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WEAPONS RESEARCH DIVISION

Closed Vessel examination of two samples of American cool Propellant

H. A. Flint

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Summary

In connection with U.S. - U.K. collaboration in the gun wear problem, two samples of a cool propellant, supplied by the U.S. authorities, have been examined by the Closed Vessel method for comparison with the British equivalent. The composition was similar to the British F.527/155 formulation consisting mainly of nitrocellulose, nitroglycerine, picrite and dibutylphthalate, with a nominal flame temperature of 1950°K. One sample was in cord form, and the other was multitube. For the purpose of the comparison, results were already available for cord, multitube (M.T.) and slotted tube (S.T.), F.527/155 manufactured by C.S./E.R.D.E. from the same mix of ingredients.

The rate of burning constant for the American cord sample was found to be about 5 % greater than that of the British. This is considered to be a reasonably good match.

No evidence of erosive burning of the American M.T. sample was apparent, and the geometrical form function was therefore used in deducing rates of burning from the Closed Vessel experimental results. On this basis, the American M.T. was some 13 % slower-burning than the American cord.

In the case of the British M.T., there was some evidence of erosive burning; consequently, as is usual in such cases, constant burning surface, associated with an appropriate increase in web thickness, was assumed in the rate of burning calculations. On this basis, the rate of burning constants for the British cord and multitube were in very close agreement: the spread between the cord, M.T. and S.T. was, in fact, little more than 1 %. Bearing in mind the different assumptions made, the British M.T. was about 9 % faster-burning than the American M.T.

When fired at a loading density of 0.2 grams per c.c., the maximum pressure produced by the American M.T. sample is about 13 % less in the American vessel than in the considerably larger British vessel. Of this, little more than 3 % is attributable to difference in heat lost by conduction to the vessel walls, and the remainder is thought to be due either to a greater energy loss through expansion of the vessel or compression of the obturation in the American design, or to an inaccurate assessment of vessel volume.

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A.R.E. Reference - File W.R. 111/2.

Closed Vessel examination of two samples - Ex.6638 and Ex.6641 - of an American cool propellant, and a comparison with the equivalent British composition.

(1) Introduction

In connection with the development of cool propellants for prolonging gun life, the U.S. and U.K. have recently exchanged samples of the F.527/155 formulation for gun trials, this composition showing some promise of being suitable for ultimate Service use. The U.K. have sent the U.S. 750 lb. samples of each of three sizes of multitube and one size of slotted tube for trial in the 3-inch/70 gun; and approximately the same quantity of each of three sizes of multitube for trial in the 17 pr. gun, together with a small sample of 0.1-inch diameter cord for Closed Vessel test, have been received in this country.

In addition to the special sample of cord, (lot Ex.6641), a sample of the smallest size of multitube supplied by the U.S. (lot Ex.6638), was received for Closed Vessel examination.

Closed Vessel results for composition F.527/155 in both multitube and slotted tube form have already been reported (ref.1). In addition, samples of this composition in all four of the common Service shapes, (i.e. cord, tube, slotted tube and multitube), pressed from the same mix of ingredients, have recently been the subject of another investigation, not yet reported. Thus, it is possible to make a comparison between American and British F.527/155.

During the visit of the U.S./Canadian Mission to this country in the autumn of 1949, the U.S. Bureau of Ordnance representative referred to a discrepancy of some 20% between the force constant for F.527/155 as calculated from thermochemistry and the figure deduced from the results of closed bomb tests in the U.S. This matter was given particular attention in the present experiments.

(2) Propellant data.

(a) Nominal compositions:-

	American %	British F.527/155 %
Nitrocellulose	20.0(13.15% N_2)	20(13.2% N_2)
Nitroglycerine	8.28	8.86
Picrite	60.0	60.0
Dibutylphthalate	9.72	8.50
Centralite	2.0	2.64
Calculated flame temperature (T_0)	1889 °K	1950 °K
Calculated force constant (λ_0), tons per sq.in./gm.per c.c.	51.59	
Co-volume (η) c.cs. per gm.	1.068	
Ratio of specific heats (γ)	1.31	

(b) American lot no. Ex.6638: shape, multitube.

Analysis:-	%
Nitrocellulose (13.15% N)	20.17
Nitroglycerine	9.35
Picrite (British, 20,000 cm^2/c.c.)	59.05
Dibutylphthlatate	9.50
Centralite	1.93
Total volatiles	0.0
Ash	0.11
Density	1.65 grams per c.c.
T_0 (calculated from analysis)	1941 °K
λ_0 (" " ")	52.66 tons per sq.in./gm.per c.c.
η	1.068

Dimensions:-	inches
External diameter	0.1318
Diameter of perforations	0.0129
Inner web	0.0223
Outer web	0.0242
Average web	0.0233
Length	0.3337

(c) American lot no. Ex.6641; shape, cord

Analysis:-	%
Nitrocellulose (13.15% N_2)	20.21
Nitroglycerine	9.11
Picrite (British, 20,000 cm^2/c.c.)	59.54
Dibutylphthlatate	9.21
Centralite	1.93
Total volatiles	0.34
Ash	0.06
Density	1.66 grams per c.c.
T_0 (calculated from analysis)	1957 °K
λ_0 (" " ")	52.98 tons per sq.in./gm.per c.c.
η	1.068

Dimensions:-	inches
Diameter	0.1002
Length	6.45

(d) British F.527/155, lots E.R.D.E.2811A(cord), 2811C(multitube) and 2811 I(slotted tube).

All three samples processed from the same single incorporation of fresh ingredients.

Nominal composition, T_0 , λ_0 and η assumed, i.e. $T_0 = 1950\ ^{\circ}K$

$\lambda_0 = 52.9$

$\eta = 1.06$

Picrite used - normal Naval grade.
Density - 1.609 grams per c.c.

Dimensions:-

Lot E.R.D.E. 2811 A cord -	0.052 ins. diameter.		
Lot E.R.D.E. 2811 C multitube -	external diameter	0.290 ins.
	perforation diameter	0.030 ins.
	mean web	0.050 ins.
	length of grain	0.697 ins.
Lot E.R.D.E. 2811 I slotted tube-	external diameter	0.159 ins.
	hole diameter	0.053 ins.
	annulus	0.053 ins.
	slot area = 18% of total.	

(3) Experimental method (see Ref. 4,5,and 6 for descriptions of apparatus).

For conventional propellants, a Closed Vessel loading density of 0.2 grams per c.c. is employed. At this loading density, Δ , however, the very cool propellants (e.g. those with an adiabatic flame temperature less than 2200 $^{\circ}K$) produce comparatively low maximum pressures, (less than 14 tons per sq.in.) and it is now the practice, in such cases, to increase the loading density to 0.25 grams per c.c. for normal determinations of the rate of burning law. As the nominal volume of the vessel is 700 c.cs., this loading density corresponds to a charge weight of 175 grams. Ignition is effected by means of a bag containing about $1\frac{1}{4}$ gram of gunpowder wrapped around a fuse-wire, with an additional gram of gunpowder sprinkled over the charge.

The vessel body is enclosed in a water-jacket for maintaining the standard temperature of 80°F for normal rate of burning assessments, and the charge is kept at this temperature in an incubator for about 24 hours before firing.

The piezo-electric recording apparatus records the rate of pressure rise ($\frac{dP}{dt}$) against pressure, and is so designed that a calibration grid is superimposed on the record, each pressure step corresponding to one ton per sq.in., and each $\frac{dP}{dt}$ step corresponding to a pre-set number of tons per sq.in. per sec., in the present case 200 for Ex.6638 and 50 for Ex.6641. Specimen records are reproduced at C and D in Fig. 1.

Thus, for the determination of rate of burning laws, three rounds of each of the two U.S. samples, Ex.6638 and 6641, were fired in the 700 c.c. Closed Vessel at a nominal loading density of 0.25 grams per c.c. and a charge temperature of 80°F. In every case, a travelling microscope was used to measure $\frac{dP}{dt}$ at pressure intervals of one ton per sq. in. The calculations for rate of burning, etc., were carried out on the mean results for the three rounds in each case. Similar results for F.527/155 lots E.R.D.E. 2811 A (cord), 2811 C (M.T.) and 2811 I (slotted tube) were already available from a previous investigation.

The American Closed Vessel firings of Ex.6638 were carried out in a vessel of 200 c.cs. nominal capacity, (U.S. reference: File no. BL - 138 - 100 - 1), at a nominal loading density of 0.2 grams per c.c. In this case, also $\frac{dP}{dt} - P$ recording was used, calibration being in the form of a series of dots on the record, at distances apart corresponding to known voltages. Thus, for the American type of record, an example of which is given at A of Fig. 1, it is necessary to perform simple calculations to convert the calibration voltages into units of tons per sq.in. and tons per sq.in. per second before rates of burning can be calculated.

For direct comparison with the American record, a single round was fired at the American loading density of 0.2 grams per c.c. The maximum pressure reached in this round was considerably greater than the mean of the three American rounds. An estimate was then made of the loading density required in the British vessel to give the same maximum pressure as that reached in the American firings, and three rounds were fired at this loading density. The three records so obtained are reproduced at E, F and G of Fig. 1.

(4) Results

(a) Cord shape.

From the mean measurements of each of the three sets of records, rates of burning were calculated as follows:-

$$- D.\frac{df}{dt} = \frac{D}{2P_m}.\frac{dP}{dt}.\frac{1}{\sqrt{1 - \frac{P}{P_m}}}$$

where D = the initial cord diameter
Df = the cord diameter at some stage during burning when
P = the pressure, (i.e. f = 1 initially, and = 0 at the end of burning),
P_m = the maximum pressure of the firing, and the value of
$\frac{dP}{dt}$ = that corresponding to the pressure P.

$- D.\frac{df}{dt}$ is, of course, the rate at which the propellant stick diameter is decreasing during burning.

This calculation does not take into account burning at the ends of the propellant sticks. To correct for this, the approximate rate of burning is divided by $1 - \frac{a(1 - 2f)}{2 - a(1 - f)}$, where $a = \frac{\text{cord diameter}}{\text{stick length}}$,

and $f = \sqrt{1 - \frac{P}{P_m}}$. In the present instance, a = 0.02 for the American sample, and 0.0104 for the British sample. Thus, the correction is small, being the greater for the American sample, for which it amounts to - 1% at the commencement of burning (i.e. at f = 1), and + 1% at the end of burning, when f = 0, changing sign at f = 0.7525. The corrected rates of burning are then multiplied by $\sqrt{1 + \frac{\eta - \frac{1}{\delta}}{\lambda_0}P}$ to correct for the effect of the propellant shape, (ref.2). In this last expression, P is the pressure, as before, δ is the density of the solid propellant, η is the co-volume of the propellant gases, and λ_0 is the uncooled force constant for the propellant, using the correct co-volume;

i.e. $P(\frac{1}{\Delta} - \eta) = \lambda_0$

where Δ = the loading density.

The corrected rates of burning are plotted logarithmically against pressure in Fig.2. In both cases, the plotted points lie on good straight lines up to a pressure of about 3.5 tons per sq.in., and on different straight lines at pressures in excess of this value; i.e. in both cases there is a marked change in burning law (which may be expressed in terms of βP^{α} by virtue of the linear relationships in Fig.2, P being the pressure and β and α constants), in the region of 3.5 tons per sq.in. Fig.2 indicates that there is a marked difference in burning law between the American and British samples in the pressure range of from 1 to 3 tons per sq.in., but this is not important in the gun, as only a small fraction of the charge is consumed when the pressure has reached 3 tons per sq.in. It is at once evident from the graph that the index α in the burning law for the American sample is a little greater than for the British sample. The values of α and β for the two samples were determined by a least-squares method, with the following results:

for Ex 6641 $$-D\frac{df}{dt} = 0.771\ P^{0.740}$$

for F.527/155, lot E.R.D.E. 2811A, $$-D\frac{df}{dt} = 0.820\ P^{0.698}$$

These index laws of burning are, of course, of little use for internal ballistic purposes, for which linear burning laws are required on grounds of mathematical simplicity. It is customary to convert such index laws to their linear equivalents, by a method described elsewhere (ref.2).

$$\text{i.e.}\quad -D\frac{df}{dt} = \beta_{1\,(24)}P$$

the suffix 1 denoting that α has been adjusted to unity, and the suffix 24 denoting that this adjustment has been made for a maximum true pressure in the gun of 24 tons per sq.in.

For Ex.6641, $\beta_1(24)$ = 0.395 inches per sec./ton per sq.in.,

and for F.527/155 lot E.R.D.E. 2811A, β_1 (24) = 0.376

Thus, in effect, the American sample burns some 5% faster than the British sample.

In some internal ballistic theories, (e.g. the British R.D.38), the force constant used is that for which the co-volume of the propellant gases is assumed to be equal to the reciprocal of the propellant density. This form of force constant is denoted by λ_1

$$\text{i.e.}\quad P\left(\frac{1}{\Delta} - \frac{1}{\delta}\right) = \lambda_1$$

λ_1 will, of course, vary with Δ (i.e. with the maximum pressure), but it has been shown (ref.2) that the appropriate value of λ_1 to use when certain assumptions (including $\eta = 1/\delta$) are made is that corresponding to the pressure at all-burnt, i.e. 75% of the maximum pressure approximately. Thus, for a maximum gun pressure of 24 tons per sq.in., λ_1 at 18 tons per sq.in. is required. This is denoted by λ_1 (18). It should be mentioned here that rate of burning is slightly sensitive to Δ, i.e. to λ_1, but $\lambda_1\left\{-D\frac{df}{dt}\right\}$ is constant for any given pressure. For calculating $\beta_1(24)$, λ_1 (18) is the correct force constant to use, and it is necessary to introduce a correction for this when the maximum pressure of the Closed Vessel firings differs from 18 tons per sq.in. Such corrections have been made in arriving at the above values of β_1 (24)

Before $\lambda_1(18)$ can be assessed from the results of Closed Vessel firings, it is necessary to estimate the heat lost to the vessel walls during the burning of the propellant. From the results of heat loss experiments carried out in the past, the estimates are:-

For Ex.6641, heat loss = 5.2%.
For F.527/155, lot E.R.D.E.2811A, heat loss = 4.5%.

Thus, the assessments of $\lambda_1(18)$ are:-

For Ex.6641, $\lambda_1(18)$ = 60.1 tons per sq.in./gram per c.c.
For F.527/155, lot E.R.D.E.2811A, $\lambda_1(18)$ = 58.9 tons per sq.in./gram per c.c.

It is now possible to make an assessment of λ_0 from the relationship

$$\lambda_1 = \lambda_0 + (\eta - \frac{1}{\delta}) P_m$$

This gives:-
for Ex.6641, λ_0 = 51.7 tons per sq.in./gm.per c.c. (compared with 53 calculated from thermochemistry)
for F.527/155, lot E.R.D.E.2811A, λ_0 = 51.0 tons per sq.in./gm.per c.c. (compared with 52.9 calculated from thermochemistry)
i.e. on an average, the experimental λ_0 is some 3% less than the calculated value. Part of this discrepancy may be due to inaccurate assessment of heat loss. However, this does not affect the comparison of the two samples, and it is seen that the "force" of the American sample is 1.4% greater than that of the British sample.

Interpreted in terms of gun ballistics, the differences in rate of burning and force between the American and British samples are such that, for a normal ballistic level, equal charge weights of the same propellant size would be expected to produce muzzle velocities differing by some 3%, the American sample giving the higher value.

The ratio $\dfrac{\text{Rate of burning of American sample}}{\text{Rate of burning of British sample}}$ is plotted against pressure at D of Fig. 4. This ratio, originally very high, decreases almost to unity at a pressure of 4 tons per sq.in., and thereafter gradually increases with further rise in pressure.

(b) Slotted-tube shape

In this case, the approximate rate of burning (ignoring end-burning) is given by:-

$$-D\frac{df}{dt} = \frac{D}{P_m}\frac{dP}{dt}\,\frac{1}{\sqrt{(1+\theta)^2 - 4\theta\frac{P}{P_m}}}$$

where D = the annular thickness of the propellant,

$$\text{and } \theta = \frac{D^2}{\text{area of cross-section of propellant stick}} = \frac{D^2}{A}$$

= 0.159 in the present case.

This expression for rate of burning follows from the assumption that the fraction of charge burnt = F

$$= (1 - f)\,(1 + \frac{D^2}{A}f).$$

The exact relationship between F and f is:-

$$F = (1 - f)\left[1 + (\frac{D^2}{A} + a - \frac{D^2}{A}.a)\,f + \frac{D^2}{A}.a\,f^2\right]$$

where $a = \dfrac{D}{\text{stick length}}$. Thus, terms containing "a" have been ignored for the purpose of obtaining the approximate relationship. By assuming that $\theta = \frac{D^2}{A} + a$ instead of $\frac{D^2}{A}$, some allowance is made for end-burning of the sticks, and will lead to a high degree of accuracy in the present instance, as "a" is very small (= 0.01), i.e. $\theta = 0.169$. This more accurate value of θ was actually employed in calculation of rates of burning, leading to the following burning law:-

$$- D\frac{df}{dt} = 0.796\, P^{0.705} \quad \text{(compared with } 0.820\, P^{0.698} \text{ for the cord).}$$

For the equivalent linear burning law, $\beta_1(24) = 0.380$ ins.per sec./ton per sq.in. (compared with 0.376 for the cord). The difference in $\beta_1(24)$ between the cord and the slotted tube, being little more than 1%, may be due to errors of propellant size measurement, as there is no significant difference in α.

Estimated heat loss = 4.5%, and when this is allowed for,

$\lambda_1(10) = 58.8$ tons per sq.in./gram per c.c., corresponding to
$\lambda_0 = 50.9$ " " " " " "
compared with $\lambda_0 = 52.9$ calculated from thermochemical data (i.e. a difference of 4%).

(c) Multitube shape.

The expression for calculating the approximate rate of burning, up to the pressure at which the web commences to burn through, is:-

$$- D.\frac{df}{dt} = \frac{D}{C.P_m} \cdot \frac{dP}{dt} \cdot \frac{1}{\sqrt{(\theta+1)^2 - \frac{4\theta}{C}\frac{P}{P_m}}}$$

where D = mean web thickness,

$$\theta = -\frac{6 - 20a - 20\,ab}{14 + 20b + 2a + 4\,ab + 2ab^2} = -\frac{6 - 20a - 20\,ab}{y} \text{ where } y = 14 + 20b + 2a + 4ab + 2ab^2$$

$$C = \frac{14 + 20b + 2a + 4ab + 2ab^2}{16 + 24b + 2b^2} = \frac{y}{16 + 24b + 2b^2}$$

$a = \dfrac{\text{mean web}}{\text{grain length}}$ and $b = \dfrac{\text{perforation diameter}}{\text{mean web}}$

For the American sample, Ex.6638, a = 0.07, b = 0.554, C = 0.85 and $\theta = -0.150$. With perfect ignition, burning by parallel layers, and all webs equal, web break-down would occur at 85% of the maximum pressure. As the webs were not, in fact, equal, in the ideal case the thinnest web would burn through at 81% of the maximum pressure.

For the British sample, lot E.R.D.E. 2811C, a = 0.072, b = 0.600, C = 0.847 and $\theta = -0.137$. In the ideal case, the web would burn through at 84.7% of the maximum pressure.

The correct rates of burning are obtained by dividing the approximate rates by:-

$$1 + \frac{12af\,(1 - 1.5\,f)}{y\,[(1-\theta) + 2\theta f]}$$

$$= 1 + \frac{.42f - .63f^2}{14.62 - 3.82f} \quad \text{for the U.S. sample,}$$

$$\text{and } 1 + \frac{.432f - .648f^2}{15.03 - 3.70f} \quad \text{. for the British.}$$

Appropriate values of 'f' are calculated, with sufficient accuracy, from:-

$$\frac{P}{P_{max.}} = C(1 - f)(1 + \theta f).$$

$$\text{i.e. } f = -(1-\theta) + \sqrt{(1+\theta)^2 - 4\frac{\theta}{C}\cdot\frac{P}{P_{max.}}}$$

Thus, the correction amounts to about 2% at f = 1, and to zero at f = 0 (i.e. web breakdown, with equal webs).

The rates of burning, corrected in this manner, are plotted against pressure on logarithmic axes in Fig.3. In the case of Ex.6638, the points over the pressure range from 4 to 10 tons per sq.in. lie on a good straight line, suggesting a burning law of the usual index form, but this is not true of the British sample.

In Fig. 4A, the ratio $\frac{\text{Rate of burning of American multitube}}{\text{Rate of burning of American cord}}$ (=R, say) is plotted against pressure. This ratio commences at a value appreciably less than unity, presumably because of the delay in completing ignition down the perforations of the multitube shape, which leads to an under-assessment of rate of burning, it being assumed in the calculation that ignition over the complete charge surface is effected instantaneously. The shape of the graph suggests that ignition in the perforation is completed at a pressure of about 4 tons per sq.in., after which the multitube burns for a time at a rate about 13% less than that of the cord, with no indication of erosive burning. Due to the change in grain geometry brought about by the long ignition interval, web break-down occurs at a much earlier stage than would have been the case in ideal circumstances. The resultant reduction in charge burning-surface leads to an apparent decrease in burning rate in comparison with cord, and the ratio R consequently commences to decrease.

From the straight portion of the appropriate curve of Fig.3, the law of burning for Ex.6638 is:-

$$-D\frac{df}{dt} = 0.664\,P^{0.734} \quad (0.771\,P^{0.740} \text{ for the cord})$$

and $\beta_1{}^{(24)} = 0.343$, (0.395 for cord)

using the geometrical form function.
i.e. the American multitube is, in effect, 13% slower-burning than the American cord.

For Ex.6638, $\lambda_1(10) = 59.9$ (compared with 60.1 for the cord) after allowing for a heat loss of 4.1%. This corresponds to a λ_0 of 51.3, compared with 51.7 for the cord. Thus, multitube and cord agree well in force constant.

In Fig.4B (1) the ratio $\frac{\text{Rate of burning of British multitube}}{\text{Rate of burning of British cord}}$ is plotted against pressure. The ratio commences at a value much greater than unity (due, it is suspected, to a corner-burning effect), decreases rapidly to about 0.9 and then commences to increase, reaching a maximum of about 1.08. This second excess over unity is thought to be due to erosive burning of the propellant in the perforations, brought about by gas flow over the propellant burning surface, the result being to increase heat input to the propellant surface with a consequent increase in rate of burning. It is probable that erosive burning has commenced before the plotted ratio has reached unity for the second time, which occurred at about 3.5 tons per sq.in.

In any event, it is clear that ignition in the perforations was completed at an earlier stage with the British sample than with the American sample. This is to be expected, as the British sample was of a larger grain dimension by a factor of more than two. Other conditions being equal, it seems likely that the ratio $\frac{\text{perforation surface area}}{\text{perforation volume}} \left(\propto \frac{d^2}{d^3} \propto \frac{1}{d} \right)$ has some bearing on the time lag in igniting down the perforation; if taken to the ridiculous extreme of equal heat energy available from the igniter, per unit surface area of the charge, both internally and externally, there would be no ignition lag of the type under discussion, and it would seem reasonable to suppose that the lag would decrease with increase in perforation diameter (d).

The earlier internal ignition of the British multitube, relative to the American manufacture, has an adverse effect so far as erosive burning is concerned, as erosive burning is a function of (a) gas velocity, which decreases as burning proceeds, and (b) thickness of combustion zone, which also decreases with increase in pressure. These two factors are thought to be the explanation of the reduction in the plotted ratios (R) after the maximum is reached. R remains nearly constant at a value of about 0.97 over a limited pressure range, presumably when erosive burning has ceased, and then commences to decrease when the web begins to burn through at a much earlier stage than would have been the case if the assumed ideal conditions had existed.

It is apparent that, with the British sample, the use of the accurate geometrical form function makes it impossible to deduce a simple law of burning. For the multitubular propellant shape, it has been the practice, in the past, to overcome this difficulty by increasing the web size by 15% for the rate of burning calculations, and to assume that $\theta = 0$ (i.e. that the burning surface is constant).

$$\text{i.e.} \quad -D\frac{df}{dt} = \frac{1.15\ D}{P_m} \cdot \frac{dP}{dt} .$$

The factor 1.15 takes the place of $\frac{1}{C}$ in the accurate expression. The use of $\theta = 0$ instead of the calculated value of -0.124 is equivalent to a 12.4% increase in burning surface (and therefore a corresponding decrease in calculated rate of burning) at the commencement of burning, and a 12.4% decrease in burning surface (with a corresponding increase in calculated rate of burning) at burning-through of the web, with intermediate adjustments between these two stages. This is intended to represent an approximate correction for erosive burning. The rates of burning for the British multitube sample were recalculated on this basis, and the new figures, divided by the corresponding results for the cord sample, are plotted in Fig.4 B(2). It is seen that the hump due to erosive burning is now very much reduced, and the rate of burning of the multitube is comparable with that of the cord over a much wider pressure range. Also it is possible to calculate a rate of burning law for the multitube, which is:-

$$- D.\frac{df}{dt} = 0.846\ P^{0.676} \quad \text{(compared with } 0.820\ P^{0.698} \text{ for cord, and } 0.796\ P^{0.705} \text{ for slotted tube).}$$

This corresponds to $\beta_1(24)$ of 0.375, compared with 0.376 for cord, and 0.380 for slotted tube.

$\lambda_1(18)$ is 58.5, corresponding to $\lambda_0 = 50.6$, the estimated heat loss being 4.6%.

(d) General remarks

To complete the comparison of shapes, the ratio:-

$$\frac{\text{rate of burning of slotted tube}}{\text{rate of burning of cord}}$$

is plotted against pressure in Fig. 4B (3). The constancy of this ratio over a wide proportion of the burning range, in comparison with the multitubular shape, clearly demonstrates the superiority of slotted tube, on internal ballistic considerations, in this instance.

The ratio between the rates of burning of the two multitubular samples, plotted against pressure in Fig. 4C, shows once again the large difference in rate of burning between the two samples, whereas Fig. 4D shows that the difference between the two cord samples is much smaller.

The results are summarised in the following table.

Closed Vessel results for American and British samples of F.527/155 propellant

Lot No.	Shape	Size	Burning law βP^{α}		β_1 (24) ins. per sec. / ton per sq.in	Experimental force constants		Calculated
			β	α		$^{x}\lambda_1(10)^{x}$	λ_0	$^{x}\lambda_0$
American Ex.6641	Cord	0.1002	0.771	0.740	0.395	60.1	51.7	53.0
Ex.6638	Multitube	0.0233	0.664 (a)	0.734 (a)	0.343 (a)	59.9	51.3	52.7
British E.R.D.E. 2811 A	Cord	0.052	0.820	0.698	0.376	58.9	51.0	
E.R.D.E. 2811 C	Multitube	0.050	0.846 (b)	0.676 (b)	0.375 (b)	58.5	50.6	52.9 nominal
E.R.D.E. 2811 I	Slotted tube	0.053	0.796	0.705	0.380	58.8	50.9	

x Units - tons per sq.in./gram per c.c.
(a)-using geometrical form function.
(b)-assuming constant burning surface, and web increased by 15%.

Differences between experimental and calculated values of λ_0 may be due to inaccuracies in thermochemical data, estimation of heat loss, gauge sensitivity, vessel volume, recording apparatus, record measurement, etc.

(e) Comparison between American and British Closed Vessel results for propellant lot no. Ex.6638.

The data received from the U.S. on the four samples of cool propellant sent to this country (U.S. reference - File BL.-138 - 100 - 1) included the reproduction of an American Closed Vessel record (no. A.S.372) for propellant Ex.6638, together with various measurements of this and five similar records (nos. AS. 376, 380, 384, 388, and 392).

The following information on the American Closed Vessel firings was given under the above reference:-

"Actual bomb volume	181.4 c.c.
x Weight of charge-Nitrocellulose	0.10 gm.
x Weight of charge-blankfire	1.00 gm.
Weight of charge-smokeless powder	35.18 gm.

x The approximate contribution of the igniter charge to the total pressure is 800 p.s.i.

Piezo gauge crystal constant 2.51×10^{10} lb./coulomb.

Piston area 0.1105 sq.ins.

The closed bomb test records give the rate of pressure rise and pressures in terms of volts. In order to convert pressure to p.s.i. and rate of pressure rise to p.s.i./sec., the following formulae are used:-

(1) $$P = \frac{KEC}{A}$$

(2) $$\frac{dP}{dt} = \frac{KE}{AR}$$

where:- P = Pressure, in lb./sq.in.
K = Gauge constant, in lb./coulomb,
E = Pressure or rate of pressure change in volts,
A = Area of piston in sq.ins.
C = Circuit capacitance, in farads,
R = Circuit resistance in ohms.

For record AS. 372 (of propellant lot Ex.6638),
R = 180,000 ohms
C = 0.060 mf.

Each interval on the rate of pressure change or burning rate ordinate represents a value of 0.5 volts.

The first and last intervals on the pressure ordinate represent 0.50 volts, while all the other intervals represent 0.25 volts."

Assuming that the 0.1 gm. of nitrocellulose used for ignition is equivalent in force to 0.1 gm. of Ex.6638, and that the 1 gm. of blank-fire is equivalent to 0.33 gm. of Ex 6638, then the total charge is equivalent to (0.1 + 0.33 + 35.18) gms. (= 35.61 gms.) of Ex.6638. The vessel volume is given as 181.4 c.c. Thus, the loading density is

$$\frac{35.61}{181.4} \text{ gm./c.c} = 0.196 \text{ gm./c.c.}$$

In the pressure direction, 1 volt $= \dfrac{2.51 \times 10^{10} \times 0.060}{0.1105 \times 2240 \times 10^{6}}$ tons/sq.in. = 6.084 tons/sq.in.

In the $\frac{dP}{dt}$ direction, 1 volt $= \dfrac{2.51 \times 10^{10}}{0.1105 \times 180{,}000 \times 2240}$ tons per sq.in. per sec.

= 563.4 tons per sq.in./sec.

From the photostat copy of the American record no. AS. 372, values of $\frac{dP}{dt}$ (in volts) were read at pressure intervals corresponding to 0.125 volt, and the measurements, converted to tons per sq.in./sec. and tons per sq.in. respectively, are plotted in Fig. 5A (b). In the same graph are plotted the mean values of the measurements made by the Americans on the six records for the evaluation of relative quickness and relative force. These points are enclosed in squares in the graph.

A charge of Ex.6638 was then fired in the British 700 c.c. vessel, at a loading density approximating to that used by the Americans. Due to round-to-round differences in vessel volume, the loading density was not exactly equal to 0.196, but the difference was insignificant. The weight of gunpowder used was 4.5 gms., (assumed to be equivalent, in force, to 1.5 gms. Ex.6638), with 136.34 gms. of charge. Thus, the loading density was $\frac{137.84}{701.2}$ gms./c.c. = 0.197 gms./c.c., the vessel volume being 701.2 c.cs. The record obtained for this round (no.1745) is shown plotted at (a) of Fig. 5A, for comparison with the American record. It is seen that there is a considerable difference between the two records. The maximum pressure indicated by the British record corresponds to a λ_0 of 50.9, compared with a mean figure of 51.3 for the three rounds at a loading density of 0.25 grams per c.c., and the value of 52.7 calculated from the thermochemical data.

Thus, the single British record for a loading density of 0.197 gms./c.c. does not appear to be in any considerable error, so far as maximum pressure is concerned, the measured value being 12.161 tons per sq.in. The figure given by the Americans for the maximum pressure of round AS. 372, in terms of volts, is 1.729, corresponding to a pressure of 10.519 tons per sq.in., i.e. about 13.5% less than that of the British round fired at very nearly the same loading density. Also, the American values of $\frac{dp}{dt}$ are, on an average, about 17% less than the British values for the same pressures. In attempting to explain these discrepancies, the following possibilities may be considered:-

(a) Heat loss very much greater in the American vessel than in the British Vessel

(b) Inaccuracies in (i) measurement of vessel volume
(ii) gauge calibration
(iii) circuit capacitance, C, and circuit resistance, R.
(iv) calibrating voltage
(v) gauge piston size.

With regard to (a) above, the heat loss in the British vessel was estimated to be 5.1%. At a rough estimate, the heat lost to the vessel walls might be expected to be proportional to the ratio of the cooling surface area to the vessel volume, if the only variant is the vessel volume (i.e. the propellant type, shape, size and loading density are unaltered). For the British vessel, this ratio is 1.667 ins.$^{-1}$, and the figure for the American vessel is estimated to be 2.72 ins.$^{-1}$. Thus, the order of magnitude of the heat loss in the American vessel would be expected to be $\frac{5.1 \times 2.72}{1.667}\% = 8.3\%$, i.e. 3.2% greater than in the British vessel. As an approximate check on this figure, some figures given by Crow and Grimshaw (ref.3) are of interest. The figures they quote are for a nitrocellulose propellant (flame temperature, 2998°K) in cord form 0.071 cm. in diameter, fired at various densities of loading in two vessels, of 649 cm^3 and 130.7 cm^3 capacity respectively (i.e. fairly close to those of 701.2 cm^3 and 181.4 cm^3 now under consideration). At a loading density of 0.205 grams per c.c., the maximum pressures were 2616 kg/cm^2 in the larger vessel, and 2523 kg./cm^2 in the smaller vessel, a difference of 3.6% which is in good agreement with the previous estimate of 3.2%.

As a further check on the heat lost by conduction to the vessel walls, the area of the cooling surface in the British vessel was artificially increased by introducing into the chamber a steel cage of such a shape that the ratio $\frac{\text{cooling surface area}}{\text{vessel volume}}$ was 2.732 ins.$^{-1}$, i.e. very nearly equal to the figure of 2.72 ins.$^{-1}$ estimated for the American vessel. This reduced the vessel volume to 661.7 c.cs. A single round of Ex.6638 was then fired, the weight of gunpowder being 3.6 grams, and the weight of propellant 127.8 grams. Thus, the effective loading density was 0.195 grams per c.c. The measured maximum pressure was 11.818 tons per. sq.in., compared with 12.161 tons per sq.in., for the single round fired at a loading density of 0.197 grams per c.c. under normal conditions of heat loss. Correcting for the slight difference in loading density, the difference between these two pressures, due to the different amounts of cooling surface, is a little less than 2 %. Bearing in mind the fact that it is based on single firings only, this figure is in reasonable agreement with the previous estimates of 3.2 % and 3.6 %, and shows fairly conclusively that only a relatively small fraction of the amount by which the maximum pressure in the American vessel falls short of that in the British vessel when fired at the same density of loading (i.e. about 13.5 %) is attributable to a greater loss of heat by conduction to the vessel walls. There still remains a difference of the order of 10% to be accounted for.

It should be explained that the estimated 5.1% heat loss in the British vessel is intended to include all the energy losses. In addition to the loss by conduction to the vessel walls, some of the available energy is expended in expanding the vessel, and it is probable that the proportion of energy so absorbed is much greater in the American vessel than in the British vessel. Also, owing to the resilient nature of the obturating system employed, compression of the obturator in the American vessel may absorb an appreciable proportion of the available energy.

Thus, the method adopted above of scaling up the total heat loss in the proportion of ratios of $\frac{\text{cooling surface}}{\text{vessel volume}}$ may well be misleading. The most satisfactory method of estimating heat loss is from firings of a wide range of sizes, at the same loading density, of propellants of accurately-known compositions.

The second possibility b (i), that the volume of the American vessel had been inaccurately assessed, was next explored. A charge of Ex.6638, to give the same maximum pressure in the British vessel as that produced in the American vessel, was assessed, and the loading density required was found to be 0.176 grams per c.c. The charge consisted of 4 grams of gunpowder and 121.1 grams of Ex.6638. Three rounds were fired at this loading density, and the mean measurements of the three records are plotted in Fig. 5 A (c). The mean maximum pressure came a little below that of the American firings, (10.428 tons per sq.in., compared with 10.653), but agreement with the mean of the American firings, (the points enclosed in squares), is quite good. For a more exact comparison, curves of rate of burning against pressure, deduced from the British firings at Δ 0.176 and from the American firings at Δ 0.196, are plotted in Fig. 5 B, at (b) and (a) respectively. For most of the pressure range, agreement is fairly good, but, as is to be expected, the two curves diverge considerably at maximum $\frac{dP}{dt}$, i.e., when the propellant web has commenced to burn through. This follows from the fact that the mean maximum pressures were different, with the result that web break-down commenced at different pressures in the two cases. The method used for calculating rates of burning is not applicable beyond the stage of web break-down.

Much can be deduced from the relatively good agreement between the American and British rate of burning curves. In the first place, rate of burning is unaffected by heat loss, and the possibility of different heat losses in the two cases still remains. Sceondly, rate of burning is independent of vessel volume, so it is possible that the volume of the American vessel has been under-assessed. Thirdly, any inaccuracy in the gauge calibration would have appeared as a consistent difference between the two rate of burning curves, for the following reasons. The approximate rate of burning at pressure P is given by the expression

$$\frac{D}{CP_m} \cdot \frac{dP}{dt} \cdot \frac{1}{\sqrt{(\theta + 1)^2 - 4\frac{\theta}{C}\cdot\frac{P}{P_m}}}$$

θ and C are functions of the grain geometry only. The ratio $\frac{P}{P_m}$ is unaffected by inaccurate gauge calibration, as P and P_m would be equally in error. For this same reason, the ratio $\frac{dP}{dt}/P_m$ would be unaffected, and the calculated rate of burning would therefore be the same. The pressure P, however, would be in error to the same extent as the gauge calibration, and this would, of course, result in a consistent difference between the two rate of burning curves. As no such consistent difference is found, it is presumed that the American and British gauges are in agreement. Fourthly, this same reasoning may be employed to remove suspicion from the calibration voltage and the gauge piston diameter.

The remaining possibilities are inaccuracies in C and R. For the American recorded curve to agree with the British, C would need to be increased by 11.6 % (allowing for a 4 % difference in cooling), making C=0.067 μf, and <u>at the same time</u>, R would have to be reduced by about 16 % (with the same difference in cooling), making R = 151,000 ohms. The possibility that C and R are both in error by the requisite amounts would appear to be too remote to justify serious consideration.

We are left, therefore, with some doubt regarding the heat loss and chamber volume of the American 200 cc. vessel. Incidentally, for the discrepancy to be due entirely to heat loss, the heat loss would be 19.4 %, if the British experimental value of λ_0, which is about $2\frac{1}{2}$ % less than the calculated value, is assumed to be correct.

Conclusions

American F.527/155-type propellant

(1) For cord sample, rate of burning constant β_1 (24) = 0.395 ins. per sec./ton per sq.in.

(2) The multitube sample burned non-erosively, and the geometrical form-function was therefore used to calculate rates of burning, from which it was deduced that β_1 (24) = 0.343.

(3) (No slotted-tube sample supplied)

(4) The multitube was about 13 % slower than the cord in rate of burning

(5) The experimental value of λ_1 (10) (i.e. the force constant corresponding to the use of the fictitious co-volume, at a pressure of 18 tons/sq.in.) was approximately 60.0 tons per sq.in./gm.per c.c. for both samples.

(6) The mean experimental value of λ_0 for the two samples (i.e. the force constant corresponding to the correct co-volume) was 51.5, the difference between the two samples being less than 1 %.

(7) The mean value of λ_0, calculated from analysis and thermochemical data, was 52.85, the difference between the two samples being less than 1 %.

(8) The experimental λ_0 was 2.6 % less than the calculated value.

British F.527/155 propellant

(1) For cord sample, β_1 (24) = 0.376 (i.e. nearly 5 % less than that of the American)

(2) Erosive burning in the perforations of the multitube made it necessary to assume constant burning surface for the calculation of a burning law, from which it was deduced that β_1 (24) = 0.375

(3) β_1 (24) for the slotted tube was 0.380.

(4) The rates of burning of the cord, multitube and slotted tube were in good agreement, the spread being little more than 1 %.

(5) The mean value of λ_1 (10) for the three samples was 58.7, and the difference from sample to sample was not significant.

(6) The mean experimental value of λ_0 for the three samples was 50.8, the spread being less than 1 %.

(7) The value of λ_0, calculated from nominal composition and thermochemical data, was 52.9

(8) The experimental λ_0 was 4 % less than the calculated value.

---

(9) The American cord burned about 5% faster than the British cord.

(10) The American multitube burned about 8.5% slower than the British multitube. (This conclusion, however, is based on different propellant form functions).

(11) The mean experimental value of λ_1 (10) for the American samples was about 2% greater than that of the British samples.

(12) The mean experimental value of λ_0 for the American samples was about 1% greater than that of the British sample.

(13) The mean calculated value of λ_0 for the American samples was not significantly different from that of the nominal British composition.

(14) The rates of burning for the American multitube sample, deduced from the American Closed Vessel firings, are in reasonably good agreement with those deduced from the British Closed Vessel firings.

(15) When fired at a loading density of 0.2 grams per c.c., the maximum pressure produced by the American multitube sample in the American Closed Vessel is 13 % less than that produced in the British vessel.

(16) By virtue of its smaller chamber volume, a greater proportion of the available heat energy is lost by conduction to the vessel walls in the American vessel than in the British vessel, the difference being of the order of 3 %, reducing the discrepancy referred to in (15) above to 10 %.

(17) In view of (14) above, the 10 % discrepancy referred to in (16) may be due to:-

(i) a higher proportion of energy loss in the American vessel in expanding the vessel body or in compressing the obturators, or both,

or (ii) an inaccurate assessment of vessel volume,

or (iii) a combination of the above factors.

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4. A.R.E. Memo 15/50 — The design of a Closed Vessel (No. 21) for routine examination of propellants for guns.

5. A.R.E. Memo 16/50 — The design of a Piezo-Electric Gauge for Closed Vessel No. 21.

6. A.R.E. Report 18/50. — The development of a Closed Vessel Piezo-Electric Recording Equipment

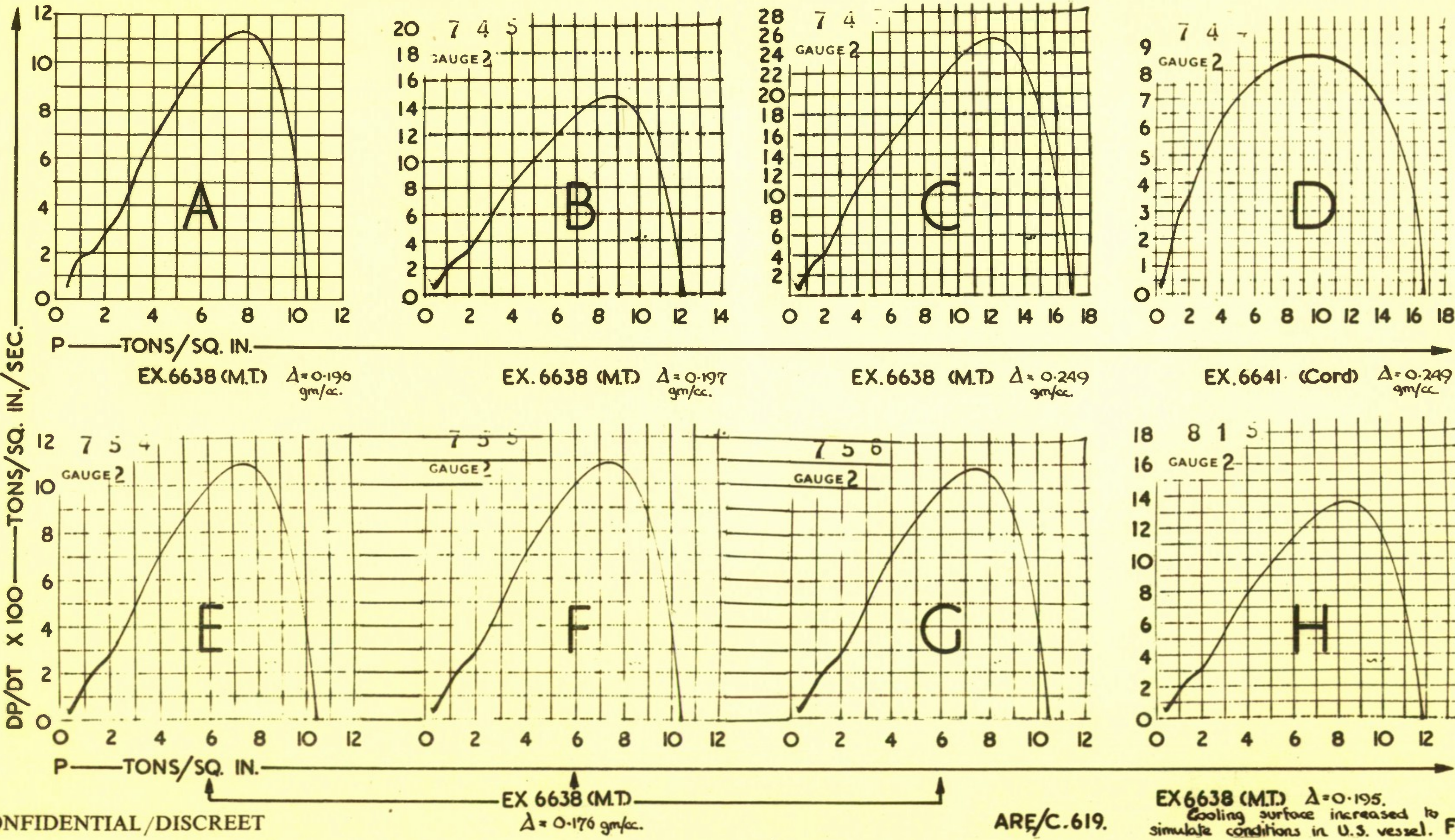

Fig. 1.

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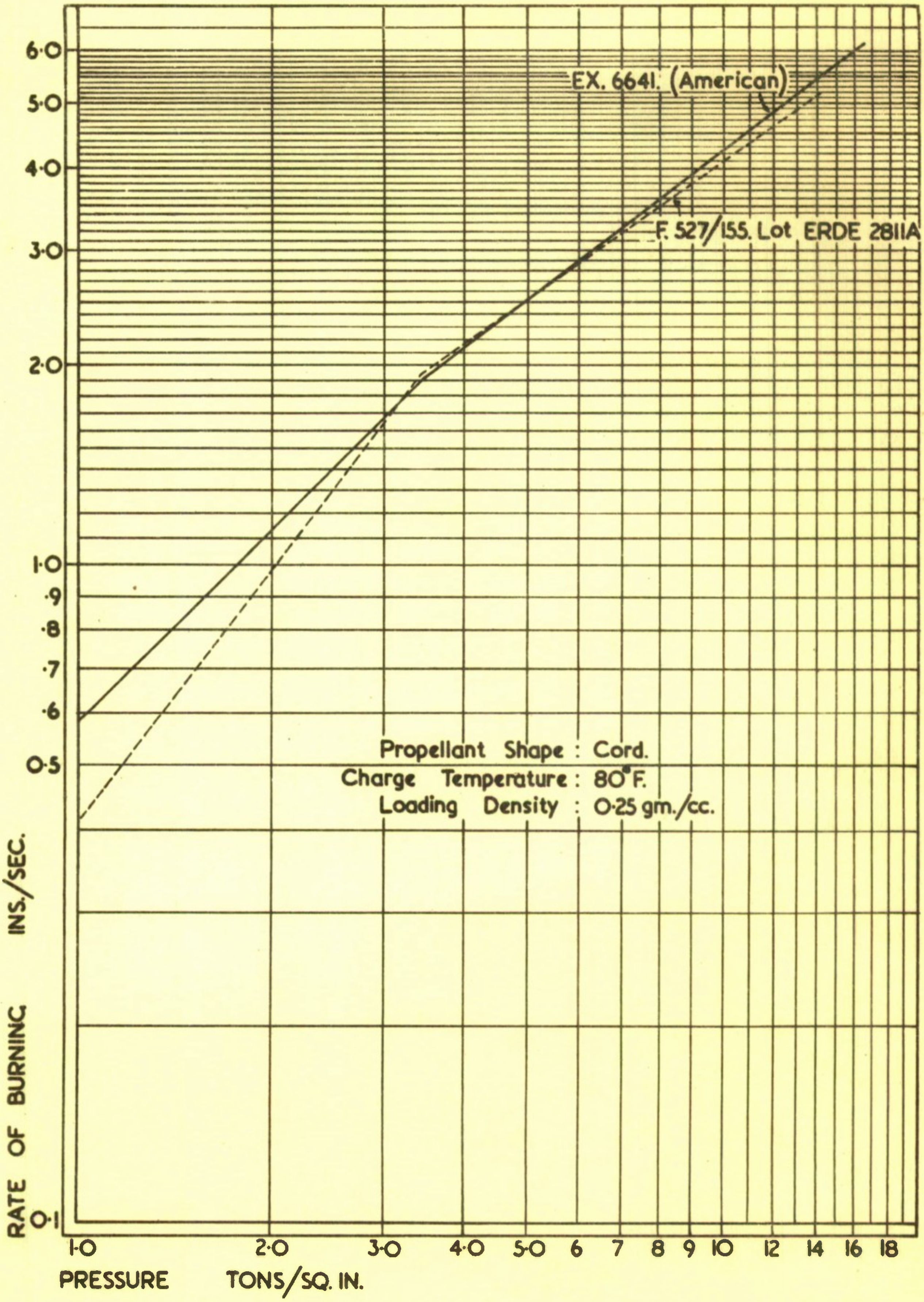
ARE/C.619.



CONFIDENTIAL / DISCREET

ARE/C. 620.

Fig. 2.

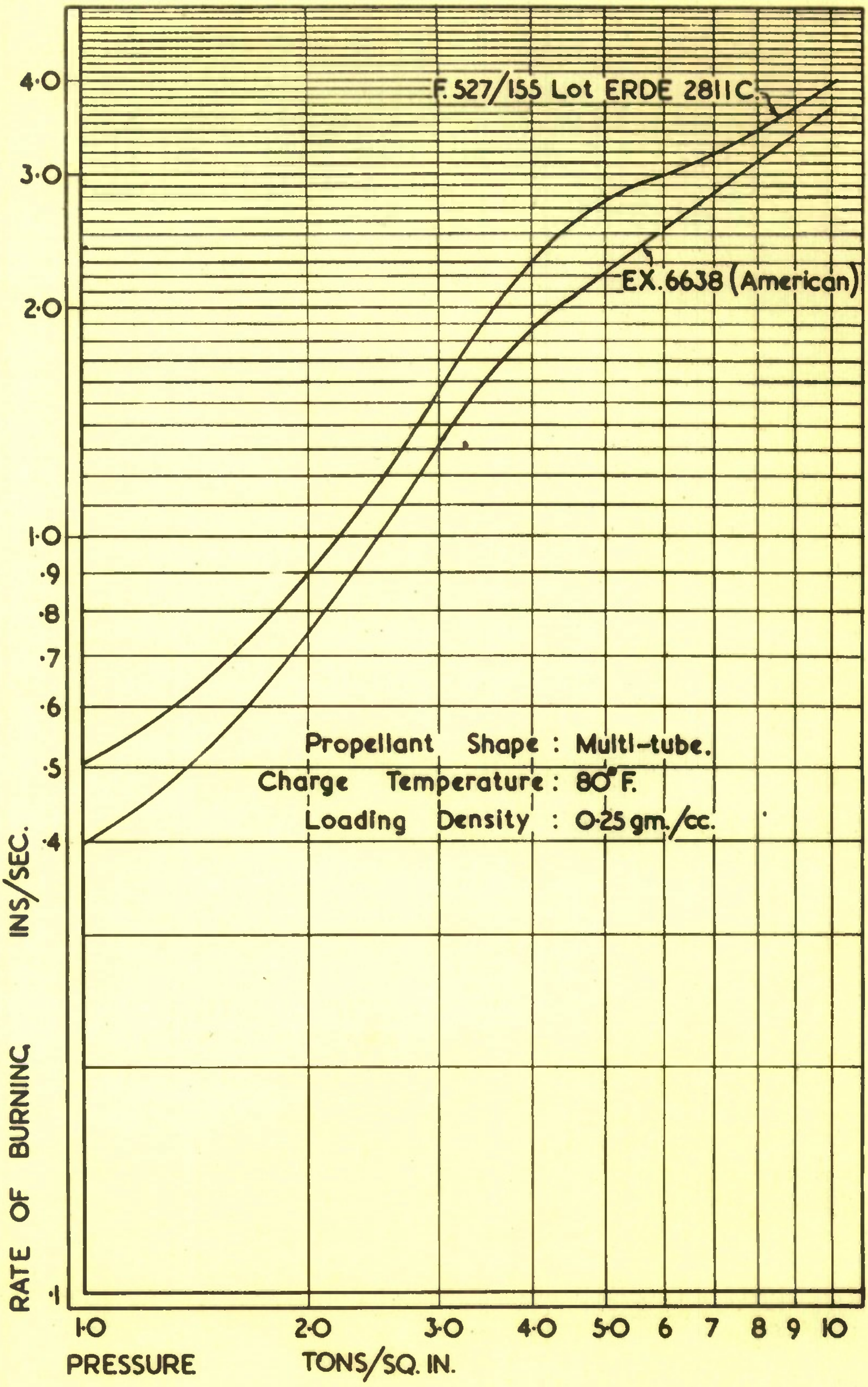

F. 527/155 Lot ERDE 2811C.
EX. 6638 (American)
Propellant Shape : Multi-tube.
Charge Temperature : 80°F.
Loading Density : 0·25 gm./cc.
RATE OF BURNING INS/SEC.
PRESSURE TONS/SQ. IN.
4·0
3·0
2·0
1·0
·9
·8
·7
·6
·5
·4
·1
1·0
2·0
3·0
4·0
5·0
6
7
8
9
10

Fig. 3.

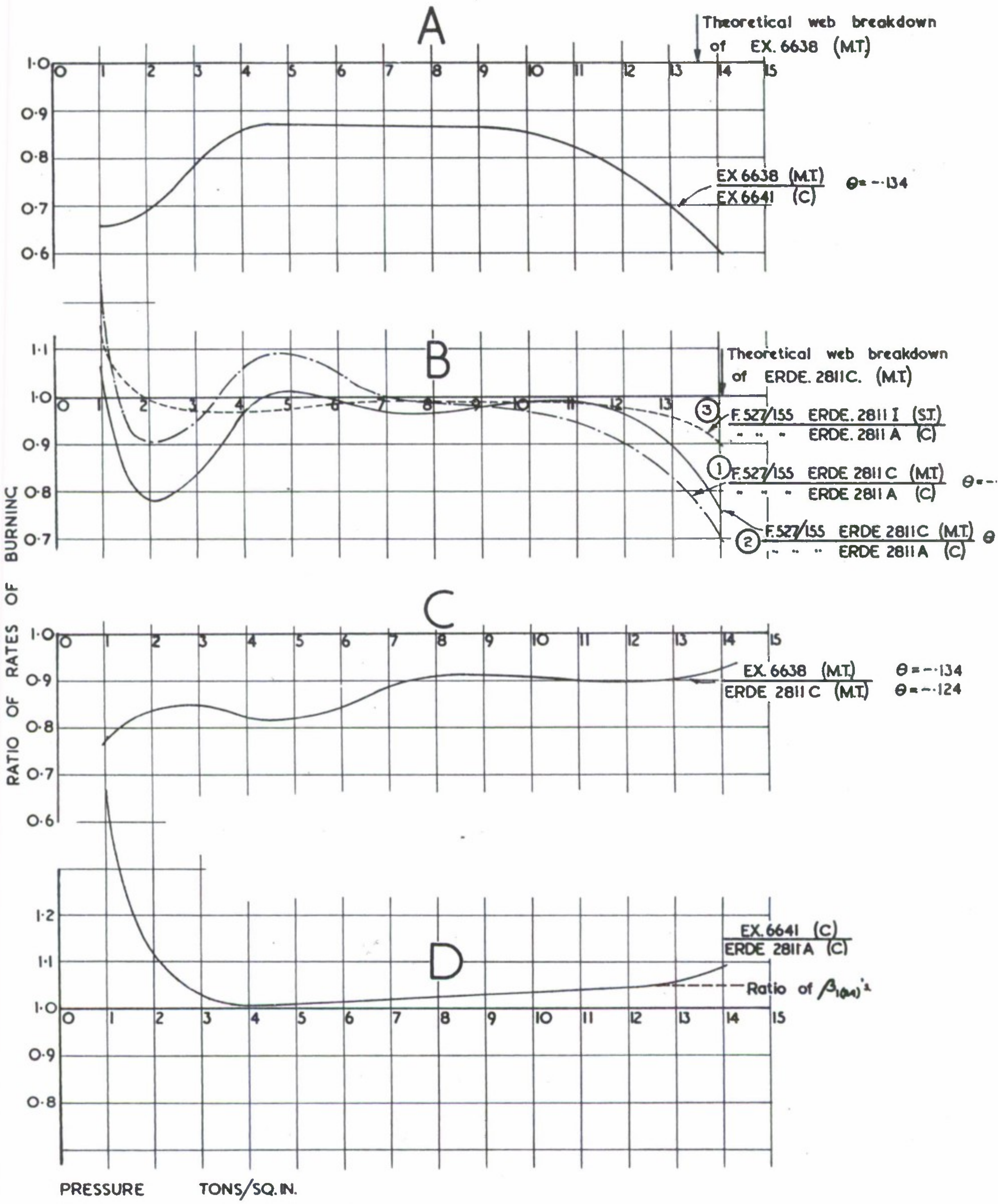
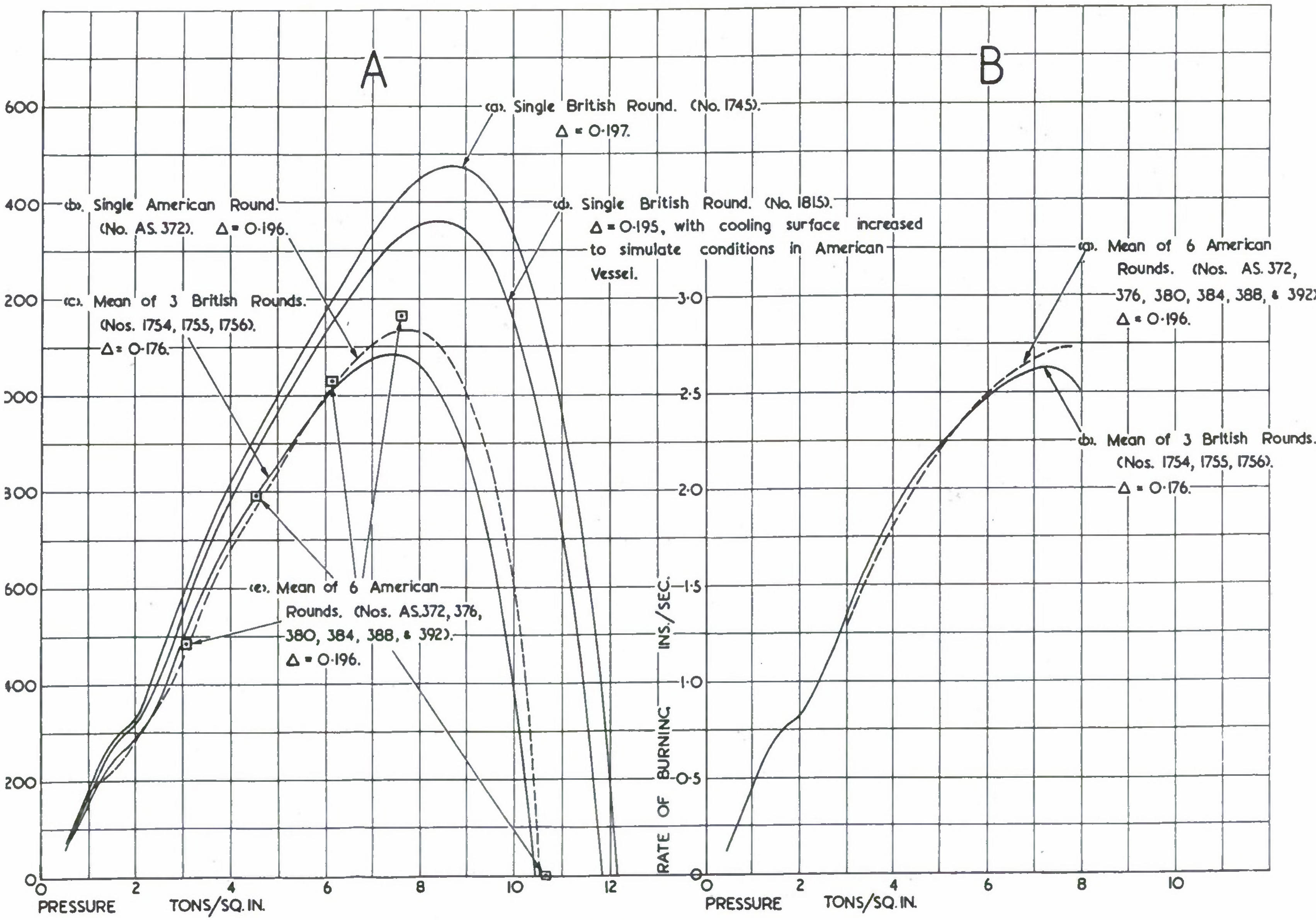

A
Theoretical web breakdown of EX. 6638 (M.T.)
EX 6638 (M.T.) / EX 6641 (C)
θ= -·134
B
Theoretical web breakdown of ERDE. 2811C. (M.T.)
3 F. 527/155 ERDE. 2811 I (S.T.) / " " " ERDE. 2811 A (C)
1 F. 527/155 ERDE 2811 C (M.T.) / " " " ERDE 2811 A (C)
θ= -
2 F. 527/155 ERDE 2811C (M.T.) / " " " ERDE 2811A (C)
θ
C
EX. 6638 (M.T.) / ERDE 2811 C (M.T.)
θ= -·134
θ= -·124
RATIO OF RATES OF BURNING
D
EX. 6641 (C) / ERDE 2811 A (C)
Ratio of $\beta_{1(\alpha 4)}$'s
PRESSURE TONS/SQ. IN.

Fig.4

—Closed Vessel Records for American EX.6638—
—(M.T.)—



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ARE/C 623

Fig. 5.

[dstl]

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[dstl] Porton Down,
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Defense Technical Information Center (DTIC)
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U.S.A.

AD#:
Date of Search: 16 February 2007

Record Summary:

Title: Closed vessel examination of two samples of American cool propellant
Covering dates 1951
Availability Open Document, Open Description, Normal Closure before FOI Act: 30 years
Former reference (Department) Memo No 9/50
Held by The National Archives, Kew

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