically constant throughout its history. Thus only the instantaneous pressures for the given value of α are of importance, and therefore the jet length should be closely related to the difference between the interaction pressures (in the metal and explosive) and the pressure of the first shock in the metal.

These arguments hold also for angles α from 45° to 60°, since in this case both interactions have almost constant pressure. It will be seen from Fig. 15 that there is indeed a very close correlation.

If α is greater than 60° conditions are somewhat more complicated, since the shock in steel passes through a complicated history in the course of which the pressure on the steel slab increases suddenly over a small area and then decreases rapidly. The region of high pressure does not remain localized but spreads behind the shock as the shock passes through the slab. Hence there will be a continuous acceleration of the matter behind the shock and this reduces the rarefaction spreading back from the free surface. This effect should become particularly important if $\alpha > 80°$, since in this case also the explosive gases begin to exert a conuous push after the first instantaneous push which gives rise to the shock.

This we believe is the main reason why the jet formation disappears at high values of α. This fact could not be explained if we considered only the instantaneous pressures, since the differences between both interaction pressures and the pressure in the first shock remain finite as α tends to 90°. This argument underlines the importance of the rarefaction wave in the jet formation.

10. The Shape of the Jet

Confirmation of the ideas just outlined can be found in the fact that the shape of the jet is essentially different for angles α above and below 60°. When α is below 60° the two sides of the jet form a sharp corner with the surface of the slab as indicated in Fig. 14. The surface outside the jet has the direction to be expected from a single shock of constant strength.

When α is above 60° the corners at the base of the jet are rounded, as would be expected from a shock which increases in strength just before it reaches the interaction lines. Eventually (at α = 75 to 80°) also the sharp peak of the jet disappears and there is only a broad protrusion of the surface under the interaction. This is in agreement with the ideas developed above, since the interaction which forces the surface out remains for all angles α up to 90°, but the mechanism by which this overpressure is confined to a small area fails to function.

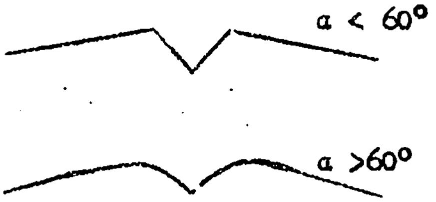

Fig. 14

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11. The Jet Velocity

It is clear that when α is above 60° we cannot expect a close relation between overpressure and jet velocity. When α is between 45° and 60° the large discrepancy between the pressure in the reflected shock and the interaction pressure of the detonation waves makes it necessary to take into account the attenuation of the shock in the steel slab. Also we have not definitely established whether Mach interaction or normal interaction occurs in this region. We confine ourselves therefore to velocities corresponding to α below 45°. Furthermore we disregard the attenuation of the shock in the slab.

The material velocity behind the first shock is calculated to be 8.4×10^4 cm/sec. The velocity of the free surface after it has been hit by this shock is about twice this value.

For $\alpha = 45°$ the tip of the jet is produced by a shock of 3.65 detonation pressures, with a material velocity behind the shock of 14.5×10^4 cm/sec. The velocity of the jet should be about twice this value. Thus:

Velocity of surface 16.8×10^4 cm/sec.
Velocity of jet 29×10^4 cm/sec.
Ratio of velocities 1.73

These velocities are calculated from the revised equation of state of steel (see LAMS-164).

A flash photograph was taken 12.3 microseconds after the detonation hit the surface of the slab; the shock takes just about 1 microsecond to run through the slab. The lower surface had moved

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1.32 cm and the jet, 2.30 cm. The photographic data gave the following velocities

Velocity of surface	11.7×10^4 cm/sec.
Velocity of jet	20.4×10^4 cm/sec.
Ratio of velocities	1.74

The smaller velocity in the experimental results can be accounted for by the attenuation of the shock in the steel slab. The close agreement in the calculated and observed ratios of the velocities is presumably due to chance, since we could hardly expect such precision from the theory.

For the $\alpha = 30^\circ$ shot there is a larger discrepancy; the values are:

	Theoretical	Experimental
Velocity of surface	16.8	7.2
Velocity of jet	22.1	11.9
Ratio of velocities	1.32	1.66

The low velocity of the free surface is rather surprising in this case and this has not yet been cleared up.

12. Attenuation of Shock.

The attenuation of the shocks in the steel slab is probably considerable, since we are dealing with spherically expanding waves. Apart from reducing the velocity of the free surface, the attenuation will also have the effect of changing the interaction angle of the shocks during the passage through the slab. In particular for angles α above 60° the interaction may change from normal to Mach interaction. This might account for the fact that the fine structure of the tip of the jet referred to above has been observed not only for small angles α but also in a shot in which $\alpha = 75^\circ$.

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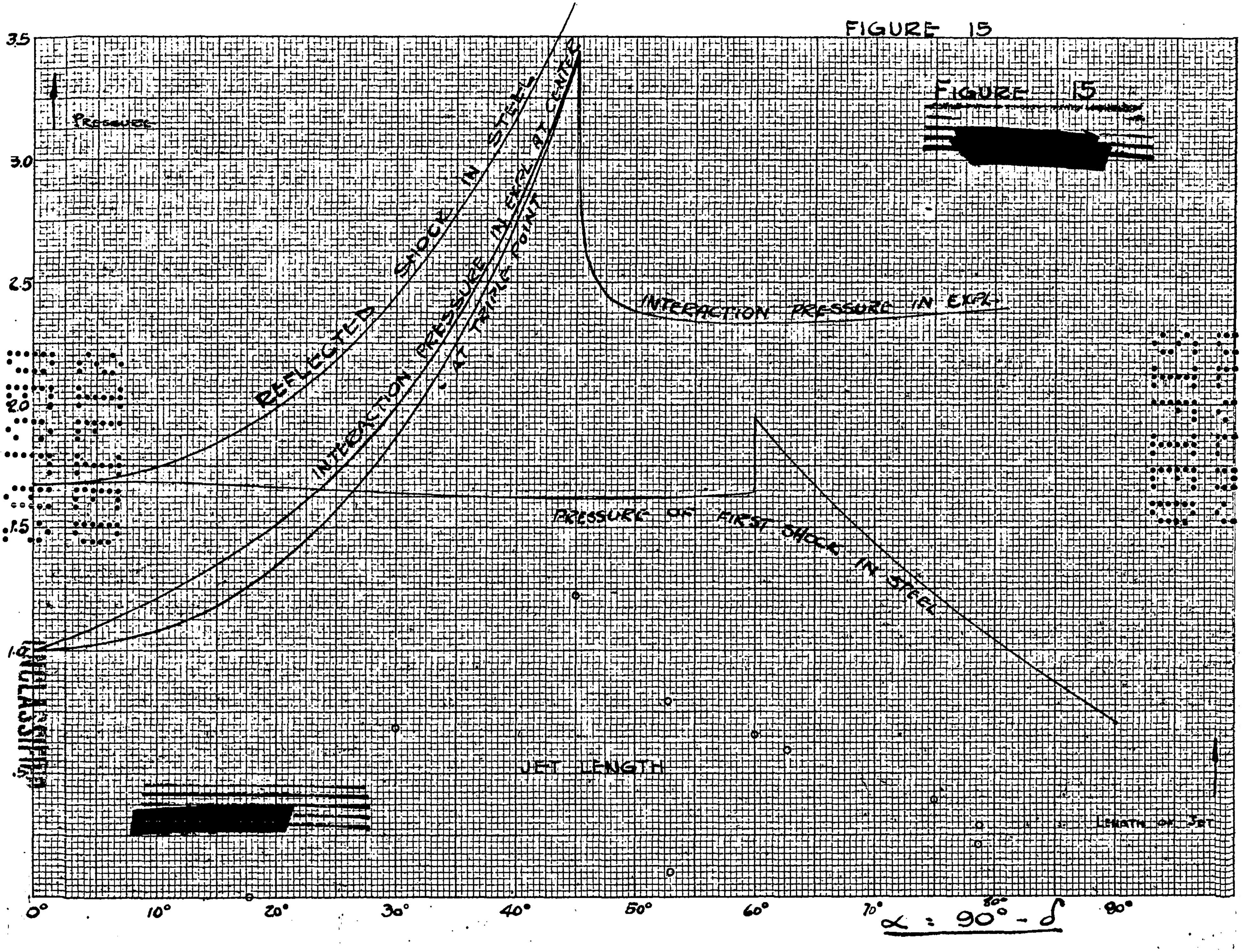
FIGURE 15



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