More recently, Shribman and Crossland[30] have published data on the detonation velocity of the following explosives, which are readily available in Great Britain:

1. *Metabel* sheet explosive, produced by Imperial Chemical Industries, Ltd., and normally provided in sheets $10 \times 5 \times \frac{1}{8}$ in ($254 \times 126 \times 3$ mm). It has a density of 1·47 g/cm^3, a detonation velocity of 7000 m/s, and an energy release of 900–1050 cal/g (3760–4500 J/g).

2. *Trimonite No.* 1, a powder explosive produced by Imperial Chemical Industries, Ltd., with a density of 1·10 g/cm^3 (and in the granulated form 0·7 g/cm^3) and an energy release of 1260 cal/g (5260 J/g). A detonation velocity is not given as it is very sensitive to thickness of layer.

3. *Trimonite No.* 3, as for No. 1 but with a density of 0·98 g/cm^3 and an energy release of 1034–1260 cal/g (4330–5260J/g).

4. *Nitroguanadine* (picrite) is a powder explosive that is extremely difficult to handle because of its light feathery nature. At a density of 0·16 g/cm^3, and a layer thickness of 1–2 in (25–50 mm), it has a detonation velocity of $\sim$ 2300 m/s and an energy release of 950 cal/g (3960 J/g).

The detonation velocity was measured by three methods: Dautriche, parallel plate with pin contactors, and insertion of pins in the explosive at a known distance apart.

For *Nitroguanadine* the detonation velocity for thicknesses from 1 to 2 in was found to be $2400\,^{+4.50}_{-4}\%$ m/s and for *Metabel* sheet explosive the detonation velocity for thicknesses of 0·125–0·5 in (3·175–12·7 mm) was $7000 \pm 5\%$, $6990 \pm 3{\cdot}8\%$, and $7100 \pm 2{\cdot}8\%$ m/s, respectively, for the three methods used. For *Trimonite No.* 1 and *No.* 3, the detonation velocity varied considerably with thickness, and the data are given in Fig. 8 and 9.

Experimental information on flyer-plate velocity is very sparse. However, Shribman and Crossland[30] give data for the explosives mentioned above. For *Metabel* sheet explosive they cite the values of the ratio V_P/V_D for various values of R, the ratio of mass of explosive to mass of flyer plate, where the explosive is uniformly distributed over the plate. They compared these data wth various equations that have been proposed and found that the best agreement was obtained with the equation proposed by Gurney[31]

$$\frac{V_P}{V_D} = \frac{0{\cdot}612R}{2 + R} \qquad \ldots [8]$$

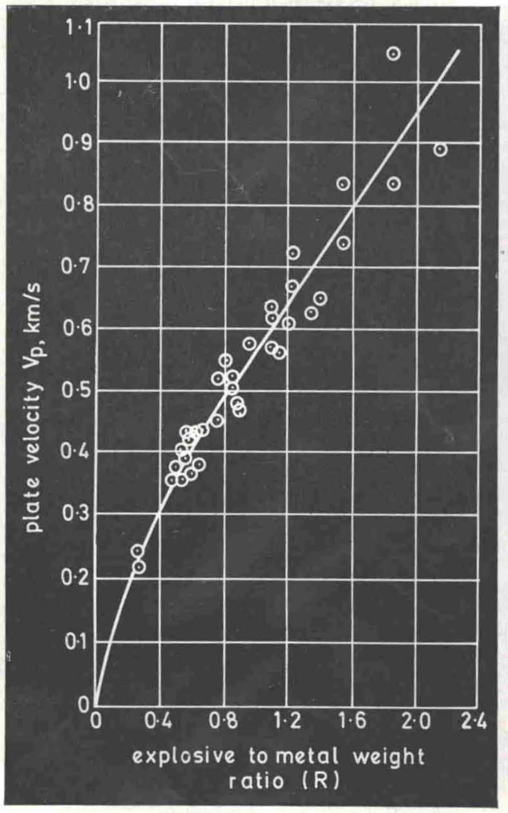
Table III gives the experimental values and those predicted by this equation.

Table I. Properties of explosives[20]

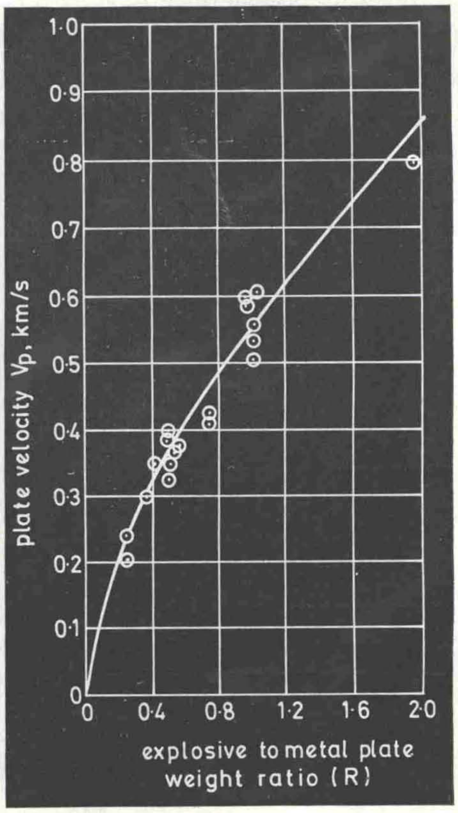
Explosive	Calorific value, cal/g	J/g	Detonation velocity, m/s	Density, g/cm^3
TNT	1080	4500	6700	1·56
RDX	1280	5350	8180	1·65
PETN	1390	5400	8300	1·70
PETN	1390	5400	3500	0·5
Tetryl	1100	4600	7850	1·71
Composition B	1240	5190	7840	1·68
EL–506D	870	3640	7100	1·40

Table II. Effect of diameter on detonation velocity[29]

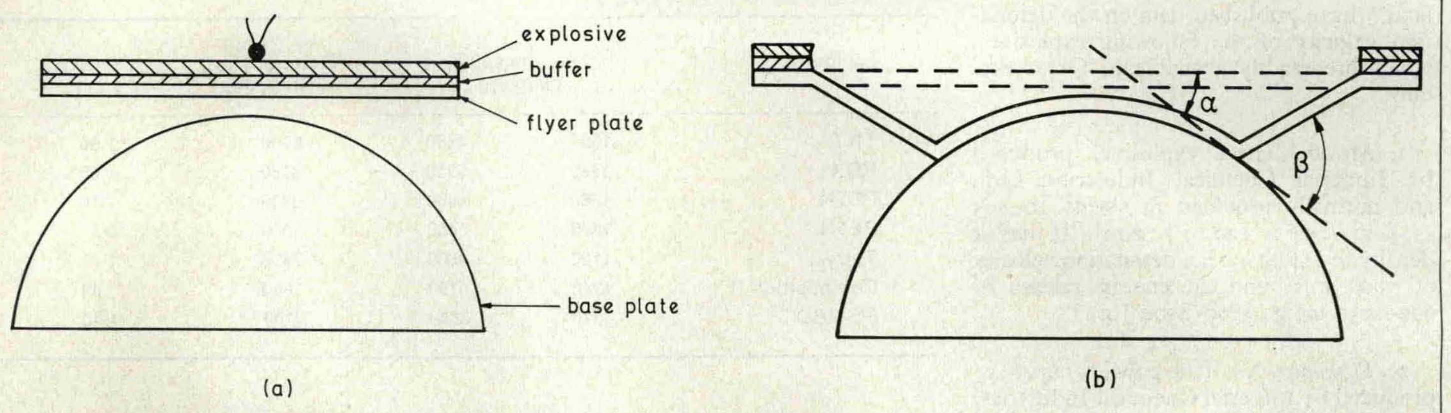
Diameter, in	mm	Velocity of Detonation, m/s: TNT powder	Nitroglycerine powder
0·75	19	3190	1830
1·25	32	3680	2250
2·00	51	4060	2610
2·5	64	4030	—
3·0	76	4100	3150
4·0	102	4560	3290
5·0	127	—	3440
6·0	152	4815	—
8·5	216	—	3920



10 Variation of V_P with R for *Trimonite No. 1* explosive. $\rho = 1{\cdot}1$ g/cm^3.



11 Variation of V_P with R for *Trimonite No. 3* explosive. $\rho = 0{\cdot}98$ g/cm^3.



12 Variable angle of incidence experiment. (a) Set-up for the variable angle of impact; (b) a short time after the initiation of detonation.

For *Trimonite No.* 1 and *No.* 3, the value of V_D varies with thickness of explosive charge and in these cases it was found that the scatter of data was a minimum when V_P was plotted against R, as in Fig. 5, 10, and 11. These values were obtained on small plates and there is some indication for very large plates with a uniform layer of explosive that the value of V_P increases significantly with the distance from the point of initiation of the detonation. Williams *et al.*[32] found it necessary to use a non-uniform thickness of charge to ensure a constant impact velocity, but no experimental data or theoretical analysis of this aspect appear to have been published.

It is also apparent from the analysis that the sonic velocities of the materials being welded are very important. The values given in the International Critical Tables[33] are shown in Table IV.

For satisfactory welds there appear to be three essential requirements. First, it is necessary that a re-entrant jet should be formed and for this to occur the main jet velocity, $V_P/\tan\beta$, must be less than or only slightly greater than the sonic velocity in the flyer plate, so that either there are no shock waves or only detached shock waves. Secondly, a hump is needed in front of the collision point, either to disrupt the oxide film or to assist in the scouring action of the re-entrant jet. This requires that $V_P/\sin\beta$ should be less than the sonic velocity in the parent plate. Thirdly, the impact pressure must be sufficiently great to produce a fluid-like behaviour necessary for the formation of a re-entrant jet, and it is also essential that the re-entrant jet velocity should be sufficiently high to give the desired scouring action. Fourthly, the flyer plate is subject to a bending action and according to Carpenter *et al.*[34] it must be able to withstand a 5% strain. There is also the possibility that a reflected tension wave in either the flyer plate or the parent plate can cause a 'spalling' failure, though this has only rarely been noted. Such a failure is more likely to occur with a high-detonation-velocity explosive, which gives a higher pressure pulse and hence a greater reflected tension pulse, and with materials that contain planes of weakness parallel to the surface. If spalling of the flyer plate occurs in flight, welding of the two pieces of the flyer plate

Table III. Variation of ratio of flyer plate to detonation velocity/ratio of mass of explosive to mass of flyer plate (*R*) for *Metabel*

R	V_P/V_D Experiment	V_P/V_D Equation [8]
0·2	0·062	0·056
0·4	0·104	0·102
0·6	0·143	0·141
0·8	0·180	0·175
1·0	—	0·204
1·2	—	0·23

Table IV. Sonic velocity of metals[33]

Metal	Velocity, m/s
Aluminium	5105
Copper	3560
Gold	2645
Platinum	2500
Silver	2080
Steel	5000
Tin	2490
Zinc	3680

Table V. Metal combinations bonded by explosive cladding [21]

METALS	ZINC	PALLADIUM ALLOY	TD NICKEL	TUNGSTEN	NICHROME	MAGNESIUM	MOLYBDENUM	COLUMBIUM AND Cb ALLOYS	PLATINUM	SILVER AND SILVER ALLOYS	GOLD ALLOYS	TANTALUM	HAYNES STELLITE ALLOY 6B ©	HASTELLOY ALLOY X ©	HASTELLOY ALLOYS B,C,F ©	ZIRCONIUM AND ZIRCALLOYS	TITANIUM AND TI ALLOYS 6Al-4V	NICKEL AND NICKEL ALLOYS ⓑ	BRONZE	CUPRO-NICKEL	BRASS	COPPER	ALUMINIUM AND Al ALLOYS	MARAGING STEEL	HADFIELD STEEL	STAINLESS STEEL, 200 SERIES	STAINLESS STEEL, 300 SERIES	STAINLESS STEEL, FERRITIC	ALLOY STEEL, AISI 4340	ALLOY STEEL, AISI 4130	LOW ALLOY STEEL, ASTM A-387	LOW ALLOY STEEL, ASTM A-302	LOW ALLOY STEEL, ASTM A-204	MEDIUM C STEEL, ASTM A-212	MEDIUM C STEEL, ASTM A-201	MEDIUM C STEEL, ASTM A-285	LOW C STEEL, AISI 1004 to 1020
LOW C STEEL, AISI 1004 to 1020	X					X	X			X		X						X		X	X	X	X			X	X	X									X
MEDIUM C STEEL, ASTM A-285						X	X			X		X	X	X	X	X	X	X	X	X	X	X	X			X	X	X								X	
MEDIUM C STEEL, ASTM A-201						X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X			X	X								X		
MEDIUM C STEEL, ASTM A-212						X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X			X	X							X			
LOW ALLOY STEEL, ASTM A-204														X	X	X	X	X		X	X	X	X			X	X						X				
LOW ALLOY STEEL, ASTM A-302														X	X		X	X		X	X	X	X			X	X					X					
LOW ALLOY STEEL, ASTM A-387														X	X		X	X					X			X	X	X			X						
ALLOY STEEL, AISI 4130																											X			X							
ALLOY STEEL, AISI 4340																											X		X								
STAINLESS STEEL, FERRITIC																	X											X									
STAINLESS STEEL, 300 SERIES				X			X	X					X				X	X			X	X	X	X			X										
STAINLESS STEEL, 200 SERIES																					X		X			X											
HADFIELD STEEL																							X														
MARAGING STEEL																																					
ALUMINIUM AND Al ALLOYS																	X					X	X														
COPPER							X					X					X					X															
BRASS																		X			X																
CUPRO-NICKEL																				X																	
BRONZE																			X																		
NICKEL AND NICKEL ALLOYS ⓑ									X		X			X			X	X																			
TITANIUM AND TI ALLOYS 6Al-4V				X				X									X																				
ZIRCONIUM AND ZIRCALLOYS																X																					
HASTELLOY ALLOYS B,C,F ©															X																						
HASTELLOY ALLOY X ©			X											X																							
HAYNES STELLITE ALLOY 6B ©																																					
TANTALUM												X																									
GOLD ALLOYS																																					
SILVER AND SILVER ALLOYS										X																											
PLATINUM									X																												
COLUMBIUM AND Cb ALLOYS		X					X	X																													
MOLYBDENUM					X		X																														
MAGNESIUM						X																															
NICHROME					X																																
TUNGSTEN				X																																	
TD NICKEL			X																																		
PALLADIUM ALLOY																																					
ZINC	X																																				

NOTES :–

ⓐ A blank space means bonding of that combination has not been attempted. It does not mean those metals cannot be explosion bonded.

ⓑ Includes Inconel,* Monel,* and Incoloy, registered trademarks of International Nickel Company.

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