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THE CLOSED VESSEL APPARATUS AT KIRKEE*

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1. The Closed Vessel—

The closed vessel at Kirkee is an ARD Type No. 21. In essence, it is a strong cylindrical chamber 6″ by 3″ diameter made in three pieces, one hollow cylinder and two end blocks. One end block carries a control valve for evacuation or release of the gases inside. It also carries an insulated electrode. The inside end of this electrode projects as a pin into the chamber. A similar pin is mounted direct on the block. For ignition, a thin nichrome wire soldered across these is exploded by the discharge from a condenser. The other end block carries a piezo-electric pressure gauge. Gas tightness at high pressures is effected by two brass rings between the end blocks and a liner in the bore, on the partially supported area principle. Erosion is high at these temperatures. Therefore, all sharp edges and corners are protected by plasticine which is used also to fill up all channels and crevices. The chamber so prepared is truly cylindrical. Its volume is therefore calculated directly from measured dimensions. It varies between 706 cc. with new brass rings and 699 cc. for old ones. The actual value for each firing is noted to an accuracy of 0·1 cc. The pressure from the chamber is communicated to the crystal of the piezo gauge by a precise cylindrical piston rod. The diameter is measured, accurately so that the thrust on the crystal can be calculated for any pressure.

Piezo Gauge. An X cut quartz crystal 0·395 in. diameter, 0·125 inch thick is used in the gauge. The electrode at the forward end is earthed through the bomb. The hinder end electrode is highly insulated and connected by a concentric shielded cable to the D.C. Amplifier. With the calibrating switch contacts etc., in the same input, considerable trouble was experienced in getting and maintaining the requisite insulation (about 250,000 megohms). Values under 100 megohms have been obtained during last monsoon. Well known remedies like Paraffin Wax, Ceresine Wax and some high insulation varnishes were tried without the requisite improvement. Curiously, the less well known, but simple beeswax-rosin composition proved successful. The components are now dessicated, and vacuum impregnated with a carefully prepared melt of beeswax-rosin mixture.

D. C. Amplifier. This is a standard German Army equipment made by Ziess Ikon. It consists of a discharge tube stabilised power supply, and a two valve amplifier. The first valve is of electrometer type, with input resistance over 10^{14} hms. The second is a high μ triode. When received at Kirkee, the output of this unit had a mains ripple of about 1 volt. The zero was also insufficiently steady and not easily reset. Considerable modification of the circuit was found necessary to reduce these defects. The present layout gives a ripple of less than 50 m V. The zero steadiness is better than 1 per cent. per hour after warming up and less than 0·1 per cent. per 10 per cent. variation of mains voltage. The overall amplification is about fifty. The frequency response is flat to 2 dbs. upto 100 kc. The amplitude response is flat to one per cent. over a range of one volt input and is corrected to 0·1 per cent. by calibration.

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Cathode Ray Tube. A 12 cm Screen Ziess Ikon Cathode Ray Tube, with electrostatic deflection plates is used to record the amplifier output. The cathode ray spot is focussed by a lens system on a vertically driven drum camera. The lens has a maximum aperture of nearly f/1·5 with adjustments for fine focussing and correcting residual spherical aberration. No technical details are available about the lens. Usually the lens is used at f/18 but even at f/28, a writing speed of 15 metres is obtainable with a cathode current of less than 10 microamperes. The definition is excellent under these conditions. Different individuals, in actual test, rarely differ by more than 0·002 cm. in the measurements of well focussed curves.

Automatic Controlling and Calibrating Unit. The unit was built at Kirkee, to get proper sequencing of the operations required for a pressure-time record. In preliminary work, a number of sources of error were noticed. Firstly, the oscillograph record was undesirably affected by the magnetic field of the coils operating the camera shutters. The amplifier characteristic was somewhat variable with warming up and it was desirable to do a voltage-deflection curve immediately before the pressure-time curve. The photographic paper could not be clamped to the camera drum tight enough to prevent a sagging error. The high resistance input easily picked up even minute leakages from high voltage points and mains and vitiated the pressure record. These have all been eliminated more or less completely by this unit. On operating a switch, the relays operating the shutters of the cathode ray tube are operated by the discharge of a condenser. There is therefore no interfering standing magnetic field. After one revolution of the drum, voltages 1·0, ·9, ·8 etc. to 0·1 and 0·0 (checked against a standard Weston cell) are fed into the input of the amplifier. The input is discharged and left insulated. The camera is allowed to run freely one more round as a check for stray pick up and then a 40 mF condenser charged to 400 volts is discharged into the thin nichrome ignition wire inside the closed vessel. This starts the explosive train. The pressure build up is recorded in succession by piezo gauge, the D.C. Amplifier, the Cathode Ray Tube and the Drum Camera. The arrangement is such that during the recording sequence no part of the automatic controller is at a voltage sensibly different from earth, and no interfering pulses are present. This eliminates spurious pick-ups and the various delays built into the recording sequence, provide (1) an accurate datum line (2) a direct voltage deflection curve and (3) a close check for the absence of spurious pick-ups and (4) an accurate zero-pressure line.

With these changes, the measurements and computation have been made considerably easier and free from ambiguity.

2. Taking a pressure-time record.

A charge of propellant sufficient to give the required density of loading is carefully sampled. The standard density of loading is 0·200. The sizes are measured, the charge is weighed and placed inside the prepared bomb. The amplifier, CR Tube, Calibrator and the motor of the drum camera are, one by one, got steady. The piezo gauge is mounted in the calibrating press. The press cam is adjusted to the required thrust. The amplifier and CR-tube having been warmed up, a calibrating record of the gauge is taken on the drum camera. This gives a series of marks corresponding to 0·0, 0·1, 0·2 etc., volts up to 1·0 volt for the overall characteristic curve of the recorder. At the end of the marks, it gives also the voltage across a silvered mica condenser, that has been charged by the piezo-gauge. The gauge is then replaced in its end block. The end blocks are then screwed in.

The bomb chamber is evacuated and filled successively with one-fifth ethylene, two fifths oxygen and two-fifths air. This gives on ignition a gas mixture very close to the common powder gases, and thus gives least disturbance to the final equilibrium. The weight of this gas is taken as part of the propellant charge (about 0·82 g).

After filling with the gas mixture ; the leads to the ignition wire and piezo gauge are connected, the room is cleared of all personnel and then closed.

With the amplifier, calibrator, C.R. tube and motor speed in steady condition, the press switch is operated. This operates in sequence,

(1) the timer shutter, which puts in millisecond marks on the sensitive paper ;

(2) the cathode ray tube shutter, which keeps open to the very end ;

(3) delays the voltage calibration marks for one revolution of the camera and thus allows the CR tube to draw an accurate zero line ;

(4) runs the voltage calibration switch which provides the overall calibration check on the amplifier, a fraction of a second before the actual recording pressure curve ;

(5) leaves the gauge input to amplifier, highly insulated and delays the firing for one more revolution of the camera to allow examination for any possible disturbances in this highly insulated condition ; and

(6) closes the firing switch which heats up the ignition wire.

The pressure-time curve is then recorded on the paper by CR Tube spot. About half a minute later, the gas is let out from the bomb and the pressure guage removed to the calibrating press and one more record taken.

The paper is developed, dried carefully to eliminate distration of paper during drying.

3. *Measurement and Computation.* The curve is aligned under the microscope for minimum sag and ripple error. The voltages due to calibrating press before and after explosion are measured. These repeat to within 0·3 per cent. in satisfactory recording. The maximum pressure voltage in the explosive is observed. The calibration curve for the explosion pressure is next calculated. These corrections with those of ripple in the datum line are applied to all readings, thus converting them all to an idealised linear scale. The maximum pressure (P max) so got is divided into 50 intervals and the pressure readings corresponding to 0·980, 0·940, 0·900 etc. to 0·02 P max. calculated. Corrections for calibration etc., are applied to each of these to convert them back to actual microscope readings and the microscope cross wires brought in to cut the curve symmetrically. The times corresponding to the various pressures are noted. The time marks are also measured. This completes the measurement.

Basis of Computation: The law of burning by parallel layers is assumed. On this basis by purely geometric methods the relation between φ the fraction burnt of charge (C) and f the fraction of web (D) left unburnt is deduced. A tabular form is then prepared giving $df/d\varphi$ for all the values of φ from 0 to 1·0 in steps of 0·02.

For long tubes *e.g.*, $\varphi = 1 - f$ and $\frac{df}{d\varphi} = -1$

and for cords, $\varphi = 1 - f^2$, $\frac{df}{d\varphi} = \frac{-1}{\sqrt{(1-\varphi)}}$

As the samples used in closed vessel are about 4-5 inches long with a size under 0·05 inches, the condition for infinite tubes and cords is sufficiently satisfied.

The burning law is assumed to be

$$- D \frac{df}{dt} = \beta \rho^{\alpha} \text{ which involves f.}$$

As however the records give only the relation P—t, the equation of state is necessary to link P with f through φ. The Abel's form of this equation would be

$$P \left[v - \frac{C}{\rho} - \left(\eta - \frac{1}{\rho} \right) C \varphi \right] = RTC\varphi \ldots\ldots\ldots\ldots\ldots (1)$$

After burning $P_{max.} [V - \eta c] = RTC \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$

From the measuring microscope, we have time readings for various pressures:

$P = \gamma P_{max.}$ $(\gamma = 0{\cdot}02, 0{\cdot}04 \ldots\ldots\ldots \text{etc.})$

Dividing (1) by (2) and rearranging we get

$$\frac{\varphi}{\gamma} = \left[1 + \frac{\eta - 1/\rho}{V - \eta C} C \left(1 - \varphi \right) \right]$$

which becomes on putting $C/V = \triangle$ = the density of loading,

$$\varphi/\gamma = \left[1 + \frac{(\eta - 1/\rho) \triangle}{1 - \eta \triangle} (1 - \varphi) \right] \ldots\ldots\ldots\ldots (3)$$

Putting $\frac{(\eta - 1/\rho) \triangle}{1 - \eta \triangle} = \delta$ where δ is

a small fraction, about 0·08 to 0·09 under normal conditions,

(3) can be arranged as

$$1 - \varphi = \frac{1 - \gamma}{1 + \delta\gamma}$$

On differentiating both sides and rearranging we get

$$\frac{d\varphi}{d\gamma} = \frac{1+\delta}{(1+\delta\gamma)^2} = 1+\delta\,(1-2\gamma)\text{ (approx.)} \quad \ldots\ldots(4)$$

The burning equation can be now rewritten as

$$\frac{df}{d\varphi} \cdot \frac{d\varphi}{d\gamma} \cdot \frac{d\gamma}{dt} = -\beta/D\ \rho^{\alpha} \quad \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

The first factor on the left is got from the tables already prepared. The second factor is got from (4), and $d\gamma/dt$, the tangent at γ is taken as identical with the chord connecting $\gamma + 0{\cdot}04$ and $\gamma - 0{\cdot}04$.

The corresponding time readings are taken and $\frac{dv}{dt}$ calculated thus

$$\frac{0{\cdot}08}{t_{(\gamma+0\cdot04)} - t_{(\gamma-0\cdot04)}} = \frac{\Delta\,\gamma}{\Delta\,t_\gamma} = \frac{d\gamma}{dt}$$

The factors on the left hand side of (5) are then multiplied together and tabulated as df/dt against values of γ. A graphical plot is then made as a first check between log (df/dt) and log γ. The points usually fit a straight line between $\gamma = 0{\cdot}12$ and $\gamma = 0{\cdot}84$. Above $0{\cdot}84$ there is a sudden sag for tubes. With cords the sag starts at $0{\cdot}80$. Rejecting these points, a least square fit is made for the other points and the values of α and β determined therefrom. The standard deviation of the data is also noted. In good records this is under one per cent.

It would be noticed that a straight line fit would be possible *i.e.*, the least standard deviation obtained only if

(1) the index law of burning is obeyed,

(2) the values of coefficients are correct in the form function $\varphi = (1-f)\,(1+\theta f)$,

(3) the values of d $\varphi/d\gamma$ due to co-volume and density of loading are correct,

(4) that the burning constant β is not varying with the fraction burnt,

(5) that the index (α) is not varying with φ,

(6) that no change of form is caused by the dynamic pressures of the gases during burning, and

(7) that there is no splintering or nonuniform ignition or nonuniform burning.

Unlike the gun, no adjustable constants to fit the firing data are available. So the method can be used as a check (more or less rigorous) on all the above seven conditions.

Force constant. After burning, the equation of state gives

$$P_{max.} (V - \eta c) = \eta R T_0 C = F C$$

This can be rearranged as

$$\frac{P_{max.}}{\triangle} (1 - \eta \triangle) = F \quad \text{........................(6)}$$

It would appear that this (particularly if $P_{max.}$ is measured at different $\triangle$s) would lead to direct and accurate values of F and η. Unfortunately, the $P_{max.}$ recorded in C. V. requires a cooling correction, whose value is known to be about 4 per cent. for normal propellants. The actual value depends on the flame temperature and density of loading in a way not yet clearly understood. The cooling curve itself shows cooling to be non-linear with time. These uncertainties make the attainable precision of direct F measurements from the closed vessel much less than those obtainable by purely physico-chemical calculations. The closed vessel figure however is a close check on the accuracy of the various assumptions made in the physico-chemical method. Experimental values of F, are repeatable to 0·2 per cent. for gun propellants but because of the uncertainties mentioned, differences of the order of 1 per cent. from calculated values occur with different compositions. This is also the experience with CSAR in UK. The method is probably capable of further development.

Co-volume. It has been mentioned that (6) gives co-volume also, if $P_{max.}$ is measured at different densities of loading. For example

$$P_1/\triangle_1 = F + \eta P_1 \qquad\qquad P_2/\triangle_2 = F + \eta P_2$$

which gives

$$\eta = \frac{P_1/\triangle_1 - P_2/\triangle_2}{P_1 - P_2} \quad \text{................(7)}$$

Although $\triangle$s can be measured to any required accuracy and $P_{max.}$ is repeatable to 0·2 per cent, η values are not so accurate. The causes are again due to the cooling corrections to $P_{max.}$ being dependant on densities of loading and only approximate. Moreover, $P_1/\triangle_1 - P_2/\triangle_2$ is a small term affected by the full errors of both P_1 and P_2 measurements. It would be noticed that the maximum error,

$$\frac{\delta \eta}{\eta} = \frac{\delta P_1/\triangle_1 + \delta P_2/\triangle_2}{P_1/\triangle_1 - P_2/\triangle_2} - \frac{\delta P_1 + \delta P_2}{P_1 + P_2}$$ with values of $\triangle_1 = 0{\cdot}2$,

$\triangle_2 = 0{\cdot}1$. and $P_1 - P_2 = 9$ tons and $\delta P_2 = \delta P_1 = 1/10$ tons.

One obtains $d\eta/\eta = 0{\cdot}13$ i.e., 13 per cent. max. error.

Of course by replication the probable error can be reduced considerably below this maximum possible error. Pressures can at present be measured only to an accuracy of 0.03 ton at best. On the whole, the best values of γ obtainable by the closed vessel cannot be expected to be better than 2 per cent. in accuracy for the present. The values from U.K. are usually calculated from Corner's formula. The closed vessel figure, however, provides an experimental check on the calculated figure.

Rate of burning constants β *and* α. It has already been shown that these are got by a least square fit to the full data from the pressure-time curve. Usually three to six separate firings are taken and the average values chosen for the final fit. The standard deviation is usually under 1 per cent. for satisfactory curves. The burning constant β is normally reliable to one per cent. and α to two per cent.

Form function It has been shown before that plots of Log $\frac{df}{dt}$ against Log γ follow a straight line only, if among other things, the form function is also correct.

For example, if in $\varphi = (1 - f)\ (1 + \theta f)$, θ is taken 0·01 in place of 0 for tube, the effect on standard deviation would be nearly two-thirds per cent. This can be shown as follows :—

$$df/d\varphi = \frac{-1}{1 - \theta + 2\theta f}$$ is the factor multiplying the observed $d\gamma/dt$.

Differentiating with reference to θ this becomes $-\frac{1-2f}{(1-\theta+2\theta f)^2}$ which when $\theta = 0$ gives $(1-2f)\,d\theta$ as the error in $df/d\varphi$. This varies from $+d\theta$ at $f=0$ to $-d\theta$ at $f=1$ the significant deviation amounting to about two thirds $d\theta$.

As tubular cordite gives a straight line fit to within 1 per cent., one might take θ for tubes in closed vessel as zero $\pm$ 0.015

Regularity of burning splintering, end burning etc. From the inspection point of view, this is very important. Unfortunately no cordite is perfect. Thus a standard burning curve has to be chosen for the comparison. Only qualitative results are available so far. But with a new method of recording rate of pressure-rise-time curves, it has been found possible to record interesting differences very clearly, between different lots of cordite. The method is being followed up quantitatively.

Delayed ignition. Ignitability of cordite is an important property taken for granted. Unfortunately, due probably to somewhat larger percentages of surface moisture, some cordites ignite somewhat after others, giving erratic burning rates and sometimes coming out unburnt from the gun. The delay between the application of the standard flame *i.e.*, almost the same as the flame of the cordite and the ignition of cordite is easily studied in the first stages of the pressure-time record. This is being followed up at Kirkee.

For moderated powders and powders with porous structures with or without moderation, no methods are yet available either for computation or study. As these form an increasing part of newer types, methods would have to be devised for their quantitative measurements and check up.

In addition many propellants though not plastic in the usual sense, are sufficiently plastic to be deformed under the pressure differences between their hollow interiors and outside. For example, some tubular cordites can bulge with differences of pressure of only 2-3 atmospheres. These pressures seem available easily under burning conditions. No computational or experimental method exists to take account of these behaviours which would affect the web size seriously. The closed vessel seems to be adaptable for all these problems, if the experiments are suitably designed.