WASC 1878

See Also - WAI 1128

Rocket Motor Studies for Reduced Vulnerability

MODEL ROCKET MOTOR STUDIES FOR REDUCED VULNERABILITY

D.J. Manners

Royal Armament Research and
Development Establishment
Waltham Abbey, Essex, England

ABSTRACT

The vulnerability of rocket motors to fragment and bullet attack has been a subject of concern in the UK for some time. A detailed study using a standardised "Model scale rocket motor" (MSM) has assessed the significance of propellant composition rheological properties and temperature, case material and construction, and fragment velocity on the response to attack by a 17g mild steel right cylinder.

Propellants assessed were extruded double-base (EDB), cast double-base (CDB) composite modified cast double-base (CMCDB), elastomer modified cast double-base (EMCDB) and composite (HTPB).

The main assessment of response was by visual examination of the MSM after attack but supporting information was obtained by measurement of blast over-pressures and internal pressures, and from video and ciné film records.

The main conclusions were that the most important factors determining the violence of response of the MSM are the frangibility of the propellant quantified by its strain rate adjusted glass transition temperature and its extensibility above that temperature, and the ease with which the case can be vented following propellant ignition.

1. INTRODUCTION

Due to the concern of the Armed Services in the response of rocket motors to attack by bullets and fragments (from fragmenting weapons) many ad hoc trials had taken place in the UK, USA, and elsewhere to examine the response of individual types of motor in individual situations, but no systematic study had been carried out. This paper reports a systematic study subsequently carried out to identify and assess the significance of various factors which affect the response to attack, using a representative mild steel fragment and a standardised model scale rocket motor.

2. EXPERIMENTAL DETAILS

2.1 The Model Scale Rocket Motor (MSM)

This is shown in Figure 1. The propellant charge was contained in, and as nearly as possible filled, a tube of 254 mm length and 127 mm external diameter. Massive steel end caps were held together by four external tie bars each 19 mm thick so that failure occurred by rupture of the tube, the end pieces remaining intact. The more violent events, however, bent or even broke one or more of the tie bars. The MSM was attacked radially halfway along its length and midway between two tie bars by a single cylindrical mild steel representative fragment 13.3 mm dia and 15.7 mm long, weighing 17.1g fired from a smooth-bored 0.5" Browning gun, and presented end-on. The propellant charge was oriented in the tube so that the maximum propellant thickness occurred along the line of attack (see Figure 2). All were fully case-bonded (except EDB, which were cartridge loaded) 6 point star-centred radially burning charges of charge design CD 167 for the HTPB propellant and CD 204 for the rest (see Figure 2) and fitted with a nozzle designed for each propellant to give a burning pressure at 20 °C of 10 ± 1 MPa (if ignited in the normal manner).

The following variables were involved:-

2.1.1. Propellant

One composition represented each of the following types of propellant: extruded double-base (EDB); cast double-base (CDB); composite modified cast double-base (CMCDB); elastomer modified cast double-base (CMCDB). Composite hydroxy-terminated polybutadiene propellant (HTPB) was represented by two compositions.

2.1.2. Types of Motor Case

There were four types of case used in these tests:

(i) 3.2 mm wall mild steel (MS) tube

(ii) 4.7 mm wall light (aluminium) alloy (LA) tube

(iii) 'Kevlar' overwound mild steel (K/MS). This was tube (i) thinned to a wall thickness of 1.7 mm for the whole length except for 25 mm at one end and 30 mm at the other, and wound with 'Kevlar' dry strands to restore original bursting strength.

(iv) 'Kevlar' overwound light alloy (K/LA). This was tube (ii) having similar treatment to tube (iii) but with wall reduced to 2.2 mm.

All cases had a design static bursting pressure of 30 ± 4 MPa.

Case types (i) and (ii) are sometimes referred to as Standard tubes.

2.1.3 Temperature

Trials were carried out at ambient (nominally 15 °C) and a range of temperatures down to -70 °C. The temperatures below ambient were measured with a chromel/alumel thermocouple embedded 30 mm deep in the end of the propellant grain. The temperatures given in the tables are those recorded just before removal of the MSMs from the freezer: tests carried out separately showed that they were within 1° of the value at the impact site, and by the time of firing (approx ½ hour) had risen by no more than 5° for the lowest temperature (-70 °C) and with negligible change at -10 °C or higher. The 'cold' MSMs were insulated with a commercial 2-part rigid polyurethane foam cast in situ, with a moulding sheet wrapped round the end-caps. The cured foam had negligible resistance to the fragment.

2.1.4 Fragment Attack Velocity

The velocity at impact with the target MSM was either 525 ± 25 m/s ('slow') or 925 ± 25 m/s ('fast').

2.2 Instrumentation

The fragment velocity was monitored by two timing screens which consisted of aluminium sprayed on to a card to form a sinuous strip in such a way that the passage of the projectile broke the continuity of the conducting path. Previous calibration related the velocity measured by these cards to the velocity of impact at the target (attack velocity). The cards also provided an indication of the angle of flight of the fragment; the circular disc cut out of each card showed that the fragment hit the target end-on in every attack.

Blast overpressure data were obtained from H3B piezo-electric side-on pressure gauges[1] mounted level with but 10°-15° off-set from the flight path of the fragment front and rear of the target.

Firings were monitored throughout by high speed ciné (at 2000 pictures per second) enabling the speed of reaction to be assessed and sometimes a general estimate of the speed of flying debris. A closed circuit television system was used to observe the firing and record any long term effects (longer than 1 second).

3. TRIALS RESULTS AND DISCUSSION

Since the MSM does not closely resemble any practical type of rocket motor, results from individual trials are of little or no direct value in themselves; it is by comparison that conclusions may be drawn on the effect of variation of individual parameters on the response. The response of the MSM to fragment attack ranged from straightforward burning with "torching" through the orifice made by the fragment on impact (and sometimes another hole made by egress of the fragment) to complete disruption of the motor case. The results have been divided into six categories as follows:-

(1) Burning (B). The propellant combusts without opening the case further than the hole or holes caused directly by the ingress and (if appropriate) egress of the fragment (Figure 3).

(2) Mild Pressure Burst (MPB). The case opens up from the hole of ingress or egress of the fragment. The resulting orifice will be generally rhombic in shape, and the movement of the metal will not carry it beyond the two tie-bars nearest the point of opening (Figure 4).

(3) Pressure Burst (PB). The case opens more widely than in category 2, and the movement of the metal will carry it beyond the two tie-bars nearest the point of opening. The dislocation may result in some of the metal being pulled out from within the end caps. Some further cracking of the case may occur, but no fragmentation (Figure 5).

(4) Pressure Burst Plus (PB+). The opening of the case, as in categories 2 and 3, is sufficiently vigorous for the moving metal to strike one or two tie-bars violently enough for one or more small pieces of the casing to be split off by the impact (Figure 6). This needs to be carefully distinguised from category 5.

(5) Mild Explosion (ME). Fragmentation of the case occurs (without intervention of the tie-bars), but a substantial part of it remains in situ (Figure 7).

(6) Explosion (E). Fragmentation of the case occurs to a greater degree than in category 5, and no substantial part of it remains in situ (Figure 8).

In categories 3 to 6 one or more tie-bars were sometimes broken. In most cases propellant (unburnt and/or burning) was ejected in events more violent than category 1. The most violent explosion observed involved the rupture of three tie-bars, and there has been no evidence of detonation. The categorisation of the responses was by visual assessment of the remains of the motor; blast overpressures were used only in a supportive role.

The programme was carried out in two stages.

3.1 Stage 1

This consisted of a series of preliminary trials carried out at ambient with a range of three different propellants (EDB, CMCDB and HTPB), two case materials (MS and LA - see section 2.1.2), and two attack velocities (see section 2.1.4), to identify what sorts of reactions would occur. A summary of these results given in Table 1.

TABLE 1. STAGE 1 RESPONSES

Light Alloy						Mild Steel					
HTPB		CMCDB		EDB		HTPB		CMCDB		EDB	
Slow	Fast	Slow	Fast	Slow	Fast	Slow	Fast	Slow	Fast	Slow	Fast
MPB PB	PB+ PB+	PB+ PB+	ME ME	ME ME	ME -	B B	PB+ PB+	B B	ME ME	PB+ PB+	E MPB

It can be seen that the responses were more violent with the 'fast' fragment. The only exception to this was one of the 'fast' attacks of the EDB propellant in mild steel tubing, where the fully traversing fragment apparently caused sufficient venting at the rear of the tube to prevent the 'Explosion' response of the replicate test where the fragment was non-traversing.

In general there was no difference between the tube materials for 'fast' attacks. Only at the 'slow' speed did the mild steel tube give consistently lower responses. This may have been due to the fragment being slowed down more by the mild steel than the light alloy, leaving very little energy left for damaging the charge, whereas at the 'fast' speed there was always enough energy left for severe charge break-up in both cases.

Comparing the different propellants the EDB (hard and frangible) produced the most violent responses in general, with the CMCDB (less hard and less frangible) producing marginally less violent responses, and the HTPB propellant (rubbery)producing the mildest responses. The unburnt propellant collected up after the EDB firings consisted of numerous splinters and jagged lumps ranging from a few millimetres to a few centimetres across whereas the pieces collected after the CMCDB and HTPB firings were larger, more rounded and less numerous.

3.2 Stage 2

The propellant break-up and the possible advantage of quick venting observed in the first stage led to further trials to include additional propellants, modified cases, and lower temperatures than ambient.

The results of these trials are given in Table 2 (Double-base propellants) and Table 3 (Composite propellants) on page 29-9. Each propellant is identified by its calorimetric value in kilojoules per kilogramme, rate of burning (R_b) at

10 MPa pressure and 20 °C, and its true strain at maximum load, e_m* (at a true strain rate, R*, of 1 minute^{-1}) for each test temperature. Note that strains for CMCDB at -6 and -11 °C, are probably 15%-20% higher than the true figures as this propellant was tested before the use of a photographic method to measure elongations. The propellant temperature and the strain at maximum load have been plotted against the violence of response (on a vertical scale which is purely arbitary) for each propellant (Figures 9, 10, 12-15).

The blast output was measured at 1 metre in front of and behind the target (attacked MSM) and the maximum blast output given in the tables is the greater of these two.

3.2.1 Effects of Propellant Characteristics and Temperature

An initial trial with the composite propellant used in Stage 1 (designated HTPB/1) indicated an increase in violence due to lowering of the propellant temperature. Further trials were then carried out with this propellant (plotted in Figure 9) and three types of double-base propellant (plotted in Figure 10), which showed the significant increase in violence of response which occurred when the propellant temperature was below a certain value, which can be related to the glass transition temperature. One result of a test at room temperature on the hard EDB propellant was plotted on Figure 10 for reference.

The glass transition temperatures (Tg) of these four types of propellant have been measured on a Rheometrics Mechanical Spectrometer[2] by Stenson[3,4] and are given as -50 °C, -58 °C, -60 °C and -83 °C, for CDB, CMCDB, EMCDB and HTPB propellants, respectively, at unit strain rate (min^{-1}). However, his results show that Tg is strain rate dependent and high extrapolation shifts these values to -20 °C, -28 °C, -36 °C and -56 °C, respectively (indicated on the graphs by the broad arrows) at the strain rate occurring during fragment attack (of the order of 10^6 min^{-1}). Frangibility of the propellant is considered to be an important factor and at the Tg a propellant becomes brittle resulting in increased violence of response.

For EMCDB and HTPB/1 propellant the change in response occurred about the shifted Tg but for the others the change occurred at temperatures higher than the shifted Tg. This was thought to be because HTPB and, to a lesser extent, EMCDB were more extensible than CDB and CMCDB in the temperature range approaching the respective Tg values, as shown in Figure 11. Following this a more flexible HTPB propellant was tested and the results (Figure 12) showed a more or less steady increasing violence with a lowering of temperature. As the elongation of this HTPB propellant (HTPB/2) was over 50% greater than that of HTPB/1 at room temperature and the response at that temperature was only MPB, a link with elongation at maximum load (e_m*) was suggested.

Plots of violence of response against strain at maximum load seem to confirm this relationship but the results can still be split into two groups: Figure 13, for the composite propellants, shows a minimum response of mild pressure burst (MPB) at 38% strain whereas Figure 14 for the double-base propellants shows that a minimum response of 'Burning' (B) was attained at a strain around 15% and above, except for the CMCDB propellant (denoted by CM on the graph) which seems to be more in line with the HTPB strain results.

The difference between the plots in Figures 13 and 14 is paralleled, in general, by a difference in propellant energy. The double-base propellants except the composite modified one, have a calorimetric value of around 4500 kilo-joules per kilogramme whereas the composite propellants, including the composite modified double-base propellant, range from 6400 to 7500 kJ/kg. However, this is not a complete explanation as it also appears that burning rate may have some effect particularly with the high energy propellants: the highest response for a given strain is obtained with CMCDB propellant which is among the highest in energy and burning rate.

Another factor which may affect the violence of response is the propensity of particulate filled propellants to de-wet when maximum elongation is reached causing separation of binder and filler and vastly increasing the surface area. At the high strain rates experienced in an attack 'shock' de-wetting may occur, ie almost instantaneous partial separation of filler and matrix, which may account for the generally more violent responses of HTPB and composite-modified propellants. The existence of this phenomenon, and the energy factor, could be checked by trials on a higher energy unfilled propellant or, preferably, a lower energy (around 4500 kJ/kg) HTPB propellant.

3.2.2 <u>Effect of Type of Motor Case</u>

A final factor considered in these trials was the effect of the type of case. As previously explained, most of these trials were carried out using the standard tube (MS and LA) but some trials have been carried out using Kevlar overwrapped tubes (MS and LA) with HTPB/1 propellant and EDB propellant (1 trial). Figure 15 shows the dramatic reduction in violence of response for HTPB/1 propellant when used in Kevlar overwound tubes, both MS and LA, for temperatures down to below -50 °C. These cases were weakened by the cutting of the Kevlar by the fragment and the remaining thin metal wall then eroded quickly enough to confine the response to 'burning'. The graph also shows much more clearly the abrupt increase in violence of response which occurred at or near the shifted glass transition temperature, as already discussed in the previous section. Note that although the violence seems to be reduced above this temperature there is no mitigation below it; the violence of response from both standard and overwound tubes being the same.

The one trial with EDB, carried out at room temperature, showed the Kevlar overwrapping reduced the violence of response only one category but further work could be carried out over a range of temperatures to see if that reduction can be maintained down to low temperatures.

4. GENERAL CONCLUSIONS

(1) To minimise the violence of response to fragment attack the propellant must be extensible and maintain that extensibility down to low temperatures.

(2) The strain rate adjusted glass transition temperature of the propellant is the lowest temperature at which minimum violence of response occurs and for some propellants, which have poor low temperature strain capabilities, this temperature is much higher than the strain rate adjusted glass transition temperature.

(3) The energy of the propellant seems to influence the amount of extensibility required for a given response in a Model Scale Motor: the more energetic the propellant the higher the required elongation. However this effect may be due to 'shock' de-wetting, ie rapid separation of filler and binder, in the composite and composite modified propellants. Further work with high energy unfilled propellants is required for conclusive evidence.

(4) Use of a case designed to give rapid venting to an attacked charge will greatly reduce the violence of response.

REFERENCES

1. Baker W E — Explosions in Air, Fig 7.5, page 169. University of Texas Press, Austin and London ISBN 0-292-7200-3.

2. Macosko C W, Weissert F C, — Application of Rheometrics Mechanical Spectrometer to Rubber testing, Rubber and Related Products: New Methods for Testing and Analysing ASTM STP 553, 1974 pp 127-141.

3. Stenson R — The Rheometrics Mechanical Spectrometer: Characterisation of HTPB Gun stocks by Viscometry and Eccentric Rotating Disc Rheometry. MOD ERDE TR No 229, Waltham Abbey, Essex (Not necessary available to members of public or to commercial organisations).

4. Stenson R — An Appraisal of Dynamic Testing of Solid Propellant. Part 1: Double-Base Systems. MOD unpublished report.

STAGE 2 RESULTS

TABLE 2 DOUBLE-BASE PROPELLANT

Case	Propellant temp, °C	Response Category	Strain at max load,%	Blast at 1 m kPa
CDB: Cal Val 4495 kJ/kg; R_b 20.5 mm/s				
MS	A	B	35	-
MS	-6	PB+	11	150
MS	-11	E	5½	160
LA	-6	MPB	11	60
LA	-10	PB+	6	210
LA	-22	PB+	3	55
LA	-34	E	1	110
EDB: Cal Val 4520 kJ/kg; R_b 21.0 mm/s				
MS	A	E	3	390
K/MS	A	ME	3	115
EMCDB: Cal Val 4640 kJ/kg; R_b 16.0 mm/s				
MS	A	B	120	
MS	-33	B	28	
MS	-37	B	20	
MS	-41	E	10	160
LA	-22	B	50	
LA	-34	B	26	
LA	-43	ME	8	140
LA	-48	ME	2	55
CMCDB: Cal Val 7460 kJ/kg; R_b 24.0 mm/s				
MS	A	PB+	38	80
MS	-11	E	21	130
MS	-6	ME	25	120

TABLE 3 COMPOSITE PROPELLANTS

Case	Propellant temp, °C	Response Category	Strain at max load,%	Blast at 1 m kPa
HTPB/1: Cal Val 7070 kJ/kg; R_b at 10 MPa, 24.0 mm/s				
MS	A	PB+	23	150
MS	A	PB+	23	125
MS	-34	PB+	19	130
MS	-53	ME	15	160
LA	A	PB+	23	110
LA	A	PB+	23	85
LA	-34	PB+	19	115
LA	-51	PB+	16	85
LA	-62	ME	14	70
LA	-70	ME	12	110
K/LA	A	B	23	3
K/LA	-35	B	19	20
K/LA	-50	B	16	20
K/LA	-70	ME	12	56
K/MS	A	B	23	16
K/MS	-52	B	16	24
K/MS	-71	ME	12	140
HTPB/2: Cal Val 6400 kJ/kg; R_b at 10 MPa, 16.9 mm/s				
LA	A	MPB	38	60
LA	-31	PB+	27	160
LA	-42	PB+	23	120
LA	-60	ME	16	120

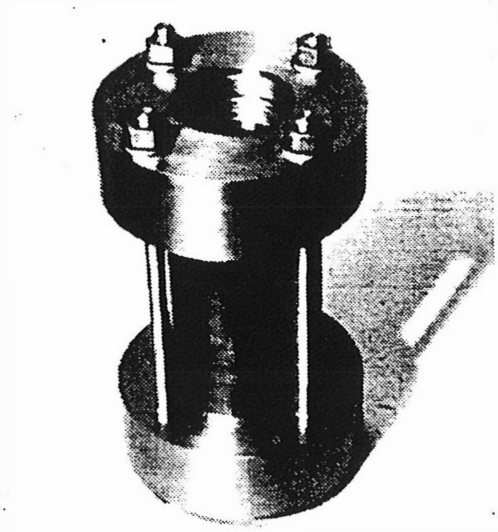


FIG 1. MSM (without nozzle)

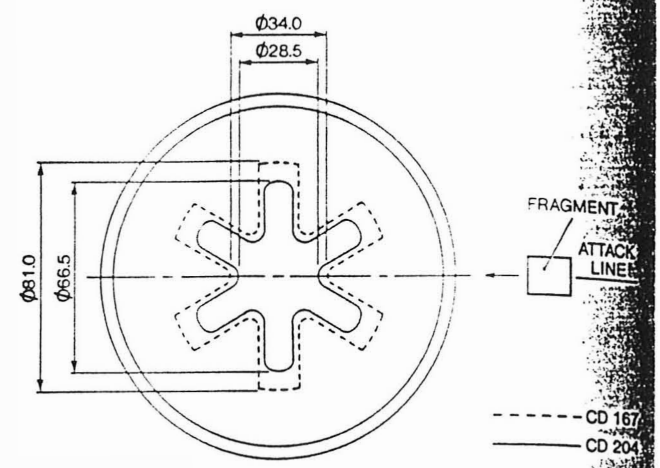


FIG. 2 CHARGE END VIEW AND LINE OF ATTACK

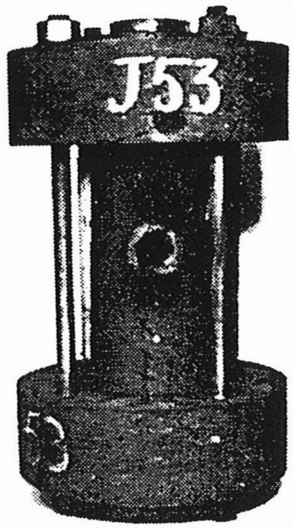


FIG 3. BURNING (B)

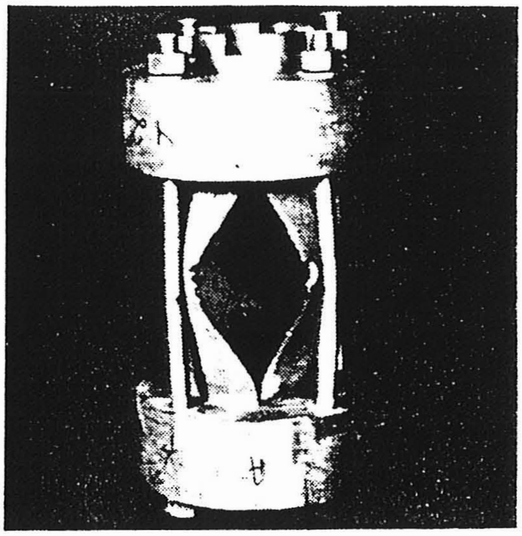


FIG 4. MILD PRESSURE BURST (MPB)

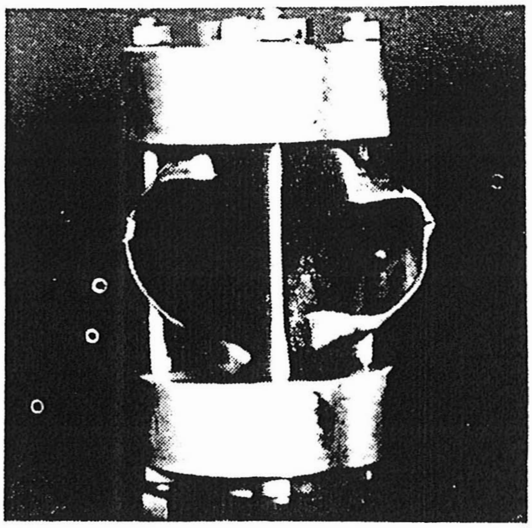


FIG 5. PRESSURE BURST (PB)

FIG 6. PRESSURE BURST PLUS (PB+)

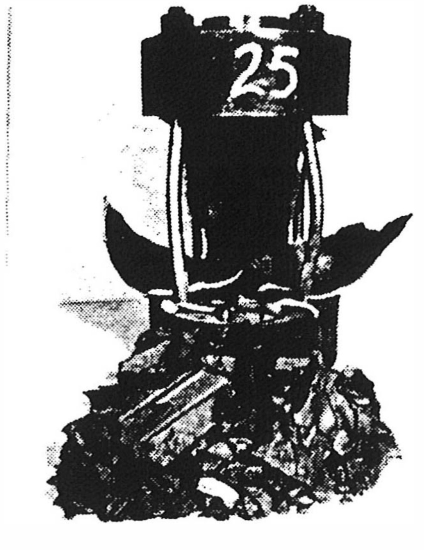


FIG 7. MILD EXPLOSION (ME)

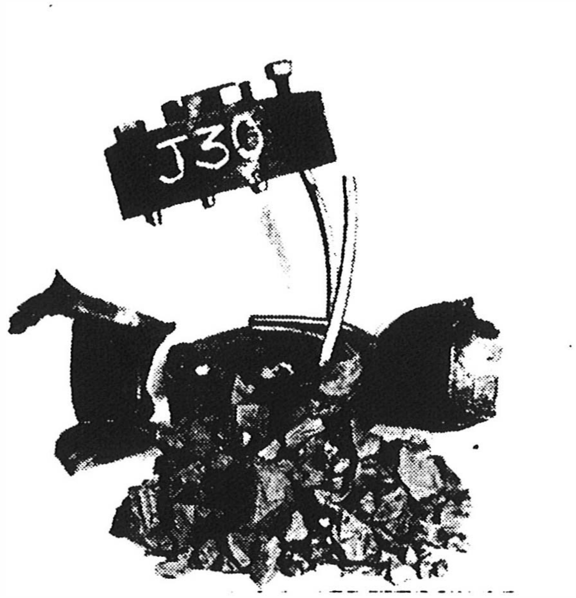


FIG 8. EXPLOSION (E)

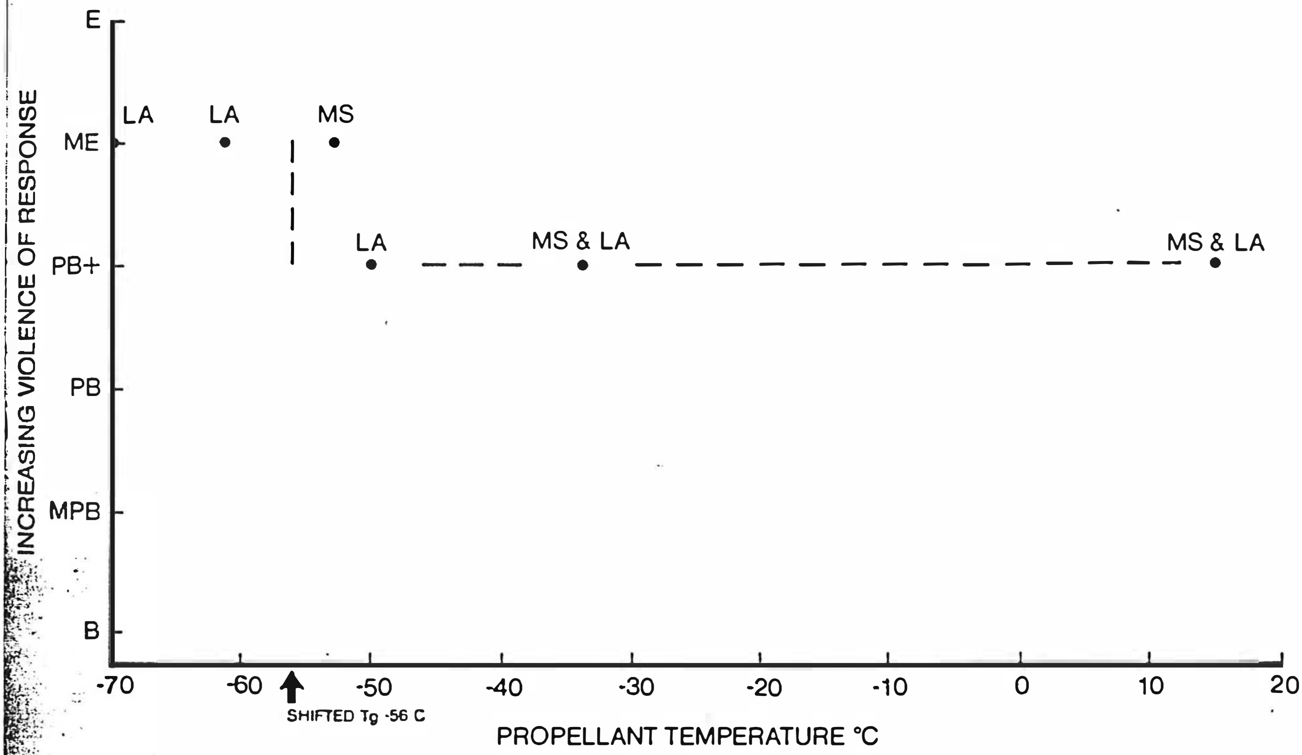


FIG. 9 EFFECT OF TEMPERATURE ON RESPONSE TO FRAGMENT ATTACK AT 925 ± 25 m/s ON HTPB/1 PROPELLANT IN STANDARD TUBES

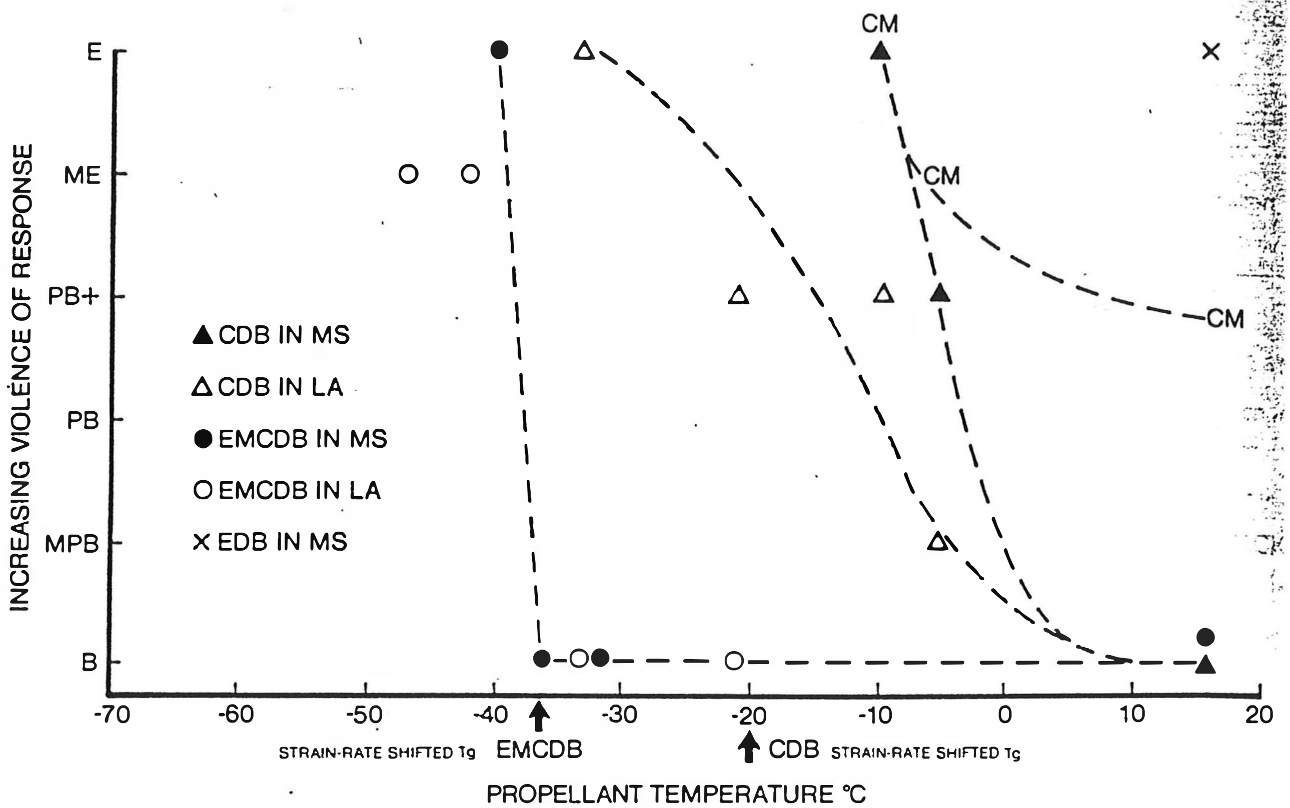


FIG. 10 EFFECT OF TEMPERATURE ON RESPONSE TO FRAGMENT ATTACK AT 925 ± 25 m/s ON DOUBLE-BASE PROPELLANTS IN STANDARD TUBES

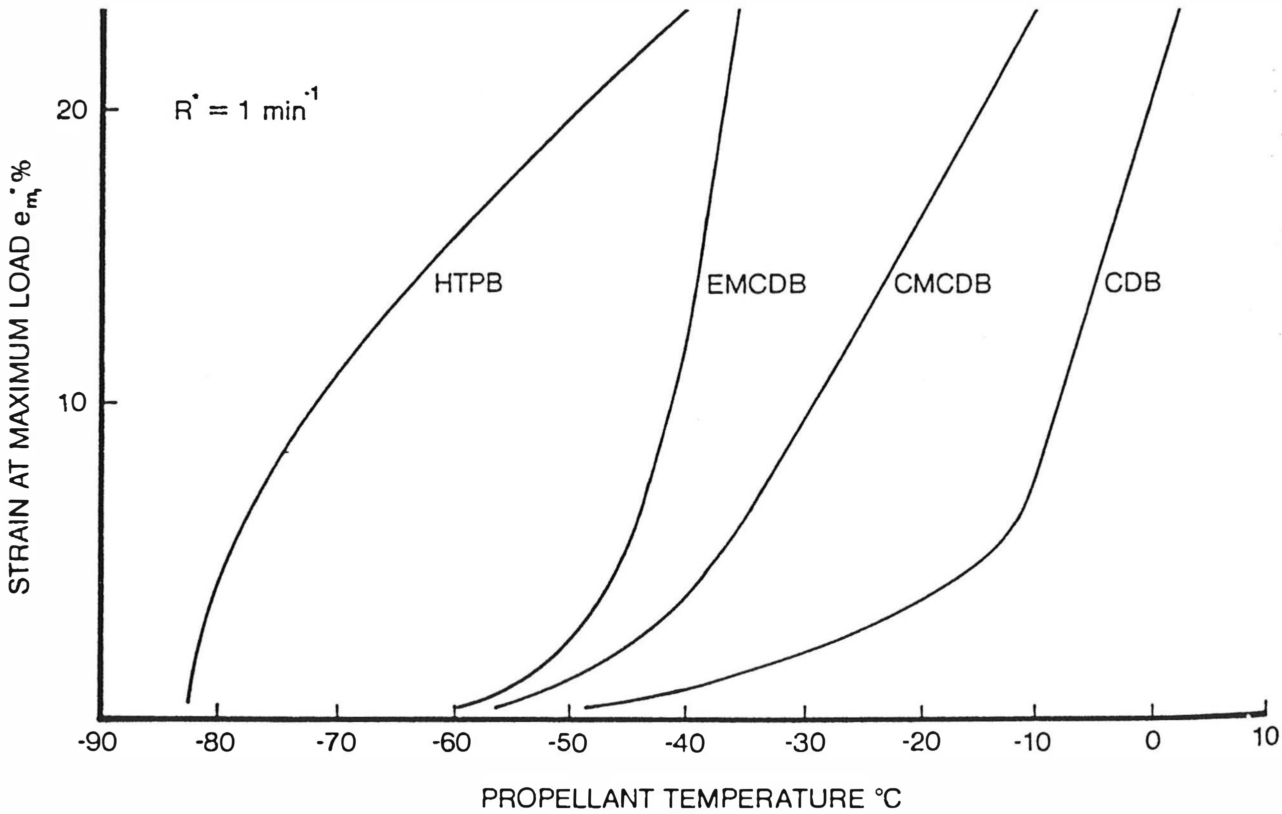


FIG. 11 EFFECT OF TEMPERATURE ON STRAIN CAPABILITY ABOVE THE Tg

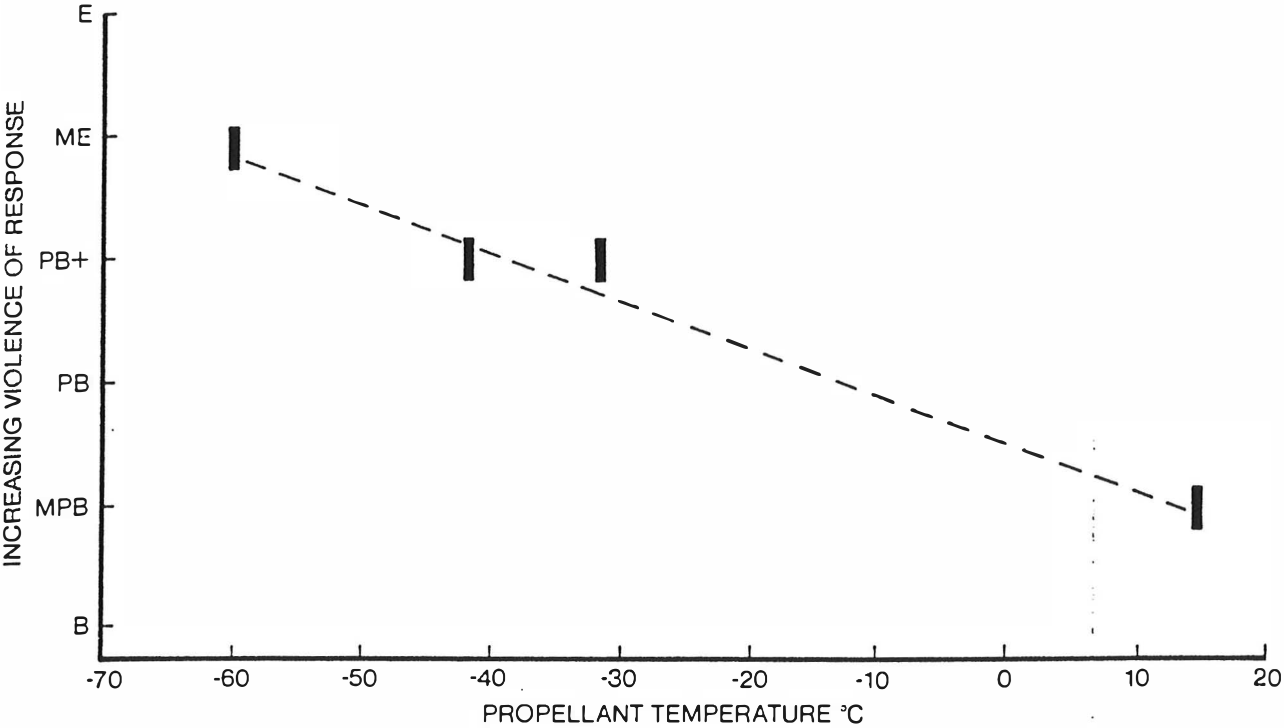


FIG. 12 EFFECT OF TEMPERATURE ON RESPONSE TO ATTACK BY 17g MS FRAGMENT AT 925 ± 25 m/s ON HTPB/2 PROPELLANT

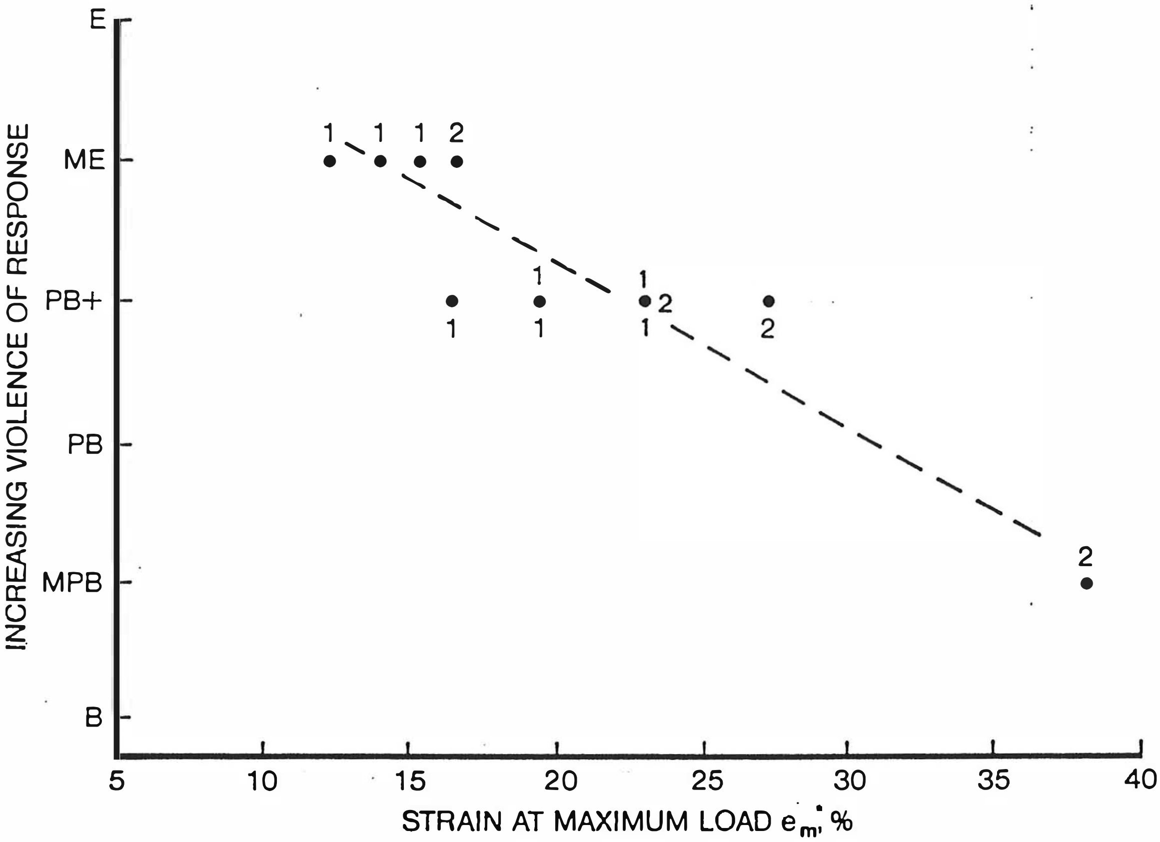


FIG. 13 EFFECT OF HTPB/1 AND HTPB/2 PROPELLANT STRAIN CAPABILITY ON THE RESPONSE TO FRAGMENT ATTACK AT 925 ± 25 m/s IN STANDARD TUBES

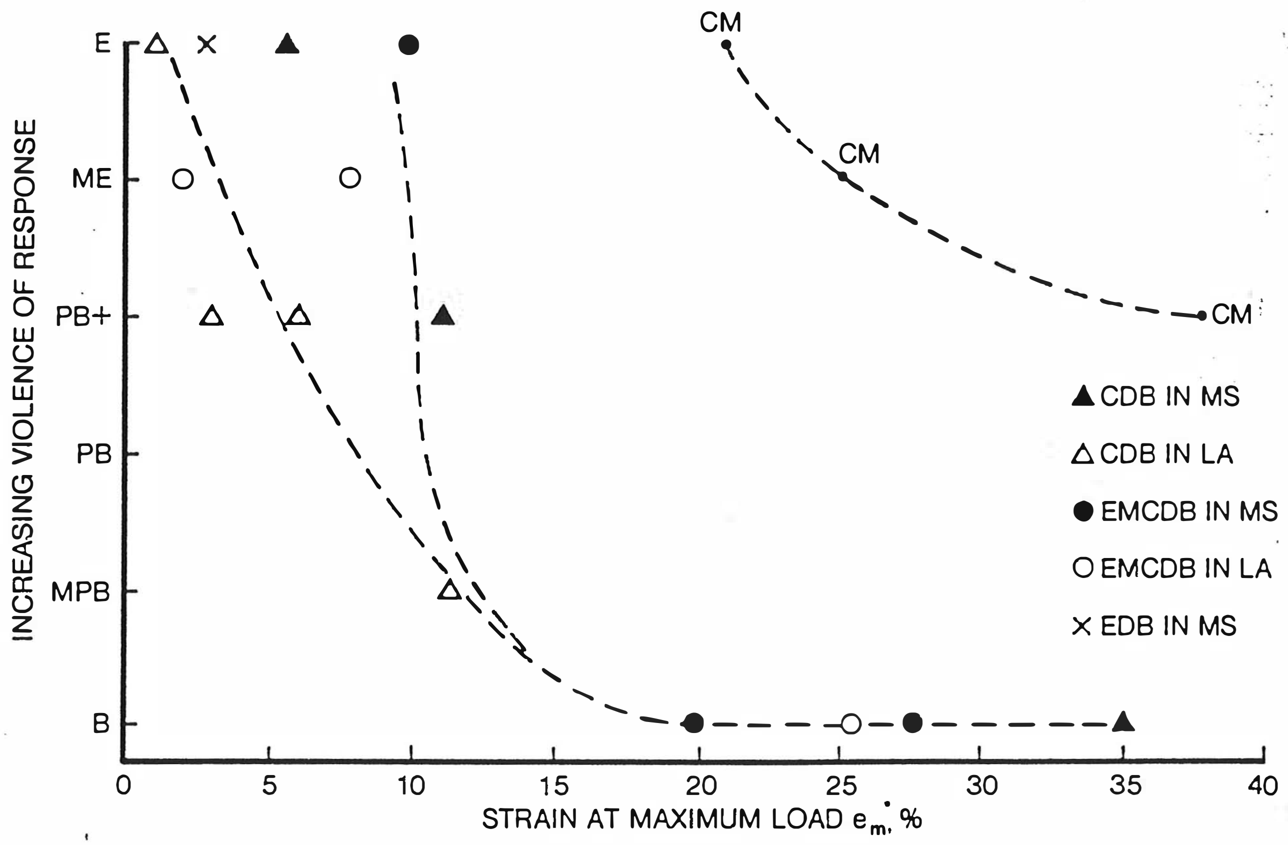


FIG. 14 EFFECT OF DOUBLE-BASE PROPELLANT STRAIN CAPABILITY ON THE RESPONSE TO FRAGMENT ATTACK AT 925 ± 25 m/s IN STANDARD TUBES

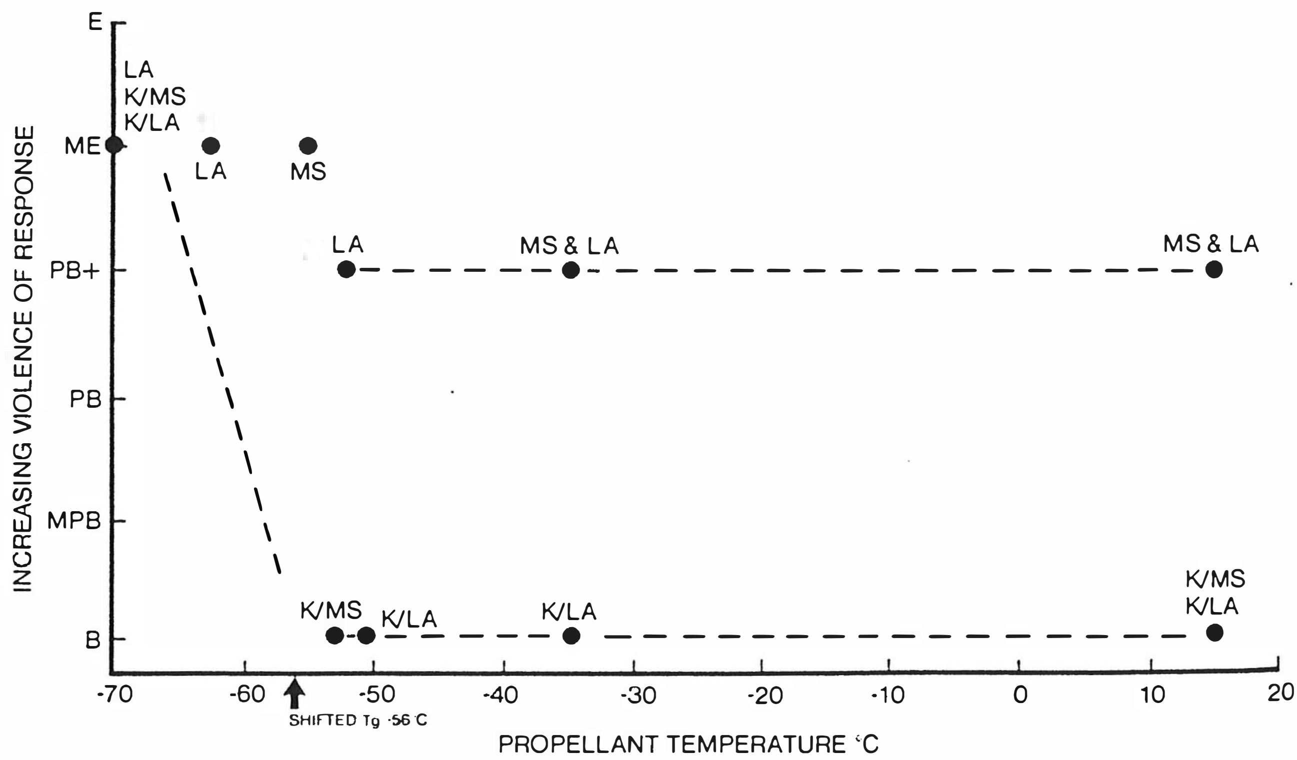
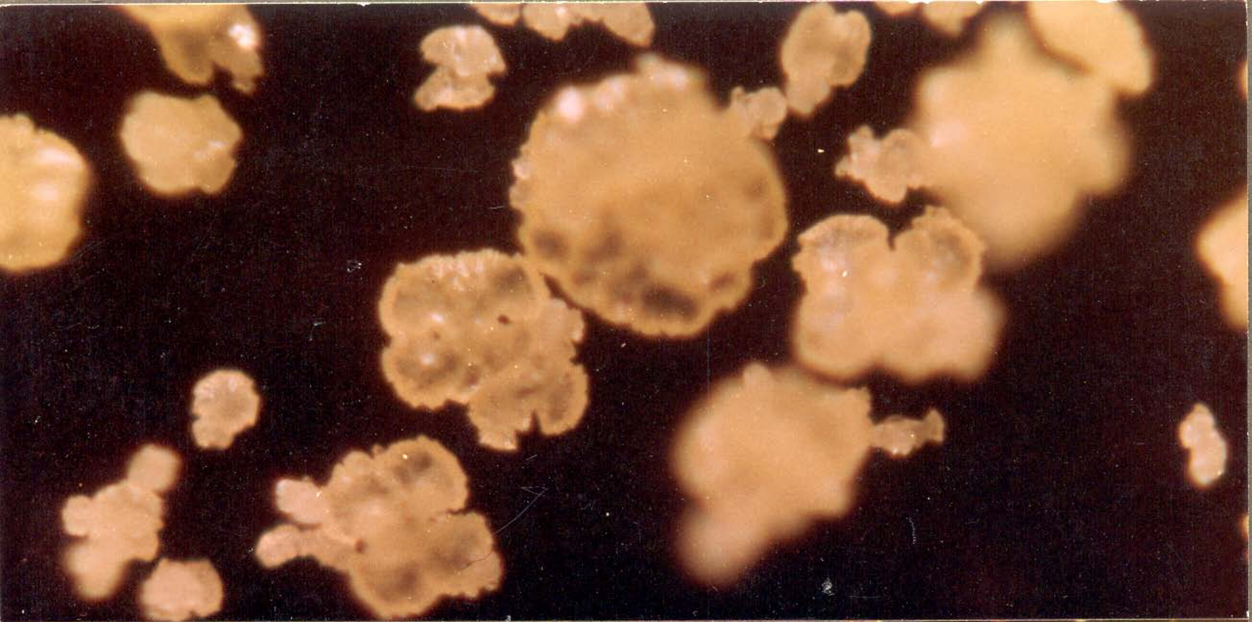
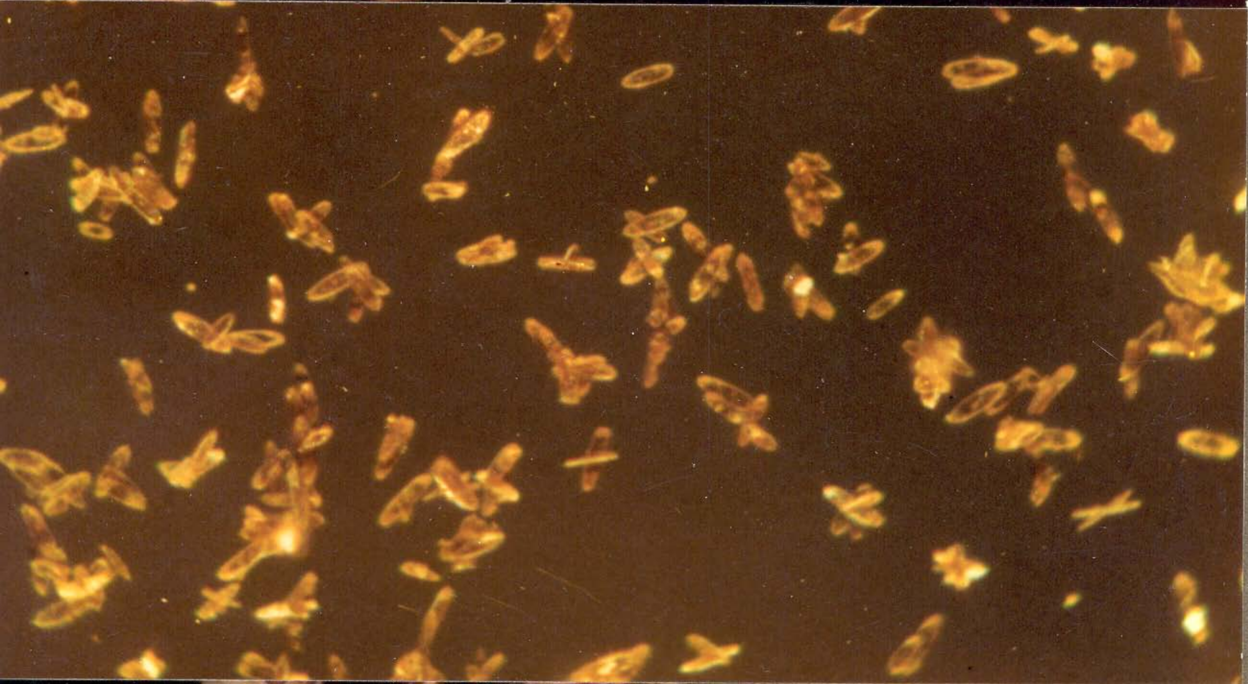


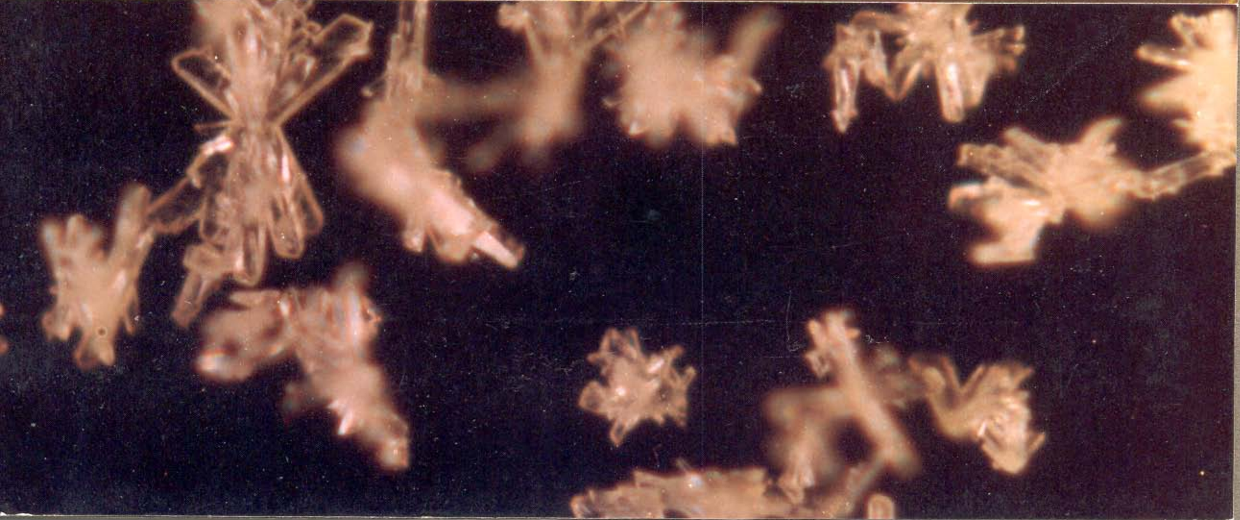
FIG. 15 EFFECT OF DIFFERENT CASE MATERIALS ON RESPONSE TO FRAGMENT ATTACK AT 925 ± 25 m/s ON HTPB/1 PROPELLANT


J75


10
cm

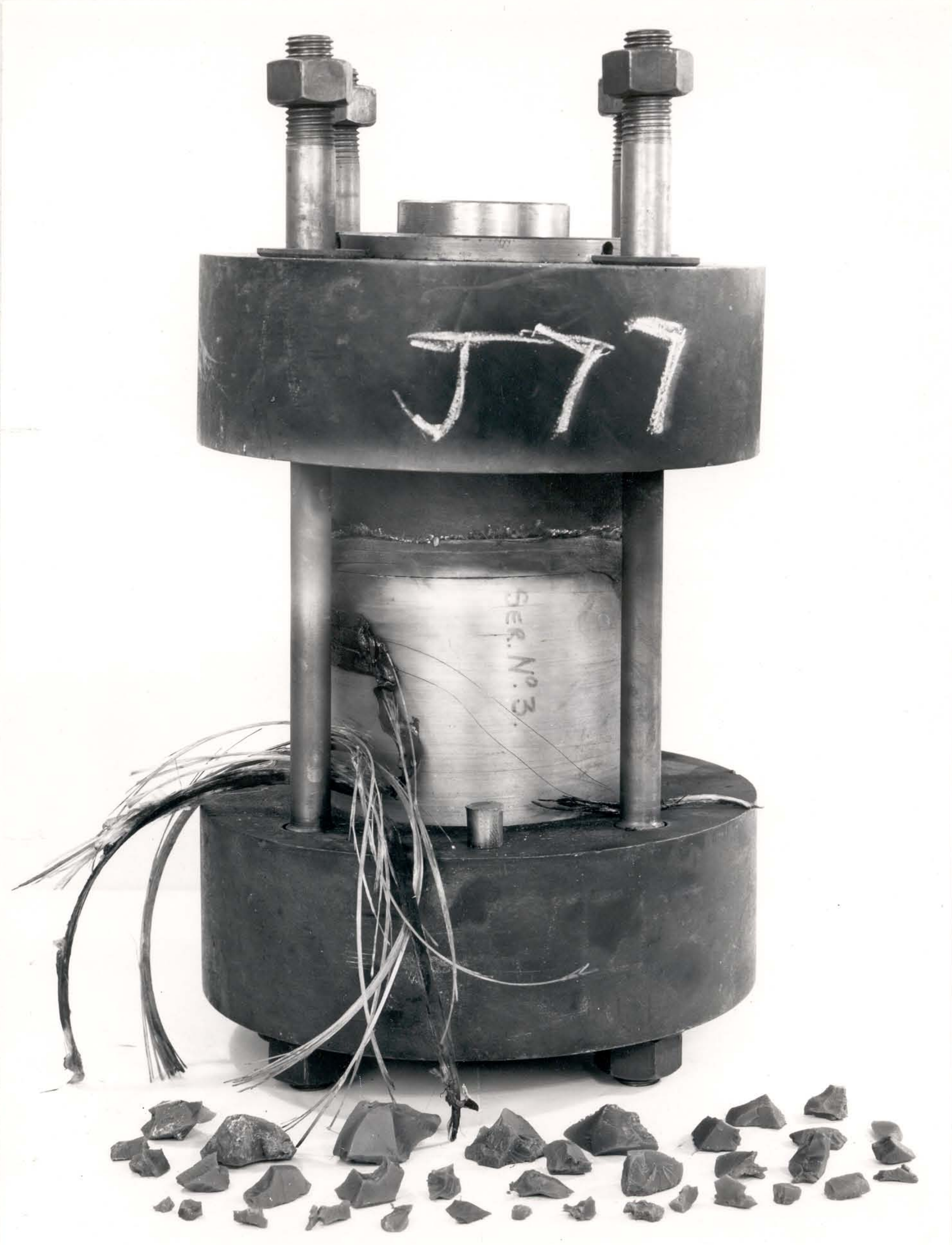


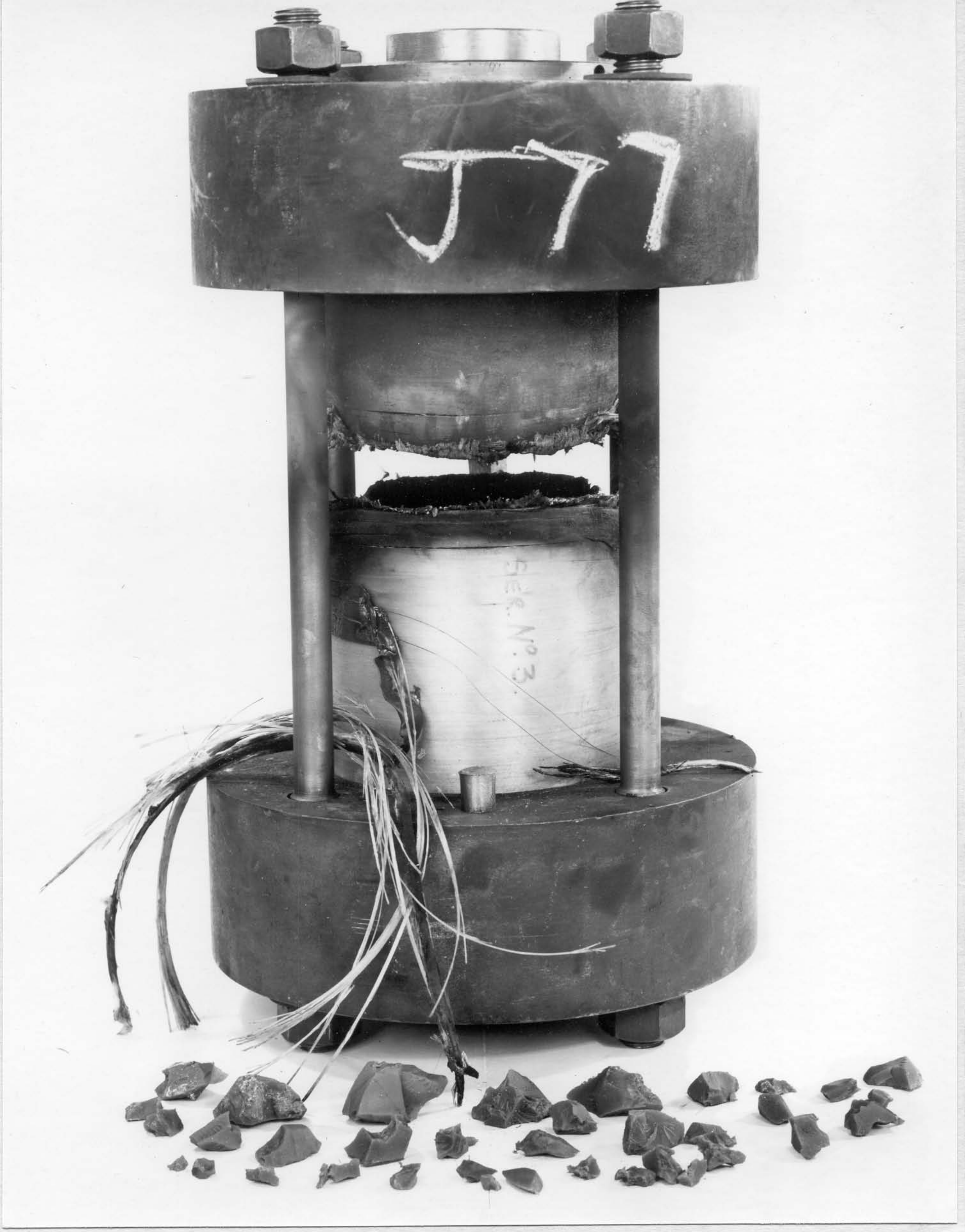





J80


J80


J77
SER. Nº 3.


J77

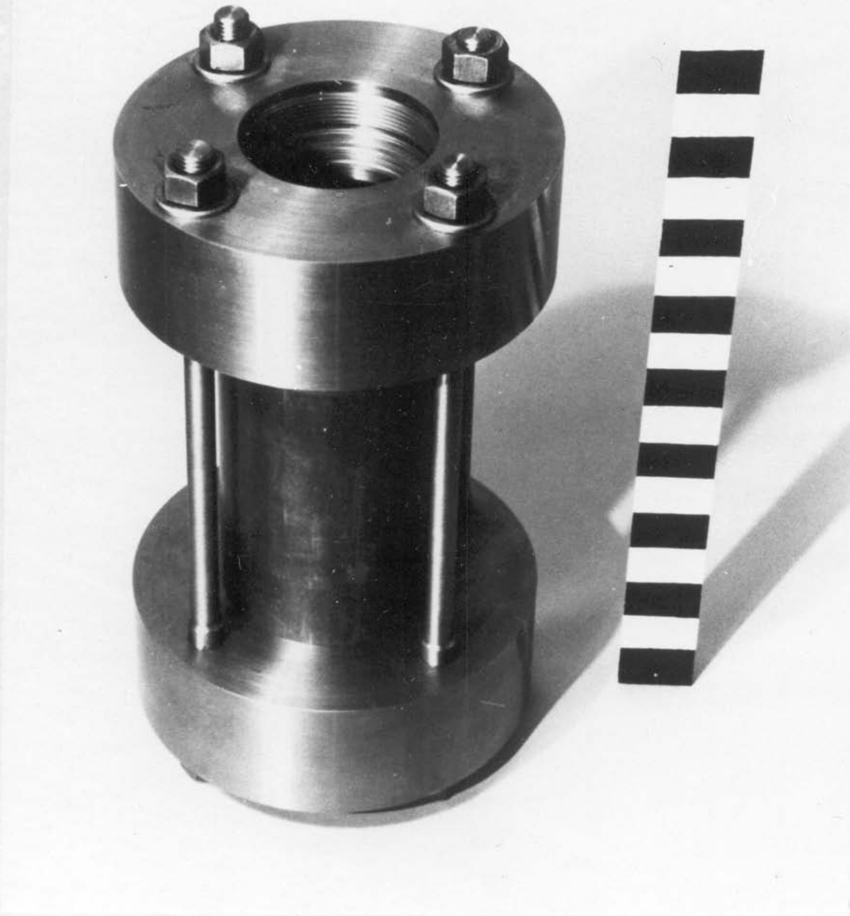


FIG. 1 STEEL VESSEL BEFORE CLOSURE
(SCALE IN INCHES)

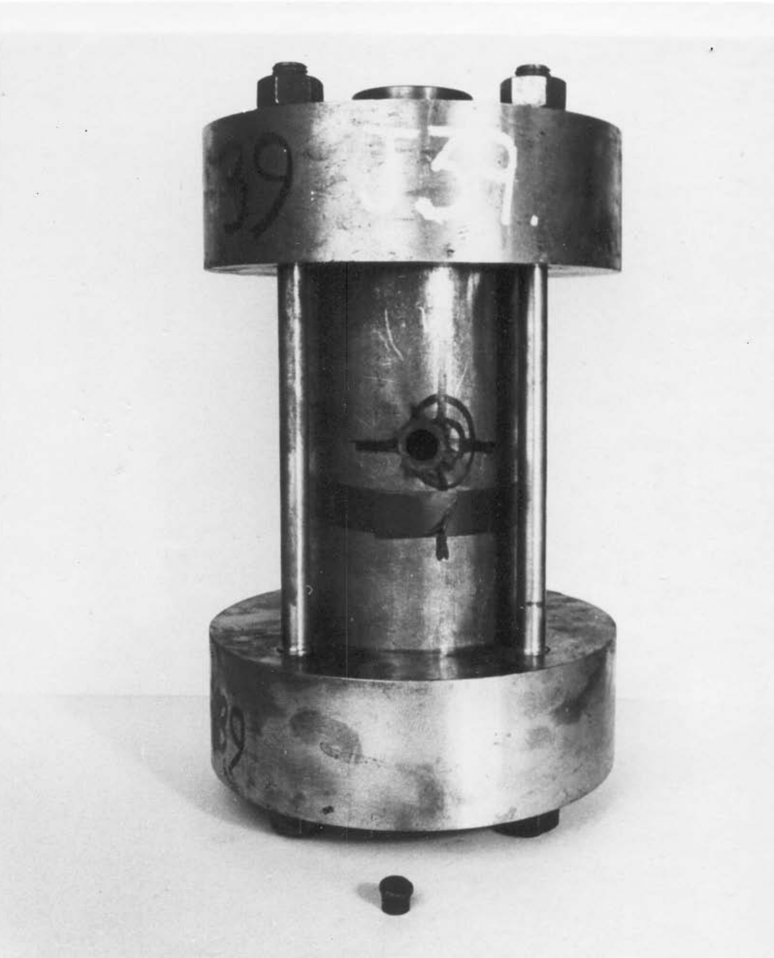


FIG.2 BURNING (EXPT. № 517)

FIG.5 MILD EXPLOSION (EXPT. № 507)

FIG. 6 EXPLOSION (EXPT. Nº 502)

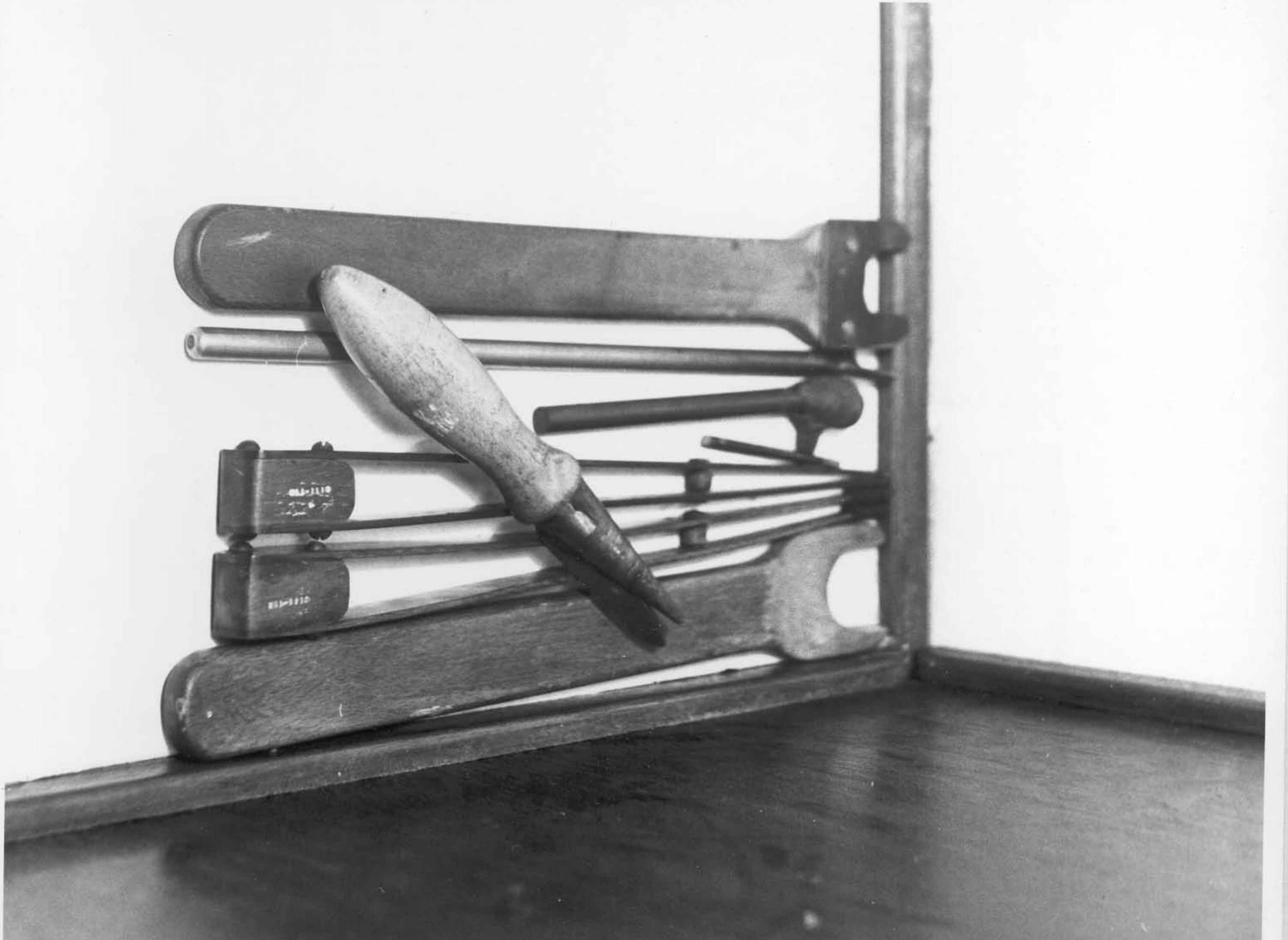

J76.

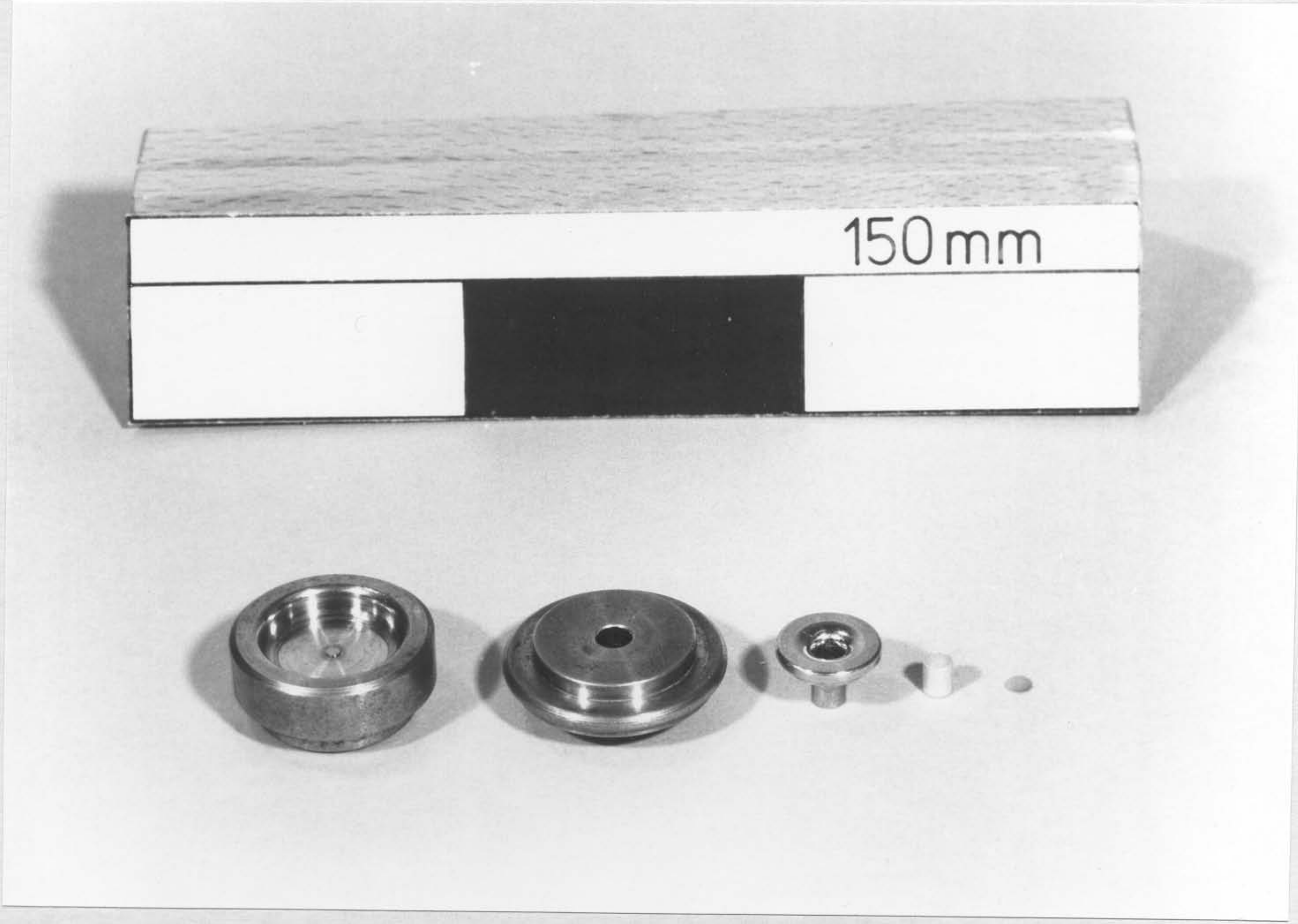

J76.


J78


150 mm


150 mm




150mm


RD
2428
1700ft/sec


HTPB
1750


23


24