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AIR MINISTRY
S.D. 732J

(FIRST EDITION AUGUST, 1955)

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JOINT SERVICES TEXTBOOK OF GUIDED WEAPONS

PART 9

FC

THE DESIGN OF SOLID PROPELLANT ROCKET MOTORS

MINISTRY OF SUPPLY

Prepared by direction of the
Minister of Supply

J. R. C. Helmore

BEST AVAILABLE COPY

Promulgated for the information and guidance of all concerned

By Command of Their Lordships	By Command of the Army Council	By Order of the Air Council
J. G. Lang	G. W. Turner	M. J. Dean
Admiralty	War Office	Air Ministry

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34		
35		
36		
37		
38		
39		
40		

LIST OF CONTENTS

Section 1—GENERAL CONSIDERATIONS

	Para.
Introduction	1
Solid versus liquid propellant motors	4
Scope of this Part	8
Main components of a solid propellant motor	10
Notation and Units	13
Elementary internal ballistic theory	14
Erosion factor	20
The general approach to design	24

Section 2—THE PROPELLANT CHARGE

	Para.
Types of solid propellant	33
Mechanism of burning of solid propellants	35
Functional limitations of solid propellants	38
Dependence of burning rate on pressure	38
Dependence of burning rate on temperature	42
Erosive burning	44
Colloidal propellants	50
Composite propellants	57
General limitations	58
Manufacturing limitations of solid propellants	62
Colloidal propellants	62
Composite propellants	66
The relation between performance and geometry of rocket charges	70
Web thickness	79
Selection of a charge design to suit a given requirement	81
Inhibition of burning of colloidal propellants	88
Materials used for inhibitors	90
Techniques for inhibiting cordite charges	94
Effect of stress on properties of the propellant	107
Cordite charges	108
Plastic propellant charges	112
Effect of hot storage on propellants	117
Flash and smoke	126
Colloidal propellants	127
Composite propellants	130
Radio attenuation	131
Regularity of burning	133

Section 3—THE MOTOR BODY DESIGN

	Para.
General considerations	137
Essential design principles	148
Motor tube design	148
End design	155
The choice of materials	159
Manufacturing considerations	164
Methods of obturation	171
Obturators to assist thermal insulation	173
Obturators used to seal end closures	176

Section 4—THE IGNITER

	Para.
Igniting compositions	177
Flashless ignition	182
Igniter shock	184
Design of igniter containers	186
Location of the igniter	186
Principles governing the design	188
Choice of materials	193
Description of typical housings	199
The maintainer igniter	206

Section 5—THE NOZZLE

	Para.
General considerations	209
Nozzle theory	211
Thrust	218
Multiple, inclined, and spring nozzles	224
Use of different nozzle sizes	227
Materials used in nozzle construction	229
Nozzle extension tubes	236

Section 6—THE OVERALL DESIGN

	Para.
Introduction	241
Design of a rocket boost motor	244
Design of a rocket sustainer motor	255

Appendix A—MANUFACTURING CONSIDERATIONS ASSOCIATED WITH ROCKET MOTOR BODIES

	Para.
General considerations	A1
Introduction	A1
Requirements for rocket motor tubes	A2
Industrial methods of steel tube manufacture	A4
Manufacturing tolerances allowed for rocket motor tubes	A5
Steel tubes	A13
Heavy weight	A13
Medium weight	A14
Light weight	A33
Deep-drawn tubes	A60
Summary	A69
Light-alloy tubes	A75
Plastic tubes	A83
Introduction	A83
Choice of reinforcing fibre	A86
Method of manufacture	A89
End closures	A94
Summary	A96
Strip wound tubes	A97
Introduction	A97
Principles of design	A99
Principles of manufacture	A102
Preparation and assembly of tube	A105
Properties of strip wound tubes	A106
Inspection and testing of rocket motor tubes	A109
Mean diameter, ovality, and bow	A109
Measurement of wall thickness	A110
Pressure testing	A113
Nozzles	A115
Introduction	A115
Problems of nozzle manufacture	A118

REFERENCES

INDEX

LIST OF ILLUSTRATIONS

	Fig.
The main components of a solid propellant rocket motor	1
Variation of erosion factor for typical propellant	2
Variation of rate of burning with pressure for typical propellant	3
Variation of rate of burning with pressure for typical platonized and unplatonized propellants	4
Erosive burning of cordite	5
Variation of pressure with time for 3-in. rocket using SU cruciform charge at 0° F	6
Variation of minimum pressure with temperature for 3-in. rocket using SU and SU/K charges	7
Change in charge shape of 5th November rocket	8
Variation of charge shape and perimeter for typical charges	9
Variation of charge shape and perimeter for typical inhibited perforated charges	10
Relation between the charge length and its diameter	11
Migration of nitroglycerin into unplasticized samples of cellulose acetate and ethyl cellulose	12
Cordite charge supported on tabs	13
How tabbed charges are supported	14
Stripped cruciform charge	15
Mould used in hot moulding process	16
Plastic coating expansion mould used in the stress relief technique	17
Coating operation in stress relief technique	18
Coating machine used in stress relief technique	19
Cracks in cordite charges due to hot storage	20

	Fig.
Distension of coating on solid cord charge due to hot storage	21
Fragment of cruciform charge after bursting	22
Elimination of flash from cordite charges	23
Flash intensity during burning for 2-in. rocket with charges containing varying proportions of potassium cryolite	24
Elimination of smoke from plastic propellants	25
Pressure curves for 9-in. rocket fired at −40°C showing elimination of secondary peaks	26
Pressure curves for 5-in. rocket showing pressure oscillations	27
Variation of pressure with time of burning for different ambient temperatures	28
Influence of length/diameter ratio on motor body weight	29
Shapes of four existing rocket motor bodies	30
Specific proof strength of rocket materials at elevated temperatures	31
Attachment of ends in plastic tubes	32
Obturation to assist thermal insulation	33
Obturation to seal end closures	34
Photomicrographs of various grades of magnesium powders	35
Initial shock produced by igniter	36
Typical paper carton igniter and method of housing	37
Metal igniter housing used in 9-in. rocket	38
Igniter used in 4-sec. assisted take-off unit	39
Variation in critical pressure with time of maintenance for SU/D propellant	40
Typical convergent-divergent nozzle	41
Variation of expansion ratio with pressure for diverging portion of a nozzle	42
Multiple nozzle block showing inclined nozzles	43
Guided missile showing inclined nozzles on boost motors	44
Valve nozzle	45
Section through nozzle made from reinforced resin	46
Cross-section of typical supersonic blast tube	47
Slotted tubular charge	48
End-burning cavity-type charge	49
Mean diameter, ovality, and bow	A1
Typical medium diameter rocket motor body tube	A2
Hot swaging process	A3
Mayfly rocket motor tube	A4
Stages in manufacture of cold-drawn Mayfly tube	A5
Stages in manufacture of thin-walled Mayfly tube	A6
Composite method of manufacturing Mayfly tubes	A7
Mayfly tube fabricated from sheet	A8
Tools used for preforming sheet metal	A9
Machine used for longitudinal welding of medium weight tubes	A10
Portable grinder for smoothing longitudinal welds	A11
CECO dropstamp used for sizing external diameter of tube	A12
Broaching equipment	A13
Gosling rocket motor tube	A14
Brake press used for preforming metal sheet	A15
Equipment used for longitudinal welding of light weight tubes	A16
Clamping fixture to facilitate longitudinal welding	A17
Backing bar	A18
Stretch forming rig	A19
Welding machine used for circumferential welding	A20
Backing bars used during circumferential welding	A21
Buzzard motor tube	A22
Stages in the manufacture of Buzzard motor tubes by deep drawing	A23
Tapered tube produced by further deep drawing of Buzzard tube	A24
Modified Mayfly tube produced by deep drawing	A25
Demon light-alloy boost motor	A26
High strength light-alloy rocket tube	A27
Manufacture of high strength light-alloy rocket tubes	A28
Principle of alignment telescope	A29
Measurement of rocket tube wall thickness	A30
Pressure testing rocket tubes	A31
The conditions of gas flow in a nozzle	A32
Typical canted nozzle	A33
Dome and cone method of nozzle manufacture	A34
Combined plastic nozzle and rear end closures	A35

LIST OF TABLES

	Table
Formulations of typical colloidal propellants	1
Formulations of typical composite propellants	2
Performance data for typical solid propellants	3
Effect on rocket performance of decreasing body weight and increasing charge weight	4
Materials considered for motor tube manufacture	5
Predicted surface temperatures and melting points for nozzles made from various metals	6
Design data for solid propellant rockets	7
Design and performance details of solid propellant rocket motors	8
Composition of steel used for cold-drawn Mayfly motor tube	A1
Compositions of materials used for fabricated Mayfly motor tubes	A2
Properties of manganese steels after heat treatment	A3
Compositions of steel used for light weight tubes	A4
Properties of SAE 4130 before and after heat treatment	A5
Hardness readings before and after heat treatment	A6
Composition and properties of steel used for deep-drawn tubes	A7
Composition and properties of light alloy DTD 464A	A8

THE DESIGN OF SOLID PROPELLANT ROCKET MOTORS

Section I

GENERAL CONSIDERATIONS

INTRODUCTION

1. The use of solid propellants for rockets dates back many years. History records that at least as early as the 13th century, the Chinese used a weapon called the 'arrow of flying fire'. This was a very crude and elementary rocket based on the use of a solid propellant; it consisted of an arrow to which was attached a package of incendiary powder. Through the years, various references to rockets can be found in the records of military events, and these rockets were all weapons based on the use of a solid propellant. It was not until the end of the 19th century that a liquid propellant rocket motor was developed by an engineer from Peru who made the first practical working rocket motor of this type.

2. Since the end of World War 1, all the major combatant powers have been engaged on rocket development and this has led to many examples of rocket propulsion. As examples of units using solid propellants we may cite the following :—

(1) rocket motors to assist the take-off of aircraft*

(2) anti-tank weapons for use by infantry, e.g. American Bazooka

(3) rockets fired by aircraft, and multiple barrage weapons.

The development of liquid propellant rocket motors is best typified by the following German applications :—

(1) the well-known V2 missile

(2) the Messerschmidt 163 rocket propelled piloted aircraft.

More recently much work has been done on the development of rocket motors for guided weapon applications, both main sustainer and boost motors.

3. In designing a rocket motor for a specific project it must be decided whether to use a solid propellant motor or a liquid propellant motor. Some of the factors involved in making this decision will now be considered.

Solid versus liquid propellant motors

4. A solid propellant rocket motor comprises relatively few components and in this respect it is very simple in comparison with a liquid propellant motor. It consists essentially of a container or chamber in which combustion of the propellant takes place, and a convergent-divergent nozzle through which the products of combustion escape as a jet. These two components, which are usually though not necessarily made of metal, constitute the 'motor body'. Since the propellant is solid it is incapable of being transferred from one part of the rocket to another and it is therefore stored inside this motor body.

5. This fact constitutes the first major difference between solid and liquid propellant motors. It means that the solid propellant motor body must not only be large enough to contain all the propellant, but it must also be strong enough to withstand the loads imposed by gases at full combustion temperature and pressure. With a liquid fuel motor the propellant can be stored elsewhere in a tank, which will not be subject to combustion conditions, and delivered to a separate small combustion chamber at the required rate. On the other hand the mere fact that the solid propellant is all stored in the combustion chamber means that all the complexities of feed systems, valves, lines, and injectors are completely eliminated. An obvious conclusion which follows from this is that increase in size favours the use of liquid rather than solid propellants. Although ingenuity in detail design may exert a considerable influence on whether one type or another is more suitable for specific requirements, nevertheless the conclusion stated, if treated as a very broad generalization, is essentially true.

6. The second important factor influencing the selection of solid or liquid propellant for any given requirement arises from the manner in which the propellant burns. Solid propellant charges burn down in parallel layers, and just like logs of wood or sticks in a fire, their time of burning is controlled by their minimum dimension. The longer therefore that the motor is required to burn, the thicker must be the minimum dimension of the propellant charge.

7. It is clear from this that motors for very long and very short burning times are most conveniently based on liquid and solid propellants respectively; for intermediate burning times, both time and size are used as the main determining factors in the choice between liquid and solid propellants. The full significance of this will be appreciated later when some indication is given of the possibilities of solid propellant motor

* Assisted take-off units using a liquid propellant motor have also been developed.

design. Of course other factors must be taken into consideration also, for example, relative cost, reliability, availability, safety and transport on land or in H.M. ships. A comparison between solid and liquid propellant rocket motors is given in Part 10—The design of liquid propellant rocket motors.

Scope of this Part

8. This Part of the Textbook will deal with design problems related to solid propellant rockets (corresponding problems for liquid propellant motors are covered in Part 10). The remainder of this Section first describes the main components of a solid propellant motor and the notation and terms used in this Part. This is followed by a brief outline of the elementary internal ballistic theory used in design, and the Section concludes with a short review of the design requirements as a whole, leaving the detailed design consideration to a later Section.

9. The design problems relating to the main components of the rocket, i.e. the propellant charge, the motor body, the igniter, and the nozzle, are covered by Sections 2 to 5. The final Section, on the overall design, draws together the considerations of the preceding sections and indicates the types of compromise that are necessary in finalizing the overall design. The general procedure from specification to design and clearance is illustrated by consideration of specific examples.

MAIN COMPONENTS OF A SOLID PROPELLANT MOTOR

10. In the field of solid propellant rocketry, as in every other technical field, certain special terms are in general use and before the design problems can be considered in any detail it is desirable that these terms should be explained. This applies particularly to the component parts of the rocket.

11. For this reason an extremely simple diagrammatic sketch of a solid propellant rocket motor is shown in fig. 1 and the names of the main components are shown. The meaning and significance of these terms will be almost self-evident in some cases, but for completeness elementary definitions are given below. In some parts of the literature on this subject, notably that emanating from overseas, alternative terminology is used, but throughout this Part the terms shown in fig. 1 and described here are employed.

12. The definitions of the main components are as follows :—

Motor tube—The vessel in which the propellant is housed and in which combustion occurs is normally referred to as the motor tube.

Propellant charge—In British parlance the propellant is referred to as a charge. The term charge covers the complete propellant and the charge weight is the total weight of actual propellant loaded. Where the charge is in more than one piece, the separate pieces are usually called sticks.

Inhibitor—This is a coating of inert material applied to part of the propellant surface to prevent burning of the charge over that area.

Head end plate—This component partially or wholly covers the forward end of the motor tube. Its form varies quite widely from motor to motor. In certain cases it may be a flat plate screwed into the tube ; in others it may be an internally threaded cap which fits over the end of the tube ; in British Service 2-in. and 3-in. rockets it is in the form of a ring held in place by steel pins. In some more advanced designs this component is eliminated completely by forming the tube into a dome at the head end.

Thrust plug—In most applications the head end plate is provided with a central hole and in use this must be

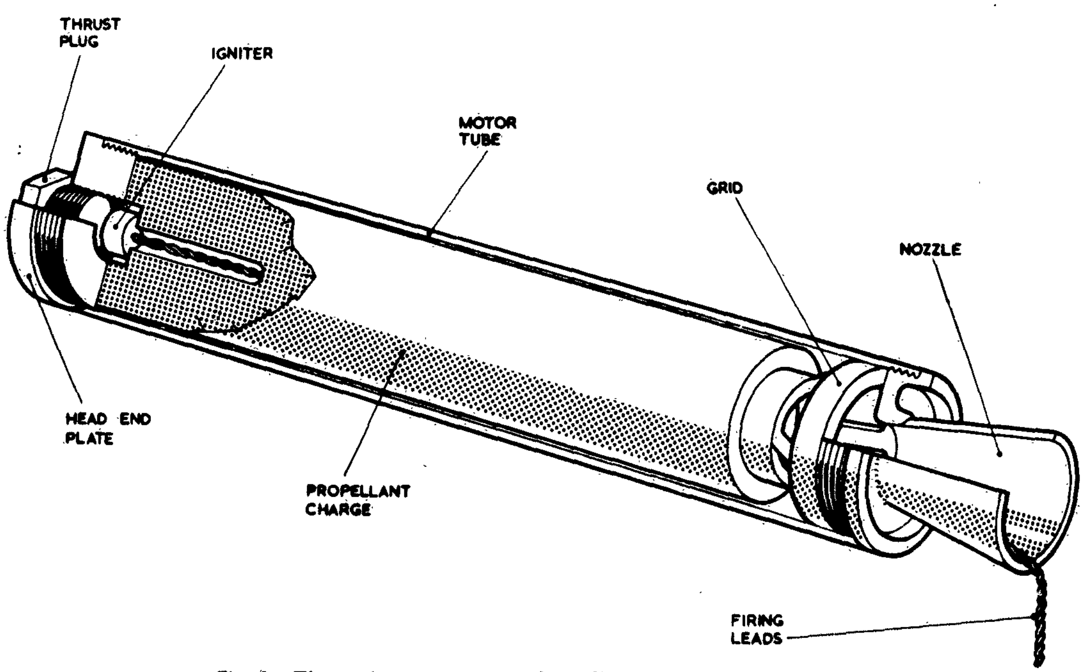


Fig. 1. The main components of a solid propellant rocket motor

completely closed. This is done by means of a thrust plug, in some cases a simple plug, in others a spigot at the base of a warhead.

Nozzle—At the open end of the motor tube the rocket is provided with a convergent-divergent nozzle, which converts the thermal energy of the combustion products into kinetic energy in the jet.

Nozzle end plate—This is essentially the connection piece between the motor tube and the nozzle itself. Frequently the nozzle and its end plate are combined in one integral component (see fig. 1).

Grid—With some designs of motor it is necessary to support the charge away from the entrance to the nozzle, in order not to impede the gas flow from the burning propellant. This is done by means of a grid.

Igniter—Ignition of a solid propellant rocket is achieved by the burning of a small quantity of pyrotechnic composition. This is normally housed in a simple light container near the closed end of the motor tube, and is initiated by means of a low-tension electric fuse.

NOTATION AND UNITS

13. For convenience of subsequent reference the mathematical symbols used in this Part are listed below.

Units

In Section 1 and 5 absolute units (pounds mass, poundals, feet, and seconds) are used. In Section 2 units are chosen which, although not necessarily consistent, are those commonly employed in design work and performance measurement.

Symbols

A_d = area of cross-section of the bore of the motor tube

A = area of gas conduit, i.e. the area of the cross-section of motor tube not filled by charge, through which the combustion gases flow

A_s = area of cross-section of propellant charge

A_t = area of cross-section of nozzle at its throat or minimum section

A_e = area of cross-section of nozzle exit

a = a constant in the equation $B = a + bp$ relating rate of burning and pressure

B = general symbol for the rate of burning of the propellant, i.e. the rate of recession of its burning surface

B_0 = rate of burning of the propellant at zero gas velocity, i.e. the rate of recession of the surface with no gas flow over it

$\bar{B}$ = mean rate of burning of the propellant with gas flow over the burning surface

b = a constant in the equation $B = a + bp$ relating rate of burning and pressure

C = contribution of energy to the gas stream supplied per unit mass of propellant

$\sqrt{2C}$ = maximum velocity which would be attained by the propellant gases if expanded to zero pressure

c = velocity of sound; also a constant in the equation $B = cp^q$ relating rate of burning and pressure

D = external diameter of propellant charge

d = internal diameter of motor tube

d_t = nozzle throat diameter

F = hoop stress in motor tube

$f(A_t/A)$ = erosion factor

g = gravitational acceleration

K = a constant in the prediction formula, a function of γ, σ and $2C$

l = charge length

M = mass of the complete rocket projectile

m = mass of the propellant charge

N_D = nozzle discharge coefficient or the mass of gas crossing unit area of nozzle throat per unit time per unit of reservoir pressure

P = perimeter of burning surface of charge

p = static pressure of propellant gases

Q_0 = rate of production of propellant gases

Q_t = rate of discharge of propellant gases through nozzle throat

q = pressure exponent in the law of burning $B = cp^q$

S = area of burning surface of charge

S.I. = specific impulse, i.e. the impulse supplied per unit weight of propellant, or the thrust imparted to the rocket when unit weight of gas is discharged per unit time (in the latter form the term specific thrust is used)

T = thrust or the forward force developed by the rocket

t = wall thickness of motor body tube

t_B = time of burning of the propellant charge

T.I. = total impulse, or the integral of the thrust over the entire burning period. It is also the momentum given to the rocket and in a steady state is equal to the product of the propellant charge weight and the specific impulse

V = all-burnt velocity of the complete rocket projectile

v = velocity of gases

w = web thickness of propellant

γ = mean ratio of specific heats at constant pressure and constant volume of the propellant gases

λ = ratio A/A_t

ρ = density of propellant gases

σ = density of solid propellant

π = reduced variable for pressure; equal to $p_0/2C$

Suffix

$_0$ = value at closed end of combustion chamber; also indicates reservoir pressure

$_e$ = value at nozzle exit

$_t$ = value at nozzle throat

ELEMENTARY INTERNAL BALLISTIC THEORY

14. In designing a rocket motor it is necessary to be able to predict the pressure developed at any stage during burning; for example, a knowledge of the peak pressure (see para. 23) is necessary in determining strength requirements. From internal ballistic theory the pressure p can be found; an outline of the mathematical theory involved is given here. For a full treatment of rocket internal ballistics the reader is referred to Part 2 of the Textbook (The fundamental principles of rocket propulsion), where the equations quoted in the following paragraphs are established.

15. It is assumed that a 'steady state' exists in the motor, that is, the rate of production of gas Q_0 from the burning charge is equal to the rate of efflux Q_t through the nozzle. From the principle of conservation of mass we may write

$$Q_0 = Q_t \qquad \ldots(1)$$

If $\overline{B}$ is the mean rate of burning of the propellant, σ the density of the propellant, and S the total area of burning surface, the rate of production of gas is given by the equation

$$Q_0 = \sigma S \overline{B} \qquad \ldots(2)$$

If the area of the nozzle throat is A_t, and the gas velocity and density there are v_t and ρ_t respectively, then the rate of mass efflux through the nozzle is given by the equation

$$Q_t = A_t \rho_t v_t \qquad \ldots(3)$$

16. From equation 1 we may write

$$\sigma S \overline{B} = A_t \rho_t v_t \qquad \ldots(4)$$

If it is further assumed that the gas velocity over the surface of the charge is so small that the mean rate of burning $\overline{B}$ of the propellant can be represented by B_0, the rate of burning under zero gas velocity, and that the pressure over all points of the charge is the same as the head end pressure p_0, we have

$$\sigma S B_0 = A_t \rho_t v_t \qquad \ldots(5)$$

In practice, of course, the assumption that the gas velocity is zero is not valid; this point will be discussed in para. 20.

17. If the contribution of energy to the gas stream per unit mass of propellant is C, and γ is the mean ratio of the specific heats of the products of combustion, then the equation of conservation of energy in a compressible fluid stream is given by Bernoulli's equation

$$\frac{\gamma}{\gamma - 1}\frac{p}{\rho} + \frac{1}{2}v^2 = C = \frac{\gamma}{\gamma - 1}\frac{p_0}{\rho_0} \qquad \ldots(6)$$

where p and ρ are the pressure and density at a section where the velocity of the stream is v.

18. The relation between pressure and density for frictionless adiabatic flow is given by the equation

$$\frac{p}{\rho^\gamma} = \frac{p_0}{\rho_0{}^\gamma} \qquad \ldots(7)$$

and the velocity of the gas at the nozzle throat is equal to the local velocity of sound (see Section 5) and hence

$$v_t = \left(\frac{\gamma p_t}{\rho_t}\right)^{\frac{1}{2}} \qquad \ldots(8)$$

From equation 6, 7, and 8 it is not difficult to derive the relations

$$v_t = \left(\frac{\gamma - 1}{\gamma + 1}\right)^{\frac{1}{2}} (2C)^{\frac{1}{2}} \qquad \ldots(9)$$

$$\rho_t = \frac{1}{C}\frac{\gamma}{\gamma - 1}\left(\frac{2}{\gamma + 1}\right)^{\frac{1}{\gamma - 1}} p_0 \qquad \ldots(10)$$

19. Substituting these values of v_t and ρ_t in equation 3 gives

$$Q_t = \frac{\gamma}{(2C)^{\frac{1}{2}}}\left(\frac{\gamma + 1}{\gamma - 1}\right)^{\frac{1}{2}}\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma - 1}} A_t p_0 \qquad \ldots(11)$$

It can be seen that the rate of mass efflux is proportional to the pressure and the throat area. The constant of proportionality is usually referred to as the *nozzle discharge coefficient* (or nozzle constant) and is denoted by N_D, which depends only on the properties of the propellant. We thus have

$$N_D = \frac{\gamma}{(2C)^{\frac{1}{2}}}\left(\frac{\gamma + 1}{\gamma - 1}\right)^{\frac{1}{2}}\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma - 1}} \qquad \ldots(12)$$

Hence we may write equation 5 as follows

$$\sigma S B_0 = A_t N_D p_0 \qquad \ldots(13)$$

Erosion factor

20. Although the relationship expressed by equation 13 is a fundamental one for the internal ballistics of solid propellant rocket motors, it assumes that the gas velocity over the burning charge surface is zero. In practice this is not so, and the rate of burning of the propellant is enhanced by the gas flow. In Part 2 (para. 292) it is shown that this gas flow effect can be taken into account by introducing a simple multiplying factor which is a function of the ratio of the area of the nozzle throat cross-section to the area of the cross-section of the gas conduit, i.e. the ratio A_t/A. This multiplying factor is called the *erosion* factor (see para. 44 for use of term erosion).

21. In order to predict the pressure developed by a rocket design at any stage of burning, it is necessary to know the magnitude of this erosion factor, in addition to the relation (equation 13) between the pressure and rate of burning of the propellant at zero gas velocity. It will be found that for practical calculations the fundamental units in which equation 13 is expressed give rise to quantities whose magnitudes make them inconvenient to handle; the units are therefore usually changed to those of normal practical usage. In addition, the quantity p_0 is replaced by π_0 where $\pi_0 = p_0/2C$.

22. Equation 13 now becomes $B_0/\pi_0 = 2CN_D A_t/\sigma S$. Since for any given propellant $2C$, N_D, and σ are constants we may write $B_0/\pi_0 = KA_t/S$, where $K = 2CN_D/\sigma$. For erosive burning, where we take account of gas velocity, we have

$$\frac{B_0}{\pi_0} = \frac{KA_t}{S} f(A_t/A) \qquad \ldots(14)$$

where $f(A_t/A)$ is the erosion factor. The magnitude and variation of the erosion factor for any propellant can be determined experimentally. A typical relationship for

propellant SU/K (at 60° C) is shown in fig. 2. It will be seen that $f(A_t/A)$ never exceeds unity and increases towards this limiting value as A_t/A decreases, i.e. as the charge burns away the effects of erosion diminish.

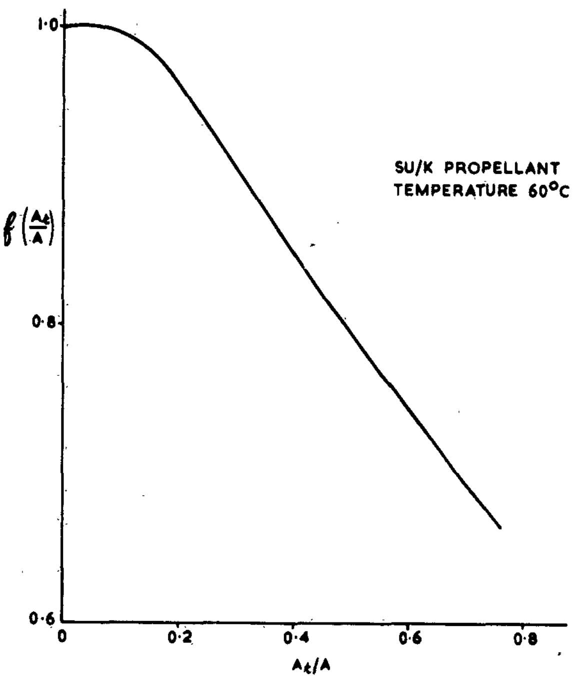


Fig. 2. Variation of erosion factor for typical propellant

23. The relation between the pressure and the rate of burning at zero gas velocity can also be determined experimentally. This relation, expressed in the form of the variation of B_0/π_0 with p_0, is shown in fig. 3 for the same propellant SU/K, again at 60° C. With curves of this nature available equation 14 is in a convenient form for predicting what the pressure will be at any stage during burning. For example, high values of A_t/A which occur at the commencement of burning give low values of $f(A_t/A)$ and lead to high initial or *peak* pressures; whereas at a later stage when A_t/A becomes small, $f(A_t/A)$ approaches unity and pressure falls to its normal working value.

THE GENERAL APPROACH TO DESIGN

24. Before discussing the detailed aspects of the various motor components, it will be of value to consider very briefly the design requirement as a whole and the essential steps that have to be taken to satisfy it. Obviously the detailed design will be influenced to a very great extent by the precise nature of the requirement and the essential steps in design can be most clearly illustrated by the selection of specific examples. However, there are equally obvious objections to using specific examples to illustrate general principles, and in this section only the broad general steps are indicated. More specific examples are dealt with in Section 6.

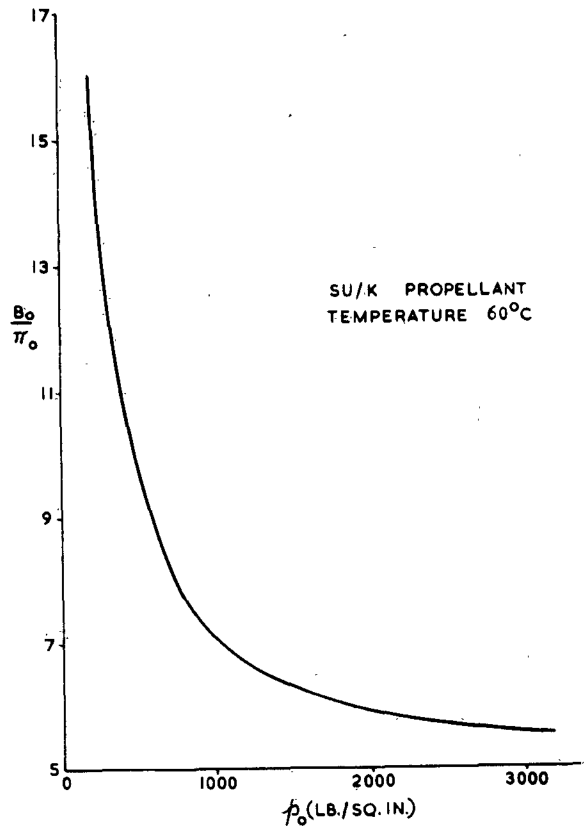


Fig. 3. Variation of rate of burning with pressure for typical propellant

25. Although the form in which the problem is first stated may vary from requirement to requirement, it is usual to be asked for a specified thrust for a specified time; this more often than not has to be supplied by the smallest or lightest possible motor. In preliminary design work it is usual to assume that the total impulse is given by the product of the specified thrust by the specified time of burning. (In general the total impulse is, of course, given by the integral of the thrust over the entire burning period and only when the thrust is absolutely constant is the relationship 'thrust × time = total impulse' strictly true).

26. The total impulse is also the product of the propellant charge weight and its specific impulse and the selection of a propellant for which a value of the specific impulse can be assumed is normally the next step in design. In practice it may be wise at this stage to consider a number of propellants, although in general, provided considerations of a special nature do not rule it out, the propellant with the highest specific impulse will be the one which leads to the highest performance motor. Once a particular value for the specific impulse has been chosen, the charge weight may be calculated by the relation 'charge weight × specific impulse = total impulse'. Since the charge weight and the time of burning are now known the rate of propellant consumption Q_0 can be found.

27. In selecting a propellant with a known specific impulse, it must be assumed that other properties such as its density, nozzle discharge coefficient, rate of burning, and erosion characteristics are also known. From this knowledge it is possible to calculate a nozzle throat area corresponding to any value of pressure, since from equations 2 and 13 we have $A_t = Q_0/N_D p_0$. The calculation of the nozzle throat area, then, is the next stage in the process; this is usually done by calculating the throat area corresponding to one or two arbitrarily chosen pressures. In doing this it is necessary to take into account any variation in the specific impulse with pressure.

28. From the erosion characteristics of the chosen propellant a value of λ, the ratio of A/A_t, is then selected. This clearly involves a compromise between a low density of loading on the one hand and considerable erosion on the other, which may lead to an excessive peak pressure. Values between 1·25 and 1·5 are common, but the full significance of this parameter is discussed later (see para. 47).

29. It is obvious that the area of the cross-section of the gas conduit follows from the relation $\lambda = A/A_t$, while the charge volume can be found from the charge weight and the charge density σ. The designer then has at his disposal the following two vital quantities :—

(1) the area of the gas conduit
(2) the charge volume.

From the time of burning and the rate of burning of the propellant at the selected pressure, the web thickness immediately follows.

30. The more detailed aspects of the design of a geometrical shape to fulfil these conditions are considered in Section 2, but it will be obvious that for different propellants and operating pressures these shapes will involve different length/diameter ratios. The design procedure usually adopted is to determine a range of length/diameter relationships for the charge and then to compute an approximate body weight for each (see Table 7, Section 6). These different ratios will in turn exert a considerable influence on the weight of the motor body. As a first approximation the motor body can be regarded as consisting of a cylindrical portion whose weight per unit length will vary as the cube of the diameter, and other minor components whose weights can be taken to vary directly with the diameter (see para. 155).

31. The selection of an appropriate material for the body will be influenced by specific features of the requirements and by manufacturing considerations, but it can be assumed that its tensile strength is known. From the tensile strength and the operating pressure it is possible to obtain a relation between the motor body diameter and the wall thickness of the tube. The basic relation involved is the well known one for thin-walled tubes, namely $F = pd/2t$, where F is the hoop stress, p the internal pressure, d the tube diameter, and t the wall thickness.

32. The wall thickness of the tube of given length and diameter can be calculated from the formula just quoted and the weight of the tube follows from a knowledge of the density of the material. The estimation of the weight of the ends is most conveniently done in a preliminary assessment by taking the weights of the ends of a known rocket and by assuming the variation in end weight to be in the ratio of the cubes of the diameters. This method is obviously very approximate, but in practice it will usually be found to be sufficiently reliable to indicate which combination of propellant composition and pressure is likely to yield the design with the lightest overall weight. Detail design of the motor can then follow.

Section 2

THE PROPELLANT CHARGE

TYPES OF SOLID PROPELLANT

33. The various types of solid propellant are considered in detail in Parts 5 and 6 of this Textbook which deal with extruded, cast double base, and plastic propellants, and pressed charges. From the standpoints of both composition and functioning they fall into two main categories depending on whether nitric esters or salts are the main ingredients; these two categories are best described as:—

(1) colloidal
(2) composite.

Included in the former class are solventless extruded cordite and cast double base propellants; typical formulations for these colloidal propellants are given in Table 1.

34. In the category of composite propellants we may class the British plastic and pressed powder compositions, and the American Thiokol and Aeroplex types. Plastic propellants are putty-like materials made from crystalline salts with a minimum quantity of a viscous liquid 'binder'. Pressed powder charges, as their name suggests, are made by consolidating the dry ingredients under pressure, while the American types are prepared by pouring a slurry of salt and polymerizable liquid into a suitable mould, and then curing. With many Thiokol formulations the liquid is polymerized to a polysulphide rubber, while with many Aeroplex formulations various polyester resins are used. Typical formulations for these composite propellants are given in Table 2.

TABLE 1

Formulations of typical colloidal propellants

Constituents	Solventless extruded cordite				Cast double base OGK
	Cool SC %	SU %	HU %	F488/649 %	%
Nitrocellulose (12·2% N_2, wood)	50·0	50·0	56·0	53·0	—
Nitrocellulose (12·6% N_2, cotton)	—	—	—	—	60·0
Nitroglycerin	35·0	41·0	43·0	38·0	28·0
Carbamite	9·0	9·0	1·0	2·0	—
2-Nitrodiphenylamine	—	—	—	—	1·7
Triacetin	—	—	—	—	8·6
Dibutylphthalate	6·0	—	—	7·0	—
Dioctylphthalate	—	—	—	—	3·4
Lead stearate	—	—	—	—	3·4
Lead salicylate	—	—	—	2·0	—
Lead 2-ethyl hexoate	—	—	—	2·0	—
Carbon black	—	—	0·1	—	—
Wax	0·075	0·075	0·075	0·2	—

TABLE 2

Formulations of typical composite propellants

Constituents	Plastic				Pressed RC3	Thiokol T13	Aeroplex AN525
	RD2302 %	RD2304 %	RD2306 %	RD2332 %	%	%	%
Ammonium picrate	5	15	28	60	—	—	—
Ammonium perchlorate	80·5	70·5	57·5	26·5	—	67	75
Ammonium nitrate	—	—	—	—	31·5	—	—
Potassium nitrate	—	—	—	—	3·0	—	—
Ammonium dichromate	—	—	—	—	4·9	—	—
Guanidine nitrate	—	—	—	—	59·1	—	—
Polyisobutene	12·5	12·5	12·5	12·5	—	—	—
Lecithin	1	1	1	1	—	—	0·05
Titanium dioxide	1	1	1	—	—	—	—
Cuprous chloride	—	—	—	—	1·5	—	—
Thiokol LP3	—	—	—	—	—	30	—
p-Quinone dioxime	—	—	—	—	—	2	—
Diphenyl guanidine	—	—	—	—	—	1	—
Styrene	—	—	—	—	—	—	12·35
Genpol A20	—	—	—	—	—	—	12·35
Hydroxy cyclohexylperoxide	—	—	—	—	—	—	0·25

MECHANISM OF BURNING OF SOLID PROPELLANTS

35. It is well known that a solid propellant burns in a rocket by parallel layers and that reaction occurs only at the exposed surface, the rate at which the burning surface recedes normal to itself being the same at all points. A number of workers have studied this problem in very great detail and a variety of theories have been developed. Those of particular importance can be studied by consulting references 1 to 5, but a very brief outline of these theories follows.

36. According to one theory (see ref. 1) it is considered that a single exothermic gas reaction is the rate determining factor in a steady state, but other workers suggest (see ref. 2 and 3) that three main stages are involved in the decomposition of propellants containing nitric esters. These stages are as follows :—

(1) the primary solid phase decomposition giving organic fragments and nitrogen dioxide

(2) the non-luminous gas phase reactions of the products of stage (1) giving nitric oxide and aldehydic molecules

(3) the luminous gas phase reaction of the products of stage (2) giving the final products.

These stages have been described as the foam, fizz, and flame reactions respectively.

37. This three-phase theory has been endorsed by other workers, one of whom considers that the controlling reaction is one which starts at the surface in the fizz zone (see ref. 4), while another goes further than this and specifically postulates that the rate determining step is the breaking of the oxygen-nitrogen bonds at the surface of the propellant (see ref. 5). However, it will be seen from this brief outline that the subject is by no means simple and further consideration is beyond the scope of this Part.*

FUNCTIONAL LIMITATIONS OF SOLID PROPELLANTS

Dependence of burning rate on pressure

38. Although the mechanism of burning itself is a complex matter and has only been studied in detail with colloidal propellants, it is well known that the burning surface recedes at a uniform rate. It is possible to express the dependence of this burning rate on the pressure quite simply by one of the equations

$$B = a + bp \qquad \ldots(15)$$

or

$$B = cp^q \qquad \ldots(16)$$

where B is the rate of burning in in. per sec., p the pressure in lb. per sq. in., a, b, and c are constants for a given temperature, and q is a constant usually called the pressure exponent. These equations adequately represent the data with all types of solid propellants (except for some notable exceptions—see para. 40), since they can be fitted to the rate of burning/pressure curves over useful parts of the pressure range.

39. The pressure exponent is very important since it can readily be shown that the pressure in a rocket motor is proportional to the $1/(1 - q)$th power of variables that affect the rate of evolution of gas, such as the rate of burning, the area of the burning surface, etc. (see Part 2, para. 362). If q exceeds unity the internal ballistics of the rocket are unstable, while the smaller q is the less dependent is the pressure on variables that affect the rate of evolution of gas.

40. Until recently all colloidal propellants had pressure exponents in the region of 0·7, but since the end of World War 2, considerable research, particularly in the U.S.A., has produced a range of compositions containing small quantities of lead salts, which have a flat region in the rate of burning/pressure curve. This flat region is known as a plateau and propellants of this type are described as *platonized.*

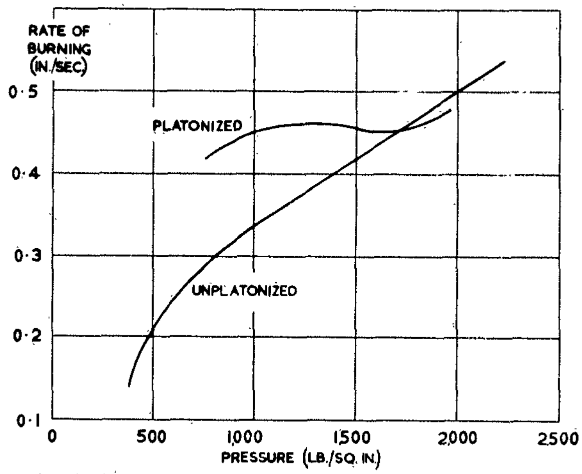


Fig. 4. Variation of rate of burning with pressure for typical platonized and unplatonized propellants

41. Variations in the rate of burning with pressure are shown in fig. 4 for typical platonized and unplatonized propellants of comparable calorimetric value. Many of those so far developed are cool propellants (see para. 52) with relatively low values of specific impulse, and platonization has not yet been achieved with hotter propellants having high values of specific impulse, but the result, even so, is of major importance. With composite propellants the pressure exponent is usually lower than with conventional colloidal propellants, 0·4 being a common figure.

Dependence of burning rate on temperature

42. Intimately associated with the pressure exponent is the effect of charge temperature, since variations in the charge temperature cause changes in the rate of burning. If the pressure exponent is high this causes a large change in the equilibrium pressure. At high charge temperatures the time of burning is shortened and the pressure may become excessive, while at low charge temperatures the pressure may become so low that the propellant will no longer burn reliably.

43. One of the most striking examples of this behaviour occurs with the British 4-sec. assisted take-off rocket. This rocket is used in the launch of naval aircraft from carriers and the requirements imposed stringent limits on both thrust and time of burning. For example, it was stipulated that the time of burning must lie between 3·25 and 4·5 sec. over the whole operational temperature range. In practice, with propellants available at the time, this was found to be impossible with a single

* The subject is considered in considerable detail in Part 2 of this Textbook.

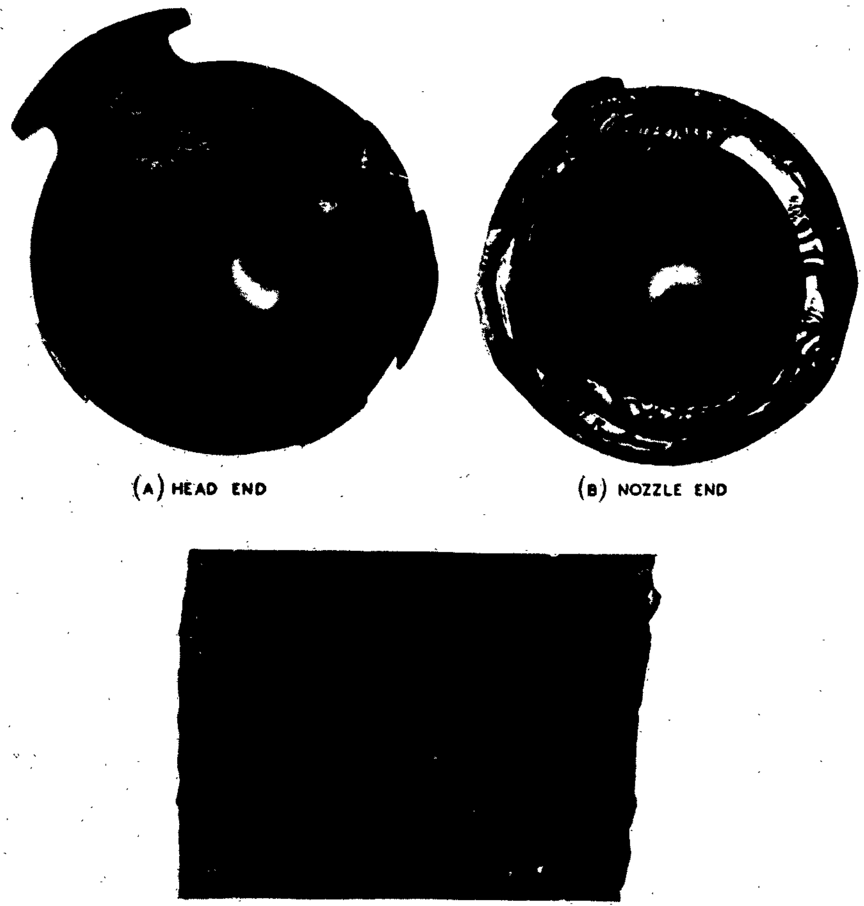
motor, and it was found necessary to provide three different sizes of nozzle to cover operational conditions in the arctic regions, the temperate latitudes, and the tropics.

Erosive burning

44. The term *erosion* was first applied in the very early stages of modern rocket development (ref. 6) as a result of the examination of fragments of cordite recovered from motors which had burst. These fragments had a rippled appearance as though the propellant had been 'eroded' by the gas stream. Furthermore, it was observed that charges from partially burned rockets were tapered, more propellant having been burned from the nozzle end than from the head end of the charge. This latter effect is illustrated in fig. 5 which shows photographs of the two ends of a partially burned tubular charge. A close-up view of the eroded propellant at the nozzle end is given in fig. 5C, and the rippled appearance is clearly shown.

45. Although the earliest suggestion was that this erosion effect was due to the mechanical scouring away of propellant by the wash of the high velocity gas stream (ref. 6), the workers in this field advanced the hypothesis that the increase in the rate of burning at the nozzle end was due to the gas velocity and that it could be correlated with the increased heat transfer through the boundary layer close to the surface of the propellant (ref. 7). If this hypothesis is related to the conception of the mechanism of burning stated briefly in para. 35, it can be considered that when the boundary layer of the main gas flow at full flame temperature is inside rather than outside the rate controlling reaction zone then there will be an increase in the rate of burning. It was also suggested that the increased rate of burning due to erosion might well be the explanation of the discrepancy between the observed and the estimated values of the peak pressures experienced in the rockets then being studied.

46. Subsequently, by using the method of interrupted burning it was shown conclusively that the rate of burning of the propellant did depend on the velocity of the combustion gases over the propellant surface as well as on their pressure and temperature. This led to the amendment of the equation $B_0/\pi_0 = KA_t/S$ (see para. 22), when it was shown that erosion could be related to the linear gas velocity and the factor $f(A_t/A)$ was introduced (ref. 7).



(A) HEAD END

(B) NOZZLE END

(C) ERODED PROPELLANT

Fig. 5. Erosive burning of cordite

47. It was explained in para. 23 how the initial or peak pressure in a rocket can be predicted. Experience during World War 2 with rocket motors containing loose tubular and cruciform charges led to the conclusion that there was a practical limit to the value of A_t/A which might be used if excessive peak pressures were to be avoided. This value was generally taken to be approximately 0·5 and as long as A_t/A was less than this, the difference between the initial peak pressure and the steady working pressure was not excessive. When this value was exceeded high pressures were always encountered. This condition was undoubtedly aggravated by the fact that with the propellants in use at the time (SU and SU/K) the value of the pressure exponent above a pressure of 1,500 lb. per sq. in. was also high. This meant that a very small increase in erosion could, in that pressure region, lead to a major increase in pressure.

48. More recently, however, it has been shown that with large externally inhibited perforated charges values of A_t/A much nearer unity can be used without accompanying excessive peak pressures. For charges of this type the prediction curves shown in fig. 2 and 3 give spurious results, and much work is required to place the phenomenon of erosion on a sound quantitative basis for large perforated charges.

49. One suggestion that has been made is that erosion ratios might be better correlated in terms of cross-sectional mass flow velocity rather than linear gas velocity. Although this parameter was considered in the very early days and rejected, it would now appear to offer promise of better correlation with large perforated charges. As far as the mechanism of erosion is concerned, there would seem to be little doubt that a threshold level exists at which erosion occurs and it may well be that there is a critical rate of mass flow down the charge conduit. One effect on overall rocket motor performance of using values of A_t/A nearer unity is that the area of the cross-section of the propellant charge is increased. This extra loading density is obviously beneficial.

Colloidal propellants

50. A serious shortcoming of colloidal propellants is that, as yet, only a relatively limited range of rates of burning can be covered, and in particular, it is not possible to obtain steady burning at a rate much below 0·15 in. per sec. This later fact has up to now largely precluded the rocket designer from using this type of composition if particularly long burning times are demanded. However some consideration is given in Section 6 to designs in which long burning requirements may be fulfilled with conventional colloidal propellants.

51. In Table 3 are quoted the burning rates for one of the coolest conventional cordites, namely cool SC, and one of the hottest HU. Included for comparison are data for SU, F488/649 a platonized extrudable composition, and OGK a cast double base (CDB) formulation. Values of specific impulse, calorimetric value,* and combustion temperature are also given in this Table. Corresponding data for composite propellants are included as well and these will be discussed in para. 57.

52. The values quoted in Table 3 for SU, which was the earliest cordite propellant used in a rocket, are generally taken as a standard of reference. Compositions with a lower calorimetric value and combustion temperature than SU are normally considered to be *cool*; compositions with higher values are considered to be *hot*.

53. It is interesting to note that with colloidal propellants as soon as the pressure is reduced to such a level that the rate of burning becomes approximately 0·20 in. per sec., then unstable burning begins to occur. The reasons for this are not fully understood but it is generally believed that when the critical pressure region is reached,

TABLE 3

Performance data for typical solid propellants

PROPELLANT	Rate of burning at 20° C (in./sec.)				Calorimetric value (cal./gm.)	Combustion temperature (° K)	Specific impulse (lb.-sec. per lb.) at 1,000 lb./in.²
	250 lb./in.²	600 lb./in.²	1,000 lb./in.²	2,000 lb./in.²			
COLLOIDAL							
Extruded Cool SC	Unstable	0·21	0·28	0·43	745	1,930	170
Extruded SU	Unstable	0·28	0·38	0·57	965	2,470	205
Extruded HU	0·30	0·45	0·65	1·10	1,225	3,030	225
Extruded F488/649	0·28	0·38	0·48	0·49	870	—	200
CDB/OGK	—	0·27	0·27	0·29	725	2,650	195
COMPOSITE							
Plastic RD2302	0·31	0·53	0·75	1·16	1,050	2,580	210
Plastic RD2304	0·25	0·39	0·50	1·71	935	2,350	205
Plastic RD2306	0·18	0·26	0·33	0·46	—	2,030	195
Plastic RD2332	0·035	0·06	0·086	0·13	—	1,380	170
Pressed RC3	0·08	0·20	0·285	0·495	—	1,710	170
Thiokol T13	0·28	0·32	0·35	0·40	—	2,300	200
Aeroplex AN525	0·16	0·22	0·28	0·30	—	2,040	200

* The calorimetric value of a propellant is defined as the energy evolved when unit mass of propellant is burnt in *an inert atmosphere* in a bomb calorimeter; it is usually quoted as so many calories per gram, water liquid, i.e. determined under conditions such that the steam formed is condensed. It should not be confused with the calorific value of a fuel burnt in *an excess of* oxygen; the latter quantity for solids and liquids is the amount of heat (in calories) given out when unit mass is burnt; for a gas a definite volume (1 cu. ft.) is used.

there is a shift in the equilibrium of the gaseous reactions and some of the nitrogen appears as nitric oxide. It is well known that the conversion of nitrogen to nitric oxide in this pressure region is endothermic.

54. In specific cases improvement can sometimes be effected by including small quantities of additives and the role of 'potassium cryolite', or more strictly 'potassium aluminium fluoride', is worthy of note in this respect.* Potassium cryolite was first considered as a possible additive to British cordites to suppress flash (see para. 126), and attention was particularly directed to a 3-in. rocket containing an 11-lb. cruciform charge of cordite SU. Investigations carried out simultaneously showed that this rocket motor would not burn reliably at or below a temperature of 0° F. The pressure/time curve for the motor has a slight depression like a saddle between one-third and half burnt (see fig. 6) and the cessation of burning usually occurred in this region. At about 0° F this minimum in the pressure/time curve occurred at a pressure of about 250 lb. per sq. in.

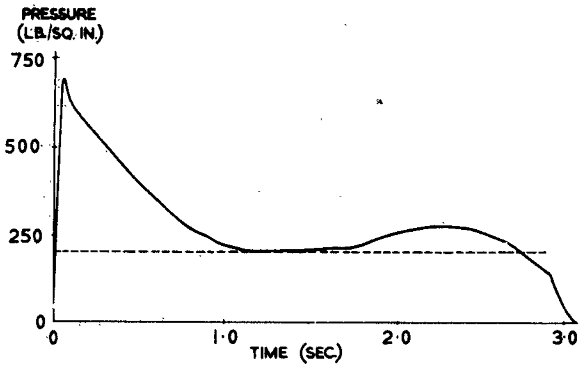


Fig. 6. Variation of pressure with time for 3-in. rocket using SU cruciform charge at 0° F

55. The addition of 2 per cent of potassium cryolite to cordite SU (giving SU/K propellant) completely eliminated these failures down to −40° F. The effect of this is shown in fig. 7 where the minimum pressure developed by the rocket motor with SU and SU/K charges is plotted against temperature. The facilities available prevented investigations being carried out below −40° F, but artificial opening out of the nozzle throat eventually produced a condition with SU/K charges in which the pressure had fallen to 250 lb. per sq. in.; under these conditions burning failures were also experienced with SU/K. With hotter propellants, burning can be maintained steadily below 250 lb. per sq. in., but again not at a rate of burning much below about 0·20 in. per sec.

56. The mechanism by which both lead salts and potassium cryolite exert their influence is by no means fully understood, but it is noteworthy that in each case there is an increase in the rate of burning over a certain pressure region for compositions containing these additives. This suggests that some sort of catalytic activity is taking place, probably at the stage of the flame reaction (see para. 36), and it is with these types

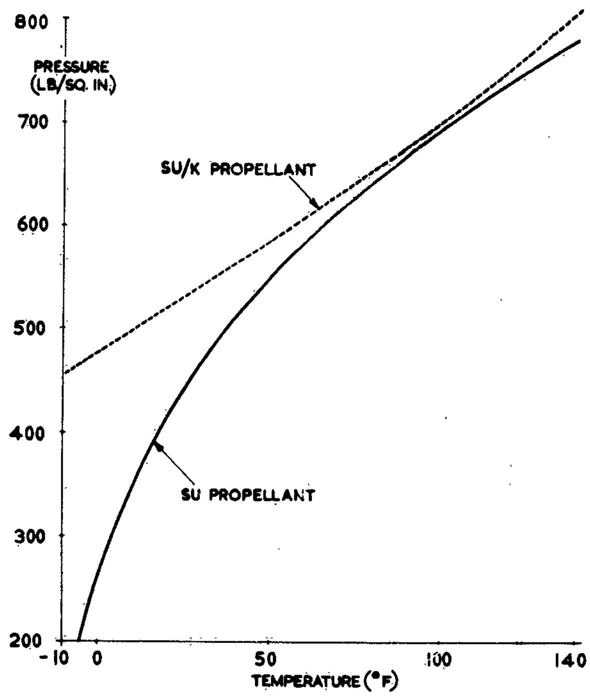


Fig. 7. Variation of minimum pressure with temperature for 3-in. rocket using SU and SU/K charges

of compositions that there seems to be the best prospect of attaining reliable burning at low pressures. (See also Part 5A of this Textbook, Section 2).

Composite propellants

57. Composite propellants do not appear to suffer from anything like such a severe restriction at low pressures, and stable burning has been obtained in some cases down to 0·03 in. per sec. With propellants of this type, however, a different type of difficulty has been encountered, namely, an excessive batch to batch variation in the rate of burning. This is believed to be due to variation in the particle size of the salts and although improved manufacturing methods may go some way to eliminating this difficulty it is likely that in this respect composite propellants, by their very nature, will always be slightly inferior to colloidal types. Another difficulty which has been encountered with British plastic propellants is that at high rates of burning and mass flow, excessive secondary peaks have been observed. Nevertheless, composite propellants undoubtedly seem to be capable of covering a much wider range of burning rates than those of the colloidal type.

General limitations

58. A more general limitation on design is imposed by the desirability that in most applications the rocket motor should be as light and compact as possible. Since the weight of the metal components increases with increase in the combustion chamber pressure, the weight of the motor can be reduced by operating at a lower pressure. However, the efficiency of conversion of the thermal energy of the propellant gases to kinetic energy also decreases with decreasing pressure. This is particularly so at very low pressure when to obtain the same

* This additive is so called by analogy with the sodium salt which is widely known as cryolite.

total impulse a greater weight of propellant must be burnt than at a higher pressure. To contain this greater weight of propellant a larger combustion chamber will be needed.

59. This increase in the charge weight and in the combustion chamber dimensions as the pressure is lowered will offset the saving in weight achieved by the lower wall thickness of the motor tube necessary to withstand the lower pressure. There will in fact be an optimum pressure for which the weight is a minimum. Other things being equal, this optimum is the chamber pressure used in practice, although an overriding consideration is that over the whole temperature range the pressure must lie within the limits of stability of the propellant.

60. It will be appreciated that this chosen pressure is not unalterable, but can be varied if there would result from this a material advantage, such as for example, a simplification in charge design. The procedure usually adopted is first of all to decide provisionally upon a reasonable working pressure, and to adjust this later if it proves desirable to do so.

61. Two other broad types of limitation which exert an appreciable influence on the selection of the propellant composition and the charge design are those arising from manufacturing problems on the one hand, and from precise details of individual requirements on the other, for example, limitations due to storage, etc. on length or diameter of the final motor. Some aspects of the former are considered in para. 62 to 69, but the latter problems are too numerous and too varied to be dealt with except as part of the problem of geometrical charge design ; this is covered in para. 70 onwards.

MANUFACTURING LIMITATIONS OF SOLID PROPELLANTS

Colloidal propellants

62. In addition to the functional limitations discussed in the previous paragraphs there are also a number of manufacturing difficulties which can, at times, impose severe restrictions on the designer. These depend largely on the availability of raw materials and manufacturing equipment. As far as extruded cordite is concerned the main ingredients are nitrocellulose and nitroglycerin, the former being made from wood pulp and the latter from oils and fats. In wartime it is clear that each of these ingredients will create supply problems and since extruded cordite was the only available propellant at the outbreak of the last war, supply considerations gave considerable impetus to the development of alternatives. The production of extruded charges also involved a large press, and strategic considerations weighed against the concentration of production in a limited number of factories where presses were located.

63. In addition to this, the size of charges which can be produced by extrusion is somewhat limited. The largest cordite extrusion press at present in use in this country has a cylinder bore of 15 in. and a capacity of 100 lb., and the largest diameter charge yet extruded from this press has a diameter of 9½ in. Experimental investigations with smaller presses have shown that by feeding the material through a shredder plate and then by extruding through a die with a very long parallel portion, it is possible to produce a charge whose diameter is more nearly comparable with that of the press cylinder. In this process the press cylinder is replenished with fresh material during the operation, the diameter of the extruded charge being unaffected since it is still contained in the die. With this method charges of 8½-in. diameter have been produced from a 10½-in. press. In order to increase the scope of the extrusion process, a press is being manufactured with a cylinder diameter of 22½ in. and a capacity of 400 lb. of cordite. The association of the long parallel die technique with this press should enable charges to be produced with diameters of the order of 16 in.

64. Attention is also being devoted to the building up of large charges by sticking asymmetric sections together longitudinally to form a complete cylindrical charge. As stated above all these experimental techniques are aimed at increasing the scope of the extrusion. Another approach to the problem where colloidal propellant charges are required is to use an alternative to extrusion as a method of manufacture. In this category is the method known as the ' cast double base ' (CDB) process in which nitrocellulose powder is packed into a suitable mould and desensitized nitroglycerin is passed through. After a curing period the whole mass is completely gelatinized and the mandrel which forms the charge shape can be withdrawn. With this technique there is far less limit to the diameter or weight of charge which can be made and successful castings up to 30 in. in diameter have been carried out in the U.S.A.

65. However this CDB process does suffer from two shortcomings. On the one hand it is relatively expensive since one of the ingredients—rifle powder—is already a fully processed propellant. On grounds of safety also it is necessary to desensitize the nitroglycerin. This results in the diluent remaining as an ingredient in the propellant and for this reason cast double base charges are usually cooler and slightly lower in performance than their extruded counterparts.

Composite propellants

66. With composite propellants a wide range of salts have been used as the main source of oxygen and the supply position varies greatly. One of the most popular oxidants is ammonium perchlorate, the production of which involves electric power. Processing of this type of propellant is generally relatively simple. With the British plastic propellants the salt ingredients are incorporated with the liquid binder in a simple dough mixer and the resulting material pressed into the required shape with a former, after the propellant has been de-aerated. This is all that is involved in the process, and the propellant which contains over 85 per cent of solid matter has the consistency of putty.

67. The American composite propellants contain less salt and the fuel normally takes the form of a polymerizable liquid. Thus with a typical Aeroplex composition, the fuel consists of a resin which is dissolved in an equal quantity of monomeric styrene ; a small quantity of catalyst to effect polymerization is also added. The charge is formed by inserting a mandrel of appropriate cross-section into the unpolymerized mass. This part of the process is extremely simple but the subsequent curing by heating frequently presents difficulties. Usually it is sufficient to apply gentle heat to start the polymerization, after which the process is self-heating. After

about two days the curing is about 95 per cent complete and the charges are then usually maintained in an oven for a further two days at a temperature of approximately 180° F. Details will of course vary from composition to composition. Inhibition is achieved by casting around the charge the same fuel loaded with inert solid matter and then polymerizing. This process takes a further two days.

68. With Thiokol type propellants the process is broadly similar and again many of the main problems arise during the curing. However, with Thiokol compositions ammonia is evolved during the compounding. Since its concentration has an important effect on the physical properties of the final propellant, it is necessary to maintain a rigid control of temperature and vacuum prior to casting.

69. With pressed powder charges no liquid is involved, the process merely involves the consolidation of a dry powder to a rock-like solid under extremely heavy loads. Although this is very simple it necessitates the use of a very heavy and powerful press for large charges. On balance, therefore, the most simple charges to produce of the composite propellant class are probably those of the British plastic type.

THE RELATION BETWEEN PERFORMANCE AND GEOMETRY OF ROCKET CHARGES

70. The process of design of a rocket charge may be divided into two stages. First, there is the translation of the performance requirements into geometrical relationships governing the shape of the charge, and secondly, there is the question of actually satisfying the geometrical relationships. Essentially the requirements are :—

(1) that the charge shall fit into a given space

(2) that it shall have a given volume

(3) that its burning surface area shall have given values at different instants as the charge burns away.

71. Except for special purposes, it is usual to try to maintain constant the propellant burning surface area throughout the period of burning of the motor. This is done because it is an advantage to work at the maximum pressure permitted by the strength of the combustion chamber, any propellant burnt at less than this pressure being burnt at reduced efficiency. When the walls of the combustion chamber are effectively protected from the propellant gases, the strength of the chamber remains unaltered during burning, so in such cases the optimum operating condition is that of maintaining a constant pressure. From the equation $B_0/\pi_0 = KA_t/S$, explained in para. 22, it will be seen that if the throat area A_t is constant, it is necessary to have a constant burning surface S in order to maintain a constant pressure.

72. Under some circumstances the strength of the combustion chamber walls does not remain constant as burning of the propellant proceeds, but decreases owing to the heating of the walls by the gases. Localized heating may cause this to happen, even when the greater part of the combustion chamber walls is effectively protected, and the weakest part of the chamber sets the limit to that of the whole. When the chamber strength decreases with time, the optimum condition is one in which the pressure correspondingly decreases, so that each particle of propellant is burnt at the maximum possible pressure. However, the need for a decreasing pressure does not necessarily mean a decreasing surface area of the propellant charge since there are two other factors which may cause the pressure to fall. First, due to the effect of the hot gas, the area of the nozzle throat may increase. Secondly, an artificially high initial pressure may be caused by erosive burning ; as burning proceeds and the charge conduit increases, the pressure will fall.

73. In certain specific applications considerations such as the foregoing may lead to some special form of burning surface recession. For example, an artifice frequently used in the design of a star centre or similar perforated charge is to have the initial burning perimeter reduced to about 80 per cent of the final perimeter. The effect of erosive burning during the early stage on the maximum pressure is less marked and a higher loading density may be possible. However, the normal design practice is to start with a shape which gives a constant burning surface area, at least for initial trials. Adjustments may be made to this later if subsequent experience suggests that this would lead to improvement in performance.

74. One of the most important steps in charge design is therefore the devising of geometrical shapes which are such that a constant or nearly constant burning surface is maintained as the surface recedes. Some of these shapes are three-dimensional, in the sense that a considerable decrease in the length of the charge is permitted, but is offset by an increase in the burning perimeter elsewhere. A typical example of such a charge shape is that often employed in the gunpowder rockets used on 5th November. This consists of a solid cylinder of gunpowder burning only from a long tapering hole along the axis of the cylinder, the diameter of the hole being equal at one end to that of the cylinder (see fig. 8). A very roughly constant surface is maintained because although the diameter of the tapering hole increases, the length of the charge decreases owing to burning from the large diameter end. The number of variants on this basic shape are considerable, but they all suffer from the same disadvantage that, as the charge length decreases, the wall of the motor tube becomes progressively exposed to the propellant gases.

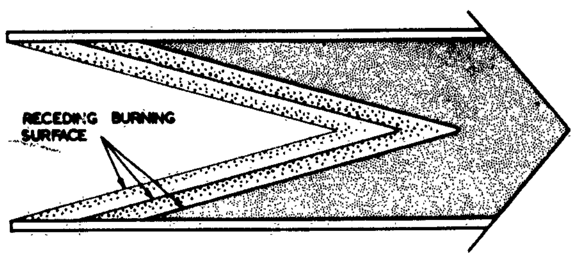


Fig. 8. Change in charge shape of 5th November rocket

75. It is more usual in practice to use a design in which the perimeter of a cross-section is maintained constant. Typical of shapes which achieve this are tubular, cruciform, and cogged charges (see fig. 9), and charges having a central hole or perforation and inhibited from burning on the outer surface. The cross-sectional shape of the hole may be varied ; some possible shapes are shown in fig. 9D and 10. The change in shape of the cross-section as the charge burns and the half-burnt position of the burning surface are shown in each figure.

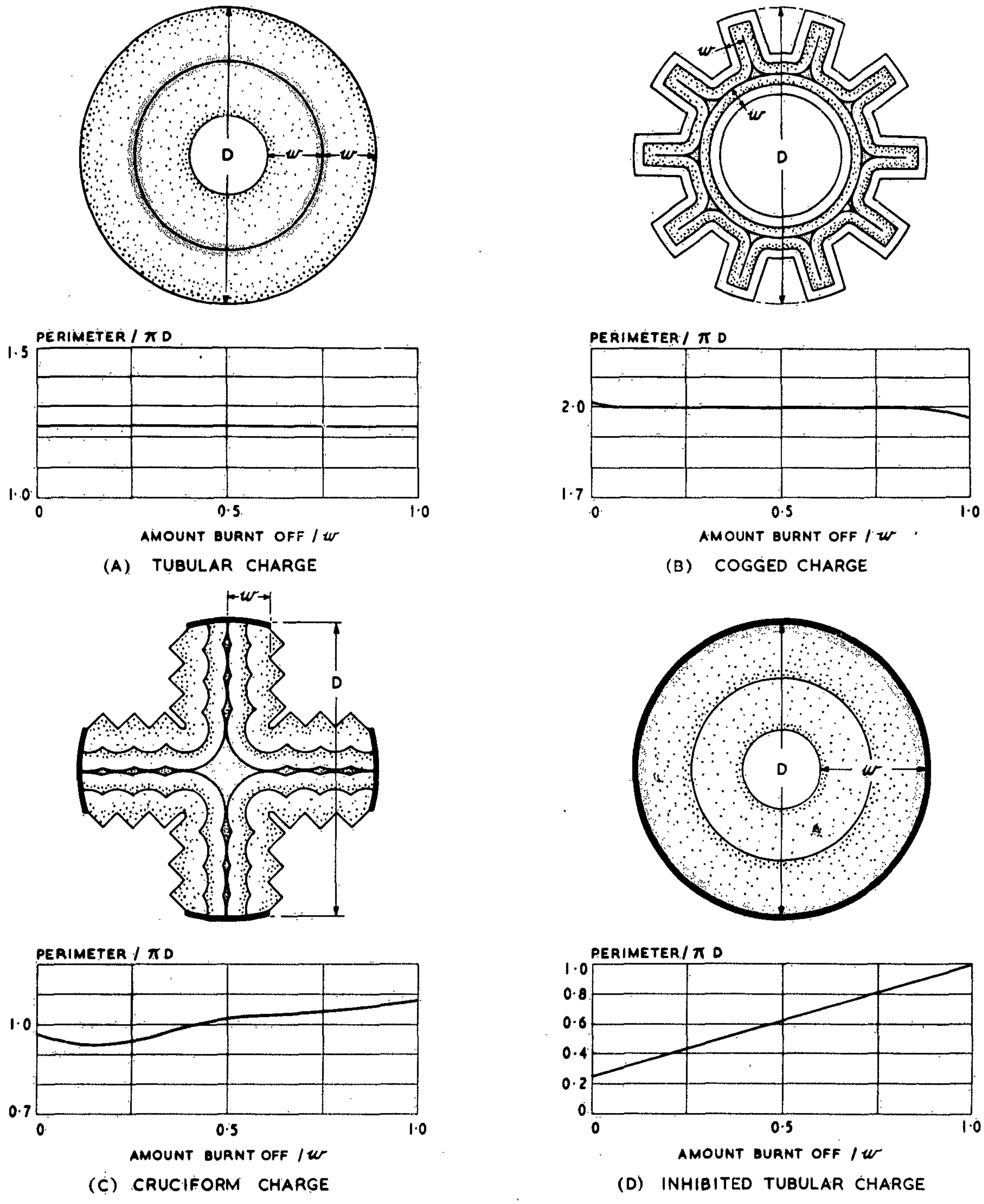


Fig. 9. Variation of charge shape and perimeter for typical charges

76. The tubular charge shape shown in fig. 9A was widely used in British rockets during World War 2. Its manufacture and inspection is particularly simple and its perimeter, as represented by the sum of the inner and outer circumferences, remains perfectly constant throughout burning. Fig. 9C shows a cruciform charge which is mechanically very superior to the tubular charge, and whose perimeter remains almost constant throughout burning. The cogged charge shown in fig. 9B has been used where a short burning time is required. In each case the graph shows the variation of the perimeter of the burning surface with the amount burnt off, D being the diameter of the charge cross-section and w the web thickness of the charge (see para. 79).

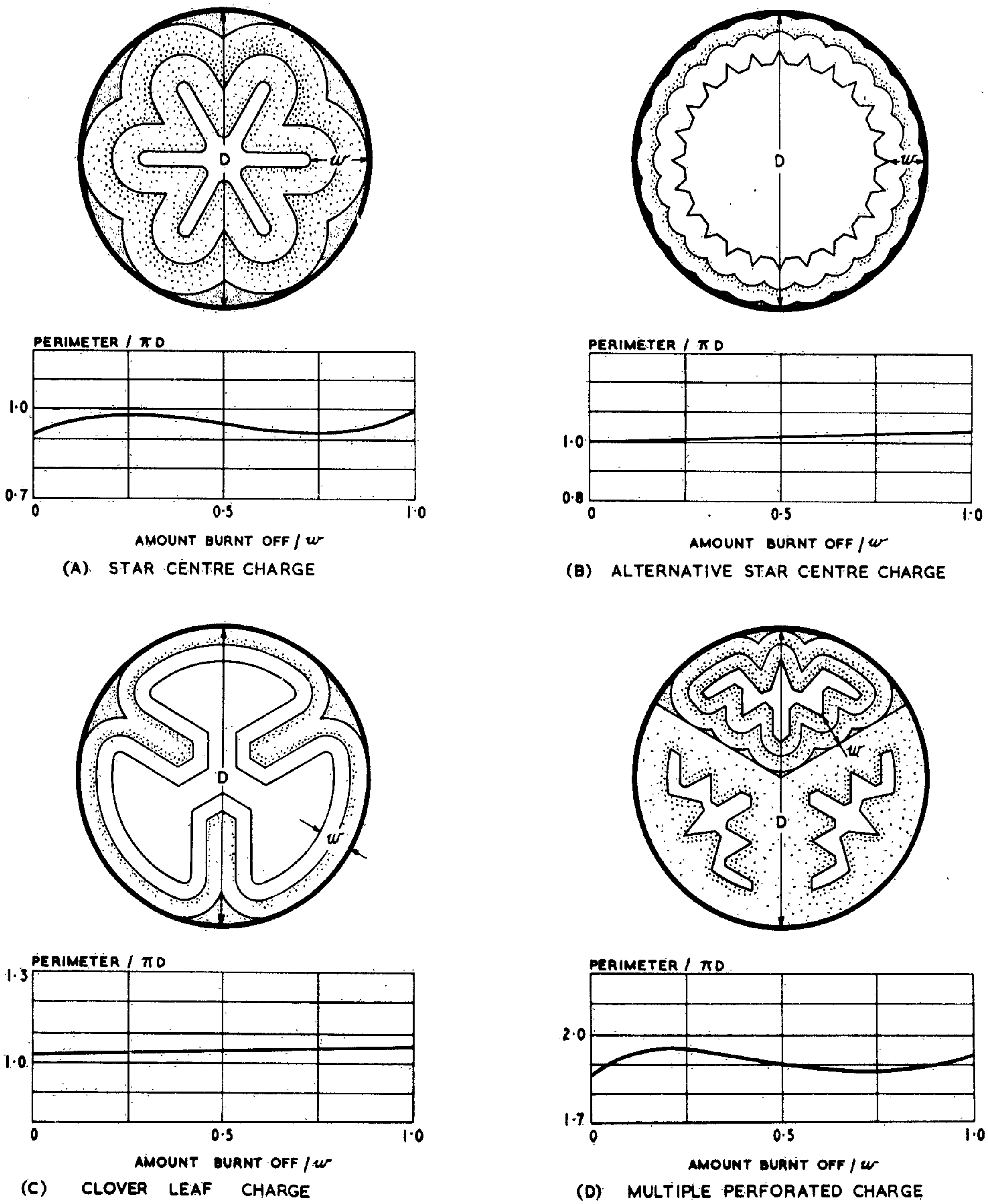


Fig. 10. Variation of charge shape and perimeter for typical inhibited perforated charges

77. The effect of inhibiting the entire outer surface of a tubular charge is illustrated in fig. 9D. It will be seen that by this means the burning thickness is doubled, while the perimeter of the burning surface increases progressively. For this latter reason it is most unlikely that such a shape would be used in practice, but it is included because it leads logically to the inhibited perforated charge shapes shown in fig. 10. These four shapes reveal something of the range of possible externally inhibited charges.

78. Another charge with a constant burning surface area which might be used consists of a solid cylinder burning only from one end face, the remainder of the

surface being inhibited. This type is frequently referred to as a *cigarette burning* charge from an obvious rough analogy. It has only special uses, since clearly it is applicable only when a low thrust is required for a long time. It suffers also from the disadvantage that as the charge burns away the motor tube wall is exposed. This is a serious disadvantage because it is in precisely this application, i.e. motors having a long burning time, that protection of the tube wall is usually essential.

Web thickness

79. The most important factor influencing the type of charge design to be used for any particular requirement is the burning time. This is due to the fact that the burning time exerts a dominant influence on the web thickness of the charge. It is difficult to devise an all embracing definition of the term 'web thickness'; its meaning is best illustrated by reference to fig. 9 and 10 in which the web thickness of the various shapes is denoted by w. Although in most of the charges illustrated the burning surface remains sensibly constant, it does so only until a thickness w has burnt away, at which stage a sharp and considerable decrease in burning surface area occurs. In these cases the small amount of propellant which remains continues to burn at a low pressure and at a correspondingly low efficiency. This remaining propellant is known as *sliver* and it is to be avoided as far as possible in rocket charge design.

80. It will be seen in particular, that apart from the plain tubular charge, some sliver remains with each of the externally inhibited perforated charges. This is a necessary consequence of these shapes, but in spite of this fact such charges are generally to be preferred because of the thermal insulation provided for the motor body wall. This thermal insulation enables a lighter tube to be used with the result that the overall performance of the motor is higher in spite of the sliver, than with say, a plain uncoated tubular charge. It will be obvious that a sliverless charge would result if the outside surface were made to correspond to the final burning contours of fig. 9 and 10, but to obtain the full value from such a charge, it would be necessary to house it in a body tube of a similar shape. This would undoubtedly introduce great difficulties, although they are possibly not insuperable.

SELECTION OF A CHARGE DESIGN TO SUIT A GIVEN REQUIREMENT

81. In Section 1 (para. 24 to 32) the design approach was only considered in general terms and was merely taken as far as the determination of charge weight and nozzle throat area. It is now necessary to consider in the light of para. 70 to 80 the precise type of charge to be used. It will be appreciated that, if possible, this should be such that it will provide adequate thermal insulation to the motor tube. Assuming this, the following general approach outlines a convenient method of determining the relation between the length and diameter of the charge.

82. The rate of mass efflux from the nozzle throat is given by $Q_t = m/t_B$, where m is the mass of the charge and t_B the total burning time. From equation 11 and 12 we have $Q_t = N_D A_t p_0$, and hence we may write

$$A_t = \frac{m}{N_D t_B p_0} \qquad \ldots(17)$$

For externally inhibited charges the area A of the gas conduit is given by the equation $A = \frac{1}{4}\pi D^2 - A_s$ where A_s is the area of the cross-section of a charge of diameter D. From the relations $\lambda = A/A_t$, $A_s = m/\sigma l$ (where l is the length of the charge), and equation 17 we get

$$\frac{\pi D^2}{4} - \frac{m}{\sigma l} = \frac{\lambda m}{N_D t_B p_0}$$

whence

$$l = \frac{m}{\sigma\left(\frac{\pi D^2}{4} - \frac{\lambda m}{N_D t_B p_0}\right)} \qquad \ldots(18)$$

83. In considering any requirement where both time of burning t_B and the total impulse are given, the mass m of the charge can be calculated from a knowledge of the propellant specific impulse. The nozzle discharge constant N_D is fixed for a given propellant and the pressure p_0 and ratio λ can be arbitrarily chosen. The relation between l and D given by equation 18 can now be plotted. The resulting graph is shown dotted in fig. 11 for an application in which a total impulse of 50,000 lb.-sec. is required in 3 sec. The value of p_0 chosen is 1,000 lb. per sq. in. and λ is taken as $1 \cdot 25$. For the particular propellant considered the value of N_D is $0 \cdot 0069$ while its rate of burning (at 1,000 lb. per sq. in.) is $0 \cdot 5$ in. per sec. and its density is $0 \cdot 058$ lb. per cu. in.

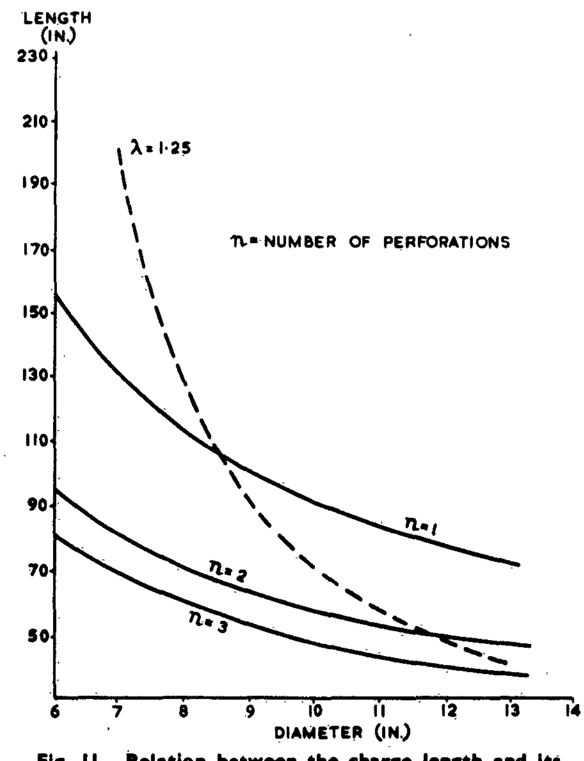


Fig. 11. Relation between the charge length and its diameter

84. Another relation which can also be readily obtained arises from a consideration of the perimeter of the charge rather than the gas conduit area. For perforated charges with one perforation, it can be assumed that, if the burning surface perimeter remains constant, its value throughout burning is equal to that of the charge

circumference. If however the charge has more than one perforation (e.g. the charge shown in fig. 10D), then the *final* value of the perimeter of the burning surface will be $\pi D + 2R \times 3$, if there are three perforations where R is the radius of the charge, and in general $\pi D + 2R \times n$ for n perforations, where $n > 1$. Thus if P is the final perimeter of the burning surface we may write $P = \pi D + 2nR$ which on rearrangement becomes

$$\frac{P}{\pi D} = \frac{\pi + n}{\pi} \qquad \text{...(19)}$$

This relation holds for all values of n greater than unity and can be easily calculated. When $n = 1$, equation 19 is replaced by $P/\pi D = 1$.

85. In the steady state conditions we are assuming $Q_0 = Q_t$ and therefore $\sigma S B_0 = m/t_B$. Since $S = Pl$ we have $m/t_B = \sigma B_0 Pl$, which on rearrangement gives

$$l = \frac{m}{t_B \sigma B_0 \pi D} \frac{\pi D}{P} \qquad \text{...(20)}$$

Equation 20 provides the second relation between l and D, and the variation of l with D can be plotted for any value of n by using equation 19. This variation is shown in fig. 11 for $n = 1$, 2, and 3. The intersection of these latter curves with that obtained from equation 18 (and shown dotted in fig. 11) gives the value of the charge length and its corresponding diameter which satisfy the required conditions.

86. In practice the required conditions themselves usually specify certain limits to the length and diameter of the motor and these of course must be taken into account in selecting the appropriate charge. Thus in the example illustrated a maximum overall external diameter for the rocket motor was stipulated ; this was 11 in. Hence the only acceptable solution under these conditions was a perforated charge with one perforation. In certain instances it may well be that there is sufficient dimensional latitude to render more than one solution acceptable. In such circumstances the charge design is no longer the limiting factor.

87. In the foregoing paragraphs the charge design problem has been considered in a general manner under the assumption that the charge is inhibited from burning on its outer surface, but without reference to how this is achieved. For colloidal propellants a separate coating is applied to the outer surface of the charge (see para. 88 to 106) and the diameter D chosen in the preceding calculations is the outer diameter of the inhibited charge. For plastic propellants whose outer surfaces are inhibited by bonding them directly to the motor tube wall, the diameter used is identical to the inner diameter of the tube.

INHIBITION OF BURNING OF COLLOIDAL PROPELLANTS

88. The purpose of inhibiting the outer surface of a charge from burning is to provide thermal insulation for the motor tube wall, which becomes weakened if exposed to hot combustion gases. Generally speaking with colloidal propellants the technique of inhibition involves the adhesive bonding to the propellant of a thermoplastic material. In the early days of extruded cordite rocket motors the charges were designed with star centres, the external diameter being slightly less than the bore of the motor tube. The annular space was filled with a plastic material in the hope that the dimensional changes due to temperature fluctuation would be catered for by the plastic flow of this 'surround'. Attempts were also made to bond the cordite to the tube by means of more rigid materials such as plasticized ethyl cellulose. Experience showed that charges inhibited by these methods were not capable of withstanding fluctuations in storage temperature (see para. 94).

89. This fact exerted a major influence on the design of rockets in use during World War 2 and on the trend of research carried out during the war. The immediate design result was the abandonment of charges inhibited by bonding. On the research side the efforts were twofold. First, it was obviously desirable to develop a new type of propellant which could be bonded to the motor tube wall* successfully, and secondly, as a safeguard against the possibility of this being unsuccessful, it was necessary to develop a suitable technique for inhibiting the outer surface of a cordite charge.†

Materials used for inhibitors

90. As already stated the material used for inhibiting coatings is a thermoplastic material. The main criteria by which an inhibitor for a coloidal propellant should be judged are as follows :—

(1) its ability to form a strong bond to the propellant, capable of withstanding the stresses imposed during temperature cycling

(2) its resistance to the migration of explosive plasticizer from the propellant to the coating and non-explosive plasticizer from the coating to the propellant ; either of these processes would cause ballistic variation on long storage.

91. These two requirements tend to be incompatible since the formation of a strong bond is significantly assisted by the intermingling of the nitrocellulose chains with those of the inhibiting material. However, two plastic materials which do fulfil this latter condition and which have been widely used are :—

(1) ethyl cellulose

(2) cellulose acetate.

With these materials it has been found that during storage at high ambient temperatures, ethyl cellulose abstracts far less nitroglycerin from the propellant than does normal cellulose acetate. Hence the rate of burning of the ethyl cellulose remains very small compared with that of the propellant (an obvious condition of good inhibition) while the consequent change in the rate of burning of the propellant itself is also small.

92. Furthermore, ethyl cellulose can be plasticized satisfactorily with as little as 10 per cent of plasticizer. There is therefore less plasticizer available to migrate into the propellant and hence less alteration in ballistic properties from this cause. On the other hand, highly plasticized cellulose acetate abstracts relatively large quantities of nitroglycerin from the propellant, while the reverse migration of inert plasticizer into the propellant is also considerable.

* The plastic propellants already referred to are of this type.
† For cast double base (CDB) propellants the ingredients are cast directly into the inhibiting coating (see Part 5B).

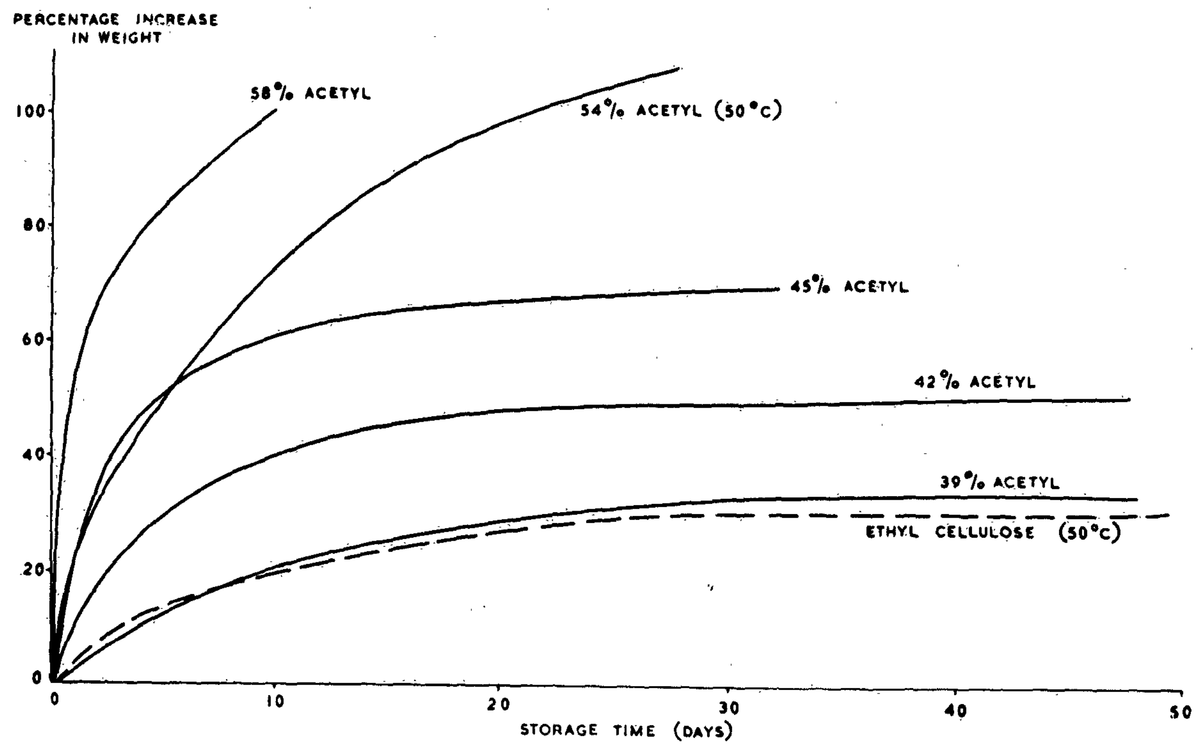


Fig. 12. Migration of nitroglycerin into unplasticized samples of cellulose acetate and ethyl cellulose

93. The migration of nitroglycerin into unplasticized samples of cellulose acetate and ethyl cellulose at 60° C is plotted against storage time in fig. 12 (in two cases a temperature of 50° C is used). The effect of migration is illustrated with *unplasticized* materials, since the counter migration of plasticizer into the propellant would prevent the percentage increase in weight being used as a simple criterion of behaviour. The dotted line in fig. 12 refers to ethyl cellulose, while the continuous lines all refer to samples of cellulose acetate with varying acetyl values. It is obvious that reduction in the acetyl value of cellulose acetate produces a plastic which compares favourably with ethyl cellulose as far as nitroglycerin absorption is concerned, although it is in fact more brittle (ref. 8).

Techniques for inhibiting cordite charges

94. As already mentioned one attempt at inhibiting cordite charges was by bonding the propellant to the motor tube wall. The particular rocket in which this method failed on temperature cycling was a 2-in. design: the immediate replacement consisted of a tubular charge 1·7 in. in diameter in a steel tube of 2·14-in. bore. With this loose tubular charge it was considered necessary to keep the charge reasonably central throughout burning. This was done by sticking six small circular discs or tabs of plastic material (each 0·80 in. in diameter and 0·17 in. thick) to the charge on a spiral as shown in fig. 13. A charge supported in this way was called a *tabbed* charge.

95. This is the first recorded case of an inert plastic being used as an inhibitor on a cordite propellant. The plastic composition used consisted of 55 per cent of cellulose acetate, 40 per cent of triacetin, and 5 per cent of carbamite. This material was originally known as dummy cordite since it had been developed in a propellant factory for trial extrusions with cordite presses; it has also been called *plastic Q*.

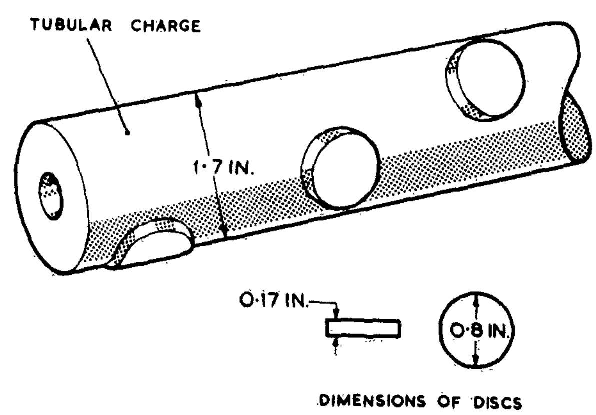


Fig. 13. Cordite charge supported on tabs

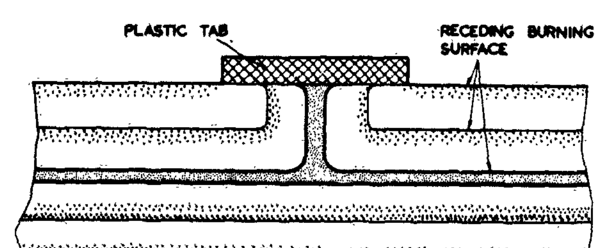


Fig. 14. How tabbed charges are supported

96. The method by which these small discs or tabs hold a charge centrally throughout burning can be seen by reference to fig. 14. As burning progresses the tab remains supported on a stalk of propellant. If the radius of the tab is not less than the web thickness of the charge the disc will be supported until the end of burning (see also fig. 5).

97. Another case of partial inhibition with a Service rocket charge is provided by the cruciform charge. Each of the four arms is coated with full length strips of the same material as that used for the tabs; each strip is 0·8 in. wide and 0·05 in. thick. These strips are put on by hand by using a cellulose acetate cement which is applied by a camel hair brush. A photograph of a portion of 'stripped' cruciform charge is shown in fig. 15.

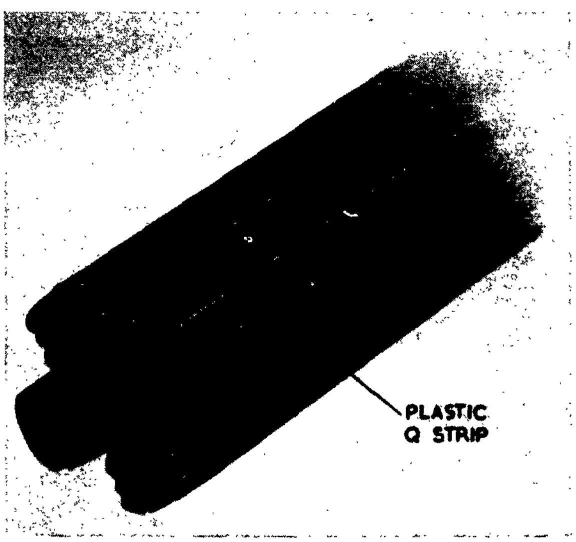


Fig. 15. Stripped cruciform charge

Hot moulding process

98. Although tabbed and stripped charges featured in most of the Service rockets used in World War 2, the most important application of inhibition is where the entire outer curved surface of the charge is coated with a thermoplastic material. This can be done by applying the coating to the charge by a combination of heat and pressure in a mould. If the operation is to be carried out at a temperature which is not too high for safe use with cordite, a fairly highly plasticized material must be used. The method used is known as the *hot moulding process* and the material chosen was again dummy cordite (ref. 9).

99. The mould usually consists of two semi-cylindrical jacketed sections, the active surfaces of which are frequently chromium plated. Provision is made for either steam or cold water to be passed through the jackets. The procedure used is to apply a coating of cement to the charge, after which it is hand-wrapped with a pre-cut sheet of dummy cordite, the outer edge of which is sealed with acetone to prevent unwrapping. The wrapped charge is then placed in the mould, previously lubricated, and the two sections are brought together. Pressure is then applied for the duration of the moulding cycle which is of the order of 3 minutes 'hot' and 1 minute 'cold'.

100. A typical mould for coating small charges held horizontally is shown in fig. 16. The bottom half of this mould can be lowered by operating the lever on the control panel, thus allowing the insertion or removal of the charge. When the charge has been inserted the mould is closed and steam or cold water is passed through the jackets while pressure is maintained on the charge.

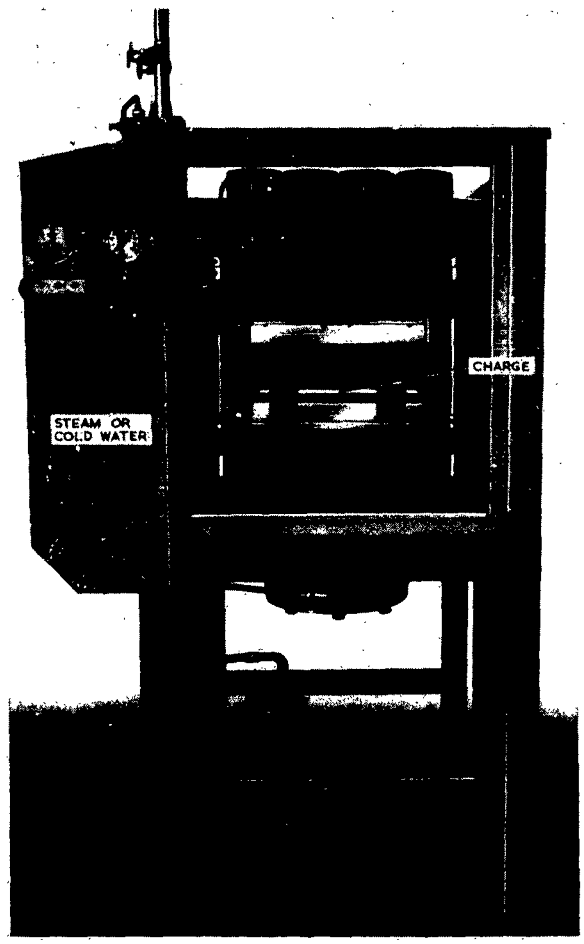


Fig. 16. Mould used in hot moulding process

101. The principal objection to this method is the need to use a highly plasticized material for the coating and as it has been shown plasticizer migration presents its own problems. It is therefore advantageous if a material can be used with a much lower plasticizer content. For this reason the *stress relief technique* was developed. This technique enables coatings of low plasticizer content—cellulose acetate and ethyl cellulose—to be used, since these plastics can be manipulated by this method at temperatures much lower than are necessary with the hot moulding process. The origin of the term 'stress relief technique' will become clearer as the method is explained.

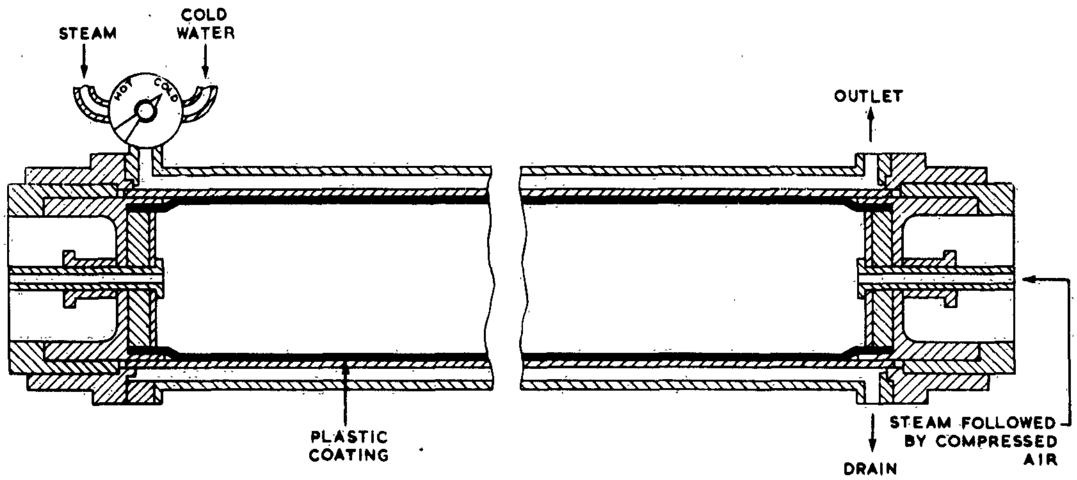


Fig. 17. Plastic coating expansion mould used in the stress relief technique

Stress relief technique

102. In this process the inhibiting coating is applied in the form of a tube, the diameter of which is initially 0·9 times approximately the diameter of the charge to be coated. This tube is first expanded in a steam heated mould by means of air pressure until its diameter is slightly larger than the diameter of the charge to be coated. The mould used is shown in fig. 17 and it will be seen how the expansion takes place. After expansion of the tube cold water is run through the jacket and the tube is kept under pressure until it becomes quite cold. Cement is then applied to the inside surface of the coating which is immediately slipped over the charge. A wooden block (about 8 in. long and of diameter slightly less than the diameter of the charge) is located at each end of the charge. These blocks enable a steam jacket to be pressed over the charge from end to end.

103. The steam jacket (see fig. 18) consists of a cylinder approximately 6 in. long with inlets and outlets for steam. The cylinder is closed at each end by metal rings, inside which are fitted rubber glands which fit tightly over the charge. These rubber glands (particularly the one at the top of the jacket) assist in pressing out traces of air remaining under the coating and assist the stress relief by slightly stretching the coating.

104. A complete coating machine of a type now in use is shown in fig. 19 with a charge in position. On the left is shown the method of applying the cement to the inside of the coating. A small reservoir of cement is retained at the top of the coating by a plunger and as the coating is slowly raised by a rotating movement cement is applied to its inner surface.

105. In choosing a cement for applying the stress relief coating two conditions have to be fulfilled. First, the cement should contain an ingredient (a solvent) which is capable of dissolving nitrocellulose and the plastic coating being applied. If a satisfactory bond is to be obtained this solvent must clearly not evaporate too rapidly under the coating conditions. Secondly, the cement must be viscous enough to ensure that an adequately thick film remains on the coating to allow sufficient wetting of the cordite and freedom from air inclusion. If, of course, the cement is too viscous then too much will be left under the coating and this will produce excessive softening of the cordite. It is clear therefore that the compositions of the cements used are quite critical.

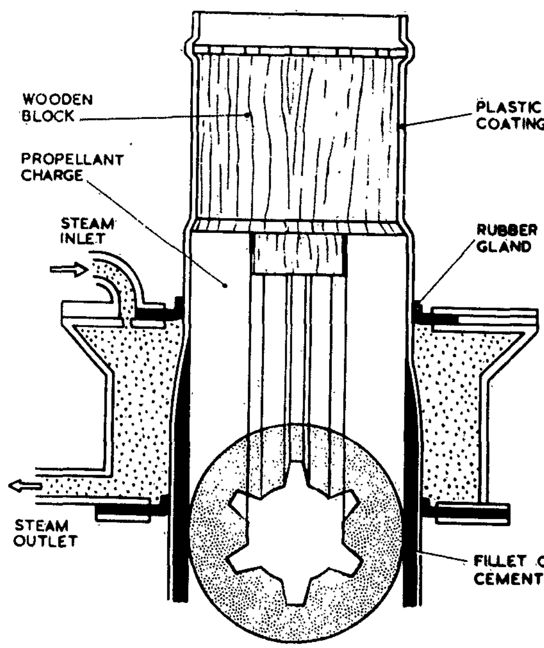


Fig. 18. Coating operation in stress relief technique

106. For stress relief coatings many formulations have been tested, but fairly exhaustive surveys have led to the following two compositions being selected :—

(1) *for ethyl cellulose coatings*—ethyl cellulose shavings 21 gm., carbamite 0·5 gm., ethyl cellusolve 500 cc., dimethyl phthalate 500 cc.

(2) *for cellulose acetate coatings*—cellulose acetate shavings 14 gm., carbamite 0·5 gm., methyl cellusolve 500 cc., dimethyl phthalate 500 cc.

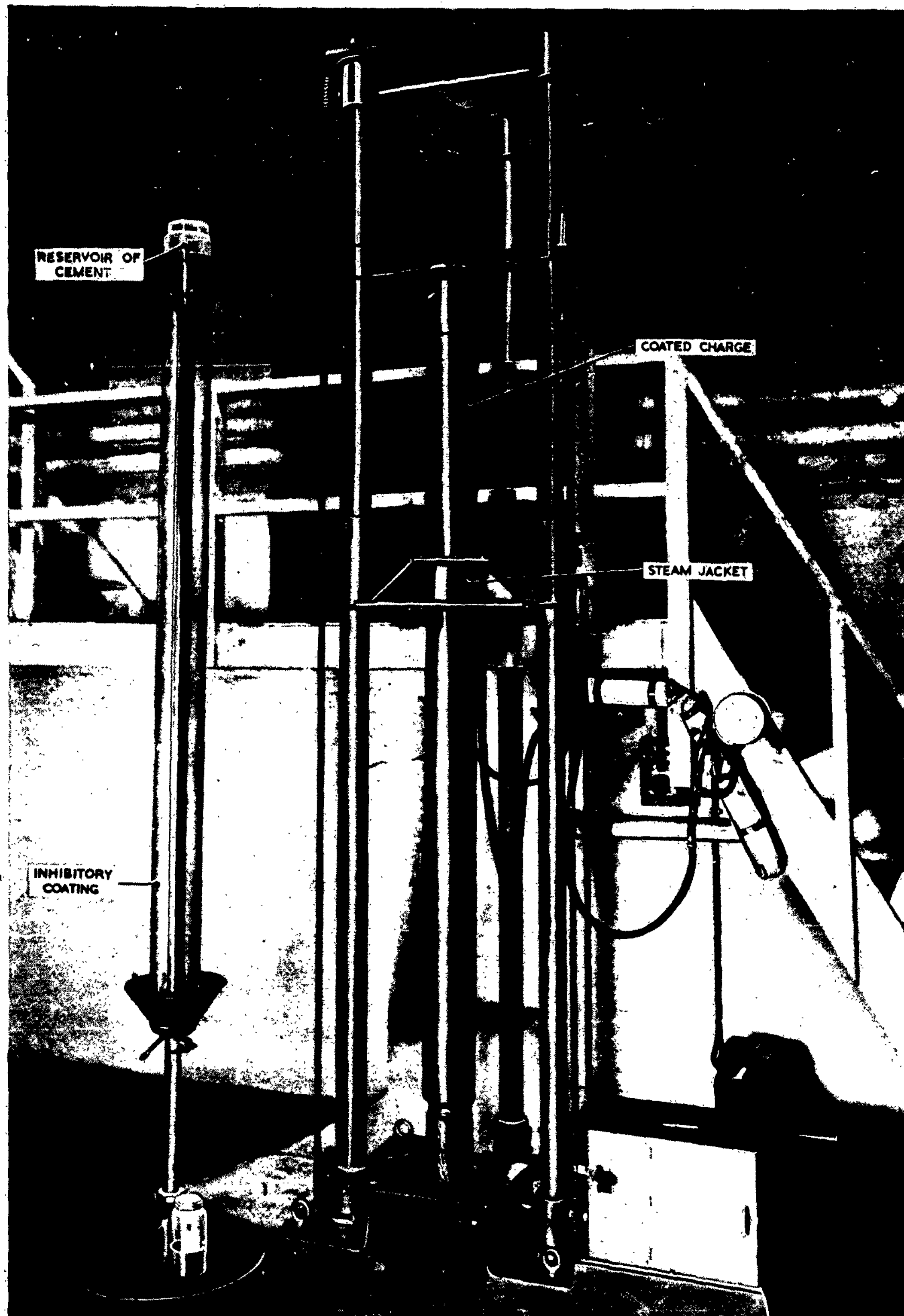


Fig. 19. Coating machine used in stress relief technique

EFFECT OF STRESS ON PROPERTIES OF THE PROPELLANT

107. Both in storage and during firing, the propellant charge in a solid propellant rocket motor is subjected to a variety of stresses, and it is necessary that it should retain its shape under conditions of rapid acceleration and rotation, as well as during rough usage and climatic storage, including temperature cycling. The relative importance of these factors varies widely depending both on the type of propellant and the charge design. In this respect the British plastic propellant is in a special category since adhesion of the charge to the motor tube wall exerts a controlling influence on the behaviour of the motor.

Cordite charges

108. With tubular cordite charges the effect of acceleration is particularly important since it adds to the effect of the differential pressure within the motor in producing a load on the rear end of the charge. Where the charge is supported on a grid, this load causes the charge to deform elastically and this elastic deformation takes the form of a transverse expansion or 'barrelling', the effect of which is to restrict the conduit and enhance the differential pressure. The effect can therefore be seen to be cumulative and aggravated by the use of soft compositions. Since it is at high temperatures that the internal pressure in the motor is a maximum and the mechanical strength of the propellant a minimum, the effect produced is a fairly sharply defined *temperature limit* above which bursts occur on projection firing.

109. The incidence of these bursts can be directly correlated with the Young's modulus of the propellant and its temperature dependence. For example, with the British 3-in. rocket filled with tubular SU charges the upper temperature limit is 86° F. It has been shown that when a harder composition is used, other things being equal, the upper temperature limit of the motor is that temperature at which the Young's modulus of this harder composition is equal to that of SU propellant at 86° F. (See Part 5A, Section 6, para. 186).

110. Another important aspect of the mechanical properties is afforded by the behaviour of long thin charges. As burning proceeds the effect of erosion is to reduce the web thickness at the nozzle end to vanishing point while a considerable quantity of propellant remains unburnt at the head end. In these circumstances the charge begins to collapse as a strut and to shorten in length. This gives rise to a loss in burning surface and a consequent tail off in the pressure/time curve. The use of mechanically stronger propellant minimizes this effect.

111. On the other hand the advantages of hard compositions are somewhat offset by the fact that they are more brittle and the effect of using too brittle a composition is particularly apparent at low temperatures when mechanical fracture may occur during rough usage, or at times, even on firing. With star centre charges the probability of this fracture occurring is aggravated if the star is badly designed and in order to minimize stress concentrations all sharp points are usually radiused. Nevertheless, the effect of elastic deformation is probably reduced to a minimum with coated star centre charges supported without grids.

Plastic propellant charges

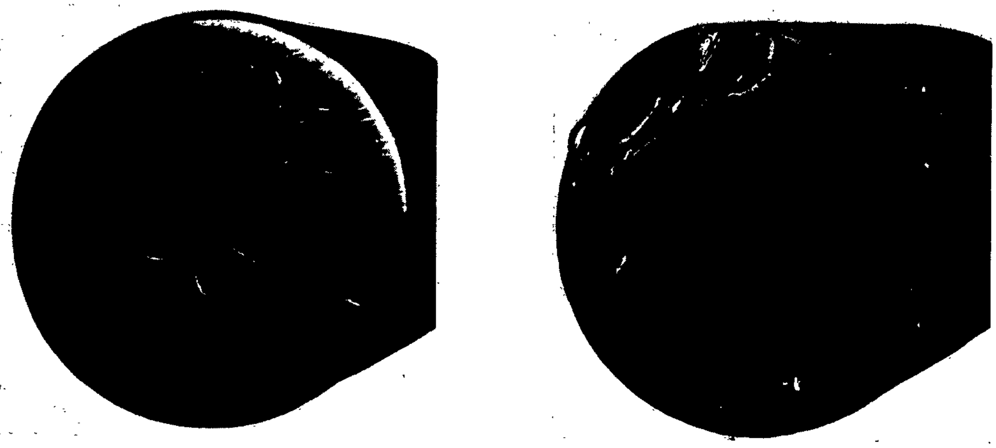
112. Plastic propellants fall into a very special mechanical category since an essential feature of their functioning is that they should retain their putty-like consistency at all temperatures. In practice plastic propellants are pressed against the inner wall of the motor tube and adhere to it. The reliability of this adhesion obviously determines the effectiveness of the inhibition of the outer surface, since the motor tube serves as the inhibitor. Although the coefficient of expansion of the propellant is ten times that of the metal, the putty-like consistency of the former allows it to expand or contract with the motor wall without the setting up of stresses large enough to cause separation or cracking, and a charge can be considered to have failed mechanically if it has deformed to an unacceptable degree or has cracked either at the wall or internally.

113. On continuous storage the weight of the charge causes a steady stress in one direction and it is necessary that the 'yield point' of the propellant at the upper temperature limit should be well in excess of this stress. Cracking and separation from the wall are effects which frequently arise from vigorous temperature cycling. In this connection the nature of the binder exerts a major influence on behaviour, since if the binder has a brittle point which is above or even close to the low limit of the cycle, a change in rheological properties will occur.

114. As shown in Table 2 plastic propellants themselves consist of approximately 80 to 90 per cent of salts with 10 to 20 per cent of binder. One of the most widely used binders has been a solution of polystyrene in poly-α-methylstyrene. This solution remains a viscous liquid over a fairly wide temperature range and has a low volatility which is sufficiently plastic to be readily extruded and moulded, but which is sufficiently firm to retain its shape under stresses normally encountered in use. A composition can be made with a viscosity of about 25,000 poises at 25° C.

115. This binder is however open to improvement in a number of respects. Compositions made from it have low cohesional strengths and charges having web thicknesses greater than 1 in. tend to crack under gravitational stresses, especially at elevated temperatures. Another defect is that both the binder and propellants made from it become brittle at low temperatures. In addition, the temperature coefficient of viscosity is rather large and this is reflected in a large temperature coefficient of plasticity of the plastic, so that propellants of normal plasticity at room temperature tend to become too soft to resist gravitational stresses at elevated temperature.

116. The lower viscosity limit for a usable binder is about 4,000 poises at 25° C. With binders of lower viscosity the strain hardening characteristics of the plastic composition are very small, so that a material containing sufficient binder (of this viscosity) to be coherent and workable, invariably flows under gravitational stresses. The upper viscosity limit for the binder is decided by the 'workability' of the plastic composition and depends largely upon the nature and the proportion of the binder used. The most promising material which has yet been developed is a polyisobutene of viscosity between 1,000,000 and 4,000,000 poises at 25° C. Preliminary indications are that plastic propellants employing such a binder will be satisfactory over the temperature range $-30°$ C to $+60°$ C.



(A) (B)

Fig. 20. Cracks in cordite charges due to hot storage

EFFECT OF HOT STORAGE ON PROPELLANTS

117. One of the principal factors which determines the suitability of a rocket propellant for Service use is the extent of its deterioration when subjected to tropical storage. Among a number of deleterious effects of hot storage, three in particular are worthy of note. One of these has already been considered, namely, the interchange of nitroglycerin and plasticizer between a colloidal propellant and its inhibiting coating. The other two are :—

(1) the loss in mechanical strength and fall in Young's modulus due to the degradation of the nitrocellulose molecule

(2) the development of cracks and fissures.

118. The production of cracks has been observed with all types of solid propellant although most markedly with cordite charges. It has been found that in certain cases cracks develop after as little as two weeks at 140° F. The effect which is illustrated in fig. 20 has been observed with both star centre and solid cord charges, although particularly with the latter.

119. It has also been observed that when the charge is coated, the cracks extend rapidly under the coating although once this is punctured further extension ceases. These experiments suggest that cracking is due to the gas which is formed by the slow decomposition of the cordite, collecting at surfaces of discontinuity (which correspond probably to surfaces of the original sheets from which the charge was extruded). The gas is unable to escape rapidly enough by diffusion through the cordite to avoid a pressure being developed at these surfaces, with the result that cracks are developed and slowly extended by this pressure.

120. Confirmation that gas evolution is connected with cracking is shown by fig. 21 which illustrates a solid cord charge to which had been fitted a cellulose acetate coating using no cement. On storage the cellulose acetate had bonded at the ends of the charge under its stress relief pressure. However, cracks appeared in the middle of the charge and the gas evolution associated with the cracks was evidently sufficient to prevent bonding at this point, and the pressure of the gas produced was such as to cause marked distension of the coating. The gas theory readily accounts for the shorter time which solid cord charges take to develop cracks as compared with perforated charges of the same diameter, since the latter have a thinner web of cordite through which the gases are able to diffuse more readily.

Fig. 21. Distension of coating on solid cord charge due to hot storage

121. Examination of different types of cordite has revealed that the tendency to develop cracking also varies widely with composition. For example, charges of 4·3-in. solid cord in SU composition cracked after three weeks at 140° F whereas tubular charges of the same external diameter (internal diameter 0·8 in.) in RS composition, showed no cracks after 28 weeks under the same storage conditions.

122. It is generally considered that the use of carbamite as a stabilizer gives rise to high gas evolution rates, and it is also possible that replacement of the nitroglycerin by a more stable ester would reduce the gas evolution rate still further. The Americans have claimed that the presence of dinitrotoluene has a beneficial effect in this respect. In order to test some of these views a special composition known as F487/37 was prepared in which the proportion of ingredients was as follows :—

diglycol	39%
gun cotton (13·2% N) ...	30%
nitrocellulose (12·2% N) ...	30%
carbamite	1%

This composition in the form of 4·3-in. cord charges showed no cracks after 6 months storage at 140° F. Work has also been carried out on the use of alternative stabilizers, and 2-nitrodiphenylamine appears to be extremely promising.

123. It is possible that other factors operate in addition to the composition in influencing the cracking life. It may be speculated that undesirable physical properties such as low tensile strength would aggravate any cracking propensity. The presence of flaws, as a result of poor cordite pressing conditions, would moreover serve to act as nuclei for the accumulation of gas and the stress accumulation in such flaws would readily initiate cracking. The incidence of visible flaws as a result of poor marrying of the cordite surfaces during extrusion of cordite is well known, of course, and occasionally these flaws or inclusion of air lead to catastrophic results on firing without hot storage being required to cause further deterioration. Unsatisfactory marrying may also give rise to microscopic flaws or weaknesses which would not be shown up by the usual visual examination or physical tests, but would be revealed either by an increased tendency to crack, or in some cases, by bursts occurring on firing.

124. In general terms, however, it may be said that the composition of the cordite is of more importance as regards actual cracking life on hot storage than the physical condition of the cordite resulting from the extrusion process. It is of interest that the flaws which do occur during extrusion are most frequently found with solid cord charges. Thus with the 3-in. cruciform charge a fine capillary running through the centre of the charge is often visible on close scrutiny. The effect of firing such a charge is illustrated by fig. 22 which shows a photograph of a fragment recovered from the resulting burst.

125. It is interesting to note that the most severe cracking which has occurred with plastic propellants has been with a composition in which a solution of 16 per cent of nitrocellulose and 6 per cent of carbamite in 78 per cent of diethylene glycol dinitrate was used as the binder. It was demonstrated that this cracking was due to gas evolution from the binder. Plastic compositions of this type also become very soft after prolonged hot storage and this is also probably due to thermal degradation of the nitrocellulose. The use of polymerized hydrocarbon binders has not completely eliminated the tendency to cracking, but it has drastically reduced it. For example, a charge with a 3½-in. web thickness was stored for 14 months at 140° F before small cracks developed.

FLASH AND SMOKE

126. A feature of solid propellants which has at times proved seriously troublesome is their tendency to produce either a blinding flash or alternatively large volumes of smoke. With colloidal propellants the former has been the case, while with composite propellants of the plastic type the latter is often more serious.

Colloidal propellants

127. The first serious attempts to suppress flash were made in 1941 when a number of different salts were incorporated into the cordite then in use. A wide variety of additives were investigated and those substances which contained potassium were found to be by far the most effective in suppressing the flash. The first

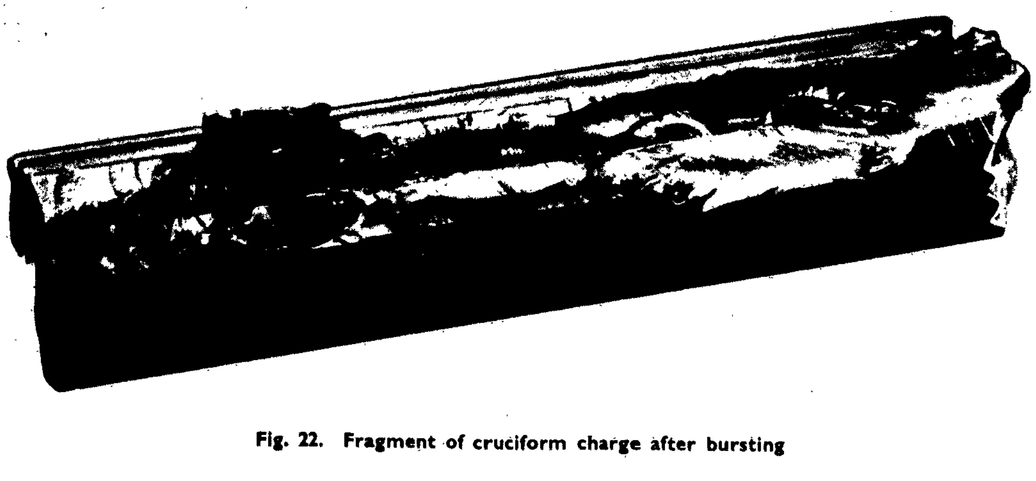


Fig. 22. Fragment of cruciform charge after bursting

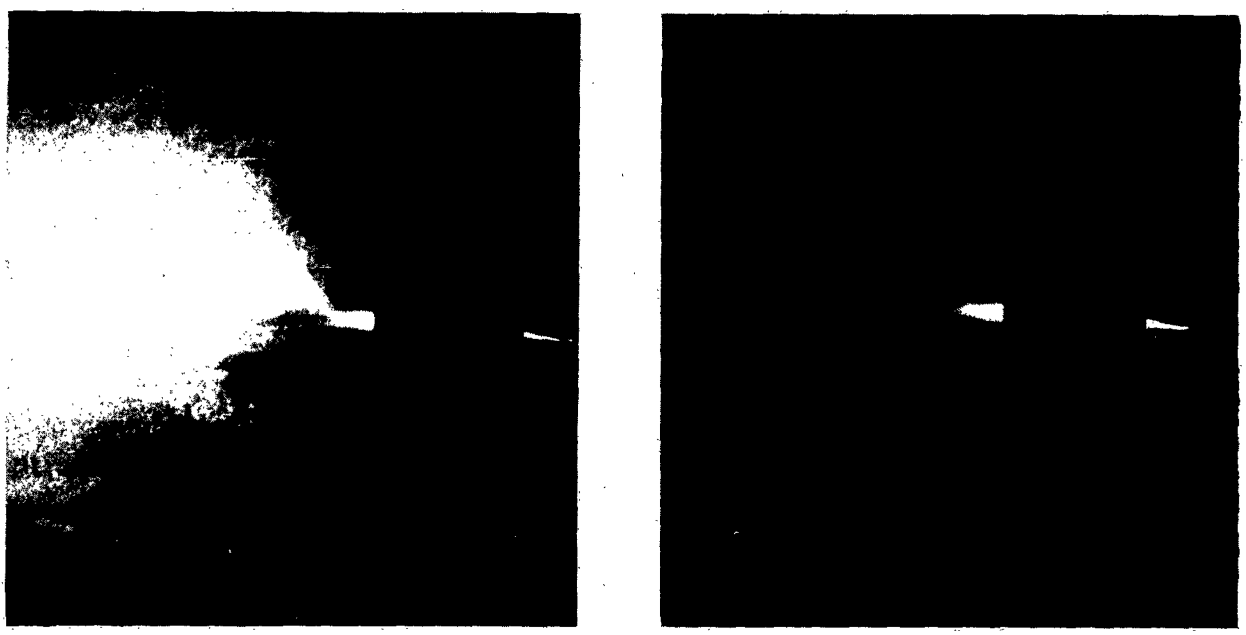
charges of this type were made by adding the salt to the cordite sheet during the rolling process. This was obviously not an entirely satisfactory procedure and it was at once realized that a preferable one would be to add the salt during the wet mixing operation. Unfortunately, most potassium salts are soluble in water, but since potassium aluminium fluoride is in equilibrium with a gaseous phase containing 10 per cent of potassium fluoride it was decided to use potassium aluminium fluoride (called potassium cryolite—see para. 54) and it has since been used in all British colloidal propellants where the absence of flash is a requirement. Propellants containing added potassium cryolite are indicated by the addition of the letter K to the title; thus SU becomes SU/K.

128. One difficulty which has been experienced with platonized colloidal propellants is that the addition of potassium salts to the composition destroys the plateau. Two methods of overcoming this effect on the rate of burning/pressure curve without loss of flash suppression have been developed. One involves the coating of an anti-resonance rod (see para. 135) with a suitable potassium salt. The other which is applicable to the cast double base process involves the use of two casting powders blended together, one containing the potassium salt and the other the platonizing agent (see ref. 21). Fig. 23 shows the jets of British Service rockets filled with SU and SU/K propellants. In fig 23B it will be seen that the flash has been completely eliminated and the amount of smoke produced is negligible.

129. Another aspect of flash production which became apparent only after the introduction of SU/K propellant into Service rockets was the fact that brilliant flashes can be produced if a flashless jet impinges on an obstruction. Such an obstruction may arise from the design of the launcher, or it may occur when two adjacent jets interfere with each other. In such cases pulses of flame are observed. Similar pulses were also observed during the firing of rounds with propellants containing very small quantities of potassium cryolite. Measurements of the intensity of illumination of the flashes throughout burning with charges containing 0, ½, 1 and 2 per cent of added potassium cryolite are shown in fig. 24. It was from these results that the percentage of salt to be included in SU/K propellant was fixed between the limits 2 and 2½ per cent.

Composite propellants

130. With plastic propellants the circumstances are rather different; most of the early propellants contained sodium nitrate and although they were flashless, smoke production was excessive. Fig. 25A shows a jet from a 4-sec. assisted take-off motor filled with propellant RD2043 containing 35 per cent of sodium nitrate. Replacement of the sodium nitrate by ammonium perchlorate results in a marked reduction in the amount of smoke; in fact, when the humidity is low many perchlorate propellants give little or no smoke at all. Disappearance of the smoke frequently leads to the production of a bright flash (see fig. 25B) and effort is being devoted to its elimination where perchlorate propellants are concerned. Certain propellants incorporating copper chromite or cupric oxide have shown some promise, but the real difficulty is to suppress the flash with the minimum loss of specific impulse.



(A) SU propellant (B) SU/K propellant

Fig. 23. Elimination of flash from cordite charges

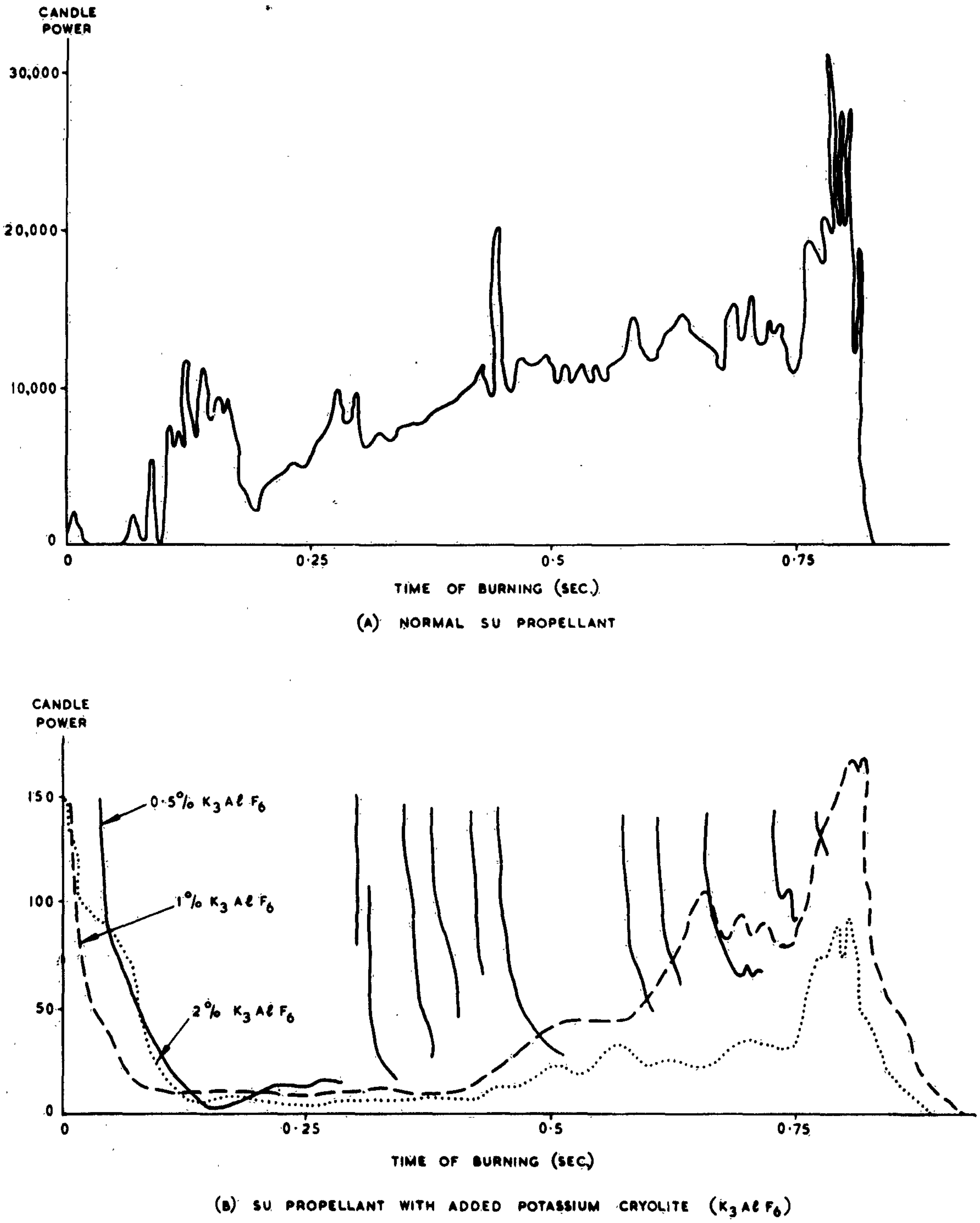
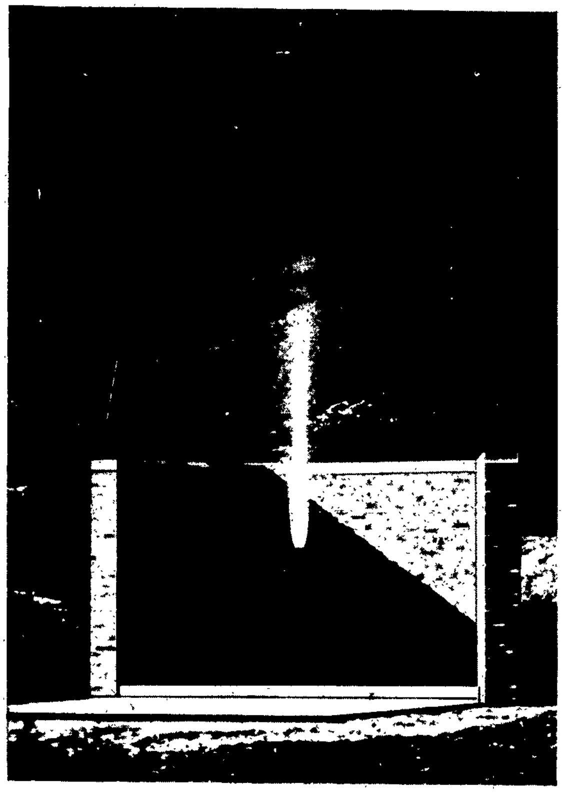


Fig. 24. Flash intensity during burning for 2-in. rocket with charges containing varying proportions of potassium cryolite

(A) Propellant containing sodium nitrate



(B) Propellant containing ammonium perchlorate

Fig. 25. Elimination of smoke from plastic propellants

RADIO ATTENUATION

131. Another phenomenon related to flash production which is of particular importance with guided missiles is radio attenuation. At any early stage in the development of the first beam-riding missile the probability of interference with guidance signals on passage through the flame was recognized. Early fundamental work suggested that free electrons in the flame would prove to be the most probable cause of such attenuation at microwave frequencies. Such electrons would be provided by thermal decomposition of elements of low ionization potential, such as sodium or potassium, and it was estimated that relatively minor amounts of these substances would produce sufficient electrons at temperatures of the order of 2,000° K to cause appreciable attenuation. Subsequent experience has confirmed this viewpoint, alkali metals having been shown to produce serious attentuation, whereas halogen ions suppress it.

132. In spite of the effect of potassium ions in producing attenuation, however, it has been found that when flash is suppressed the attenuation disappears also. Presumably this is due to the flame temperature being lowered. This observation is important since, as stated in para. 127 to 128, potassium salts are most effective in suppressing flash.

REGULARITY OF BURNING

133. Although burning in a solid propellant rocket motor usually proceeds in a smooth and regular manner and the pressure developed in general agrees closely with that calculated from the prediction equation, there

are two phenomena which have been observed that provide exceptions to this general rule. These are :—

(1) the production of secondary peak pressures

(2) the development of self-sustaining oscillations in the pressure.

134. The occasional production of secondary peak pressures throughout the burning period is sometimes of such considerable magnitude that they can cause the motor to burst (ref. 10). During the early development of the 2-in. and 3-in. rocket with tubular charges about 20 per cent of the rounds fired exhibited some degree of secondary peak. The cause of these peaks is by no means fully understood although methods were found for their elimination. With uncoated tubular charges they are possibly due to differences in pressure between the two conduits. Partial confirmation of this is afforded by the fact that the drilling of a number of small holes through the web produces completely regular burning. It is now normal practice for all British rockets containing tubular charges to have them drilled in this fashion.

135. An interesting alternative method of eliminating secondary peaks employs a metal strip placed axially down the central conduit of the tubular charge This technique has been widely followed in the U.S.A. where many designs of motor contain *anti-resonance rods* whose purpose is to eliminate secondary peaks. These rods are so called because the phenomenon is thought to be due to resonance in the gas stream. Similar rods are also frequently included by the Americans, with single-conduit star centre charges, although the magnitude of the peaks with these latter charges is usually much smaller than with tubular charges. One particular 9-in. motor containing a star centre cordite charge is of interest in that, with propellant SU/K it has given pronounced peaks at low temperatures only (using propellant F565/14 peaks were obtained at air temperature also). With this motor the use of anti-resonance rods did produce a striking effect, which is shown in fig. 26. In general, secondary peaks have not often been encountered with plastic propellant motors and then only when the rate of mass efflux was very high. In these cases the inclusion of anti-resonance rods produced no appreciable effect.

136. The development of self-sustaining oscillations in the pressure/time curve is a completely different type of irregularity, which occurs with certain motors at low pressures, but gives oscillations of considerable magnitude. Typical examples obtained with an early design of the Service 5-in. 4-sec. assisted take-off unit are shown in fig. 27. In certain cases the amplitude of the oscillations die away throughout burning as shown in fig. 27A, while in others the amplitude increases until burning ceases altogether as shown in fig. 27B. A third type of oscillation which has been observed is illustrated in fig. 27C. Here a period of oscillatory burning at low pressure is followed by steady burning at the normal pressure. The reasons why these oscillations occur are not fully understood, although it is known that they only arise at low pressures. The full explanation undoubtedly involves a more thorough understanding of the mechanism of burning of the propellant charge.

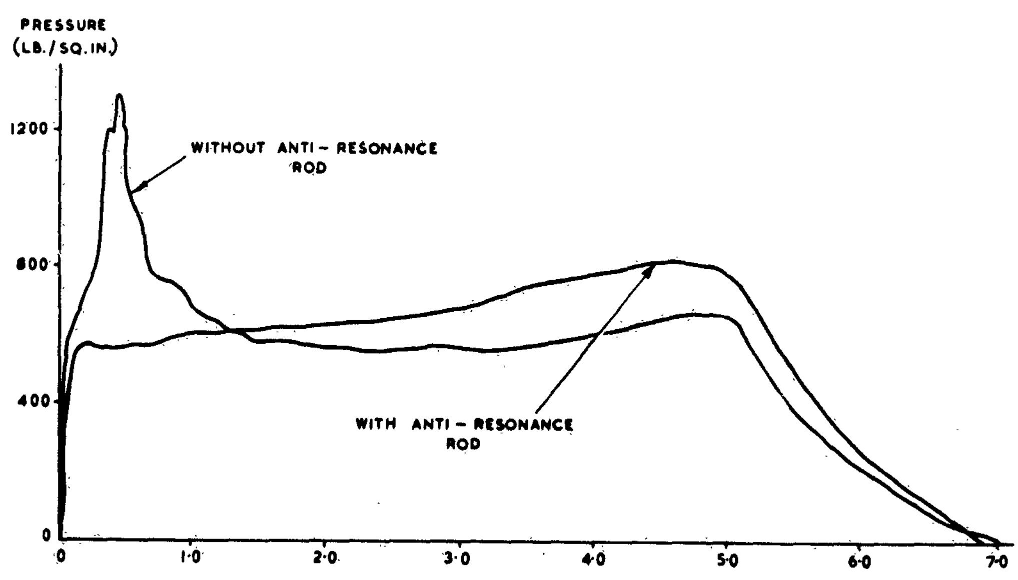


Fig. 26. Pressure curves for 9-in. rocket fired at −40° C showing elimination of secondary peaks

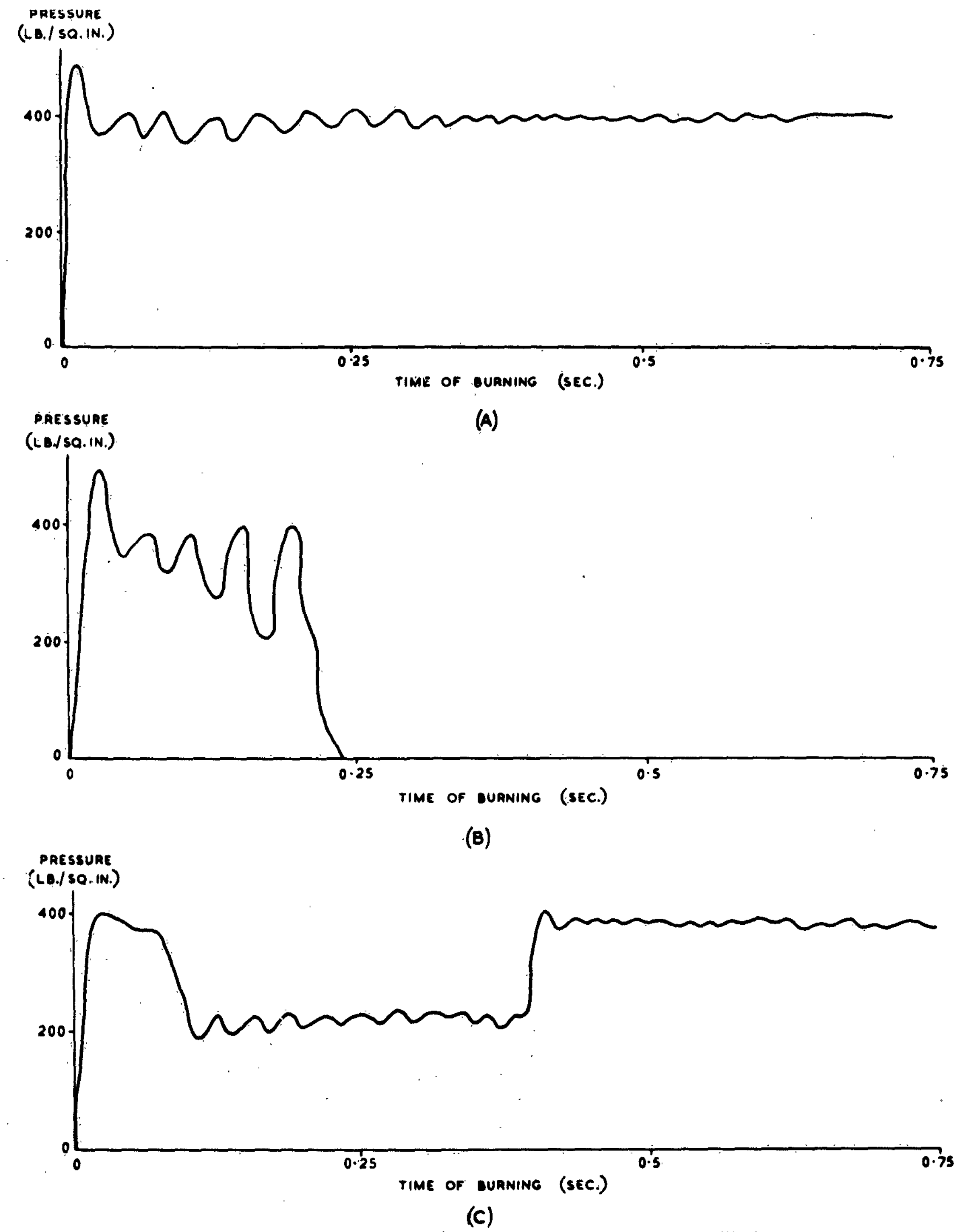


Fig. 27. Pressure curves for 5-in. rocket showing pressure oscillations

Section 3

THE MOTOR BODY DESIGN

GENERAL CONSIDERATIONS

137. The rocket motor illustrated in fig. 1 was of very simple construction and that sketch was primarily included to show the essential components that make up such a motor. In this section the motor body design is considered in greater detail. For this purpose it can be presumed that with any engine or power unit it is desirable :—

(1) to obtain the maximum output of power per unit weight of fuel consumed

(2) to obtain this output from the minimum deadweight relative to the fuel weight.

The first of these requirements is primarily a function of the propellant composition and the efficient utilization of it, while the second is mainly concerned with the detailed body and charge design.

138. As stated in Section 1 the propellant compositions which yield the maximum amount of energy will normally be those with a high specific impulse (S.I.). It is shown in Part 2 of this Textbook, Section 3, that

$$\text{S.I.} \propto \left(\frac{\theta}{M}\right)^{\frac{1}{2}} \qquad \ldots(21)$$

where θ is the combustion temperature of the propellant in degrees absolute and M is the molecular weight of the gaseous products of combustion. Thus the propellants yielding the maximum amount of energy will be those which have the maximum combustion temperature coupled with combustion products having a low molecular weight. The specific impulse will also be influenced by the expansion ratio of the nozzle (see Section 5) and by the operating pressure, since the equilibrium products of the combustion reaction will be affected by the pressure.

139. From these considerations it is clear that as far as the propellant composition is concerned the maximum output of energy will be obtained by burning a hot propellant at a high pressure. However, if this is done the motor body may have to be heavier to withstand this high pressure combined with the extra thermal stresses caused by the hot propellant. The optimum motor for any requirement, therefore, will involve a compromise between the factors tending to improve propellant performance and those affecting motor body weight. The exact nature of this compromise will vary from one requirement to another and will also be influenced by the state of advancement of research on various alternative materials of construction.

140. The advantage to be gained from reducing the weight of the motor body will also depend on the nature of the application. In this connection requirements can be broadly divided into three categories as follows :—

(1) high performance unguided rocket missiles and guided weapon boosts

(2) aircraft assisted take-off units

(3) long burning sustainer motors for guided weapons.

Most of the motors so far developed have been from category (1) where the power of the motor is required to accelerate a given mass or payload to a certain velocity. The magnitude of the velocity attained serves as a useful criterion of the performance of the motor and a simple expression for this velocity which shows its dependence on both propellant performance and weight characteristics can be derived.

141. In Part 3 of this Textbook, Section 2, it is shown that

$$V = v \log_e \frac{M}{M - m} \qquad \ldots(22)$$

where V is the all-burnt velocity of the rocket in vacuo, v the efflux velocity of the combustion gases, M the gross mass of the complete rocket assembly and m the mass of the propellant loaded. Examination of this equation reveals that a reduction in the weight of the motor body produces the largest increase in the all-burnt velocity when the payload is small relative to the weight of the motor body, particularly when the charge weight/body weight ratio in the motor is low. Conversely when the payload is large relative to the weight of the motor body, an appreciable reduction in the weight of the motor body produces a much smaller improvement in overall performance.

142. The magnitude of these effects is conveniently illustrated in Table 4, where two rocket motors of equal weight have been taken, one with one-third propellant weight to two-thirds deadweight, the other two-thirds propellant weight to one-third deadweight. To each have been added payloads equal to half and twice the total motor weight. The value of $\log_e M/(M - m)$ has been calculated for each combination, together with the effect of reducing the motor body weight by 10 per cent. Assuming that the efflux velocity of the combustion gases is unaltered the percentage increase in the all-burnt velocity will be the percentage increase in the term $\log_e M/(M - m)$. Similar calculations have been carried out to show the effect of increasing the charge weight by 10 per cent and these are also included in Table 4. It will be seen that the improvement in performance is greater when the charge weight is increased than when the motor body weight is reduced.

TABLE 4

Effect on rocket performance of decreasing body weight and increasing charge weight

	Charge weight $33\frac{1}{3}$ Motor body weight $66\frac{2}{3}$ Payload 50	Charge weight $66\frac{2}{3}$ Motor body weight $33\frac{1}{3}$ Payload 50	Charge weight $33\frac{1}{3}$ Motor body weight $66\frac{2}{3}$ Payload 200	Charge weight $66\frac{2}{3}$ Motor body weight $33\frac{1}{3}$ Payload 200
$\frac{M}{M-m}$	$\frac{150}{116\cdot7}$	$\frac{150}{83\cdot3}$	$\frac{300}{266\cdot7}$	$\frac{300}{233\cdot3}$
$\log_e \frac{M}{M-m}$	0·252	0·588	0·118	0·252
$\frac{M_1}{M_1-m}$ (10% less body weight)	$\frac{143\cdot3}{110}$	$\frac{146\cdot7}{80}$	$\frac{293\cdot3}{260}$	$\frac{296\cdot7}{230}$
$\log_e \frac{M_1}{M_1-m}$	0·265	0·606	0·120	0·255
Percentage increase in V	5	3	2	1
$\frac{M_2}{M_2-m_2}$ (10% extra charge weight)	$\frac{153\cdot3}{116\cdot7}$	$\frac{156\cdot7}{83\cdot3}$	$\frac{303\cdot3}{266\cdot7}$	$\frac{306\cdot7}{233\cdot3}$
$\log_e \frac{M_2}{M_2-m_2} = \log_e \frac{M_2}{M-m}$	0·273	0·631	0·129	0·273
Percentage increase in V	8	7	9	8

143. The figures quoted in Table 4 emphasize the necessity to consider a motor as part of its application rather than in isolation. For example, it is obvious that if a massive payload is being called for, then a considerable improvement in motor body design will produce only a relatively small increase in overall performance.

144. To relate Table 4 to practical realities the assembly covered by the first column corresponds approximately to a wartime unguided rocket with a relatively light head, such as the 2-in. U.P. The second column illustrates an application such as the high velocity 2-in. air-to-air rocket. The third is very close to the wartime 3-in. rocket with the 60 lb. HE head, while the fourth might be regarded as closest to the conditions of a guided weapon boost; these latter conditions would probably be reflected more accurately by a payload intermediate between those shown in columns 2 and 4.

145. For aircraft assisted take-off units the all-burnt velocity expression shown in equation 22 is obviously no longer a satisfactory criterion. For applications of this type factors of safety are much higher and weight considerations of lesser importance. This will be particularly so if the motor is jettisoned immediately after take-off, since if this is done weight may only be of importance in so far as it affects handling, raw material costs, etc. If, of course, the unit is to remain attached to the aircraft throughout its full flight then the same criteria which control the weight of the aircraft must apply. In general terms, however, weight is of lesser importance with this type of application.

146. The third main class of motor referred to in para. 140 is the guided missile sustainer which may have a time of burning of $\frac{1}{2}$ minute or longer. Here the motor represents an appreciable fraction of the total missile weight and since it is present throughout the full flight the need for light weight construction is particularly important. It might be said in fact that the weight considerations which are normally applied to aircraft power unit designs are also appropriate to the guided missile sustainer.

147. Another important requirement of a guided missile is that it should have high manoeuvrability. For a manoeuvre of a given lateral acceleration the lift force required will be proportional to the weight, assuming fixed dimensions. Since lift and drag are proportional for a given design, the drag and the necessary thrust will also be proportional to the weight. In general terms therefore a 10% increase in deadweight without dimensional changes will necessitate a 10% increase in power. This increase in power will, however, almost inevitably call for a motor with dimensional increases, when the drag will be increased. For this reason it is also important to keep the body weight to a minimum.

ESSENTIAL DESIGN PRINCIPLES

Motor tube design

148. Typical examples are shown in fig. 28 of the types of pressure/time curves which are obtained when a solid propellant is fired at three widely different temperatures representing arctic, temperate, and tropical conditions. Two features are apparent with these curves. In the first place it will be seen that there is a considerable variation in the time of burning from one temperature to another, and in the pressure developed. This is due to the fact that most solid propellants, and indeed all those which had been accepted for use in the British Services

up to 1955, possess a rate of burning which is sensitive to pressure and temperature. Secondly, it should be noted that there is a peak pressure at each temperature which is higher than the steady working pressure.

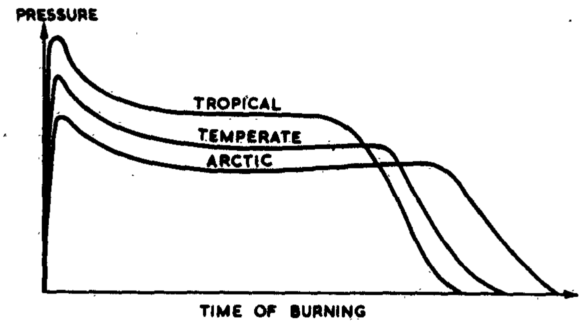


Fig. 28. Variation of pressure with time of burning for different ambient temperatures

149. Although this peak pressure may occur initially as illustrated, or later in burning as described in para. 131 to 136, the motor body must obviously be designed to withstand the maximum pressure developed at any firing temperature. It is to this pressure therefore that the safety factor is related. This will obviously result in a greater safety factor being available elsewhere during the steady working pressure phase, and also during the entire period of burning at low firing temperatures. The actual level of pressure to be selected for any design will depend both on the nature of the requirement and the propellant compositions available. Further consideration is given to this question in Section 6.

150. The formula applied to the motor tube design is the standard one relating the hoop stress of the material to the pressure, diameter, and wall thickness (see para. 31), viz. $F = pd/2t$. From this it is clear that for a motor of a given diameter and a material of a given strength, the wall thickness is directly proportional to the internal pressure. It follows that if the designer has to cater for excessively high peak pressures, he can only do so by thickening and consequently increasing the weight of the motor tube, unless he changes to a higher strength material of construction. Alternatively, if such pressure peaks are absent a saving in motor tube weight can be achieved. Hence from the engineering design standpoint it appears that, provided the motor tube retains the full strength throughout burning, the ideal pressure/time curve will be a true rectangle.

151. In designs where the motor tube gets excessively hot and consequently loses some of its mechanical strength, it will be preferable if the pressure/time curve falls slightly to compensate for this loss. Among British Service rockets it is of interest that the design with the highest initial peak pressure, viz. the 3-in. rocket, is also one where the case gets particularly hot because the charge burns on its outer surface. This means that the extra thickness of motor tube which has to be provided to withstand the initial peak pressure is also necessary later in burning at the lower working pressure because of the loss in strength of the material.

152. The cause of the initial peak with most motors is the erosive burning of the charge; and although knowledge of this phenomenon is far from complete, it now appears possible to design a charge in such a way that a high initial peak pressure can be avoided. Certainly it has been found that with large externally inhibited star centre charges, it is possible to have quite a small conduit to throat area ratio (i.e. a high loading density) without producing an excessive erosion peak. With such charges therefore the overall performance of the motor will be high, since the charge weight will be high, the thermal effects on the motor tube much reduced, and the initial peak pressure largely eliminated. When the platonized propellants now under development are freely available it will be possible to reduce still further the weight of the case for use in tropical and temperate conditions, since no increase in pressure will occur on firing at high temperatures.

153. One fundamental aspect of engineering design about which there is no general agreement concerns the magnitude of the safety factor and the precise strength value of the material to which the factor should be applied. This to some extent arises from the extremely short time of operation of many solid propellant motors compared with normal industrial practice. It raises, for example, the question of whether the pressure can be allowed to exceed that corresponding to the proof strength of the material. Certainly it would appear not unreasonable to allow transient peaks to exceed this value as long as the ultimate bursting pressure is not reached. It is by no means certain, however, what duration constitutes a transient peak as opposed to a steady pressure and this subject is one which merits further study. A convenient rough rule which is frequently used is to regard any pressure which persists for 0·1 sec. as steady.

154. For general design work it is often most satisfactory if the proof strength of the material is taken and the pressure p_p corresponding to this strength related to the steady working pressure p_w developed by the charge at the upper temperature limit. The safety factor is given by the ratio p_p/p_w; a factor of 1·1 is probably the minimum that can be taken for this relationship with safety. Where the proof strength and ultimate tensile strength of the material do not differ by a great margin, as is the case with some high tensile steels, then it may be preferable to relate the design to the bursting pressure of the motor body in question. For applications such as aircraft assisted take-off units, of course, it is desirable to use a higher safety factor and a figure of 2 to 2·5 is more appropriate.

End design

155. In the foregoing paragraphs consideration has primarily been restricted to factors influencing the design of the parallel portion of the motor tube, but in practice for motors of large diameter, the design of the ends exerts even more influence on the overall weight. This effect is especially marked when the ratio of length to diameter is low and this is well illustrated by fig. 29. In this figure five idealized pressure vessels are shown in which the volume available for a cylindrical charge has been kept constant and the wall thickness of the parallel portion made proportional to the diameter. By taking

the weight of the vessel shown in fig. 29A as unity, calculation shows that the weights of the other vessels are 1·34, 1·17, 1·65 and 4·33 respectively. The reduction in weight which results from the use of hemispherical rather than flat ends is particularly striking.

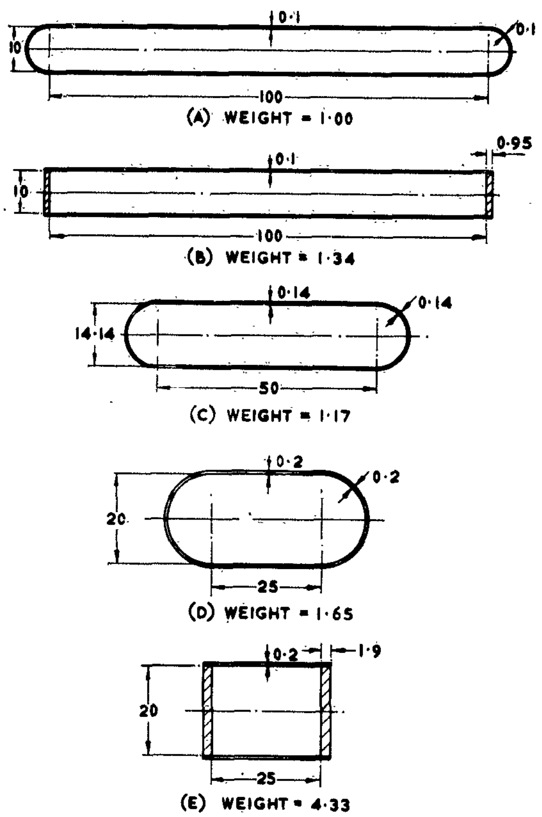


Fig. 29. Influence of length/diameter ratio on motor body weight

156. If these vessels are considered purely as pressure vessels, there is no necessity for the wall thickness of the hemispherical ends to be more than half that of the parallel portion, but on practical grounds it is reasonable to make them the same. With such a type of construction it may be assumed as a rough approximation that the weight per unit length of the parallel portion varies as the square of the diameter, while the weight of the ends varies roughly as the cube of the diameter.

157. The weight contributions of the ends are, in fact, of such great importance that at times they can be the dominant factor in the motor design. For any given requirement it would appear at first sight that the highest performance motor on a weight basis is likely to be obtained by using the highest performance propellant, because the total weight and volume of charge required to give the same thrust/time relationship will be less.* However, it is usually true that the highest performance propellants also have the greatest rates of burning, and examination of a range of compositions for any requirement will frequently indicate that the optimum charge shape for a fast burning propellant will be shorter and of larger diameter than the optimum shape for a slower composition because a thicker web must be used with the greater rate of burning. The extra weight of the ends of the motor tube needed by the larger diameter charge may therefore outweigh the saving in charge weight and each requirement must be treated on its own merits. An example of the effect of length/diameter ratio on overall weight is given in Section 6, Table 7.

158. One minor drawback of the hemispherical end which is sometimes important is that it is slightly wasteful of length and for certain applications it may be preferable to use a semi-ellipsoidal end of the type shown in fig. 30B, C and D. This figure indicates the exact shapes of four existing motor bodies, in only one of which is the head end hemispherical. It may also be noted that the semi-ellipsoidal end design will result in a slight weight saving compared with a hemisphere if the wall thickness is made uniform with that of the parallel portion throughout.

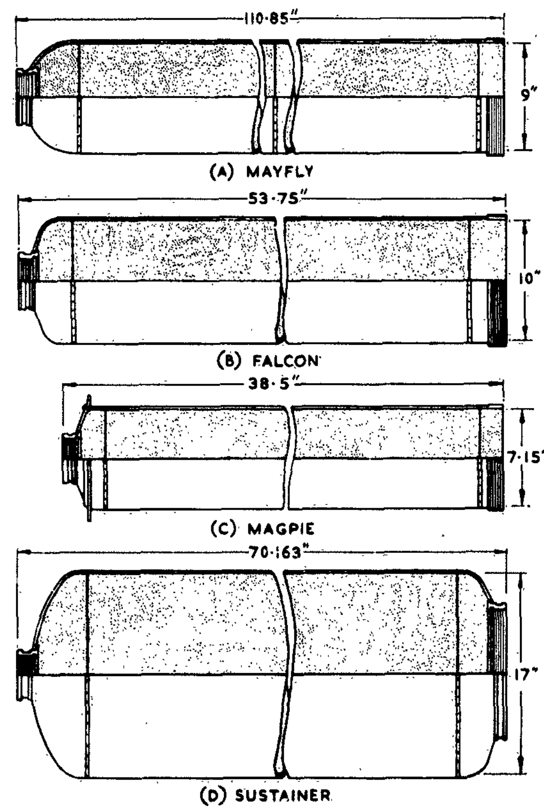


Fig. 30. Shapes of four existing rocket motor bodies

THE CHOICE OF MATERIALS

159. One of the major decisions which the rocket designer has to make is the selection of the material for constructing the motor body and nozzle. Considerations affecting the nozzle are given separately in Section 5 and

* In small unguided rockets the important criterion is frequently to obtain minimum time of flight to the target. Hence a fast burning propellant to give high acceleration is desirable. The resulting high mass rate of discharge of propellant gases demands a larger nozzle with a corresponding large gas conduit to avoid trouble due to erosive burning. The fastest propellant does not therefore give the best loading density or the highest all-burnt velocity. The criterion will be the best compromise to give the minimum time to target at what is considered to be the most usual service range of operation.

in this section we shall examine only the factors influencing the choice for the rest of the motor body, particularly the motor tube. Among these factors the most important are the following :—

(1) the specific proof strength, or ratio of the proof strength to the density of the material, with particular reference to the strength at the elevated temperatures encountered in practice

(2) the availability, particularly in wartime

(3) the ease of working and manipulation

(4) the basic cost of the material and in particular the cost of producing the finished motor body.

TABLE 5

Materials considered for motor tube manufacture

STEELS	a mild steel (0·15% carbon) a low alloy chrome molybdenum steel (SAE 4130) a high tensile nickel chrome steel (SAE 4340 or En 24)
ALLOYS	an extra high strength aluminium alloy (precipitation hardening type) (DTD 683) a high strength aluminium alloy (DTD 130A or RR 56) a medium strength weldable aluminium alloy (AW 10) a castable magnesium alloy (ZI 1) a titanium alloy (7 per cent manganese)
REINFORCED PLASTICS	a resin impregnated glass fibre plastic Durestos*

* Durestos is an asbestos reinforced plastic, the reinforcement being long fibre chrysotile asbestos and the plastic being a water soluble phenol formaldehyde resin.

160. The materials which have been considered to date include steels of various types, light alloys, titanium alloy, and reinforced plastics. These materials are listed in Table 5. A comparison of the specific proof strengths of these ten materials is shown graphically in fig. 31. These curves have been derived from figures for proof strength at various temperatures gleaned from a number of sources, which are listed in ref. 12 to 17.

161. One feature of these curves which is particularly noteworthy is the very high specific proof strength of the resin impregnated glass fibre, although the curve also illustrates a sharp deterioration in the strength with heat. The graph for glass fibre shown by a continuous line is, however, only present practice, which is estimated as 80 per cent of its ultimate strength. The immediate potential of glass fibre is shown by a dotted line. Since in many solid propellant motors the time during which the motor body tube is subjected to high pressure and temperature simultaneously is extremely short, the deterioration in strength of glass fibre may not be of great importance. Coupled with this, glass fibre plastics have such good thermal insulating properties that in practice it is usually only the inner layers that are affected. Because of this, and the fact that demands on the metal industry would be eased, considerable effort is being applied to the development of methods of fabricating glass fibre motor bodies and to the design of appropriate end closures (see para. A83).

162. It is well known that light alloys suffer from the drawback that their strength drops off markedly above about 200° C, a fact well illustrated by fig. 31. In practice, therefore, since the thermal conductivity of these alloys is reasonably high they do not appear to be particularly well suited for motor body design. This

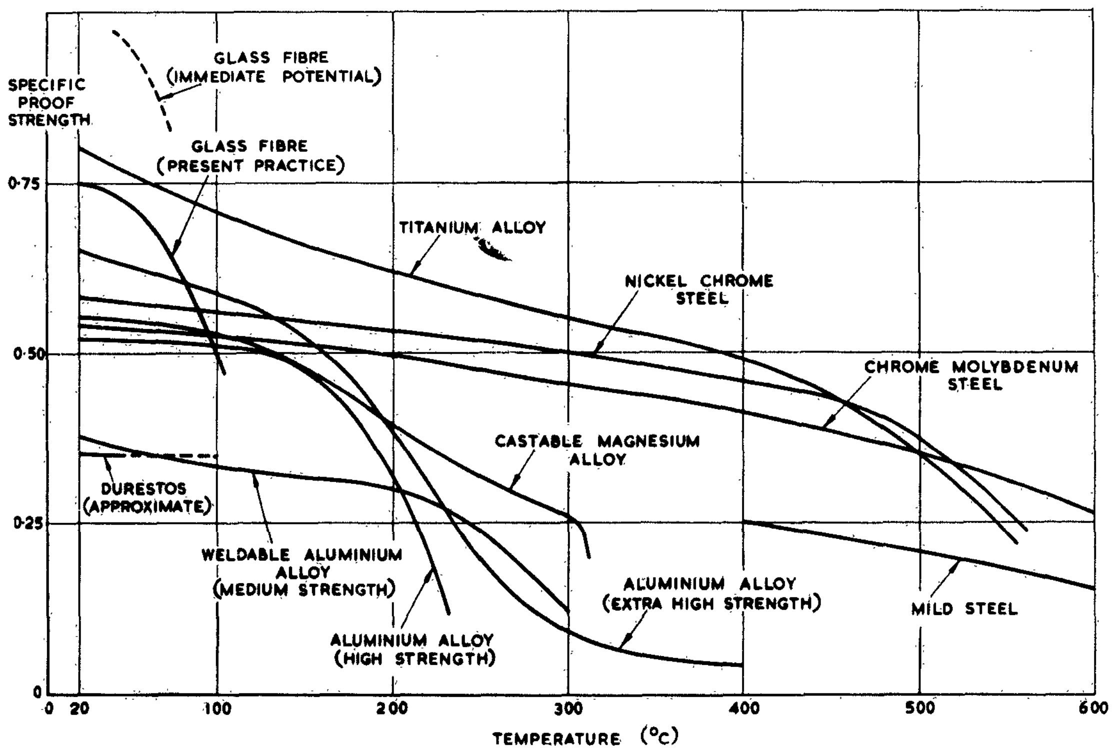


Fig. 31. Specific proof strength of rocket materials at elevated temperatures

would, of course, not be true if the motor body could be kept really cold, and because of this light alloys have been associated with some success with plastic propellants.

163. Another possible application of light alloys occurs when the motor tube has to take bending and buckling loads. An example of this is a guided weapon sustainer motor operating at low pressure. If the motor tube is designed purely as a pressure vessel in high tensile steel, then it will almost certainly be too thin to take the extra loads which would result from making the motor an integral part of the structure. The extra rigidity required for this purpose can probably be obtained with less weight penalty by using a light alloy instead of steel. For general motor applications, however, light alloys in their present state of development do not appear to offer any striking advantages. At the present time, therefore, since reinforced plastics are not yet fully developed, it is almost certainly true that the most practicable material for general motor body construction is steel.

MANUFACTURING CONSIDERATIONS

164. Since the problem of rocket motor body manufacture is essentially separate from that of design, the subject has been given special treatment in Appendix A. It is desirable, however, to indicate here the broad requirements which the manufacturer has to satisfy and to give some indication of the methods of solution. The requirements involve essentially the need to work to tight tolerances in respect of bow, ovality, and straightness on the one hand, and wall thickness on the other.

165. It will have been appreciated from Section 2 that colloidal propellants are those most widely used. The propellant charge by its nature will have its own tolerances of bow and ovality. In order that the motor should have the highest possible performance, it is essential that the density of loading should be as great as possible ; hence the external diameter of the charge should be as near as tolerances permit to the bore of the motor tube. The influences of bow and ovality are obvious. It is also desirable that the wall thickness of the motor tube should be maintained within the narrowest possible limits. If this is not done the weight variation of the bodies will be great and if this weight spread is associated with similar variations in the charge weight, the effect on the overall performance will be cumulative. Hence the manufacturing requirement is for the minimum bow and ovality coupled with the minimum weight spread.

166. As far as the manufacturing methods are concerned with glass fibre tubes, attention is being given to the use of the glass in the form of roving yarn, tape, and cloth, and the glass is impregnated with either cold-setting polyester resin or ' contact ' phenolic resin. Epoxy resins have not yet been greatly used, largely on account of their high cost and the lack of knowledge of their characteristics. One of the most promising methods

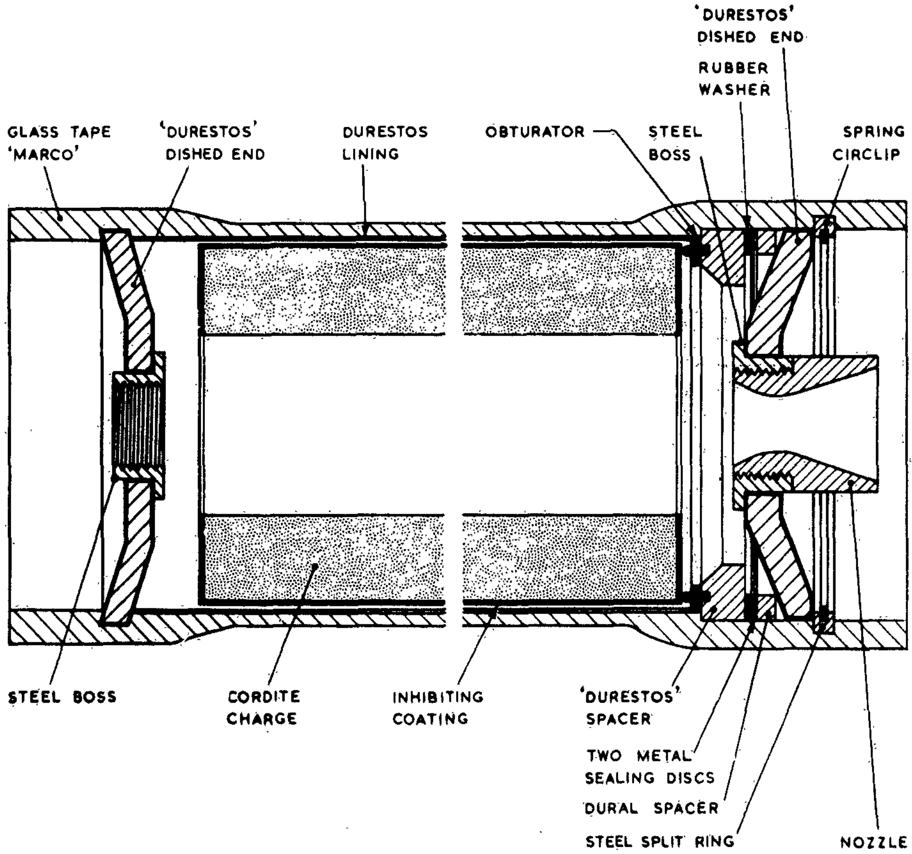


Fig. 32. Attachment of ends in plastic tubes

so far developed employs the glass in the form of flat multiple fibre tapes which are wound helically on a mandrel in two directions. It is believed that an ultimate tensile strength as high as 45 tons per sq. in. may eventually be achieved with this type of material.*

167. One problem however which remains to be solved is the attachment of the ends. Fig. 32 indicates one scheme which has been successfully tested. In this design the head-end closure consists of a moulded disc, or dish-shaped end, which is concave towards the outside. The distortion of this disc under pressure, forces the edges more firmly into the tube wall. The closure at the nozzle end, which must be detachable so that the propellant charge may be inserted, is also dish shaped. This is held in by a snap ring with an O-ring seal. Although closures of this type are considered suitable for tubes up to 10 in. diameter with a design pressure of 2,000 lb. per sq. in., there is still considerable scope for further development. (See Appendix A, para. A83).

168. Of light-alloy tubes the most favoured manufacturing method is extrusion followed by machining. For high strength tubes, the extrusion stage is followed by drawing down to the final dimensions over a mandrel and suitable heat treatment is applied at appropriate stages. Difficulties have arisen, but prototype tubes up to 5 in. in diameter have been successfully produced. (See para. A75).

169. With steel tubes the production methods in use in this country are hot rolling, cold drawing, deep drawing, and fabrication from sheet. Hot rolled tubes are not suitable for rocket motor bodies since they cannot be produced to the diameter/thickness ratio required. Cold drawing is in use as a basis of production for motor tubes of medium tensile steel, but it has so far proved difficult to produce tubes with a diameter/thickness ratio greater than 100, and special precautions have to be taken to reduce the ovality and bow to the acceptable limits. Deep drawing is a technique which has been developed considerably in recent years and offers great promise. Some indication of possibilities of this method is described in Appendix A.

170. One of the most widely used methods is fabrication from sheet. For example, the 3-in. Service rocket tube is manufactured in this way and during the war, production was maintained at a rate of one million per year. Subsequently, motor tubes of diameters up to 18 in. have been made and active development work is now proceeding with the welding of higher tensile steels. The special considerations associated with this method are discussed at length in Appendix A.

METHODS OF OBTURATION

171. With many designs of solid propellant motors it is frequently necessary to introduce an obturator or gas seal. Functionally, obturators are of two main types as follows :—

(1) those which assist the thermal insulation of the motor body

(2) those which are used to seal end closures where screw threads are undesirable.

* Another method similar to this employs strips of spring steel or aluminium alloy which are wound helically on a removable mandrel. This method is discussed under the heading ' strip wound tubes ' in Appendix A, para. 97.

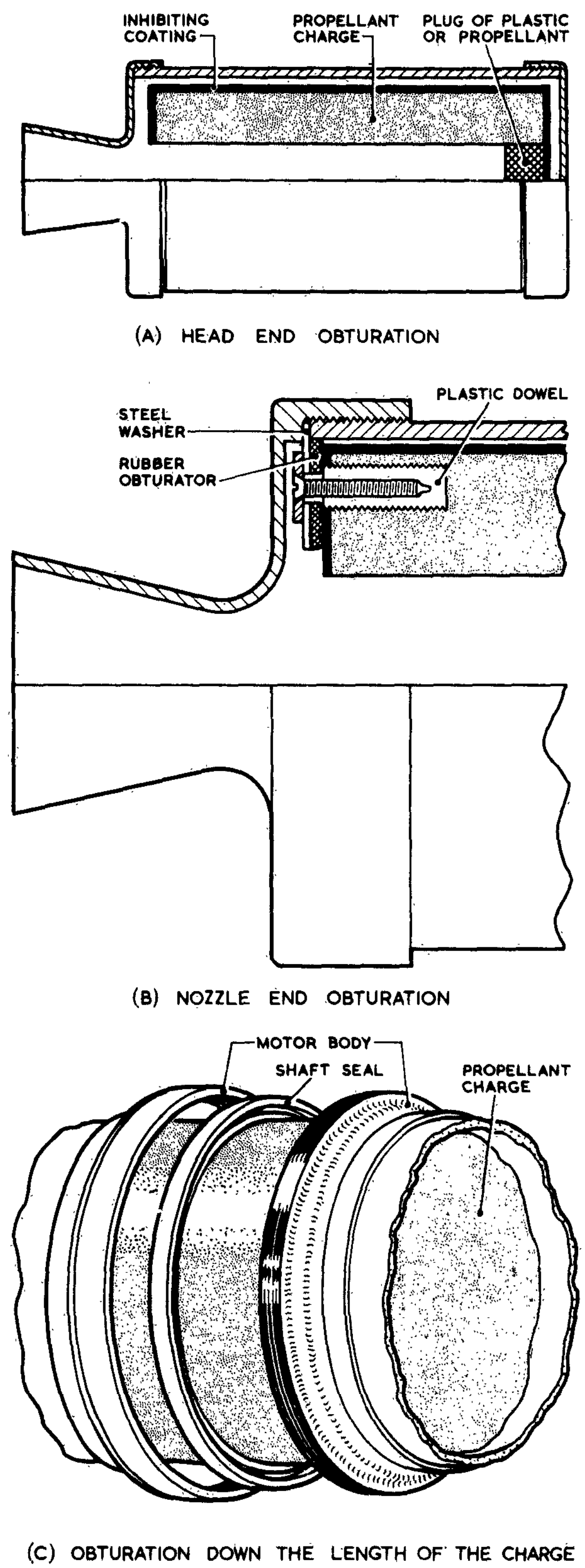


Fig. 33. Obturation to assist thermal insulation

172. It has already been indicated in Section 3 that the choice of materials for constructing the motor body is influenced by temperature considerations. To ensure that the most efficient use is made of the material forming the motor tube it is desirable to use the propellant as a thermal insulant. With plastic propellants which are bonded to the motor tube wall this thermal insulation is achieved in an ideal manner. But with colloidal propellants inhibited on the outer surface it is necessary to leave a gap between the propellant charge and the motor tube. This gap is open to the entry of hot gases and by virtue of the differential pressure acting between the head and nozzle ends of the motor gases are forced into it. Not only does this result in excessive heating of the body, but it also results in the inhibitory coating of the propellant being eroded away. These defects in design can be rectified by incorporating an obturator between the charge and the motor body.

Obturators to assist thermal insulation

173. Three systems of obturation of this type have been investigated (ref. 11), where the obturation is carried out in one of the following three positions :—

(1) at the head end
(2) at the nozzle end
(3) at a position down the length of the charge.

The first system has proved effective with a number of short rocket motors. One method used is shown in fig. 33A, where obturation is achieved by using a plug of plastic or propellant to seal the head end. When the ratio of the length to diameter is large, however, there is a tendency for bursts to occur due to the delay in pressurizing the annular gap by gas which has first to travel down the conduit.

174. The system most widely used with externally inhibited charges is that carried out at the nozzle end, since efficient obturation is assisted both by the differential pressure acting down the conduit and by the acceleration set back force. Various methods have been investigated, one very positive type being illustrated in fig. 33B. In this method a number of plastic dowels are screwed into the sliver regions of the charge. These dowels take retaining screws which pass through holes in a rubber obturator to which is bonded a steel washer, which is in turn retained between the end plate and the motor tube. The holes in the obturator and washer are deliberately enlarged to accommodate transverse expansion of the charge when the motor is subject to variations in temperature.

175. The system where the obturation is carried out at a position down the length of the charge (see fig. 33C) has the advantage that obturation is independent of the position of the charge relative to the motor since the seal is not made on an end face, and distortion of the charge during stowage does not impair the efficiency of the system. Erosion of the coating is also minimized by having half of the annular space filled with gas from each end. Against these advantages is the fact that the system normally requires a local increase in motor diameter to accommodate the U-type shaft seal used.

Obturators used to seal end closures

176. Of the obturators used as gas seals with unscrewed end closures one of the most widely favoured types is the simple rubber O-ring. This has been incorporated in a number of large motors where the end plate is held in position by a snap ring or similar device. With smaller motors a different type of obturator which has been highly effective is that used with the Service unguided 2-in. and 3-in. rockets. These motors are closed by means of a shell ring held in the tube by spring-loaded steel pins. An obturator in the form of a pressed steel cup is cemented to the under side of the shell ring as shown in fig. 34.*

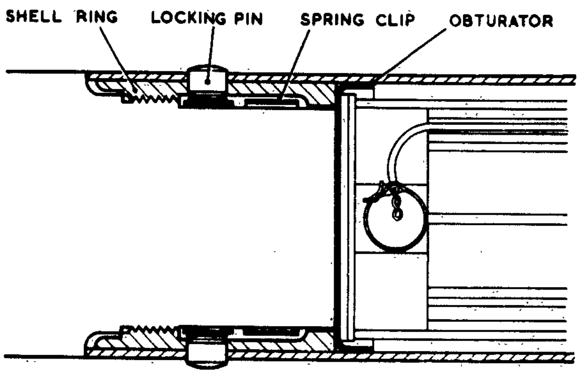


Fig. 34. Obturation to seal end closures

* The charge and igniter housing are also shown in fig. 34 ; this will become clearer on referring to para. 201 and fig. 37B.

Section 4

THE IGNITER

IGNITING COMPOSITIONS

177. The purpose of the igniter as its name implies is to initiate the burning of the propellant proper. The actual mechanism of ignition is intimately associated with the mechanism of burning. As stated in Section 2 this latter process is by no means completely understood, although burning clearly starts by thermal decomposition of the surface layer of the propellant. It has been shown that this thermal decomposition can be effectively initiated by passing either a stream of hot gases or hot particles over the propellant. American designs of solid propellant rocket favour the former method, while most British designs use the latter. This British preference largely results from extensive investigations carried out between 1937 and 1943 with a variety of relatively small rockets.

178. A number of compositions were examined, including a mixture containing magnesium powder and an oxidizing agent, nitrate-silicon mixtures widely used for priming pyrotechnic compositions, gunpowder, cordites of small size, and composite igniters such as small cordite in conjunction with a composition known as SR371. It was concluded that the first type was the most effective and the composition originally selected was known as SR354. Subsequently composition SR371 was preferred ; it is a much more free-flowing powder and is safer to manufacture and easier to fill than SR354. This leads to a more even distribution of ignited particles which probably contributes to its slightly superior effectiveness as an igniter.

179. The precise composition of SR371 is as follows :—

magnesium powder, grade 5	42%
potassium nitrate	50%
acaroid resin	8%

The acaroid resin is included as a protective agent and desensitizer. Considerable investigations were also carried out with analogous compositions in which the grade of magnesium was varied. Fig. 35 shows photomicrographs of various grades of magnesium powders which were tried out. As a result the final composition preferred was SR371C in which the percentage of magnesium powder was made up of 10 per cent of grade 5 and 32 per cent of grade 3.

180. Of the other grades the compositions made from grades 4 and 6 were found to be useless because they burn too quickly and are to be avoided. These two grades are made by a different process and have a lower bulk density and a greater surface area ; the compositions made from them burn much more rapidly than SR371C. Compositions made from grade 0, the coarsest grade made by the carding process, give the best results from this class of magnesium, but ignition is erratic as might be expected from the use of such large particles. Compositions based on aluminium (grade A2) were also investigated, but it was found that for equivalent functioning a much finer size of particle was necessary. This leads to less desirable conditions of manufacture and a more sensitive product.

181. Although effective as igniters, compositions containing magnesium suffer from the disadvantage that they are sensitive to friction and that they react chemically with water ; so that they may even ignite spontaneously or become inert. The choice of potassium nitrate as an oxidizing agent was made because of some advantage in this respect. Another disadvantage of magnesium compositions is the bright flash which occurs in firing the igniter. However, no troubles of this kind have so far occurred in service, although millions of rounds have been fired with igniters of this composition.

Flashless ignition

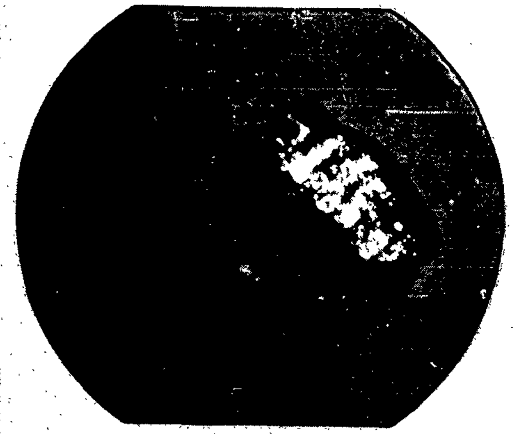
182. In spite of the fact that magnesium powder compositions are generally most effective there are certain applications in which the dazzling flash produced is tactically quite unacceptable. In such cases it will be necessary to revert to a type of gunpowder. The change from an igniter filled with SR371 to one filled with gunpowder G12 results in a drop in the intensity of illumination from approximately 10,000 to 100 candle power. At the same time to secure equally effective ignition it is necessary to double the weight of igniting composition approximately.

183. An even lower order of illumination (about 10 candle power) can be achieved if sulphur-free gunpowder is used, but in such cases the weight of composition needed is roughly three times the weight of SR371 required for reliable ignition. In general, coarse grades of gunpowder such as G12 and SFG12 are preferred, since these restrict ignition peaks and shock. The use of meal powder is less desirable.

Igniter shock

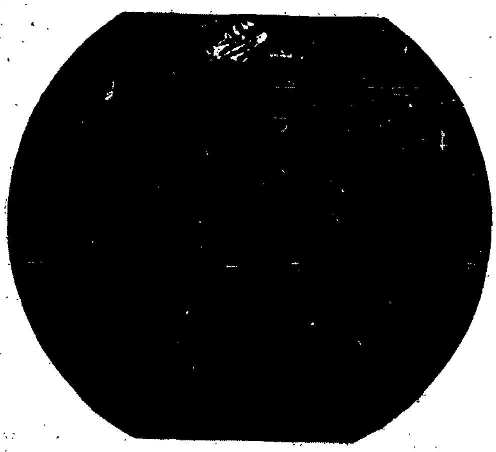
184. In certain cases when the igniter is fired the development of a severe shock can be extremely serious. The phenomenon can be defined as the development of a transient thrust of magnitude not less than 20 per cent of the sustained thrust developed during the main period. In general the transient peak is followed by a short period of no thrust and this appears before any pressure rise is observed. It should be noted that the precise phenomena recorded are to some extent a function of the method of supporting the rocket during firing and of the frequency response of the instrumentation system in use.

185. Fig. 36 shows shock phenomena obtained in the static firing of a typical guided weapon boost motor using gunpowder G20 as an igniter in one case and SR371C in the other. The curve for the gunpowder igniter is typical of many but that with SR371C has been selected as the worst ever obtained with this type of composition.

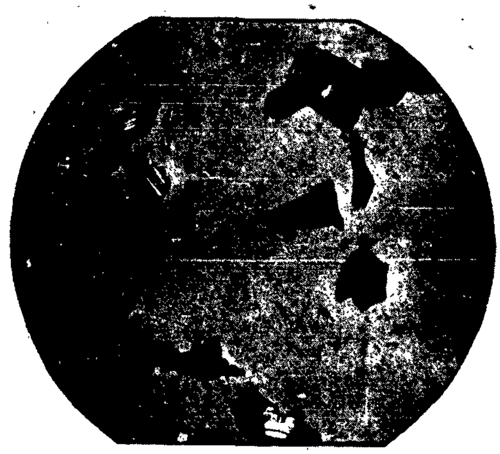


GRADE O

GRADE A2



GRADE 3



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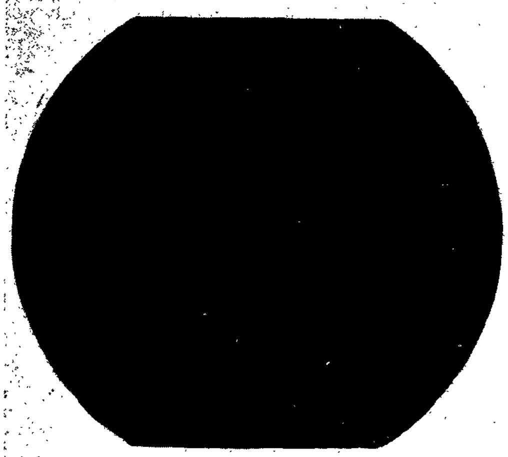
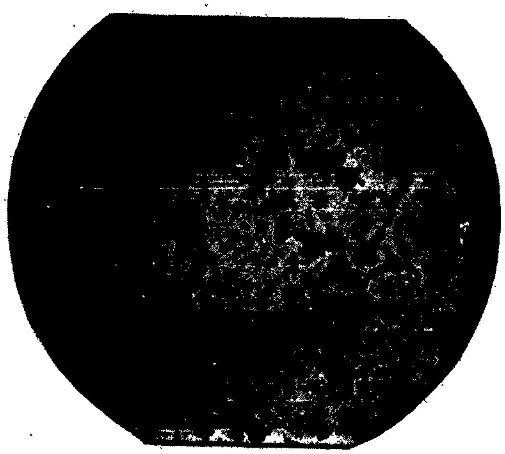


GRADE 5



GRADE 6

Fig. 35. Photomicrographs of various grades of magnesium powders

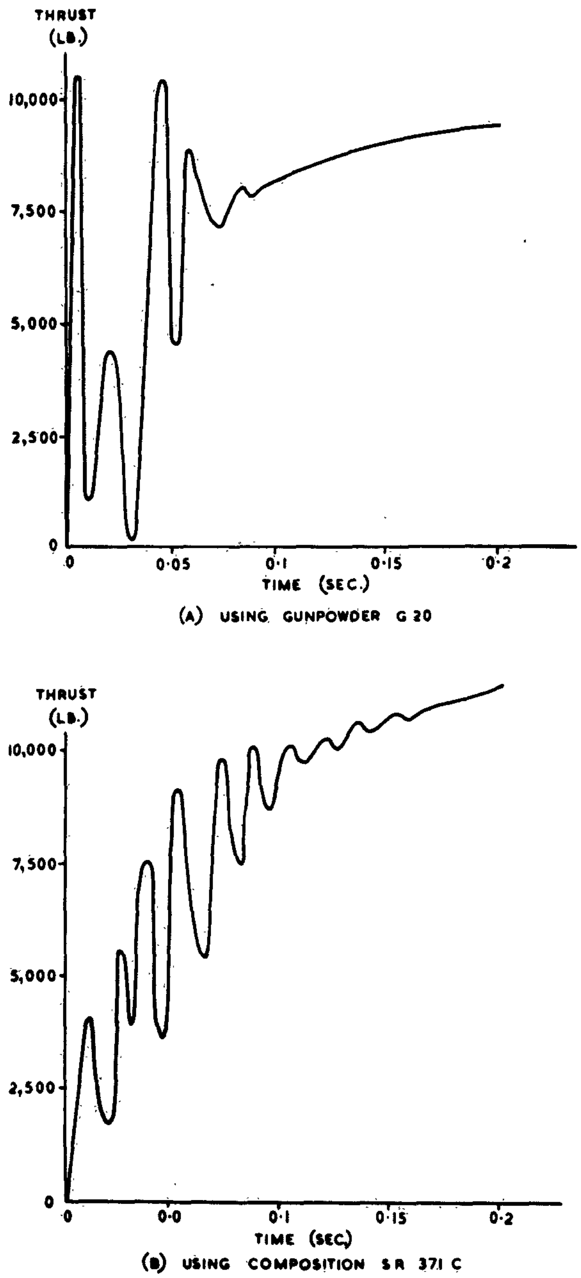


Fig. 36. Initial shock produced by igniter

DESIGN OF IGNITER CONTAINERS

Location of the igniter

186. In almost all solid propellant rocket motors the igniter is placed at the closed end of the motor body. This location was decided on early in the development of rockets as a result of experiment. As might be expected, it is the most effective position because the igniter products have to pass over the propellant before they can escape through the nozzle.

187. Some designs of rocket motor have been ignited reliably, however, from a container placed at the nozzle end. The two important requirements of such an igniter are :—

(1) that it must throw some of its contents up to the closed end of the motor

(2) that it must remain in place while it ejects its contents.

If these requirements are fulfilled, then the design has the merit of being easily replaceable should it become defective, without breaking down the motor ; it also avoids long leads passing through the motor.

Principles governing the design

188. The main principles which govern the design of igniter containers can be divided in those which affect

(1) storage

(2) firing.

During storage the container must be adequately sealed to retain the composition without leaking and to be resistant to moisture. As stated in para. 181, igniting compositions are usually sensitive to friction and must not be allowed to escape into the body of the rocket motor where they might be trapped between metal surfaces. Moreover, loss of composition from the igniter may cause an ignition failure when the round is fired.

189. Protection from moisture is desirable to cover the period before the igniter is assembled into the round, and to serve as a second line of defence in case the complete round should be badly sealed. The container must also be strong enough to withstand the stresses to which it may be subject, in particular the effect of dropping the round, so that charge impacts on the housing must not be overlooked.

190. If made of metal the container must be rigid enough to avoid grinding friction between parts to which the igniting composition may have access, and for the same reason it should be firmly anchored in the round. To use the propellant charge as a support for a housing is thought unsound, especially if the housing is of metal.

191. During firing there are three main factors governing the design of igniter containers ; these are as follows :—

(1) major parts of metal or other rigid material must withstand the burning propellant and remain in position so as not to block the nozzle. This point could perhaps be waived in some rocket designs, but it is usually sounder to adhere to it

(2) unless it is very light in weight the container must be anchored during burning so that under set back it does not exert a force on the propellant which may lead to charge break up in the later stages of burning when the web thickness has been reduced

(3) the products of combustion from the igniter itself should flow over the propellant surface and not be blocked by incombustible parts of the housing, or directed against cold metal surfaces.

192. In addition to these factors the mass, size, and complexity of the container should bear reasonable relation to those of the remainder of the whole round. Simplicity in design is obviously to be aimed at, but must

not be pressed at the expense of safety and reliability. Igniters are much less complicated than the fuzes in shells, but must be equally safe and reliable.

Choice of materials

193. The different materials suitable for making igniter containers fall conveniently into three classes as follows :—

(1) textiles
(2) plastics
(3) metals.

The actual choice may be restricted either by compatibility or by availability. These three classes of material will now be considered in turn.

Textiles

194. A wide variety of paper, cardboard, and fabrics has been used for the construction of containers. These materials possess one notable advantage over all others in that the manufacture of containers can begin without delay once the design of the rocket is settled. This can be all-important when igniters are required urgently, and it was for this reason that containers made from textiles were used in early designs of British Service rockets. They are, however, not to be recommended for service, since they generally suffer from two main disadvantages.

195. First, they are mechanically weak and need a strong surround to prevent damage. Secondly, they are comparatively slow to fill and to waterproof, mainly because of the number of operations involving adhesives and varnishes. However, as an interim measure pending the manufacture of a more suitable container made from alternative materials, they can be very effective, particularly if they are suitably housed, as for example, in castellations cut in the end of the propellant charge. Because of their light weight they do not suffer damage under rough usage when snugly housed ; and provided their volume is not too great this method of location can often be adopted with satisfactory results (see fig. 37B). When this arrangement is not possible, or is undesirable, the container has to be located clear of the end of the charge and surrounded by a strong distance piece. Both of these methods have been used.

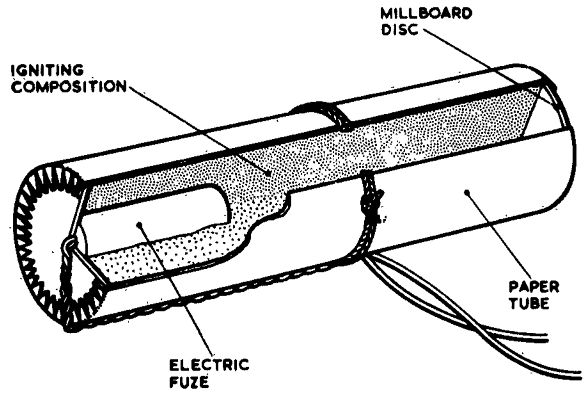
Plastics

196. In general plastic materials have not been particularly popular for igniter containers. Thermosetting plastics tend to be brittle and appropriate cements tend to be incompatible with cordite. Thermoplastic materials on the other hand are prone to attack by nitroglycerin. Polystyrene and polythene are virtually the only materials of this type which are not softened by contact with cordite. Although each of these materials has been investigated neither is wholly satisfactory. Polystyrene is brittle and exhibits cracking and crazing ; polythene usually needs heat for sealing which is clearly undesirable.

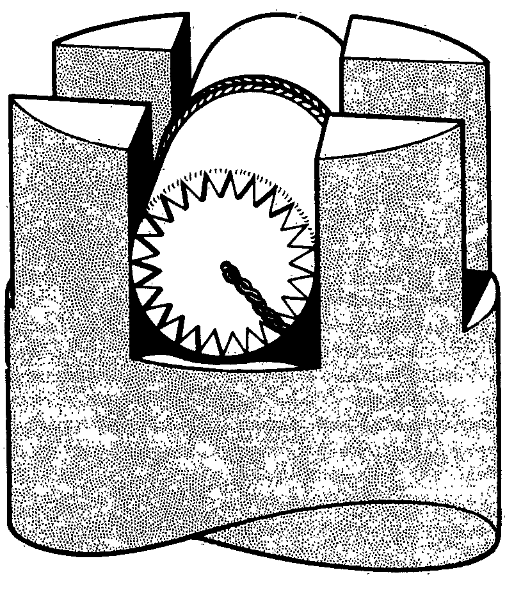
Metals

197. In general, metal containers have been found most satisfactory for housing the igniter composition. Their main advantage is their strength and ability to withstand rough usage. The metal which is usually used for the main body of the container is steel or aluminium. With steel the housing is usually pressed or deep drawn, although malleable iron castings are also suitable. Provided the surfaces of the metal are lacquered with a suitable material such as Akard lacquer, the compatibility with cordite and igniting compositions is satisfactory. Flash holes can be cut and so arranged that the ejected igniting material flows evenly over the propellant.

198. The chief disadvantage of metal is that it may present surfaces between which sensitive compositions may be exposed to friction and impact, and for this reason metal containers must be firmly anchored in the motor tube. Sound anchorage is necessary also in view of the weights of metal containers compared with those of textile materials.



(A)



(B)

Fig. 37. Typical paper carton igniter and method of housing

DESCRIPTION OF TYPICAL HOUSINGS

199. Although igniter housings are frequently used in more than one design of rocket motor a very large number have been made and it is obviously only possible to describe and illustrate a few typical examples. A paper carton igniter which has been widely used in British Service rockets is illustrated in fig. 37A. It consists of a paper tube serrated at both ends, each set of serrations being bent over and stuck to a millboard disc which forms the closure. One millboard disc is slotted to accommodate the leads of an electric fuse which is located inside the carton, and closure is effected at this end first so that filling may commence.

200. Filling consists of adding the igniting composition by increments; light consolidation is used (sufficient to provide some mechanical strength to the igniter) and the open end is closed by a millboard disc as already described. The fuse leads are then brought round and tied to the centre of the carton. Finally, the whole igniter is coated, first with shellac (which is allowed to dry), and secondly with an air-drying bakelite varnish.

201. Igniters of this type have been used in both the 2-in. and 3-in. rockets, in which they are located in castellations cut in the head end of the propellant (see fig. 37B). These are made large enough to accommodate the igniter and protect it from damage under rough usage. The size of the carton is limited by the need to provide castellations strong enough to give it adequate protection. The greatest asset of igniters of this type is the speed with which they can be manufactured and for this reason they are frequently valuable as a temporary measure for initial firings of a new motor design.

202. For Service motors, however, it is preferable for the reasons given above to contain the composition in a metal housing. This can conveniently be done by providing an adaption at the head end of the motor to which the igniter housing can be attached. A simple design of this type as used in the 9-in. rocket is shown in fig. 38.

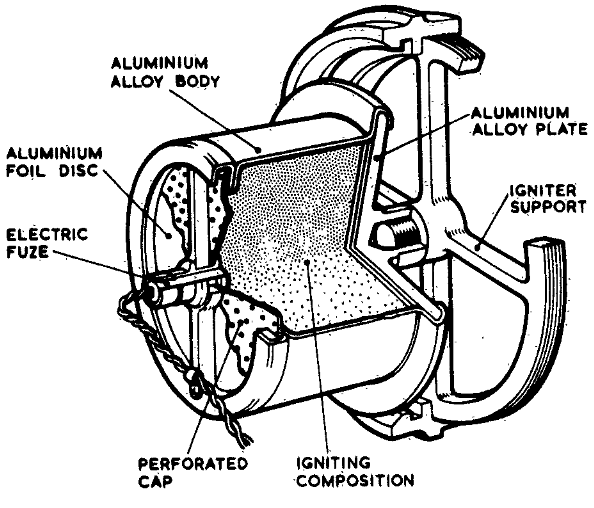


Fig. 38. Metal igniter housing used in 9-in. rocket

203. The metal igniter housing illustrated in fig. 38 consists of a thin aluminium-alloy body which is closed at one end by a perforated aluminium cap, through which is a fitted sleeve containing the electric fuse. The perforations are closed by an aluminium foil disc 0·005 in. thick. At the other end the container is closed by means of an aluminium-alloy plate, which is inserted after the container has been filled with igniting composition. Sealing is effected by pressing the wall of the body over the chamfered edge of the plate. This aluminium-alloy plate carries an internally threaded boss for attachment to the head end plate or igniter support.

204. In each of the types of igniter container already described the electric leads pass through the motor and emerge through the nozzle. In certain applications this is not acceptable and in these cases an additional complication is introduced in that provision must be made for insulated bushes which must remain gas tight throughout burning. Fig. 39 shows the igniter used with the British 4-sec. assisted take-off unit.

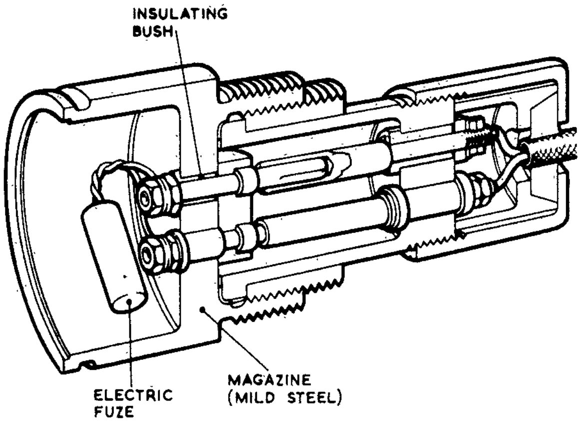


Fig. 39. Igniter used in 4-sec. assisted take-off unit

205. The igniter illustrated in fig. 39 consists of a mild steel magazine which is screwed into a threaded hole in the head end plate of the motor. Two holes are drilled through the base of the magazine and insulating bushes are fitted into these holes. The electrical connection is made to two metal pins which pass through these bushes and the electric fuse is connected to the two ends of these pins which protrude into the magazine. After the magazine has been filled with igniting composition, it is closed by means of an aluminium foil disc retained in position by means of a millboard washer and a perforated tinplate lid, which is swaged into a groove on the outside of the magazine.

The maintainer igniter

206. It will be noted that each of the designs just described contain the igniting composition entirely in the form of loose powder. A study of the burning of an experimental 2-in. rocket motor filled with a charge of SU/D propellant has revealed that steady burning can be obtained at a pressure down to approximately 600 lb. per sq. in. when the paper carton igniter (fig. 37) is used. If the pressure is reduced below this critical value by enlarging the nozzle throat burning becomes unreliable. This unreliability can be removed, however, by prolonging the burning of the igniter.

207. This can be done by incorporating in the loose powder some of the igniting composition in the form of pellets. These pellets burn for a much longer time than the loose composition and the supply of energy from the igniter is maintained until burning becomes stable. With the particular assembly used it was found that for each reduction in pressure a longer time of maintenance was required. The actual results are illustrated in fig. 40.

208. For rocket motors burning at relatively high pressures maintainer igniters will probably not prove to be necessary, but in applications where the thrust is required for long times, such as in guided weapon sustainer motors or aircraft assisted take-off units, it may be essential to burn the propellant at the lowest possible pressure. In such cases the maintainer principle may prove to be vitally important. Variation in the time of burning of the pellets may be achieved by changing their size, composition, or degree of consolidation; one or all of these methods may be convenient. It is also necessary to retain the pellet in position as long as possible.

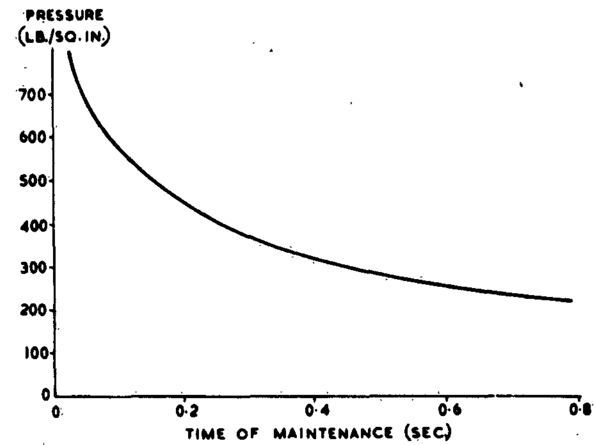


Fig. 40. Variation in critical pressure with time of maintenance for SU/D propellant

Section 5

THE NOZZLE

GENERAL CONSIDERATIONS

209. The nozzle in a rocket motor performs two essential functions ; these are :—

(1) to restrict the rate of escape of gas from the combustion chamber, thus maintaining the pressure within the chamber at a value suitable for the combustion of the propellant

(2) to change the energy of the propellant gases into kinetic energy, the gain in kinetic energy being equal to the ' heat drop '.

210. On making the calculations for a gaseous fluid which starts from rest and is discharged into a region of much lower pressure, it is found that the gain in the specific volume is greater than the gain in the velocity ; that is, that the ratio of the specific volume to the velocity increases. In fact, it is found that this ratio *at first* falls and then reaches a minimum before it finally increases. If the heat drop corresponding to the large decrease in pressure is to be utilized to the full in imparting kinetic energy to the gas stream the proper form of conduit must be one whose cross-section first contracts to a narrow throat and then enlarges to an extent that is determined by the available fall in pressure. In a rocket the conduit is the nozzle ; the original development of such a nozzle (see fig. 41) was due to de Laval and is called a convergent-divergent nozzle.

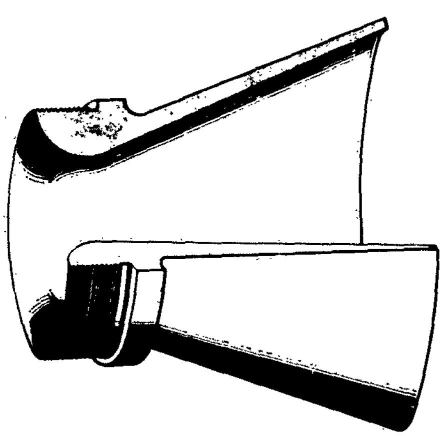


Fig. 41. Typical convergent-divergent nozzle

Nozzle theory

211. While it is not intended in this Part to consider the theory of the nozzle at great length, there are some simple relationships which are so important that they must be quoted for completeness. A full treatment of the theory of the rocket nozzle will be found in Part 2 of this Textbook, Section 3.

212. Particular importance is attached to the point where the ratio of the specific volume to the velocity passes through a minimum and which is known as the throat. At any point the rate of efflux of gas per unit area is given by the relation $Q/A = \rho v$, where Q, the rate of mass efflux, is a constant. This relation can be rewritten

$$\frac{A}{Q} = \frac{1/\rho}{v} = \frac{\text{specific volume}}{\text{velocity}}$$

Thus the ratio of the specific volume to the velocity is a minimum when A is a minimum, i.e. when Q/A is a maximum.

213. It is shown in Part 2 that Bernoulli's equation can be written

$$\frac{\gamma}{\gamma-1}\frac{p_0}{\rho_0} = \frac{\gamma}{\gamma-1}\frac{p}{\rho} + \tfrac{1}{2}v^2 = \text{constant} \quad \ldots(23)$$

where p_0, ρ_0, are the pressure and density at the entrance to the nozzle, and p, ρ, v the pressure, density, and velocity respectively at some section along the nozzle. From equation 23 we can derive an expression for v as follows

$$v = \left[\frac{2\gamma}{\gamma-1}\left\{1-\left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}}\right\}\frac{p_0}{\rho_0}\right]^{\frac{1}{2}} \quad \ldots(24)$$

Substituting for ρ in the relation $Q/A = \rho v$ from the adiabatic relation $p/p_0 = (\rho/\rho_0)^\gamma$ and using equation 24 gives

$$\frac{Q}{A} = \rho_0\left(\frac{p}{p_0}\right)^{\frac{1}{\gamma}}\left[\frac{2\gamma}{\gamma-1}\left\{1-\left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}}\right\}\frac{p_0}{\rho_0}\right]^{\frac{1}{2}}$$

This latter equation may be rearranged to give

$$\frac{Q}{A} = \frac{2\gamma}{\gamma-1}\,p_0\rho_0\left[\left(\frac{p}{p_0}\right)^{\frac{2}{\gamma}} - \left(\frac{p}{p_0}\right)^{\frac{\gamma+1}{\gamma}}\right]^{\frac{1}{2}} \quad \ldots(25)$$

214. It is easy to see from this that the maximum value of Q/A will occur when the differential coefficient of the expression inside the square brackets is zero, that is, when

$$\frac{2}{\gamma}\left(\frac{p}{p_0}\right)^{\frac{2-\gamma}{\gamma}} - \frac{\gamma+1}{\gamma}\left(\frac{p}{p_0}\right)^{\frac{1}{\gamma}} = 0$$

or

$$p = p_0\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \quad \ldots(26)$$

In other words, at the throat or minimum section the pressure has a value which depends only on the pressure at the entrance to the nozzle, that is, the pressure at the

nozzle end of the combustion chamber, and the thermodynamic properties of the gas. This pressure at the throat is frequently referred to as the critical pressure and is designated by the symbol p_t.

215. It will be noted that it is completely independent of the outside pressure, although of course, it has a lower limiting value, namely, that of the pressure of the atmosphere outside the motor. As long as this lower limit is exceeded the gas stream will emerge as a jet and be effectively *choked* at the throat. It is obvious then that choking will occur when

$$p_t = p_0\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} > p_a$$

where p_a is the atmospheric pressure; or alternatively, we may say that choking will occur when the ratio of the chamber pressure to the atmospheric pressure exceeds

$$\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}$$

This ratio is not particularly sensitive to small changes in γ and is approximately equal to 2. For example, when $\gamma = 1{\cdot}25$, a typical value for British rockets, we have

$$\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}} = \left(\frac{2{\cdot}25}{2}\right)^5 = 1{\cdot}8$$

This means that effective choking will occur when the combustion chamber pressure exceeds two atmospheres.

216. The velocity at the nozzle throat follows readily from equations 24 and 26, which give

$$v_t = \left\{\frac{2\gamma}{\gamma-1}\left(1-\frac{2}{\gamma+1}\right)\frac{p_0}{\rho_0}\right\}^{\frac{1}{2}}$$

or

$$v_t = \left(\frac{2\gamma}{\gamma+1}\,\frac{p_0}{\rho_0}\right)^{\frac{1}{2}}$$

By using the adiabatic relation $p_0/\rho_0{}^\gamma = p_t/\rho_t{}^\gamma$ we can show that

$$v_t = \left(\frac{\gamma p_t}{\rho_t}\right)^{\frac{1}{2}} \qquad \ldots(27)$$

that is, the gas stream has the velocity of sound in the conditions prevailing at the throat.

217. In the divergent portion of the nozzle the velocity increases, although the rate of mass efflux remains constant (this is shown in Part 2, Section 4). This may be expressed by saying that the heat drop down to the pressure at the throat determines the rate of mass efflux, and that the remainder of the heat drop is utilized in giving added velocity to the stream. This extra heat drop would of course be wasted if there were no divergent portion to the nozzle. In practice it is frequently convenient to dispense with the divergent portion for the very early firings of a new design. The resulting device is referred to as a *choke*, and obviously a range of different sizes can be manufactured more easily than the corresponding complete nozzles. From what has already been said the combustion chamber pressure will be entirely fixed by the size of the choke, although the full thrust will not be developed.

Thrust

218. No attempt has yet been made in this Part to consider the principles of rocket thrust; such information will be found in detail in Part 2. However, it is desirable at this point to state the basic thrust equation. The thrust in a rocket is given by the relation

$$T = Qv_e + (p_e - p_a)A_e \qquad \ldots(28)$$

where the suffix e means the value of the quantity at the exit section of the nozzle. It will be seen from equation 28 that the thrust T is composed of two parts. The first term, which may be called the *momentum thrust*, is the product of the rate of mass efflux and the efflux velocity of the gases. The second term called the *pressure thrust*, is the product of the exit area of the nozzle and the difference between the exit pressure and atmospheric pressure. When these two pressures are equal the pressure thrust term is zero.

219. Examination of equation 28 immediately reveals two interesting facts, namely,

(1) that the thrust is independent of the actual velocity of the rocket missile

(2) that the thrust increases as the atmospheric pressure is reduced.

For solid propellant rocket motors it is desirable to design the nozzle in such a way that the jet escapes as a smooth stream and so that the energy of expansion is utilized to the full. The optimum thrust will be obtained when

$$\frac{\partial T}{\partial p_e} = 0$$

that is when

$$Q\frac{\partial v_e}{\partial p_e} + A_e + (p_e - p_a)\frac{\partial A_e}{\partial p_e} = 0$$

By differentiating Bernoulli's equation and the adiabatic relation when they are applied to conditions at the exit section of the nozzle, we can show that

$$\frac{\partial v_e}{\partial p_e} = -\frac{1}{\rho_e v_e} = -\frac{A_e}{Q}$$

Thus the optimum thrust will occur when

$$(p_e - p_a)\frac{\partial A_e}{\partial p_e} = 0$$

or $p_e = p_a$, since $\partial A_e/\partial p_e = 0$ only at the throat.

220. If the expansion is too small, even though the pressure thrust term is then positive, the utilization of energy will not be complete since the gain due to the pressure thrust will be more than offset by the lower efflux velocity. If, on the other hand, the expansion is too great the jet may separate from the nozzle walls or a shock wave may be produced, in which case the most efficient conversion of energy will not be achieved. Hence in practice it is usual to aim at a compromise between these conditions. This compromise usually involves some under-expansion since over-expansion often leads to exit diameters greater than the motor tube diameter. With under-expansion also the loss in thrust can be partly compensated for by a saving in weight.

221. The ratio of the exit area of a nozzle to its throat area is called the *expansion ratio* and can be derived by applying equation 25 to conditions at the exit section and throat section in turn. This gives

$$\frac{A_e}{A_t} = \left[\frac{\left(\frac{p_t}{p_0}\right)^{\frac{2}{\gamma}} - \left(\frac{p_t}{p_0}\right)^{\frac{\gamma+1}{\gamma}}}{\left(\frac{p_e}{p_0}\right)^{\frac{2}{\gamma}} - \left(\frac{p_e}{p_0}\right)^{\frac{\gamma+1}{\gamma}}}\right]^{\frac{1}{2}} \qquad \ldots(29)$$

Fig. 42 shows the relation between the expansion ratio A_e/A_t of the nozzle and the pressure ratio p_0/p_e for a series of gases whose specific heat ratio γ varies from 1·10 to 1·40. For example, for rockets working at a combustion chamber pressure of 1,000 lb. per sq. in. with a specific heat ratio of 1·25, the correct expansion ratio is about 8 to 1.

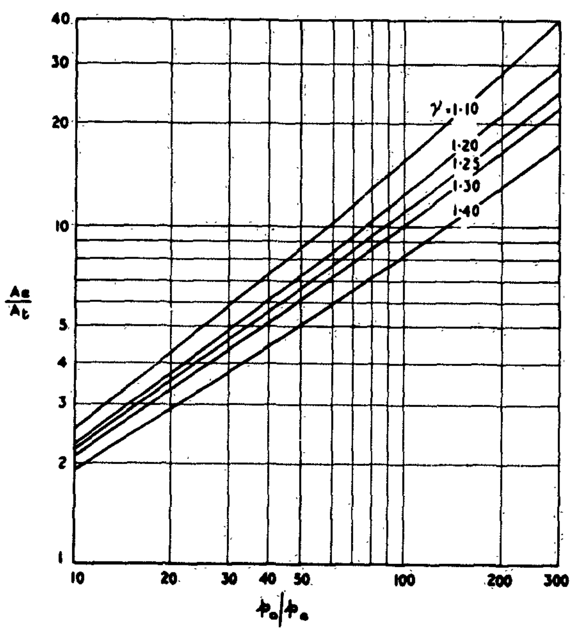


Fig. 42. Variation of expansion ratio with pressure for diverging portion of a nozzle

222. As well as deciding the expansion ratio the rocket designer has also to fix the actual nozzle shape. Since the kinetic energy of the gases in the convergent section is relatively small, almost any smooth curve will suffice for that section. The selection of the divergence angle is considerably more critical, since if the cone is too long excessive wall friction will occur, while if the angle is too large separation and turbulence losses may become prohibitive. In practice, therefore, it is usual to use a divergent cone half angle of about 15 degrees.

223. In addition to determining the magnitude of the thrust, the nozzle also directs it. Ideally, of course, the axis of the jet will follow the axis of the nozzle exit cone, but in practice surface and other irregularities cause asymmetry, with the result that the two axes probably will not be coincident. Coupled with this asymmetry is the fact that, owing to the engineering tolerances involved in the manufacture of both motor body and nozzle, the line of the nozzle axis will probably not pass through the centre of gravity of the rocket. Distortion of the components through pressure and temperature stresses during firing may cause further misalignment. The net result will be a turning couple, which in the case of an unguided rocket will give rise to dispersion. With a guided missile these effects are not likely to be so serious, although they may be important with boost motors if the missile does not come under control until after the boost phase.

MULTIPLE, INCLINED, AND SPRING NOZZLES

224. Although the majority of solid propellant rocket motors use single straight-through nozzles of the types described in para. 209 to 223, for certain applications it is desirable, if not essential, to fit a less convenient type. For example, many of the solid propellant motors developed by the Germans used multiple nozzles and they were designed in such a way that the rocket was rotated at a speed sufficient to make it gyroscopically stable, the rotation being produced by inclination of the jets. The German practice employed a ring of small nozzles around the circumference of a base plate. The type used with the 15 cm. Wurfgranate, which is quite typical, is shown in fig. 43. In this there were 22 inclined nozzles.

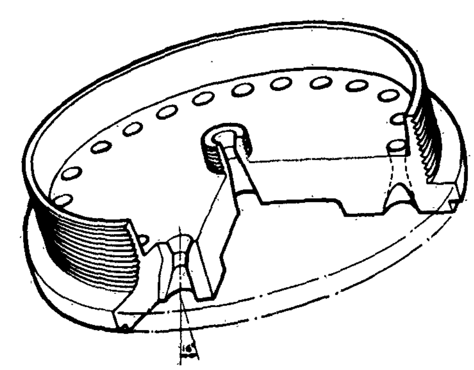


Fig. 43. Multiple nozzle block showing inclined nozzles

225. Another example where inclination of the nozzles is employed is with boost motors on guided missiles. Where a number of boosts are used in a 'wrap-round' configuration it is frequently necessary that the thrust of each should pass through the same point, and also that their jets should not impinge on any tail control surfaces. This can most conveniently be done by angling the nozzles. Some loss in forward thrust occurs, of course, but since the angle of inclination is usually small the amount of thrust loss is not great, the forward component of the thrust being proportional to the cosine of the angle of inclination of the nozzles. An arrangement of twelve boost motors round a main missile body is shown in fig. 44 and the inclination of the nozzles is clearly visible.

226. Another interesting example of an unconventional nozzle is shown in fig. 46, which shows the mechanism of a valve nozzle. This spring-loaded device was used by

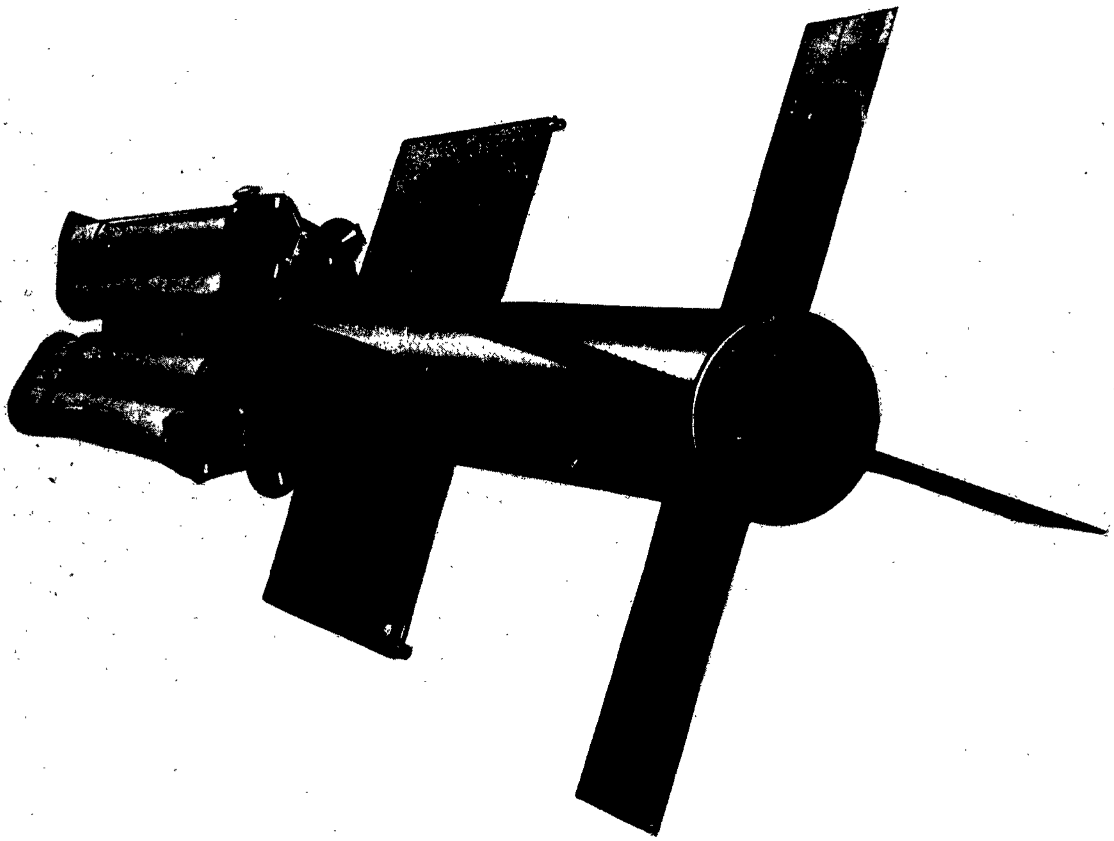


Fig. 44. Guided missile showing inclined nozzles on boost motors

the Germans in their assisted take-off units. The particular motor itself had two conventional convergent nozzles, together with one of the type illustrated in fig. 45. It is clear that such a device offers a relief if any abnormally high pressure is developed. Although nozzles of this type were used quite widely by the Germans their behaviour was somewhat erratic.

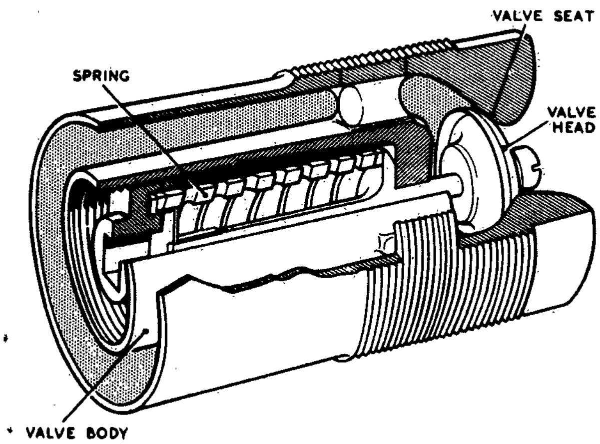


Fig. 45. Valve nozzle

USE OF DIFFERENT NOZZLE SIZES

227. The sensitivity of many solid propellants to changes in ambient temperature has already been discussed. For certain applications it is necessary to keep the thrust and time of burning within narrow limits over a wide temperature range, and where this is the case the valve nozzle appears to provide an elegant solution. It is a solution, however, which is not without its difficulties because the behaviour of the spring is frequently uncertain. An introduction to the theory of a variable nozzle of this type will be found in Part 2 of this Textbook, Section 5.

228. On account of this uncertainty in behaviour the British 4-sec. assisted take-off motor is provided with three nozzles, the throat diameters of which differ slightly from each other. The difference is just sufficient to produce the same thrust/time curve when the motor is fired with the appropriate nozzle under arctic, temperate, and tropical conditions. Although this complicates storage slightly, it has not proved unduly embarrassing in practice. The ideal solution, of course, is to use a platonized propellant and modern developments are tending in this direction.

MATERIALS USED IN NOZZLE CONSTRUCTION

229. Throughout this Part the assumption has been tacitly made that the nozzle retains its dimensions throughout burning, even though the temperature of the gases passing through it frequently exceeds the melting point of the material. This assumption is broadly true and is so, because with heat absorbing materials, the heat is usually removed from the surface sufficiently fast to keep the surface temperature of the material below its melting point. Nozzle material may be broadly divided into two categories—heat absorbing and heat resisting. In the former group belong the metals which have been used most widely in solid propellant motor design; while in the latter are ceramics, resin impregnated asbestos, and graphite.

230. Of the metals used one of the most suitable is undoubtedly mild steel. Its thermal conductivity is high, while it has obvious advantages from the standpoint of availability. Stainless and alloy steels have been found to be much less effective for the short burning times usually encountered in solid rocket motors, and this is due to their lower thermal conductivity and the fact that the melting point of alloys is usually lower than that of the pure metal.

231. Values are shown in Table 6 of the predicted surface temperature of nozzles made from a variety of metals when used on a cordite rocket motor operating at a pressure of 2,500 lb. per sq. in. for 0·5 sec. The melting points of the metals used are included for comparison. The superiority of mild steel over stainless steel on this basis can be clearly seen.

TABLE 6

Predicted surface temperatures and melting points for nozzles made from various metals

Metal	Predicted surface temperature (° C)	Melting point (° C)
Stainless steel	1,460	1,500
Mild steel	1,115	1,430
Iron	955	1,535
Molybdenum	675	2,620
Chromium	575	1,615
Aluminium	565	659
Copper	510	1,083
Silver	485	960

232. In the field of non-metallic heat resisting materials, ceramics have in most instances been found unsuitable owing to their lack of mechanical strength. One heat resistant material, however, with which strikingly successful results have been obtained, consists of phenol-formaldehyde resin reinforced with long fibre chrysotile asbestos (Durestos). This is moulded either as a 'flock' of impregnated random fibres under high pressure (about 1,000 lb. per sq. in.), or as a matted 'felt' which may be cut and cured under pressures varying from contact to about 500 lb. per sq. in. Flock is readily moulded into complicated shapes, but has poor strength—often no more than about 1,000 lb. per sq. in. ultimate tensile strength in the moulding. Felt cured under medium pressure can give up to 10,000 lb. per sq. in. in relatively simple shapes.

233. The mechanism of survival under the effect of the hot exhaust gases appears to be that the surface of the resin in contact with the hot gases becomes charred to a depth of about 0·05 in. to a charcoal-like substance well laced with asbestos fibres. This has sufficient erosion resistance and thermal insulation to prevent further deterioration of the main body of the moulding.

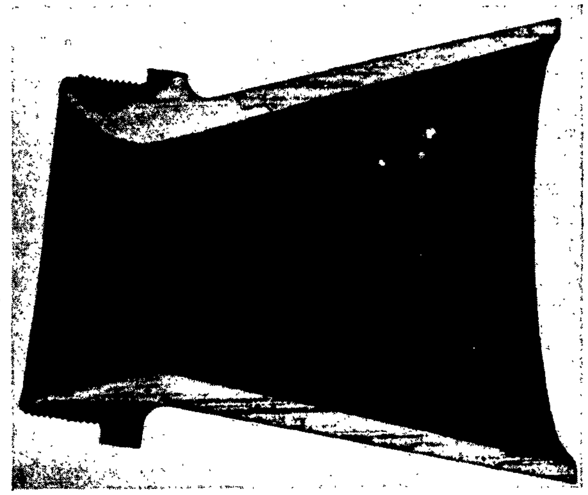


Fig. 46. Section through nozzle made from reinforced resin

234. A section through a nozzle which has been moulded from flock and used during the firing of a boost motor which had burnt for 3 sec. at 1,000 lb. per sq. in. with SU/K propellant is shown in fig. 46. The maximum increase in throat diameter was 0·05 in. on an initial value of 2·55 in. The nozzle weight was 3½ lb. compared with 7¼ lb for a comparable nozzle in steel. It will be seen therefore that in view of the low density the effect on overall performance will be significant, while the full-scale production of nozzles for all sizes of motor is greatly facilitated by the use of conventional moulding techniques with the plastic materials. Another method of achieving a saving in nozzle weight is described in para. A129, where a light-alloy forging lined with Durestos is used. An alternative technique which simply involves the coating of a light-alloy nozzle with a Bakelite cement has had considerable success.

235. It is possible that for long burning times somewhat different materials may be preferable. Experience with long burning times is much less than with short, although both tungsten carbide and graphite have been successful in runs up to 1 min.

NOZZLE EXTENSION TUBES

236. With certain designs of guided missile it is necessary that the rocket motor itself should be located near the centre of gravity of the missile, but have its nozzle efflux emerging at the rear end. This necessitates the introduction of an *extension* or *blast tube* (also called a *tailpipe*) capable of conducting the hot combustion gases. Such a tube may be introduced into the motor before the entry to the nozzle throat, in which case the

gases pass down it subsonically, or after the throat when the passage is supersonic. On theoretical grounds the loss in thrust is likely to be greater in the supersonic case; information of the actual difference is somewhat conflicting but it is likely with most designs to be at least 5 per cent. Against this thrust loss must be set the fact that the pressure in the supersonic tube will obviously be lower since the kinetic energy of the gas is greater. Less strength in a hoop-wise direction will be required for a supersonic tube and this will usually mean that it weighs less.

237. Whichever type of blast tube is chosen it will clearly be necessary that the material used for its construction should have good thermal insulating properties and good resistance to erosion by the effluent gases. The need for good thermal insulation is emphasized by the fact that other components of the missile, such as the warhead or electronic equipment, will have to be closely packed round the blast tube. For this reason considerable attention has been given to the use of resinated asbestos fibre, and like the nozzles themselves, this has been used in two forms, either flock or thin felt.

238. Because the tensile strength of moulded resinated asbestos fibres is very weak by comparison with fibre glass and metals, it is frequently necessary to surround the resinated asbestos with an additional load-bearing member. This is particularly so with subsonic tubes, but the need also arises with many supersonic designs, due to the fact that the available space for the tube is frequently so restricted that the gases issuing from the throat can only be expanded to a very limited extent. A particular supersonic extension tube which falls into this category is shown in fig 47. This is a resinated asbestos tube reinforced with a thin duralumin tube around the outside. It is screwed to the end plate of the motor body just downstream from the throat.

239. Owing to dimensional limitations within the missile the maximum outside diameter available for the extension tube in this application is only 3·5 in. while the nozzle throat diameter is 2·3 in. for an internal motor pressure of 1,200 lb. per sq. in. Attempts to produce a simple resinated asbestos tube within the 3·5 in. diameter limitation were unsuccessful, the tubes failing under the hoop stress. This difficulty was overcome by shrinking a thin duralumin tube over the outside of the resinated asbestos as shown in fig. 47. At the open end where the final expansion of the gases takes place, reinforcement is most conveniently provided by winding on a few turns of glass tape impregnated with resin. Glass tape and glass cloth impregnated with polyester or phenolic resin have also been used successfully for reinforcement along the whole length of the tube in place of the duralumin.

240. One additional feature of the tube illustrated in fig. 47 which is worthy of note is the steel insert. In this application the missile design does not permit the blast tube to be supported at the rear end of the structure. The tube has therefore to be designed as a cantilever from the end of the motor body. Since the missile may be called upon to manoeuvre with a high lateral acceleration it is essential that the attachment of the blast tube to the motor body is adequately strong in bending and for this purpose the steel insert is included.

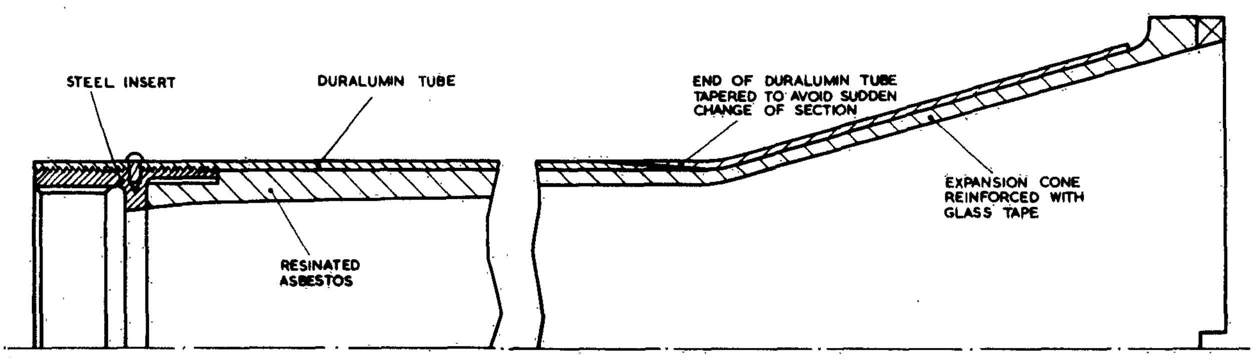


Fig. 47. Cross-section of typical supersonic blast tube

Section 6

THE OVERALL DESIGN

INTRODUCTION

241. In Section 1 a brief indication was given of the essential steps involved in the design of a solid propellant rocket motor. Subsequently the principle features of the component parts were examined in greater detail. It is desirable at this stage to reconsider the general design problem in the light of what has been said about these parts and to consider how the importance of different components is influenced by particular types of requirements. Some general indication of the influence, in so far as it affects motor body weight and density of loading, has already been given in Section 3.

242. There are three main conditions which any rocket motor, or for that matter any other piece of Service equipment, has to fulfil. These are :—

(1) that it should meet the stated performance specification

(2) that it should retain its functional reliability under all conditions of Service use

(3) that its production should be as easy and inexpensive as possible.

In many cases a fourth condition has to be added, namely :—

(4) that its development must be completed within a very short period of time.

243. It will be appreciated that the relative importance of each of these four factors will vary from one requirement to another. Thus, if the motor is needed in relatively small quantities for extremely urgent experimental investigations where the absolute maximum performance is essential, the conditions (1) and (4) will obviously be of paramount importance. On the other hand, a demand for an assisted take-off unit for passenger carrying aircraft will with equal certainty place far greater emphasis on functional reliability and cost than on the attainment of the lightest possible weight. As stated above this variation in emphasis will clearly influence the type of design produced. In every case the requirement will have to be examined in the light of its own special features.

DESIGN OF A ROCKET BOOST MOTOR

244. The interplay of the various factors is best illustrated by considering one or two specific examples. A convenient example to consider first is that of a boost motor for a Service guided weapon. One particular requirement of this type which has been examined called for a motor giving a total impulse of 50,000 lb.-sec. in 3 sec. It was stipulated that the gross weight must not exceed 400 lb. and that the external diameter should not be more than 11 in. An additional feature of the requirement which influenced the design philosophy was that, although the design was to be a Service store, an experimental version was urgently wanted in order that prototype missiles might be flown to obtain aerodynamic and guidance information. However, it was conceded that this interim version would be accepted with a burning time as long as 4·5 sec.

245. Because of the urgency it was clearly desirable to use established techniques, or at least to use materials which it was known could be relied upon to function correctly, without needing a long investigation into their suitability. On the other hand it was equally obvious from the performance specification that some advance beyond design practices then current would be essential. This latter fact is best illustrated by considering the ratio of the total impulse demanded to the gross weight permitted. This ratio from the figures quoted is 125. At the time that the problem was investigated the highest value of this ratio which had been realized with a Service rocket was 80, while even experimentally the best that had been achieved was no more than 110. The first problem therefore was to decide how the increase in performance could most conveniently and quickly be attained, and the first possibility examined was the use of a less conventional type of propellant.

246. Among such materials were plastic propellants, American composite types, and cast double base. None of these was considered entirely suitable. With the plastic there was no certainty at the time that it would be reliable in service, while with the other types there was too little practical experience to justify the belief that a suitable unit could be developed within the time scale, certainly not the time scale for the interim motor. This left only extruded cordite.

247. Of cordite compositions then available the highest value of specific impulse consistently obtained was 200 lb.-sec. per lb., although it was considered that a reasonable prospect existed of this being increased to 220 lb.-sec. per lb. This meant that the charge weight would have to be 250 lb. at the outset, with the possibility of reducing it to 230 lb. finally, if the expected specific impulse of 220 lb.-sec. per lb. were achieved. It was thus necessary to restrict the weight of the rest of the motor to 150 lb. or less.

248. Attention was therefore turned to the material which could be used to construct a motor body large enough to contain the charge yet light enough to satisfy this weight limit. The calculated strengths which might be achieved by a glass-reinforced plastic indicated that such a material could provide a satisfactory solution to the body problem ; but it was also clear that considerable development work would be necessary before the potential strength of such a material could be achieved in actual rocket bodies. In view of the time scale this could not be considered and this therefore left steel and light alloy as the two alternatives.

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249. With each of these it was quickly realized that unless the tube could be kept reasonably cool, neither was capable of giving a solution within the weight limit. If, on the other hand, the charge design were such that excessive tube wall temperatures could be avoided, then it appeared possible that an acceptable solution could be found with either. Although the density of steel is roughly three times that of light alloy, it was likely, that for a tube of the size required, a steel could be used with three times the strength of the best available light alloy. Moreover, with light alloy, since plastic propellant had been ruled out, it would be necessary to provide some additional thermal insulation, whereas with steel this could probably be avoided. It was therefore decided to examine in greater detail first the possibilities of a design using extruded cordite in a steel body.

250. The method adopted is one which can be recommended for general design work. This involves first a selection of a list of possible propellant compositions for which values of the rate of burning, nozzle constant, density, and specific impulse are known. The appropriate length-diameter relationship for the charge can then be worked out by using the method outlined in Section 2. For the requirement considered above the values of charge length and diameter which are given in Table 7 show something of the variation which can be achieved. Included in this table also are estimates of the maximum overall diameter of the motor and its gross weight.

251. From Table 7 it will be seen that in a number of cases the estimated weight exceeded the 400 lb. permitted by the specification, and that of the solutions with the propellant compositions immediately available (i.e. those with a burning rate up to 0·4 in. per sec. at 1,000 lb. per sq. in.) the lightest one was obtained with a charge of 8·5 in. diameter and 106 in. long. Of the faster burning propellants which give higher values of specific impulse, a number of possibilities with a lower overall weight were revealed. Of these solutions, it was considered from a manufacturing standpoint, that the production of a single star-section charge would involve

TABLE 7

Design data for solid propellant rockets

Propellant rate of burning (in./sec.)	Time of burning (sec.)	Number of conduits in charge	Charge diameter (in.)	Charge length (in.)	Overall external diameter of motor (in.)	Estimated motor gross weight (lb.)
0·35	3·0	1 2 3	7·3 9·4 10·3	182 87 66	8·4 10·9 11·9	413 400 399
0·35	4·0	1 2 3	7·9 10·8 12·8	132 56 42	9·1 12·5 14·8	395 398 415
0·35	4·5	1 2 3	8·5 11·7 14·6	106 49 29	9·8 13·5 16·9	390 409 456
0·40	3·0	1 2 3	7·7 10·2 11·7	145 66 49	8·9 11·8 13·5	395 392 408
0·45	3·0	1 2 3	8·2 10·8 12·3	120 55 42	9·5 12·5 14·2	385 386 405
0·475	3·0	1 2	8·4 11·6	110 50	9·7 13·2	378 395
0·50	3·0	1 2	8·6 11·7	104 49	10·0 13·5	378 393
0·55	3·0	1 2	9·0 12·4	91 39	10·4 14·3	374 393

fewer difficulties than would be associated with one having two or more conduits. It was also considered that with a composition having a rate of burning of 0·55 in. per sec. at 1,000 lb. per sq. in. it would be extremely difficult to produce a charge of 9 in. diameter.

252. For these reasons, therefore, the optimum solution appeared to be that produced by a propellant with a rate of burning between 0·475 and 0·50 in. per sec. This implied a charge of diameter between 8·4 and 8·6 in., a length between 104 and 110 in., and a gross weight of no more than 378 lb. Since these dimensions also covered those of the best interim solution provided by the existing slower burning composition, it was clear that the leading dimensions could be fixed and that detail design could follow.

253. In a requirement of this nature the detail design is best developed as static firings proceed, since by this means the design assumptions can be checked experimentally. The first step is, of course, the production of an actual charge design, followed by the manufacture of the charges. Where extruded cordite is being used, as in the example considered above, it is also necessary to decide on a technique of inhibition before proceeding further. Although valuable information can be obtained by firing charges quickly in a heavy strong vessel, it is usually unwise to carry this practice too far. It is preferable to keep charge development and body development closely integrated, and by this means to study at an early stage such problems as obturation and the possible need for thermal insulation of the motor tube.

254. Static firings will in the first place be carried out at the normal ambient temperature, but it is essential to extend these at an early stage to more extreme conditions. For example, at low temperatures ignition may be unreliable, while at high temperatures problems may arise from the softness of the propellant. As soon as the behaviour of the design over the full temperature range is shown to be satisfactory in static firings, it is necessary to project a number of rockets. This introduces extra forces due to acceleration which the design may not withstand and this aspect must be investigated before the development is complete.

DESIGN OF A ROCKET SUSTAINER MOTOR

255. An example of a motor specification totally different from that considered above and one which emphasizes quite different features would be one for a solid propellant sustainer motor to replace a bi-fuel liquid motor in a later design of guided weapon. In an example of this type where an alternative propulsion unit is already available, considerations of urgency are not quite so important and it is therefore possible to examine the requirement in the light of current research.

256. A typical specification of this type which has been considered called for a total impulse of 130,000 lb.-sec. in the form of a thrust of approximately 3,000 lb. for 40 to 45 sec. This impulse had to be provided from a unit of not more than 18 in. diameter, weighing in all not more than 900 lb. Because of the manoeuvres which the missile might be called upon to make, it was necessary that the reliable functioning of the motor should not be impaired by high lateral accelerations during burning. The approach to design was exactly the same as that followed with the boost motor, that is, consideration was given in the first place to the propellant composition together with the type of charge design which might be employed.

257. Since the thrust is required to be sensibly constant throughout burning a reasonably constant surface is necessary. From what has been said in Section 2 it will be appreciated that if this surface is to be provided by a simple star section, then with a motor diameter of 18 in. it will be difficult to provide a web thickness much greater than 3½ to 4 in. This implies that the rate of burning of the propellant composition used will have to be of the order of 0·09 to 0·10 in. per sec. Such a rate of burning will be essential unless some alternative charge design is to be employed.

258. In Section 2 some indication was given of the range of possible rates of burning attainable with different types of propellant, and attention was devoted to the manufacturing aspects. From what was said in that section it will be realized that the production of an 18-in. diameter star centre charge in extruded cordite which will have a rate of burning of 0·09 in. per sec. is not yet a practicable proposition. Recent advances in the cast double base field indicate that it may soon be possible to produce a colloidal propellant with such a low rate of burning since the latest compositions are approaching this rate; and on the manufacturing side attention is being given to the production of large diameter charges by extrusion (see para. 63).

259. Since much lower rates of burning have already been attained with composite-type propellants, their use for this type of application is immediately attractive. Two types which have been studied in British rocket circles are the plastic and the pressed powder propellants and each merits serious consideration. Unfortunately the reduction of the rate of burning to the low value specified will involve also a reduction in the specific impulse and 170 is probably the highest figure that can be hoped for with plastic propellants. This implies a charge weight of approximately 765 lb. leaving only 135 lb. for all other components. Design studies with plastic propellant have shown that such a weight of composition can be contained in a motor whose total weight is no more than 880 lb. Whether a large plastic propellant motor of this type will be capable of withstanding the acceleration forces is a point which has not yet been established.

260. The pressed powder charge with its greater rigidity may well be superior in this respect. On the other hand the amount of inhibiting material which has to be applied to the charge will render it extremely difficult to meet the weight limit imposed. The development of large sustainer motors has, in fact, not yet advanced to a sufficient stage that a clear choice can be made between these two alternatives.

261. Although the simple star section is a particularly convenient type of charge design, a number of alternative designs have been considered. The object of these has primarily been to find a way of using higher performance colloidal propellants with higher rates of burning. Two of these conceptions are worth noting. In the first place an appreciable increase in web thickness can be achieved by employing a charge in the form of a slotted tube as shown in fig. 48.

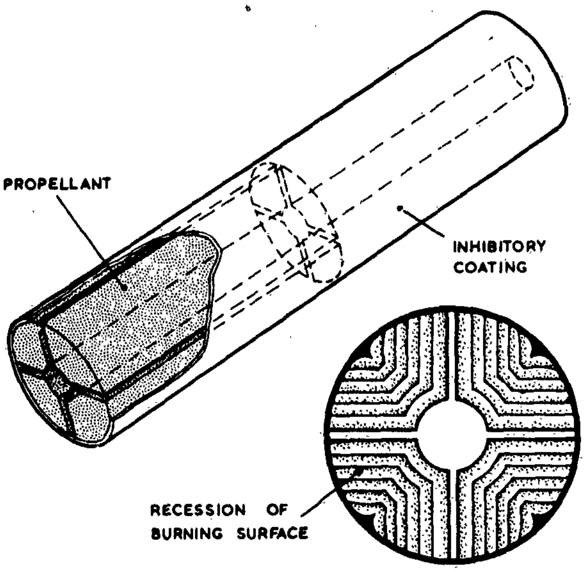


Fig. 48. Slotted tubular charge

262. It will be seen from fig. 48 that the slotted part of the charge, which is located in practice at the nozzle end, consists of four solid segments, the area of whose burning surface decreases, while that of the tubular part increases. By suitably adjusting the lengths of the two parts a surprisingly constant burning surface area can be achieved with a thicker web than would be obtained with a simple star section. One difficulty with this type of charge, however, is that at the base of the slots the inhibiting coating is in contact with the full gas flow throughout burning. Since the normal coatings are not likely to withstand such conditions, it is clear that some additional thermal insulation will be required if a light weight metal body is employed. A charge design of this type can be very conveniently produced in very large size by the cast double base process and when this design is associated with one of the newer low burning rate compositions (para. 258), it has been shown that a convenient solution can be found for the requirement in para. 256 by using cast double base propellants.

263. Another type of design which suffers from a similar drawback is where the charge burns from the end rather than parallel to its axis. Obviously with such a design little difficulty will be encountered in achieving long times of burning, but instead there will be the problem of providing adequate surface area to supply the necessary thrust. In practice a partial solution to this difficulty has been achieved with a charge made up by compositing together a series of short lengths each containing cavities of known dimensions. Such a charge is illustrated in fig. 49 in which the contour lines indicate the recession of the burning front. Inspection of the burning contours shows that the burning surface area rises and falls repeatedly, and so the thrust and pressure will naturally do likewise. The type of pressure/time curve produced by such a design is also illustrated in fig. 49.

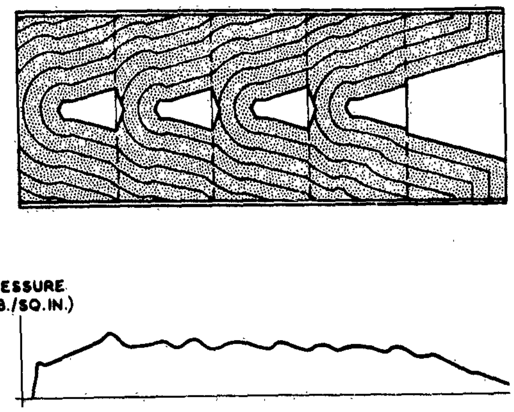


Fig. 49. End-burning cavity-type charge

264. Even with a device of this nature to increase the burning surface area, the thrust given by end-burning designs is still limited, and when this is taken into conjunction with the amount of thermal insulation needed by the body, it will be realized that such designs may not offer the best solutions for high performance sustainer motors, even though the specific impulse of the propellant is higher. A preliminary design study using a cast double base propellant, which has been carried out in connection with the specification quoted above, has indicated that whereas the impulse can be provided by only 728 lb. of propellant, the gross weight of the unit will be 904 lb.

265. In each of these design studies referred to above a steel motor body has been considered. Since, however, the achievement of low rates of propellant burning may involve operating at low pressures, it is probable that the simple hoop stress formula for body design will require only an extremely thin tube, especially if a high tensile steel is used. Such a tube, though adequate as a pressure vessel, will probably not be adequate to withstand some of the other loads to which it may be subjected. This will be particularly so if the overall design requires bending loads to be taken by the motor body. In such circumstances it will probably be preferable to use a lighter material than steel in order to provide the necessary structural rigidity. With composite propellants burning from star centres this can probably be done conveniently with light alloys, but with hotter propellants a much better long term solution is likely to be provided by reinforced plastics.

266. From these considerations it will be seen that the design of a guided weapon sustainer motor raises many completely different issues from that of a boost motor. At the present time a number of such developments are in hand in the U.K. and details of these are given in Table 8 which summarizes the characteristics of many British rockets.

TABLE 8

DESIGN AND PERFORMANCE DETAILS OF SOLID PROPELLANT ROCKET MOTORS

	OVERALL DETAILS			MOTOR BODY DETAILS								PROPELLANT CHARGE DETAILS							IGNITION DETAILS		
				Motor tube				Nozzle		Tailpipe											
	Overall length (in.)	External diameter (in.)	Gross weight (lb.)	Material	Length (in.)	Internal diam. (in.)	Wall thickness (in.)	Material	Throat diam. (in.)	Material	Supersonic or subsonic	Type	Charge design	Composition	Weight (lb.)	Length (in.)	External diam. (in.)	External inhibitor material thickness (in.)	Composition	Weight of composition (gm.)	Total impulse (lb.-sec.)
2-in. Target motor Mk. 2	20·3	2·25	6·0	Steel	20·3	2·14	0·054	Steel STA5/V3	0·80	—	—	EDB	Cogged	SU/K	1·3	11·4	2·12	Loose charge	SR371C	15	240
2-in. Aircraft rocket motor No. 1 Mk. 1	28·54	2·0	5·5 (including fins)	Steel	24·24	1·94	0·028	Steel	0·89	—	—	EDB	Star centre	HU/K	1·94	20	1·76	EC	SR371C	7·5	400
2-in. Rocket Mk. N9	30·8	2·25	8·0	Steel	30·8	2·14	0·054	Steel STA5/V3	0·80	—	—	EDB	Tubular	SU/K	2·5	21·9	1·72	Loose charge	SFG12	20	480
2-in. XP motor	35	2·01	7·4	Steel	26·1	1·94	0·035	Mild steel	0·87	—	—	PP	Star centre	RD2317	3·8	26·0	1·94	Case bonded	SR371C	8	675
2-in. ABC motor	35	2·0	6·5	Steel	31·0	1·93	0·035	Steel EN2	0·65	—	—	EDB	Star centre CD 18	F488/649	3·0	28·25	1·76	EC 0·05	SR371C	5	—
3-in. AA LOKI	66	3·0	18·5	Light alloy AW15	59·95	2·88	0·061	Durestos	1·7	—	—	PP	Star centre	E2040	13·2	58·8	2·88	Case bonded	SR371C	25	2,650
3·75 in. XC rocket	54·7	3·75	39	Steel	46·6	3·62	0·064	Steel	1·3	—	—	EDB	Star centre	F488/649	17·25	43·0	3·43	CA	SR371C	22	3,500
5-in. Aircraft rocket motor, No. 5	—	—	—	Steel V9	41·0	4·7	0·15	Steel V3	1·72/1·83/1·95	—	—	EDB	Tubular	SU/K	—	—	4·3	Loose charge	SR371C	13	4,300
Stork	54	6·1	72	Steel V9	43·1	4·7	0·15	Mild steel	1·3	—	—	EDB	Star centre CD 29	F488/745	30·5	42·5	4·5	EC 0·075	SR371C	33	6,250
5-in. LAP 1	64·7	5·0	66·5	Light alloy DTD 464	57·8	4·6	0·20	Steel V3	1·66	—	—	PP	Star centre CD 7	RD2212	39	55·0	4·6	Case bonded	SR371C	17	7,700
5-in. LAP 2	63·5	5·0	71·5	Light alloy DTD 464	57·8	4·6	0·20	Steel V3	1·3	—	—	PP	Star centre CD 8	RD2201	43·5	55·0	4·6	Case bonded	SR371C	17	8,300
Demon	111	7·3	196	Light alloy DTD 464	98·25	6·375	0·215	Steel EN3	2·55	—	—	EDB	Star centre CD 10	SU/K	111	92	6·15	EC 0·075	SR371C	58	22,000
Magpie	75	8·55	90	Steel DTD 124A	38·75	7·1	0·064	Steel DTD 126	2·15	Asbestos-phenolic overwrapped glasscloth	Supersonic	EDB	Star centre CD 20	F488/649	59	35·8	6·9	EC 0·075	SR371C	50	11,500
Ladybird	39·5	8·8	96	Steel 45 ton U.T.S.	29·0	8·0	0·12	EN 3/53	1·5 Arctic 1·63 Temperate 1·75 Tropical	—	—	EDB	Star centre CD 2	RS/K	54	23·7	7·75	EC 0·075	SR371C	32	9,700
Scarab	64·5	8·8	176	Steel 45 ton U.T.S.	53·0	8·0	0·12	EN 3/53	2·1 Arctic 2·25 Temperate 2·5 Tropical	—	—	EDB	Star centre CD 2	RS/K	108	47·4	7·75	EC 0·075	SR371C	32	19,500
Buzzard	100	9·95	209	Steel 45 ton U.T.S.	53·75	9·0	0·09	EN 15	2·3	Asbestos-phenolic	Supersonic	EDB	Star centre CD 4	SU/K	139	49·5	8·7	EC 0·10	SR371C	50	26,000
Mayfly	124	9·82	393	Steel 45 ton U.T.S.	111	9·0	0·09	Mild steel BSS 15	3·3	—	—	EDB	Star centre CD 15	DU	268	106	8·65	EC 0·10	SR371C	100	53,000
Falcon	99	10·75	232	Steel SAE 4130	53·75	10·0	0·064	EN 16	3·2	Asbestos-phenolic overwrapped glass tape	Supersonic	EDB	Star centre CD 23	F488/649	148	49·5	9·65	EC 0·13	SR371C	50	29,500
Gosling	132	11·10	493	Steel SAE 4130	118·3	10·0	0·064	SEA 4130	4·0	—	—	EDB	Clover leaf	F488/649	317	112	9·65	EC 0·13	SR371C	100	63,000
Red Angel	78·2	11·25	550	Steel STA5/V6	73·0	10·5	0·375	Steel	6 × 1·55	—	—	EDB	3 Tubular sticks	RS/K	182·5	62·2	4·8	Loose charges	G7	450	35,000
Bullpup	117·75	12·5	556	Steel SAE 4130	104·2	11·6	0·08	Throat—SAE 4130 Cone—mild steel	3·64	—	—	CDB	Clover leaf	SRS1/25	370	99·7	10·9	CA 0·22	G4 G7 Ballistite	210 150 90	70,000
Bulldog	128·4	17·4	1,125	Steel SAE 4130	107·40	16·2	0·09	SAE 4130	6·15	—	—	CDB	Multi-concentric	OIO	743	102	15·5	CA 0·235	G4 G7 Ballistite	420 300 180	140,000
Foxhound	108 (+ tail-pipe)	16	1,260	Steel SAE 4130	103·6	15·6	0·09	Carbon	2·4	Asbestos phenolic in light alloy	Subsonic	CDB	Plain tube Slotted tube	AID/4	550 215	60·8 27·6	14·85	CA 0·25	G4 G7 Ballistite	75 55 35	145,000
Ratcatcher	122·2	17·5	785	Light alloy	66·45	17·1	0·2	Steel lined durestos	2·4	Steel lined durestos	Subsonic	PC	Star centre	MRC 12	540	59	16·4	China clay Guanidine nitrate 0·2	G12 pellets	26 × 24 gm.	87,400
Elkhound	124 (including tailpipe)	17·9	855	Steel SAE 4130	73·0	16·95	0·048	Laminated delanium	2·43/2·52/2·57	Asbestos phenolic in light alloy	Subsonic	PC	Star centre	RC 6	625·5	60·35	16·3	China clay Guanidine nitrate 0·25	G12 pellets	21 × 24 gm.	115,000
Smoky Joe	122	17·85	895	Steel DTD 124A	68·6	17·0	0·104	Graphite throat	1·8	Steel with asbestos-phenolic liner	Subsonic	PP	Star centre CD 6	RD 2332	740	—	17·0	Case bonded	SR371C	80	127,000
Wolfhound	123 (including tailpipe)	17·34	950	Steel SAE 4130	67·7	17·1	0·064	Delanium	2·1	Asbestos phenolic in light alloy	Subsonic	CDB	Slotted tube	AID/4	666	61	16·45	CA 0·2	—	—	121,000
3-in. Aircraft rocket motor No. 1 Mk. 4	55·2	3·25	29	Steel	55·2	3·09	0·08	Mild steel	1·45	—	—	EDB	Cruciform	SU/K	11·25	43·2	2·93	PQ strips	SR371C	16	2,100

EDB = Extruded double base CDB = Cast double base PQ = Plastic Q PP = Plastic propellant PC = Pressed charge EC = Ethyl cellulose CA =

RO

2 ROCKET MOTORS

Ext… mat…	IGNITION DETAILS: Composition	IGNITION DETAILS: Weight of composition (gm.)	PERFORMANCE DETAILS: Total impulse (lb-sec.)	Burning times over temperature range: sec. °F.	Burning times over temperature range: sec. °F.	Burning times over temperature range: sec. °F.	Operating pressure at normal temperature (lb. per sq. in.)	Total impulse / Gross weight	GENERAL DETAILS: Status	Application	Design agency
…se charge	SR371C	15	240	0·65 at −20	0·45 at 60	0·37 at 130	510	40	In service	Rocket target	ARDE
	SR371C	7·5	400	—	0·54 at 60	—	1,000	72	Experimental	Unguided air-to-air missile	ARDE
…se charge	SFG12	20	480	1·1 at −10	0·90 at 60	0·65 at 125	800	60	In service	Unguided air-to-air missile	ARDE
…e bonded	SR371C	8	675	—	0·52 at 60	—	1,250	92	Under development	Unguided air-to-air missile	ARDE
0·05	SR371C	5	—	0·9 at −10	0·85 at 60	0·8 at 100	—	—	Under development	Unguided air-to-air missile	RAE/RPD
…e bonded	SR371C	25	2,650	—	0·59 at 60	—	1,600	143	Under development	Unguided A.A. missile	ARDE
	SR371C	22	3,500	—	1·3 at 60	—	1,150	90	Under development	Unguided air-to-air missile	ARDE
…se charge	SR371C	13	4,300	—	—	—	—	—	In service	Aircraft ATO	RAE/RPD
0·075	SR371C	33	6,250	1·7 at −40	1·6 at 60	1·45 at 140	1,800	87	Experimental	Air-to-air GW boost	RAE/RPD
…e bonded	SR371C	17	7,700	—	1·6 at 60	—	—	115	Experimental	GW boost	RAE/RPD
…e bonded	SR371C	17	8,300	3·0 at 32	2·7 at 60	2·4 at 140	1,400	116	Experimental	GW boost	RAE/RPD
0·075	SR371C	58	22,000	2·7 at 32	2·3 at 60	2·0 at 100	1,000	112	Experimental	GW boost	RAE/RPD
0·075	SR371C	50	11,500	1·85 at −10	1·65 at 60	1·6 at 120	—	128	Experimental	Air-to-air GW boost	RAE/RPD
0·075	SR371C	32	9,700	6·45 at −40 Arctic nozzle	5·75 at 60 Temperate nozzle	5·25 at 140 Tropical nozzle	550	100	Experimental	Aircraft ATO	RAE/RPD
0·075	SR371C	32	19,500	6·15 at −40 Arctic nozzle	5·40 at 60 Temperate nozzle	5·30 at 140 Tropical nozzle	550	110	Experimental	Aircraft ATO	RAE/RPD
0·10	SR371C	50	26,000	4·6 at −40	3·25 at 60	2·7 at 105	1,080	124	Experimental	Air-to-air GW boost	RAE/RPD
0·10	SR371C	100	53,000	4·6 at −10	3·5 at 60	2·75 at 100	1,150	135	Experimental	GW boost	RAE/RPD
0·13	SR371C	50	29,500	2·0 at −10	1·8 at 60	1·7 at 100	1,250	127	Experimental	Air-to-air GW boost	RAE/RPD
0·13	SR371C	100	63,000	2·6 at −10	2·5 at 60	2·5 at 120	1,300	127	Experimental	GW boost	RAE/RPD
…se charges	G7	450	35,000	4·0 at −40	3·0 at 60	2·0 at 140	750	64	Experimental	—	ARDE
0·22	G4 G7 Ballistite	210 150 90	70,000	3·5 at −10	3·25 at 65	2·85 at 105	1,150	125	Experimental	GW boost	ICI
0·235	G4 G7 Ballistite	420 300 180	140,000	2·9 at −15	2·4 at 70	2·2 at 125	1,040	125	Experimental	GW boost	ICI
0·25	G4 G7 Ballistite	75 55 35	145,000	42·0 at −5	38·5 at 70	36·0 at 125	590	115	Experimental	GW sustainer	ICI
…na clay …anidine nitrate 0·2	G12 pellets	26 × 24 gm.	87,400	—	36·5 at 68	—	360	111	Experimental	GW sustainer	ICI
…na clay …anidine nitrate 0·25	G12 pellets	21 × 24 gm.	115,000	—	31 at 70	—	450	134	Experimental	GW sustainer	ICI
…e bonded	SR371C	80	127,000	—	—	—	—	142	Experimental	GW sustainer	RAE/RPD
0·2	—	—	121,000	—	—	—	—	127	Under development	GW sustainer	ICI
… strips	SR371C	16	2,100	1·9 at −20	1·6 at 60	1·0 at 160	650	72	In service	—	ARDE

… = Pressed charge   EC = Ethyl cellulose   CA = Cellulose acetate

[To face page 54

Appendix A

MANUFACTURING CONSIDERATIONS ASSOCIATED WITH ROCKET MOTOR BODIES

GENERAL CONSIDERATIONS

Introduction

A1. The essential design principles of rocket bodies and the materials used in their construction have been considered in Section 3 of the main text. An outline of the manufacturing considerations was also given (para. 164 to 170), but as these problems were distinct from those of design further attention to the manufacturing problems was postponed. This appendix deals with these problems and discusses the methods being used and explored for producing rocket motor bodies, including nozzles. The manufacture of rocket motor tubes is dealt with first under the headings steel, light-alloy, plastic, and strip wound tubes, and the appendix concludes with remarks on problems of nozzle manufacture.

Requirements for rocket motor tubes

A2. Requirements for steel tubes may be divided into the following three classes :—

(1) *Heavy weight*—These tubes are used for testing charges under varying conditions of temperature and pressure and have a very low diameter/thickness ratio.

(2) *Medium weight*—These are tubes made from medium tensile steel—ultimate tensile strength about 45 tons per sq. in.—and having a diameter/thickness ratio not exceeding 100.

(3) *Light weight*—Tubes in this class are made from high tensile steel—ultimate tensile strength about 70 to 80 tons per sq. in.—and have a diameter/thickness ratio of not less than 150.

A3. Although most rocket motor tubes to date have been made of steel (see Table 8), the use of light alloys is being investigated and for guided weapon applications two boost motors with light-alloy bodies have been used successfully in flight trials (para. A75). Requirements for high strength light-alloy tubes have arisen (para. A80) and prototype tubes have been produced. The difficulties and expense of manufacturing light weight tubes in high tensile steel led to the examination of the possibility of using reinforced plastics for this purpose (para. A83) and some indication of the progress in this direction is given later in this appendix.

Industrial methods of steel tube manufacture

A4. Steel tubes are produced in this country by the following four methods :—

(1) *Hot rolling*—Tubes produced by this method are not suitable for rocket motor bodies since they cannot be produced to the diameter/thickness ratio required. Ovality, bow, and the variation in wall thickness are also too great to be tolerated (see para. A6).

(2) *Cold drawing*—In this process the ingot is pierced hot to form a shell, which is then mounted on a mandrel and successively cold drawn through dies of diminishing diameter ; annealing is carried out between the drawing operations. The limiting factor introduced by this method is the diameter/thickness ratio ; it is difficult to produce tubes with this ratio greater than 70 and so far impracticable to produce them with a ratio greater than 100. However, the cold-drawn tube is often used as the initial stage in the production of medium weight tubes.

(3) *Fabrication from sheet*—This is an obvious way of producing rocket tubes in both medium and high tensile steels and much development effort has been devoted to it, especially for tubes of medium diameter (9-in.) ; this appendix deals with these efforts later. During World War 2 production by this method of 3-in. tubes was maintained at a rate of about one million a year. However, these wartime tubes were not subject to such strict tolerances as those demanded by the medium diameter tubes to be discussed here and for which improved techniques are being developed. This is the only economic way in which a steel tube incorporating large changes of cross-sectional area along its length can be manufactured.* This method has the disadvantage of involving a considerable amount of welding and difficulty has been experienced in producing welds of first class quality and in avoiding distortion during the welding process and subsequent heat treatment operations.

(4) *Deep drawing*—Recent developments using this process have shown great promise and greater diameter/thickness ratios can be achieved by this method than by cold drawing. This helps towards the use of high tensile steels for rocket tubes which up to now has been restricted by the difficulties of increasing the diameter/thickness ratio by drawing, which once realized provides the main benefit of high tensile steel, namely, weight saving. Another advantage of this method is the elimination of longitudinal welding with its accompanying distortion.

Manufacturing tolerances allowed for rocket motor tubes

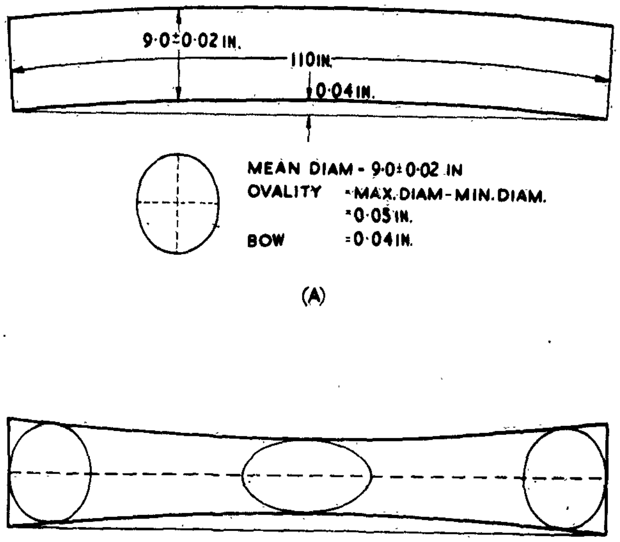
A5. Tubes produced by normal industrial practice do not satisfy the strict requirements in respect of tolerances on mean diameter, ovality, bow, and wall thickness demanded by rocket motor body tubes. This appendix explains how it is necessary to depart from industrial practice in producing rocket tubes satisfying these strict requirements.

Mean diameter, ovality, and bow

A6. Ideally the cross-section of a rocket motor body tube should be circular, but certain manufacturing tolerances are allowed. For example, in early attempts to produce a motor body for the Mayfly rocket (9-in. boost motor) the tolerance allowed on the mean diameter was

* Such changes of section are sometimes required to give strength for transmitting the thrust of the motor to the missile, for taking bending moments, etc.

$\pm 0{\cdot}02$ in. The ovality (defined as the difference between the maximum and minimum diameters of any section) which was allowed was $0{\cdot}05$ in. Bow can be defined as the amount of daylight visible between the tube itself and a plane surface over which the tube can be rolled. Based on this definition the maximum bow permitted in the Mayfly motor just mentioned was limited to $0{\cdot}04$ in. These points are illustrated in fig. A1, view A.



(B)

Fig. A1. Mean diameter, ovality, and bow

A7. As work progressed it became clear that it is very difficult to differentiate between ovality and bow. As an example consider fig. A1, where the ovality at three sections is as shown in view B. It is clear from this example that if bow is considered merely as the daylight visible when the tube is rolled along a plane surface, then the tube has bow. But bow can also be considered as the variation of the axis from straightness and on this definition the tube obviously has no bow. In view of the confusion arising it was decided to eliminate separate tolerances for variation on mean diameter, ovality, and bow and to include them under the general statement that the tube must accept a full-form cylinder gauge and lie within a cylindrical form both of which are specified. The present target is to have the full-form cylinder gauge 1 per cent smaller in diameter than the nominal internal diameter of the tube and the enveloping cylinder 1 per cent larger in diameter than the nominal external diameter of the tube. This accuracy has been achieved in medium weight tubes, but not yet consistently in light weight tubes.

A8. Tolerances on mean diameter, ovality, and bow must be kept as small as possible for the following reasons :—

(1) when colloidal propellants are used they are prepared in cylindrical form. The largest charge which can be inserted into a tube is affected by the mean diameter, ovality, and bow of the tube, and if it is assumed that the charge itself is a perfect cylinder, the problem resolves itself into inserting the largest cylinder of given length into a tube with these imperfections

(2) if the tolerances are large considerable annular space may exist between the charge and the tube. If this happens there is a probability of high temperature gas wash occurring in these spaces with consequent premature failure due to overheating

(3) when plastic propellants burning radially are used it is desirable that the web thickness should be constant. Ovality in the tube (and therefore in the charge) will obviously cause variations in web thickness. This may result in high temperature gases reaching the tube wall prematurely, with consequent local overheating and tube failures. Similar considerations apply to bow

(4) in all plastic charges the inner core shape is formed by drawing a former through the charge and it is obvious that if the tube (and therefore the charge) has excessive bow, the core cannot be located centrally in the charge.

Wall thickness

A9. Since a motor body of the smallest possible weight is usually required, material of the highest strength possible is used and consequently as thin a wall as possible consistent with the resistance to the internal pressure. In practice, considerations of ease of manufacture, cost, and the use to which the motor body is to be put may modify these requirements. As an example it will be convenient to consider a typical rocket motor body tube and a 9-in. diameter boost motor is selected (see fig. A2). It will be assumed that this tube is on the point of bursting when subject to an internal pressure of 2,000 lb. per sq. in.

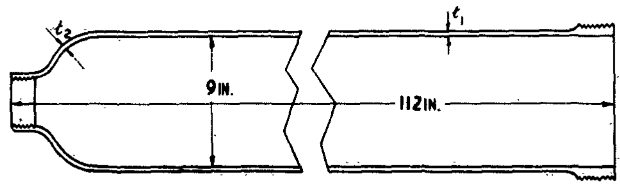


Fig. A2. Typical medium diameter rocket motor body tube

A10. The wall thickness of the tube depends on the type of material used and in calculating this thickness the well-known formula for thin walled tubes is used, namely, $F = pd/2t$, where F and p are the hoop stress and pressure in lb. per sq. in. and d and t are the diameter and wall thickness respectively in inches (see para. 31). If a mild steel of ultimate tensile strength 30 tons per sq. in. is used the normal thickness t_1 is given by the equation $t_1 = pd/2F$, which for the typical tube shown in fig. A2 becomes $t_1 = 0{\cdot}134$ in. The diameter/thickness ratio is then 67. If a medium tensile steel of ultimate tensile strength 45 tons per sq. in. were used the corresponding figures for wall thickness and the diameter/thickness ratio would be $0{\cdot}089$ in. and 100; for a high tensile steel, say an 80-ton steel, they would be $0{\cdot}050$ in. and 180.

A11. The example chosen illustrates the effect on the wall thickness and the diameter/thickness ratio of using materials of different strengths. But the calculations involved are only valid for the parallel portion of the tube and other complications at the ends must be mentioned. Since the wall is only just strong enough to resist the internal pressure it must not be weakened by

cutting a thread on it. At the nozzle end extra thickening is necessary to allow threads to be cut to take the end fittings. The head end is often bottled over and may be threaded internally to take the head end fittings. Ideally to save weight the thickness t_2 (fig. A2) should not be greater than t_1, but since in operation the head end may get hot, some thickening there is often desirable. The nozzle end must be open to the full diameter of the tube when colloidal propellants are used, as these are prepared separately in cylindrical form and inserted into the tube. But when plastic propellants are employed, it would be possible to have the tube bottled over at both ends (see fig. 30D). All these factors just mentioned affect the method of manufacture.

A12. The various methods of producing tubes for rocket motor bodies will now be considered and the potentialities of each method for producing certain types of tubes are indicated. The methods described are still largely in the experimental stage, but the results from these efforts are most encouraging. The best method may well be a compromise incorporating features of some or all of the processes; a forecast of the relative merits of these methods is given in para. A69 to A74.

STEEL TUBES

Heavy weight

A13. In the initial stages of development of a solid propellant rocket motor it is often necessary to test the charge under varying conditions of temperature and pressure. In these cases a heavy weight tube is desirable —one which is amply strong enough to resist all the conditions likely to be imposed on it. Since the charges are fired statically there is no necessity to reduce the weight to a minimum. Normally a cold-drawn mild steel tube is used for this purpose. Such tubes are often manipulated down at one end by the usual method of 'hot swaging' used in making gas bottles. The process consists of heating the end of the drawn tube to a bright red heat and then hammering it with shaped hammers to form the desired shape as shown in fig. A3.

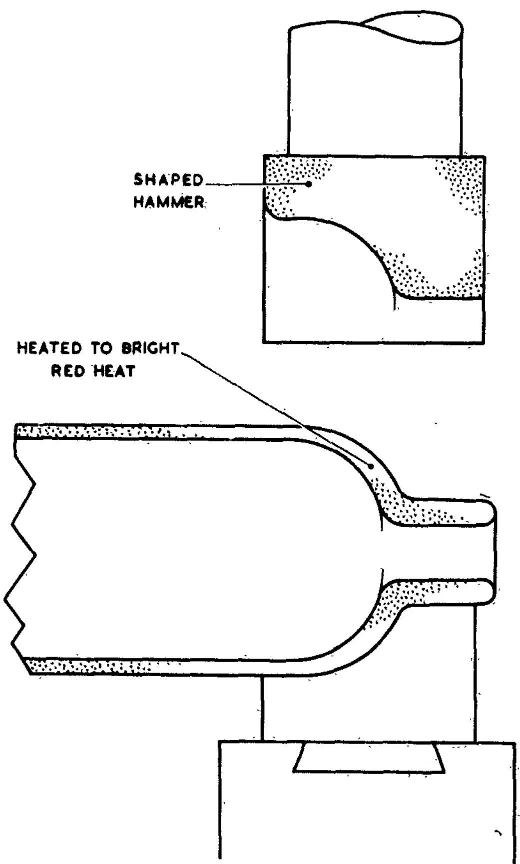


Fig. A3. Hot swaging process

Medium weight

A14. Methods by which medium weight tubes have been developed and produced fall into two main classes :—

(1) using cold-drawn tubes as a basis

(2) fabrication from sheet.

Many variants of the first method have been tried and some of these may be illustrated by the variants in the process of manufacture of a Mayfly motor tube. This has been selected as being quite typical of an average boost rocket motor of medium diameter. Fig. A4 shows this typical 9-in. motor tube and the essential dimensions are indicated. The requirement in this case was for a steel with a yield strength of 34 tons per sq. in. and a minimum ultimate tensile strength of 45 tons per sq. in.; the material chosen to meet this requirement was a low-alloy steel with the composition* shown in Table A1.

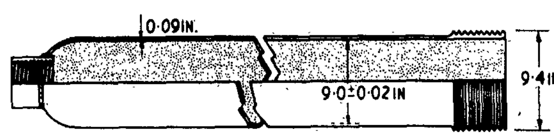


Fig. A4. Mayfly rocket motor tube

TABLE A1

Composition of steel used for cold-drawn Mayfly motor tube

Constituent	Percentage
Carbon	0·21 to 0·26
Silicon	0·35 maximum
Manganese	0·4 to 0·9
Sulphur	0·05
Phosphorous	0·04
Chromium	0·8 to 1·1
Molybdenum	0·15 to 0·25

A15. The tubes supplied by the tube manufacturers were in the first stage cold drawn to a thickness of 0·250 in. and were swaged over at one end as shown in fig. A5, view A. Normal bow and ovality tolerances permitted for tubes for industrial purposes are far in excess of those tolerable for the 0·250-in. tube used in this initial stage of the Mayfly rocket and so extra effort was required by the tube drawers to produce an exceptionally accurate tube.

* This steel is, in fact, very similar to the American specification SAE 4120.

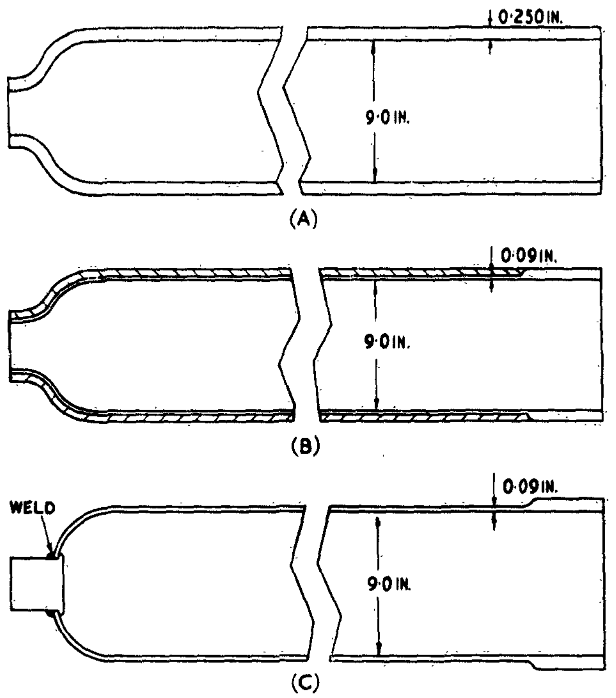


Fig. A5. Stages in manufacture of cold-drawn Mayfly tube

A16. The tubes were then mounted on an expanding mandrel and machined externally to remove the portion shown shaded in fig. A5, view B. More recently the necked end has been produced as a separate machined end ring and welded into position (fig. A5, view C). This machining method suffers from considerable disadvantages. It is wasteful of material in that about half of it is machined off as scrap. Machining of the parallel portion is done in stages, the expanding mandrel being successively adjusted to circularize the tube, and this operation is costly and difficult. Even so, it is difficult to remove all the ovality and bow and any residual errors are reflected in an uneven wall thickness.

A17. The hot swaging process used to produce the bottled end of the initial drawn tube is not capable of ensuring a very symmetrical job and it has been necessary to machine this end both internally and externally; this is a tiresome and time-wasting operation. If too much is machined off, the end may be dangerously thin somewhere; and if too little is machined off, a weight penalty has to be paid. Nevertheless, more Mayfly tubes have so far been made by this machining method than by others now to be described, but promising results in other directions make it unlikely that future motor tubes will be made in this way.

A18. Another method using a cold-drawn tube as a basis may be explained by following the process used for the thin-walled Mayfly. In this the tube is first cold drawn to a thickness of 0·187 in. and the end to be swaged over is machined to a thickness of 0·160 in. and then hot swaged (see fig. A6). The tube is next mounted on a mandrel and the parallel portion is cold drawn to the final thickness of 0·09 in. The final operation includes the welding in position of the two end rings which have already been machined to size and the ends are threaded as required.

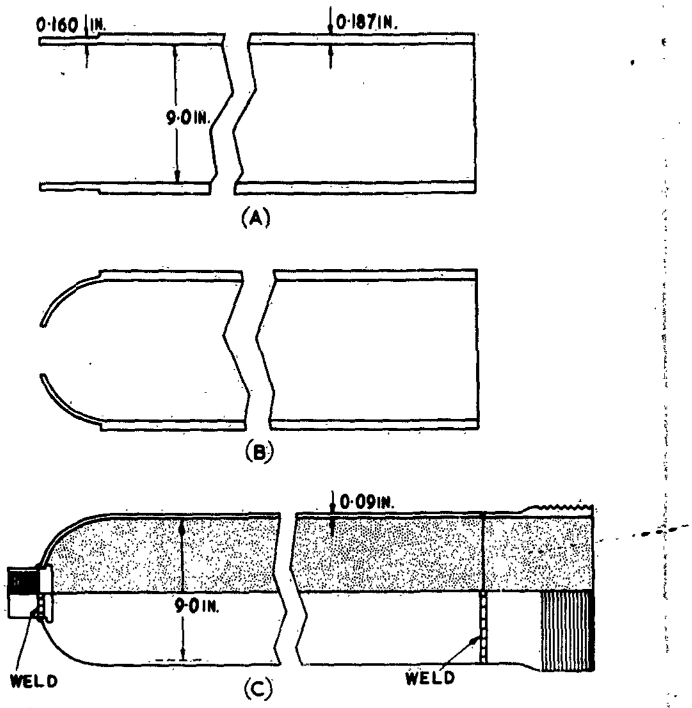


Fig. A6. Stages in manufacture of thin-walled Mayfly tube

A19. The results obtained by this method are encouraging. The casing is relatively cheap to produce and the accuracy of shape, constancy of wall thickness, and strength produced (which is increased due to the cold working) are good. Recently the requirement for the material for the finished tube has been raised to a 0·1% proof stress of not less than 50 tons per sq. in. and further development work is being done to reach this This involves certain heat treatment at an appropriate stage. Before the final cold pass in the cold-drawing operation the tubes are heated to a temperature of 900 to 920° C, allowed to cool in air (which hardens them slightly), and are then tempered at 530° C and again allowed to cool in air. The final cold pass gives a thickness reduction of about 10 per cent.

A20. Tubes treated in this way have been satisfactory in that they have all had the minimum properties required, but so far (1955) too few have been made to achieve consistent results. Nevertheless, for medium weight, medium diameter (9 in.) steel tubes this process is one of the most encouraging of all methods so far developed.

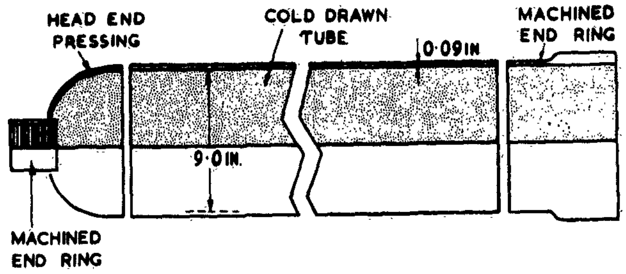


Fig. A7. Composite method of manufacturing Mayfly tubes.

A21. One other variant of the cold-drawing method of producing a tube is shown in fig. A7. This is achieved in four stages :—

(1) parallel portion cold drawn to final thickness

(2) end rings machined to necessary dimensions

(3) hemispherical end pressing produced to final thickness

(4) pieces welded together to produce finished tube.

Fabrication from sheet

A22. Development of this method has reached a stage at which it is possible consistently to produce medium weight tubes and some hundreds of tubes have been manufactured in this way. As a typical example the operations involved in the manufacture of a Mayfly motor tube will be briefly described. This is assembled from the components shown in fig. A8, view A. The tube is fabricated from sheet, the elliptical head end piece is pressed to shape, the head end bush is machined leaving excess metal on its external diameter, and the nozzle end ring blank is also machined leaving excess metal on both the internal and external diameters (this excess metal is removed during final machining after assembly). The components are welded together to give the finished tube shown in fig. A8, view B.

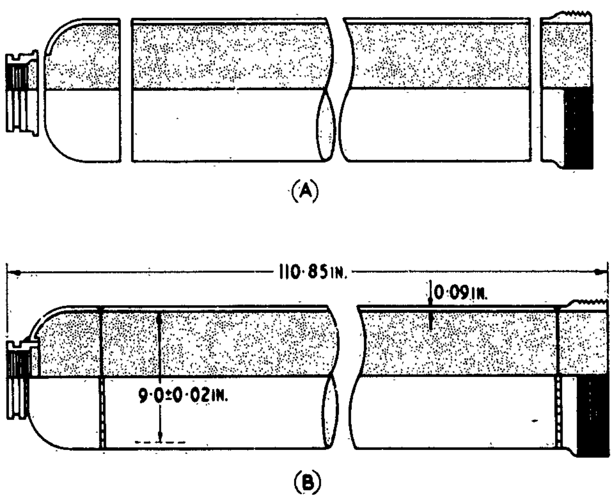


Fig. A8. Mayfly tube fabricated from sheet

A23. The materials chosen for this assembly are DTD124A for the tube and end pressing, and S92 or EN14A for the end ring and bush. These are manganese steels intended for welding and are in common use in this country and readily available. Their compositions are shown in Table A2. The various components are first made from these materials in the softened condition and it is not until after assembly that the tube is heat treated to give it its final properties (see para. A31). The properties of the steels used when suitably heat treated are shown in Table A3.

TABLE A2

Compositions of materials used for fabricated Mayfly motor tubes

Constituent	DTD124A (sheet)	S92 (bar and forgings)	EN14A (bar and forgings)
Carbon	0·18 to 0·26	0·15 to 0·25	0·15 to 0·25
Silicon	0·3 max.	0·10 to 0·35	0·10 to 0·35
Manganese	0·135 to 1·75	1·3 to 1·70	1·3 to 1·70
Nickel	0·40 max.	0·40 max.	0·40 max.
Chromium	—	0·25 max.	0·25 max.
Molybdenum	—	0·10 max.	—
Sulphur	0·05 max.	0·05 max.	0·06 max.
Phosphorous	0·05 max.	0·05 max.	0·06 max.

A24. The techniques involved in fabricating the tube from sheet on which much development work has been done, especially the longitudinal and circumferential welding processes, will now be considered. The tube is made from softened DTD124A. Various operations of preforming, rolling, welding, and heat treatment have to be carried out and these all require some dimensional allowance. So the material is first sheared (leaving excess metal on the length of the tube) to such a width that the diameter will finally be correct to within $\pm$ 0·02 in.

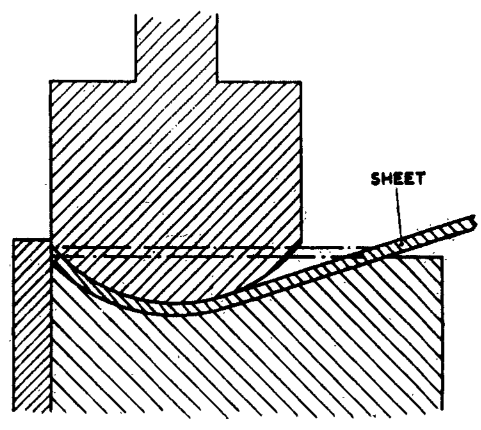


Fig. A9. Tools used for preforming sheet metal

TABLE A3

Properties of manganese steels after heat treatment

Material	Proof stress (tons per sq. in.)	Ultimate tensile strength (tons per sq. in.)	Elongation on 2 in. (per cent)
DTD124A	0·1% about 45	about 50	about 12
S92	0·1% $\not<$ 31	40 to 55	$\not<$ 20
EN14A	SIMILAR		

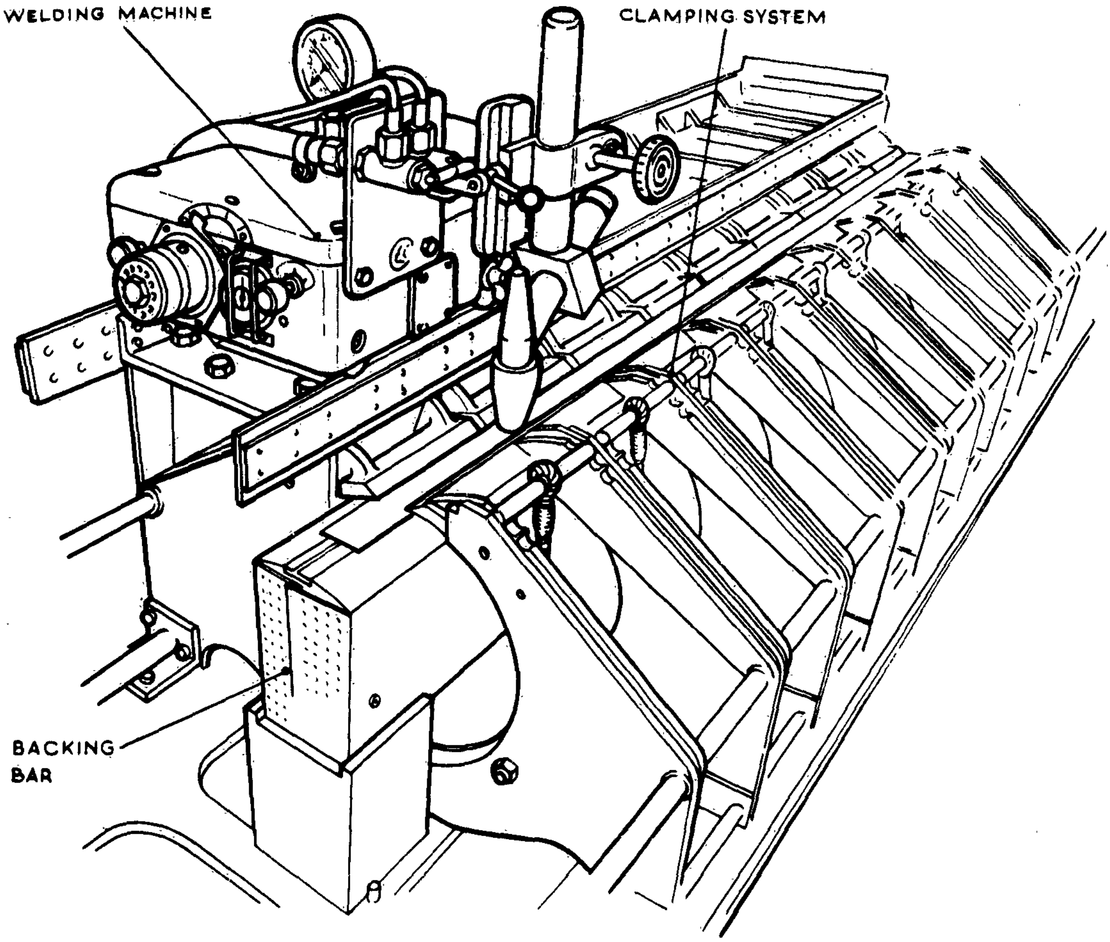


Fig. A10. Machine used for longitudinal welding of medium weight tubes

A25. The edges of the sheet are now preformed in a brake press with the tools shown in fig. A9, and then rolled in power rolls to the diameter required. After stress relief for 30 min. at 650° C (in a vertical position) and cooling in air, the tube is ready for longitudinal welding.

A26. Much development work has been done in producing a suitable fixture for this operation. One form of such a fixture is shown in fig. A10. It is essential that the mating edges of the tube should butt closely and lie smoothly on the backing bar without waviness. Some form of clamping is thus necessary. The clamping pressure while holding the edges firmly on the backing bar must be such as to permit contraction after welding. The backing bar must be supported as rigidly as possible so that the clamping pressure does not cause undue deflection of the tube during the welding operation.

A27. Welding has been carried out both by the metallic arc process and more recently by the argon arc process. The excess weld metal both inside and outside is ground off by portable grinders as shown in fig. A11. After radiographic inspection and stress relief the ends of the tube are parted off to the finished length.

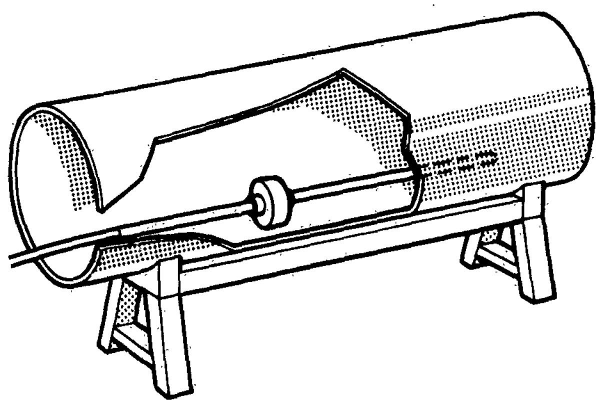


Fig. A11. Portable grinder for smoothing longitudinal welds

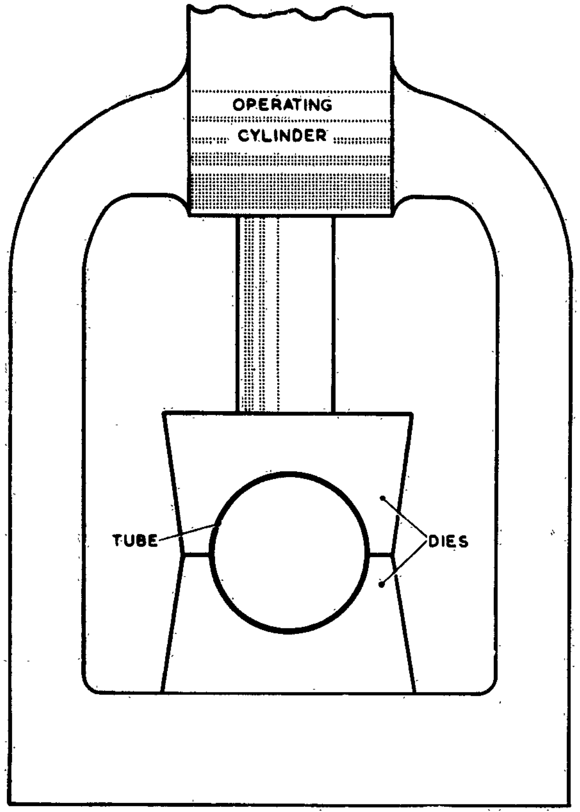


Fig. A12. CECO dropstamp used for sizing external diameter of tube

A28. If it is found necessary, the external diameter of the tube is now sized in special tools in a CECO drop-stamp as shown in fig. A12. The tube is compressed between dies having an inside diameter slightly less than the required outside diameter of the finished tubes. The dies are about 30 in. long and the tube is moved forward progressively by hand operation and rotated as required.

A29. The next operation is 'broaching' the internal diameter of the tube. The method by which this is done is illustrated in fig. A13. In this process the broaching 'dolly', which is in this case 0·020 in. larger than the nominal inside diameter of the tube, is drawn through the tube and this reduces ovality errors. As illustrated, the tube is under compression during the broaching process and there is a risk that the tube may cripple under the heavy load applied. It is proposed to redesign this fixture so that the stroke of the ram is in the opposite direction relative to the tube, thus imposing a tensile load on the tube. This will permit the use of a larger broaching dolly without the risk of crippling the tube.

A30. The tube is now ready for assembly. The head end pressing (see fig. A8) is first butt-welded to the tube by the metallic arc or argon arc process and this is followed by butt-welding the nozzle end ring blank. Both these operations employ the same circumferential welding process as that used in the manufacture of light weight tubes and which is described in para. A40 to A52. Finally the head end bush is welded into position.

A31. The assembled tube is now ready for heat treatment. After an hydraulic test for leakage at a pressure of 200 lb. per sq. in., the assembly is hardened at a temperature of 860 to 870° C, then oil quenched, tempered at 500 to 550° C, and finally air cooled. It is then ready for the final machining operations. After mounting the tube in a lathe, the first operation is to turn the external diameter of the head end bush to its finished dimensions. The nozzle end ring blank is then finished to size and lastly the assembly is threaded at each end. A hydraulic pressure test at 1,500 lb. per sq. in. follows and after radiographic inspection the tube is ready for final protective treatment prior to despatch.

A32. The brief description given in the preceding paragraphs of the manufacture of a medium weight (medium diameter) rocket motor tube by fabrication from sheet is present practice (1955). Future development envisages the use of welding by the submerged arc process, which is much quicker than the present methods, and together with other improvements in production techniques should result in cheaper tubes.

Light weight

A33. Rocket motor tubes can be fabricated from sheet in thin-gauge high tensile steel in a similar way to that used for tubes made from medium tensile steel in the medium weight range. But the distortion consequent on welding and subsequent heat treatment is considerable and special operations have been developed and introduced to reduce these defects as much as possible (ref. 18).

A34. The steel chosen for all light weight steel tubes so far made in this country is SAE4130. This is readily obtainable in the U.S.A., but has not previously been made in this country. Its composition is shown in Table A4. The steel is used in its softened condition to produce the assembled tube and is then suitably heat treated to give the finished tube its required properties. The properties of the steel before and after heat treatment are shown in Table A5.

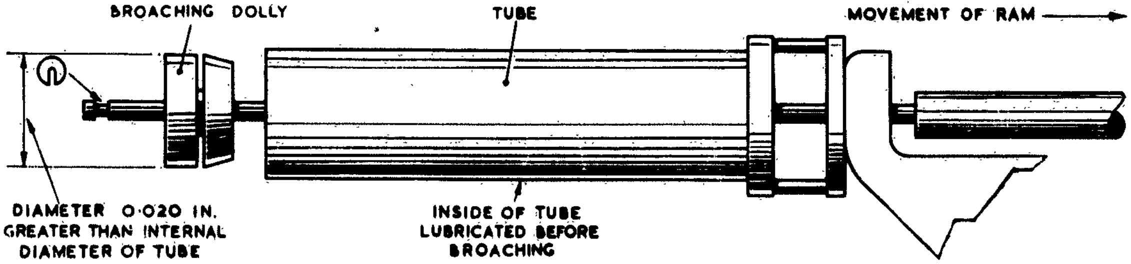


Fig. A13. Broaching equipment

TABLE A4

Composition of steel used for light weight tubes

Material	SAE4130	
	not less than (%)	not greater than (%)
Carbon	0·27	0·32
Manganese	0·40	0·60
Silicon	0·10	0·35
Chromium	0·8	1·1
Molybdenum	0·15	0·25
Sulphur	—	0·025
Phosphorous	—	0·025
Nickel	—	0·3

TABLE A5

Properties of SAE4130 before and after heat treatment

Material	SAE4130	
Property	Before heat treatment	After heat treatment
Ultimate tensile strength (tons per sq. in.)	$\nless$ 37·5, $\ngtr$ 42	$\nless$ 74
0·1% proof stress (tons per sq. in.)	—	$\nless$ 67
Elongation on 2 in. (%)	$\nless$20	$\nless$ 7*
Vickers Pyramid number	$\nless$ 180, $\ngtr$ 210	See Table A6

* This figure applies to sheets thicker than 16 S.W.G. Thicknesses required so far are chiefly 13, 14, 16, and 18 S.W.G.

A35. For widths of 52 in. the steel sheets have to be specially made by steel makers in this country and difficulties have been met in obtaining the relatively small quantities of sheet required for rocket motors and a large proportion (up to two thirds) of scrap is still produced. Nevertheless, no more readily available steel will do the same job. For widths of 40 in. and under the supply position is satisfactory.

A36. In considering the manufacture of light weight tubes and the present state of development, a typical motor tube, namely the Gosling, will be selected. The principle dimensions and the most important requirements of accuracy are indicated in fig. A14. Present deliveries of 16 S.W.G. sheet suitable for this motor body are subject to a rolling margin of $\begin{smallmatrix}+0{\cdot}014\\-0{\cdot}000\end{smallmatrix}$ in. This is insisted on by the steel makers, but is unfortunate in that some tubes up in gauge may be unnecessarily heavy. The loss of thickness produced by heat treatment and the presence of a layer of scale cause difficulties to arise in determining the initial optimum thickness, but these are being determined experimentally.

A37. As will be seen the Gosling motor tube consists essentially of a fabricated cylinder to which the two end rings are circumferentially welded. Much development work has been devoted to the fabrication from sheet of the cylindrical portion and this will be discussed now. The sequence of operations in manufacture in the present state of development will be considered and these are typical of those applying to all light weight tubes. The chief operations required are guillotining, preforming, rolling, welding, stretch forming, and heat treatment.

A38. The sheet supplied by the steel makers is 14 ft. by 3 ft. and this has first to be guillotined. The requirement is that the blank so produced shall have parallel edges and be of such a width that after the operations mentioned in the previous paragraph, all of which require some dimensional allowance, the diameter of the tube shall be correct to within $\pm 0{\cdot}02$ in.

A39. Before being rolled, the sheet is first preformed at the edges in a brake press to a 5-in. internal radius, the preform extending from 4 to 5 in. from the sheet edges, as shown in fig. A15. The sheet is then rolled in Bronx

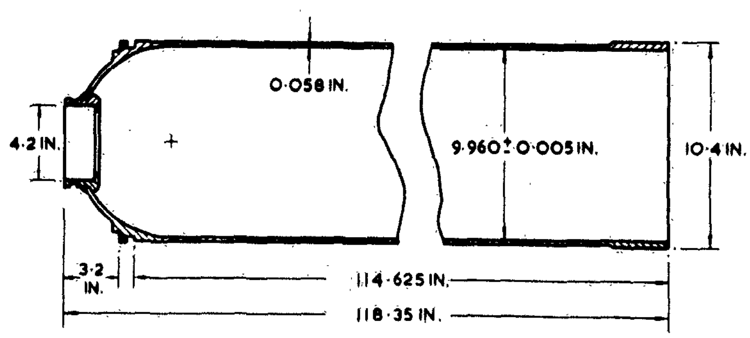


Fig. A14. Gosling rocket motor tube

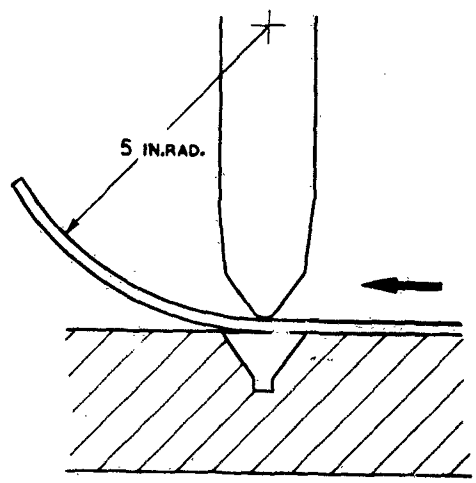


Fig. A15. Brake press used for preforming metal sheet

rolls to the diameter required. The spring back in this material is considerable and after the rolling the edges are held together by circumferential steel-tape clamps, so that the gap is closed. When the assembly is stress relieved the tube remains in the closed position. The edges of the tube are occasionaly wavy and are then hand dressed on a mandrel along the entire length. With the rather large preform the rolling time is materially decreased.

Longitudinal welding

A40. Much development work has been done on the welding of this sheet, especially to ensure that distortion is kept to a minimum. Argon arc welding, which is almost universally used, enables close control to be kept of the composition of the joint and it is possible to obtain regularly joints of about 90% efficiency.

A41. Again a suitable fixture is needed to ensure satisfactory longitudinal welding. The type used is shown in fig. A16. Because of the thinness of the sheet close butt joints are used and welding is always done from the outside. Initially attempts were made to preheat the backing bar, but although welds so made were of lower hardness, they contained defects similar to the 'tears' sometimes found in castings. Localized heating was thought to be the cause, but the possible remedy of arranging for the whole tube to be uniformly treated appeared to be too elaborate. Efforts were concentrated on making the welds without any additional form of heating and successful results have been achieved.

A42. During the welding operation the main requirement is some form of clamping arrangement which will ensure good alignment of the mating edges and which will at the same time allow sufficient flexibility to permit the weld area to contract on cooling, thus preventing the setting up of high residual stresses. The hardness of the heat affected zone of the weld after welding is of the order of 300 to 400 V.P.N. (i.e. Vickers Pyramid Numbers) —see Table 6—and metal in this condition has very little ductility. The clamping system used is shown more clearly in fig. A17. The edges of the tube are held by a number of separately controlled clamps operated by pneumatic pressure and fitted with pads to contact the tube surface. The clamping pressure applied is of the order of 100 lb. per inch of length on each side of the joint.

A43. One satisfactory backing bar used in longitudinal welding is shown in fig. A18. It includes a steel insert machined to suit the internal diameter of the tube. This insert has a groove for the weld underbead and two flats which prevent intimate contact between the underside of the tube edges and the backing bar. This reduces the heat lost by conduction and also allows some degree of

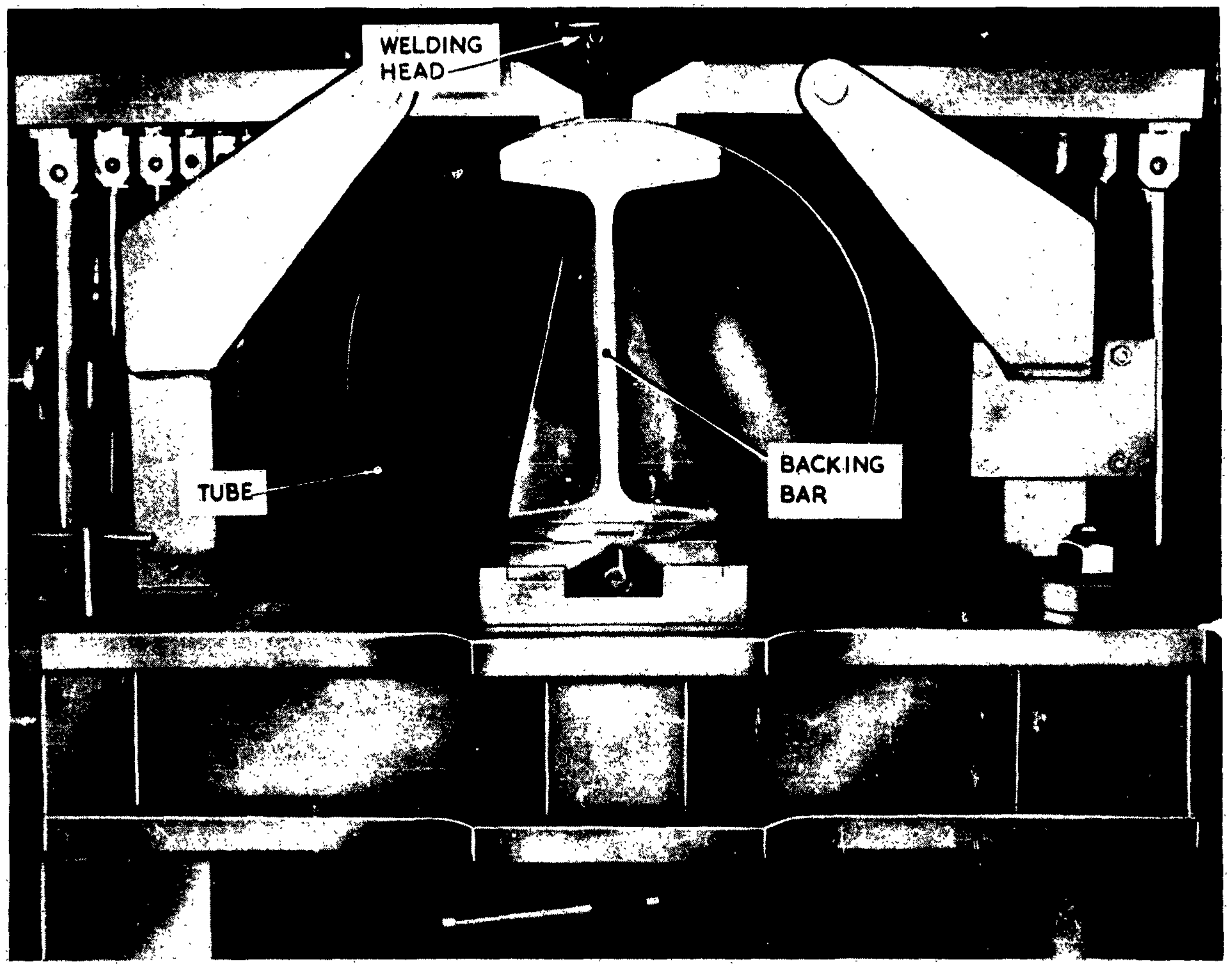


Fig. A16. Equipment used for longitudinal welding of light weight tubes

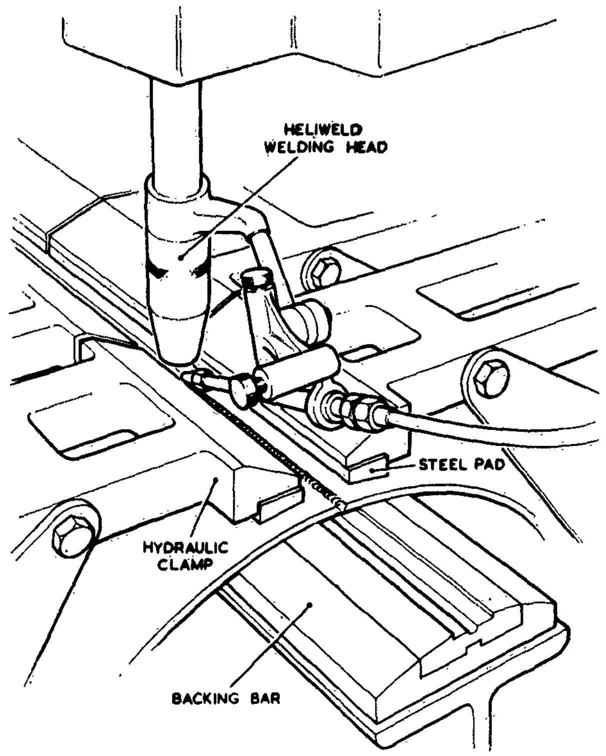


Fig. A17. Clamping fixture to facilitate longitudinal welding

flexibility in the weld. The groove in the insert is connected at intervals by 1/32-in. diameter holes to a larger groove on the underside which is supplied with argon under slight pressure. This helps to reduce oxidation on the underbead and assists in securing good fusion and even penetration of the underbead.

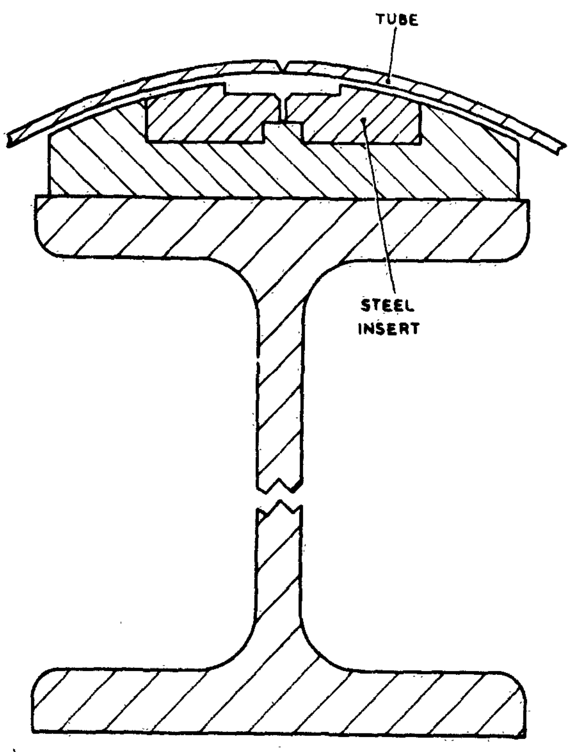


Fig. A18. Backing bar

A44. A Heliweld welding head and wire feed motor mounted on a motor-propelled tractor runs on a track parallel to the joint. This equipment which is illustrated in fig. A17 incorporates electronic arc length control and enables the arc length to be kept constant irrespective of the burn-off of the tungsten electrode or the slight curvature of the tube when the clamping load is applied.

A45. The surfaces of the parts to be welded together are first prepared by degreasing in a solvent bath followed by light shot-blasting with fine steel shot. The shot-blasting by a vacu-blast was initially done by prising open the mating edges, but this appeared to produce irregularities of the sheet edges due to the stress relieving action of the shot-blast operation. More recently a vacu-blast jig has been used for the internal surface. This has the effect of shot-blasting simultaneously the outer and inner surfaces, and the stress relieving effect is not so severe and does not introduce sufficient waviness to make welding impossible.

A46. With the Heliweld equipment, welding is carried out using DC, with the electrode connected to the negative supply terminal, and the electrode is required to touch the work to start the arc (for manual operation a HF supply is connected in series with the mains supply for arc initiation). No contamination with tungsten occurs if the electrode is cold, and a delay switch is incorporated in the set to prevent the electrode from coming in contact with the work before it has had time to cool, should it be necessary to re-strike the arc during welding.

A47. Filler wire of small diameter (0·030 to 0·045 in.) is fed into the arc pool at a predetermined speed, usually between 35 and 40 in. per min. This maintains the desired profile of the surface bead, prevents undercutting, and produces a slightly convex shape. When welding conditions are correct, less than 20 per cent of the weld metal consists of filler wire. The smaller diameter of wire, though suffering from the disadvantage that a larger wire surface is incorporated in the weld for a given weight of metal added, nevertheless, does enable close control of the addition to be effected. The filler wires are first cleaned by degreasing and wiping with steel wool and then stored in sealed containers until required for use.

A48. After the tube has been welded three intermediate operations are performed on it before proceeding with 'stretch forming'. These are:—

(1) *Grinding*—The excess metal on both the external and internal surfaces of the weld is removed by grinding. The method used is the same as that mentioned in para. A27 and illustrated in fig. A11.

(2) *Inspection*—The weld is then subjected to radiographic examination and if any defect is discovered, this is repaired either by re-welding on the automatic machine or by local manual arc welding.

(3) *Stress relief*—The next operation is stress relieving which has now been fixed at half an hour at 650° C.

Stretch forming

A49. As a result of the welding and stress relieving operations the tube suffers from a certain amount of distortion. To remove this and to produce a uniformly cylindrical shape the tube is subjected to a 'stretch forming' process. In this process the tube is inserted in

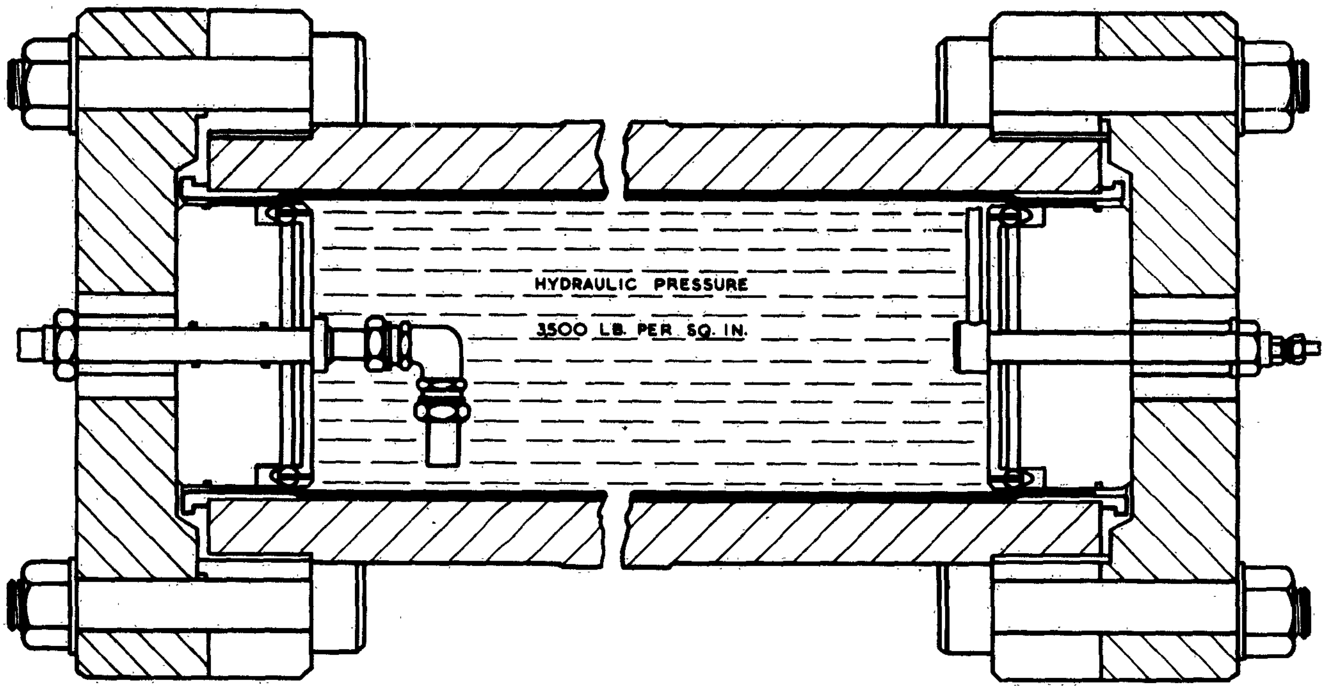


Fig. A19. Stretch forming rig

a heavy steel cylindrical die and is expanded hydraulically against the inner surface of the die. The die used in this operation is shown in fig. A19. After extensive development work the necessary expansion under a pressure of 3,500 lb. per sq. in. is now fixed at 3 per cent. For the Gosling motor tube being considered, the internal diameter of the die is 10·160 in and this produces a tube of nominal external diameter of 10·128 in. During stretch forming the standard of external grinding of the welds is most important and the present limits are fixed at 0·005 in. maximum proud of the surface externally, and 0·010 in. maximum internally.

A50. A further radiographic examination now takes place to ascertain that no defects have shown up after the stretch forming operation. The tubes are then parted off to length to be ready for assembly with the end rings which are welded circumferentially to the tube.

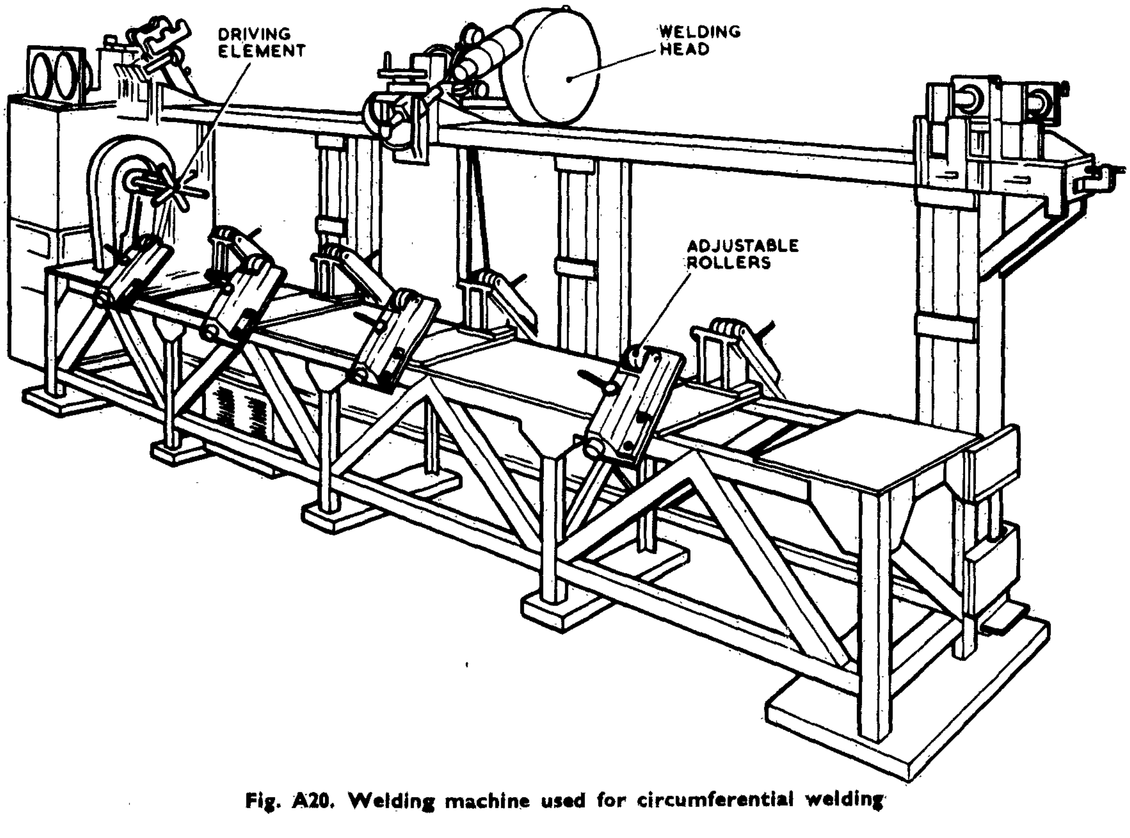


Fig. A20. Welding machine used for circumferential welding

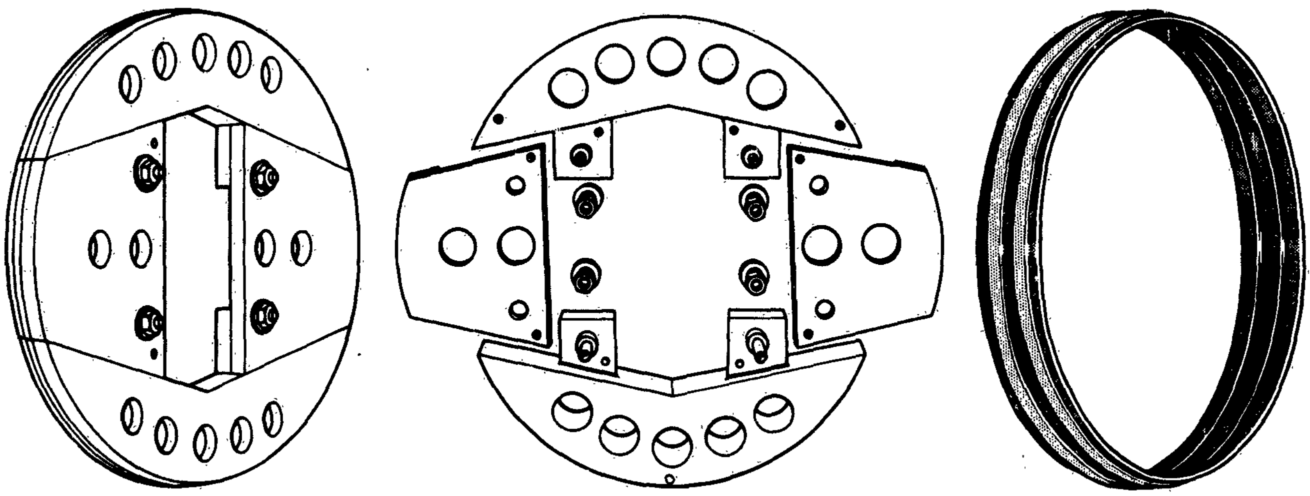


Fig. A21. Backing bars used during circumferential welding

Circumferential welding

A51. In this operation correct axial alignment and smooth rotation are most important and various rigs have been devised to ensure this. Fig. A20 shows a welding machine which allows the tube to rest on separately adjustable roller wheels, while the drive is made from one end via a modified lathe carrier. Through a gear box the speed of welding can be closely adjusted for each diameter of tube to give a welding speed of about 3 in. per min.

A52. Initially a backing bar of the form shown in fig. A21, view A, was used to hold the two mating edges firmly together during circumferential welding, but it was found very difficult to avoid transverse cracks in the weld (for removal after welding the backing bar is collapsed as shown in view B). It was thought that the cracks were due to the backing bar being too rigid to permit shrinkage during cooling. The present method is to mount the components on the backing bar and make one run using a very low current which serves to tack the mating edges together. The backing bar is then collapsed and removed. It is replaced by a preformed mild steel strip approximately 1·5 in. wide by 20 S.W.G. This strip which is shown in fig. A21, view C, is formed with a grooved profile which supports the weld penetration bead and the strip is rolled to be a good fit in the tube.

A53. The tubes are rounded by bolting on external clamping rings and these, together with the tack welds, enable good alignment to be maintained. After both end rings have been welded on, the circumferential welds are examined radiographically and any defects repaired. The assembly is now ready for heat treatment.

Heat treatment

A54. Much development work has been done on evolving a satisfactory method of heat treatment which will reduce subsequent distortion, and early efforts were concentrated on an incremental method. In this process, the tube was mounted vertically and a ring containing a row of flame jets, closely followed by a ring of water jets (which provide the necessary quenching) was passed over and down the tube. By this method it was hoped to localize the expansion and subsequent contraction of the tube. This method is still under development, but for the Gosling and similar light weight motors the present method is by heat treatment in vertical pit-type electric radiation furnaces. The tubes are first heated to a temperature of 900° C which is followed by oil quenching. They are then tempered at 420 to 480° C and finally air cooled.

A55. The weld is required to possess a similar response to heat treatment as the parent metal and this is tested by tensile specimens and hardness readings on the tube and on the weld by a portable diamond hardness testing machine. Average figures for the hardness before and after heat treatment are given in Table A6.

TABLE A6

Hardness readings before and after heat treatment

	Vickers Pyramid Numbers			
Filler wire	*Before heat treatment* Tube	Weld	*After heat treatment* Tube	Weld
A	164	379	418	391
B	164	398	396	355

A56. The heat treated tube is next machined. In threading the end rings it has been found necessary to supply additional support rings both internally and externally to prevent chatter and to machine a satisfactory thread. The chief difficulties now remaining in the manufacture of Gosling and similar light weight tubes are the effects of heat treatment and some of these will be briefly considered.

A57. Scale and decarburization of varying extent occur on most motor tubes and this may vary from nothing to several thousandths of an inch on the same tube. The amount appears to be dependent on the surface condition of the tube. Installation of a controlled atmosphere plant which will feed a neutral

atmosphere to all the furnaces is contemplated and it is thought will effect an improvement. The atmosphere can be balanced so that decarburization and oxidation do not occur.

A58. Trouble is still experienced with distortion and at present it is only possible to guarantee a distortion of not greater than 1·5 per cent instead of the 1 per cent aimed at. Measurements taken on stretch formed tubes indicate that a definite level of distortion occurs during the oil quenching process and this appears to be independent of the previous history of the tube. Further investigation is being done to determine the effects of quenching with heated oil which is kept vigorously agitated.

A59. Difficulties have arisen in obtaining the full hardness of SAE4130 on heat treatment. This applies particularly to thicker material which may be required for end fittings, attachments, etc. to the tube. Present indications are that the most important factor in obtaining full hardness is the severity of the oil quench. In another connection it has been found that the use of oil forced through jets under considerable pressure has resulted in greatly increased hardening and this will be tried out on motor tube casings and components.

Deep-drawn tubes

A60. Deep drawing as a means of producing motor tubes for solid fuel rockets possesses several attractive features, notably the possibility of producing tubes to a greater diameter/thickness ratio than that so far possible with the cold-drawing process. This is made possible by using a vertical press, whereas in the cold-drawing method the operations are carried out horizontally. The vertical press should also help to improve the accuracy of the finished product, both in control of wall thickness and in reducing bow and ovality.

A61. If the manufacture of motor tubes by deep drawing could be fully developed as a production process, the labour (and consequently the cost) should be less than that required to produce a tube by fabrication from sheet with its expensive operations of full radiographic inspection of all welding. If the tube could be produced as an integral job by this process, the elimination of welding would remove one cause of distortion, the correction of which is one of the most difficult and expensive problems of the fully fabricated process.

A62. The possibilities of using deep drawing were actively explored in industry, but unfortunately, in general, presses do not exist for producing a deep drawing of greater depth than 24 in. Thus to manufacture the Mayfly motor tube shown in fig. A4 it would have been necessary to use several deep-drawn cylinders circumferentially welded together. This might result in some distortion, but would have the advantage over longitudinal welding that under internal pressure the stress on the circumferential weld is only approximately half that on the longitudinal weld. In addition the probability of distortion is reduced and advantage could be taken of these facts.

A63. With these thoughts in mind an approach was made to industry to undertake development work in this direction, but those firms contacted were unable to accept contracts for this work. It was known that the ordnance factories making shells and cartridges in this country do possess facilities for deep-drawing tubes of much greater depth than those in industry. The requirement was explained and one ordnance factory was asked to produce the Buzzard motor tube shown in fig. A22 and a number were ordered for experimental purposes. This is a medium weight steel tube of the same diameter and thickness as the Mayfly shown in fig. A4, but only half its length.

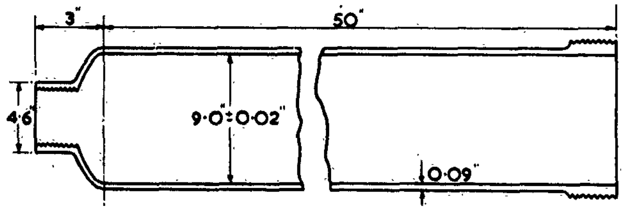


Fig. A22. Buzzard motor tube

TABLE A7

Composition and properties of steel used for deep-drawn tubes

Material	Carbon steel STA5/V2D	
Composition (per cent)	Carbon	0·17 to 0·25
	Manganese	0·40 to 0·70
	Sulphur	0·05 maximum
	Phosphorous	0·05 maximum
Properties	Ultimate tensile strength	28 to 33 tons per sq. in.
	Yield point	18 tons per sq. in.
	Elongation on 2 in.	20 per cent minimum

A64. The material chosen for the Buzzard motor tube was STA5/V2D, a carbon steel of extra deep-drawing quality. The composition and properties of this steel are given in Table A7. The operations involved in the production of this tube are shown in fig. A23 and the dimensions at each stage are indicated. The various stages in the production of the tube may be described as follows :—

(1) the shape shown is hot pressed (to the dimensions indicated) from a blank disc of metal

(2) and (3) the diameter of the tube is broken down by cold drawing to give the dimensions shown

(4), (5), and (6) the wall below the shoulder is 'ironed' and the corresponding reductions in wall thickness are 33, 33, and 40 per cent respectively. This is again a cold-drawing process

(7) the shoulder is then 'ironed' to give a 40 per cent reduction in its dimensions

(8) finally, the internal contours of the head are formed to the dimensions shown.

A65. Preliminary Buzzard tubes made by this method were very promising. The wall thickness was constant to within $\pm$ 0·004 in. and the finish and accuracy generally superior to that of the thin-walled Mayfly tube (see para. A18 to A20). Under hydraulic pressure the tubes burst at a pressure of about 2,400 to 2,500 lb. per sq. in., which (if the simple formula $F = pd/2t$ is used) would indicate an ultimate tensile strength of 55 tons per sq. in. approximately. A few tubes have been fired statically with satisfactory results and further work is being done on the remaining tubes of this trial order.

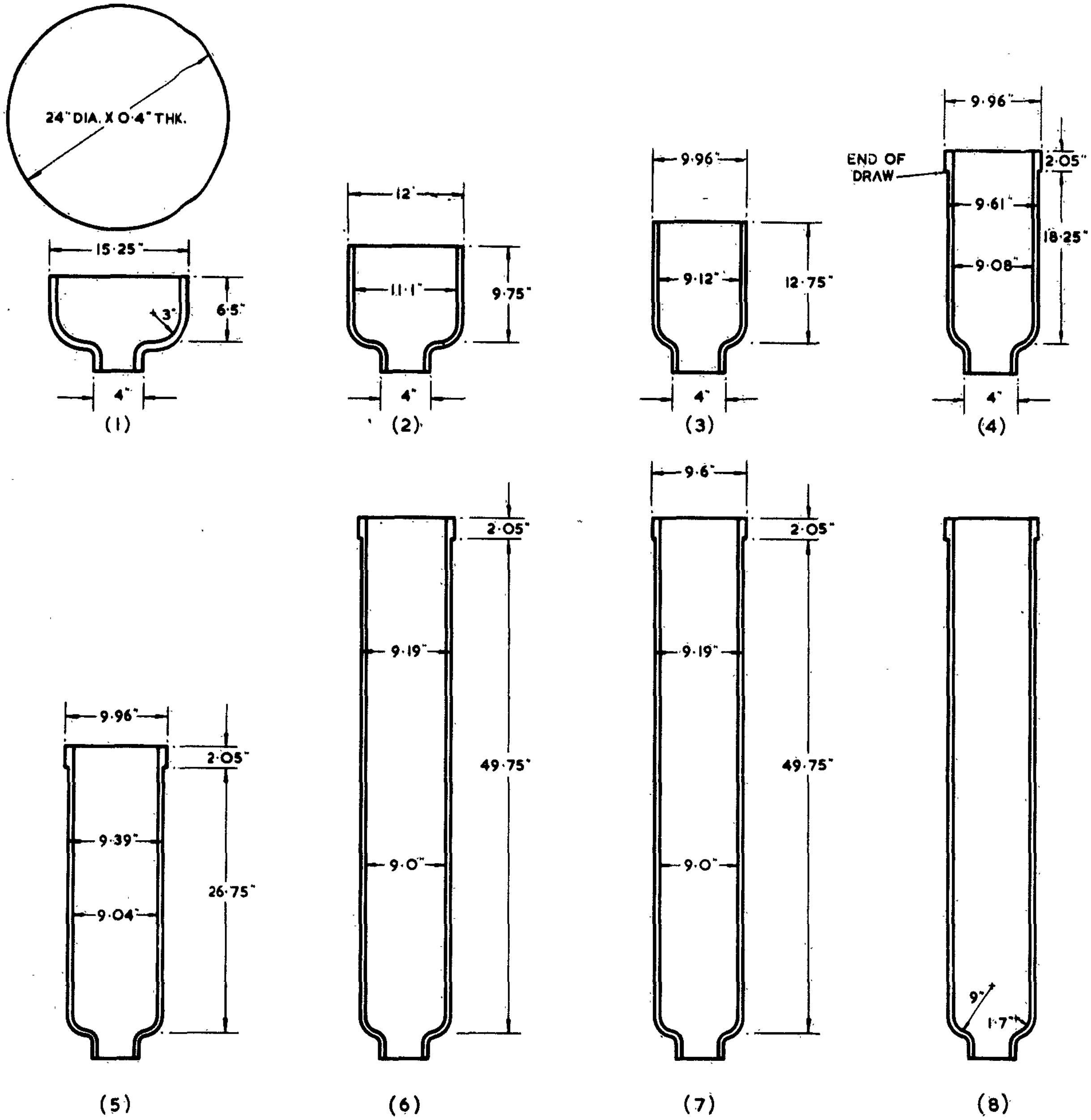


Fig. A23. Stages in the manufacture of Buzzard motor tubes by deep drawing

A66. To test out the potentialities of this method some Buzzard tubes were deep-drawn further to approximately twice their normal length. Fig. A24 shows the shape and dimensions of this resultant tube. Again the results were very encouraging. The wall thickness of the parallel portion of the tube was constant to within about $\pm$ 0·003 in. on any cross-section, although there was a general taper in wall thickness from the shoulder end to the nozzle end of about 0·012 in. This was due to the use of a tapered mandrel in the deep-drawing operation (some taper is necessary to facilitate the withdrawal of the mandrel from the tube).

A67. A few tubes were hydraulically pressure tested to destruction and all failed at an internal pressure of about 1,250 lb. per sq. in., which corresponds to an ultimate tensile strength of about 52 tons per sq. in. This strength is developed by the work-hardening effect of the drawing

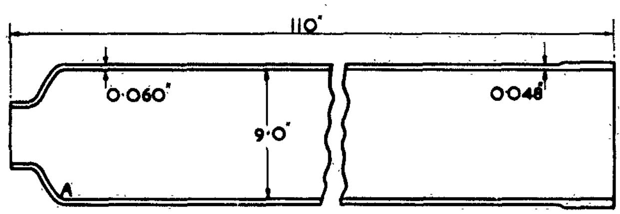
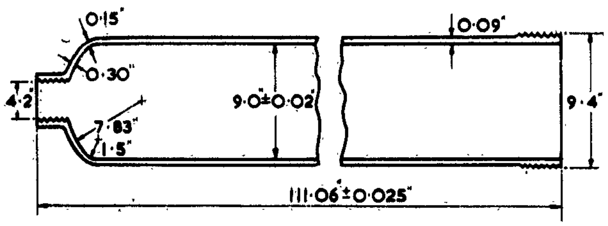


Fig. A24. Tapered tube produced by further deep drawing of Buzzard tube

operations, but there was some falling off in hardness around the portion marked A in fig. A24. This is due to the inability of the 'ironing' operation to take full effect at this section. Further work is necessary to determine how important it is that the full work hardened strength of the metal should be maintained over the head end of the tube.



(1) The tube must accept a cylinder gauge 8·91 in. in diameter by 106 in. long (see para. A4).

(2) The outer surface of the tube must lie within a cylindrical form 9·296 in. in diameter by 104 in. long (see para. A4).

(3) The tube must withstand a hydraulic test pressure of 2,000 lb. per sq. in.

(4) The permanent set after pressure testing measured on volumetric expansion should not exceed 2 cu. in. and on retesting 0·5 cu. in. (see para. A113).

(5) The weight should not exceed 92 lb.

Fig. A25. Modified Mayfly tube produced by deep drawing

A68. The initial results have proved encouraging and further work is being undertaken to produce an integral deep-drawn tube of modified Mayfly shape. This is illustrated in fig. A25 and restrictions on dimensions and properties of the finished tube are noted. This method of producing tubes has great potentialities. By eliminating welding entirely one source of distortion is removed. If the process can be developed satisfactorily (as seems probable) the cost of production should be less than with any other method. A tube produced by deep drawing as an integral job with no welding, however, has some limitations as to the shape that can be economically produced; this will be discussed in the summary which follows.

Summary

A69. In para. A13 to A68 the chief methods now being employed in the development and production of steel tubes have been briefly described. None of these methods has been developed to the point at which an accurate assessment of their relative merits can be made. Nevertheless, some forecast of the relative merits of these processes is given under the separate headings heavy weight, medium weight, and light weight tubes.

Heavy weight tubes

A70. These tubes are not likely to be required in large quantities and the cold-drawn tube is an adequate and cheap method of production.

Medium weight tubes

A71. The best method of producing such tubes will depend in part on their shape. If the shape is essentially a cylinder bottled over at one end and thickened up at the other, then the most promising method appears to be that used for the thin-walled cold-drawn tubes described in para. A18 to A20 or the deep-drawing process considered in para. A60 to A68. These methods when fully developed should be cheap and sufficiently accurate for the purposes for which they are required.

A72. If the tube incorporates lugs, strong rings, etc. (which may be required to transmit the thrust to the missile, to resist bending moments, etc.) so that the section of the tube is no longer of the simple shape shown in fig. A22, but includes changes of section as illustrated by the tube in fig. A14, then the only reasonable economic method of producing such a shape is one incorporating some form of fabrication. It is important here to bear in mind the relative advantage of circumferential welding over that of longitudinal welding (see para. A62) and the best method may well be a compromise incorporating either the cold-drawn or deep-drawn tubes as components of such a complete motor tube. This would have the effect of eliminating the present method of producing longitudinal welds of first class quality.

Light weight tubes

A73. These have so far been produced only by fabricated methods. In the light weight Gosling motor tube described in para. A33 to A59 the diameter/thickness ratio is approximately 160 and this is certainly beyond the present capabilities of the cold-drawing process. However, it does not appear to be beyond the capacity of the deep-drawing process on diameters up to 10 in.; for larger diameters it may well be beyond present capacity also. So far as can be seen at present the limit of strength of steel developed by cold working will be reached at an ultimate tensile strength of about 60 tons per sq. in. and further strength required must be developed by heat treatment of suitable steels. This, if adopted, will undoubtedly bring problems of distortion to be solved.

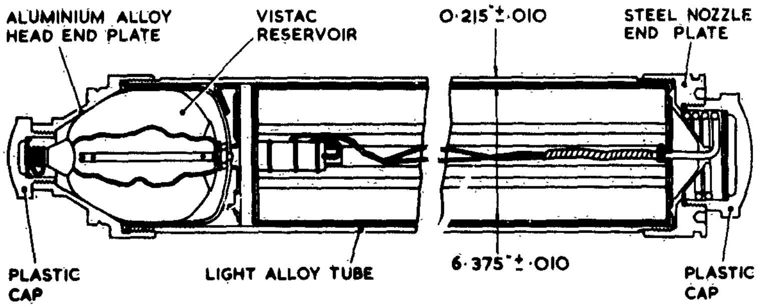
A74. The fully fabricated process described in para. A33 to A59 is more capable of being spread widely over industry at relatively short notice in wartime, while the deep-drawing process would depend on the unlikely availability of suitable presses. It is difficult to forecast with any certainty on this matter, but it does appear that for light weight tubes of 10 in. in diameter and upwards the fully fabricated methods already described, or some adaptation of them, will be the only methods economically possible in producing light weight steel tubes.

LIGHT-ALLOY TUBES

A75. The use of light alloy as a material for solid fuel rocket motor bodies has been limited by its low strength at temperatures above 200° C (see fig. 31). This has necessitated some means of insulating the body from the hot gases during burning. Both colloidal and plastic propellants have low thermal conductivities and so can act as insulators. But as explained in the main text, cordite and cast double base charges are inserted into the motor tube after manufacture and there is an annular space between the charge and the inside of the tube, which is subject to high temperature gas wash. With plastic propellant charges which are pressed directly in the tube this space does not exist and so the unburnt propellant insulates the tube from the hot gases.

A76. In this country two boost motors having light-alloy bodies have been successfully manufactured on a production basis and have been used during flight trials of a wide range of guided weapon test vehicles.* One of these is the Demon 7½-in. boost motor shown in fig. A26, and which takes a charge of extruded cordite inhibited on its outer surface. The dimensions and tolerances are indicated.

* Neither has yet been submitted for Service clearance.



(1) Bow should not exceed 0·1 in.
(2) Ovality should not exceed 0·045 in.

Fig. A26. Demon light-alloy boost motor

A77. Gas wash between the tube and the charge is prevented by filling the annular space with 'Vistac' a polymer of isobutene. The Vistac is held in a rubber bag reservoir connected with the annular space, which is thus kept filled during storage and operation.

A78. The tube is made from light alloy DTD464, a heat treatable alloy of the duralumin type, having the following properties :—

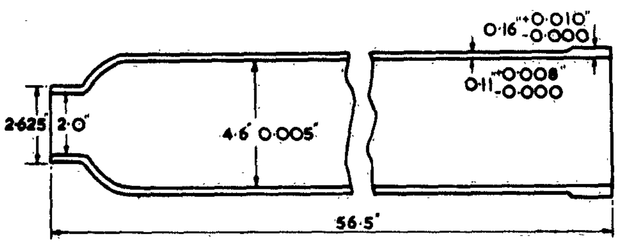
(1) ultimate tensile strength about 29 tons per sq. in.

(2) 0·2% proof stress about 24 tons per sq. in.

(3) elongation on 2 in. of 12 per cent.

The tube is extruded to the dimensions and tolerances shown in fig. A26 and no machining is done on it except threading. At the head end the end plate is of the same alloy, but as more severe conditions are experienced at the nozzle end the end plate there is of steel.

A79. The other light-alloy boost motor is the 5-in. LAP (light alloy plastic), which has a plastic propellant charge. The make-up of this motor body is generally similar to that of the Demon.



(1) Bow should not exceed 0·04 in.
(2) Ovality should not exceed 0·025 in.

Fig. A27. High strength light-alloy rocket tube

A80. Some development work has been done and is still proceeding to produce high strength light-alloy tubes of the form shown in fig. A27. This is intended to hold a plastic propellant charge. The material used is a heat treatable alloy DTD464A, with the composition and properties listed in Table A8.

TABLE A8

Composition and properties of light alloy DTD464A

Material	Light alloy DTD464A	
Composition (per cent)	Copper Silicon Iron Manganese Magnesium Aluminium	3·5 to 4·8 1·5 max. 1·0 max. 1·2 max. 0·6 max. Remainder
Properties	Ultimate tensile strength 0·2% proof stress Elongation on 2 in.	29 tons per sq. in. 24 tons per sq. in. 10%

A81. The manufacture of these high strength light-alloy tubes can be divided into a number of stages (see fig. A28) as follows :—

(1) tubes are first extruded with an internal diameter of 4·875 in. and a wall thickness of 0·25 in.

(2) these are then plug drawn to reduce the diameter to 4·87 in. and wall thickness to 0·160 in.

(3) one end of the tube is now swaged down to the bottled shape by using internally a mild steel plug dimensional of the form shown in fig. A28, view A. A 100-ton press is used and six dies are required to swage the end ; annealing takes place between each operation

(4) a mandrel of the shape shown in view B is now inserted in the tube and the tube is drawn down to a wall thickness of 0·116 in. After this operation while in position on the mandrel the shape of the tube is as illustrated in view C

(5) the mandrel is now withdrawn from the tube to give the shape shown in view D

(6) the tube is next subjected to solution heat treatment followed by quenching, after which it is placed on another mandrel with the dimensions shown in view E. The tube is cold drawn down to its final wall thickness ; this final drawing reduces the wall thickness by 0·004 in. and the diameter by 0·087 in. and gives the tube shown in fig. A27

(7) precipitation heat treatment for four hours at 185° C now takes place. The reduction in thickness which can be applied after solution heat treatment is limited in practice to between 3 and 6 per cent. If more than 6% reduction is applied by cold working the ductility is considerably reduced; while if less than 3 per cent is achieved the distortion due to the heat treatment cannot be corrected.

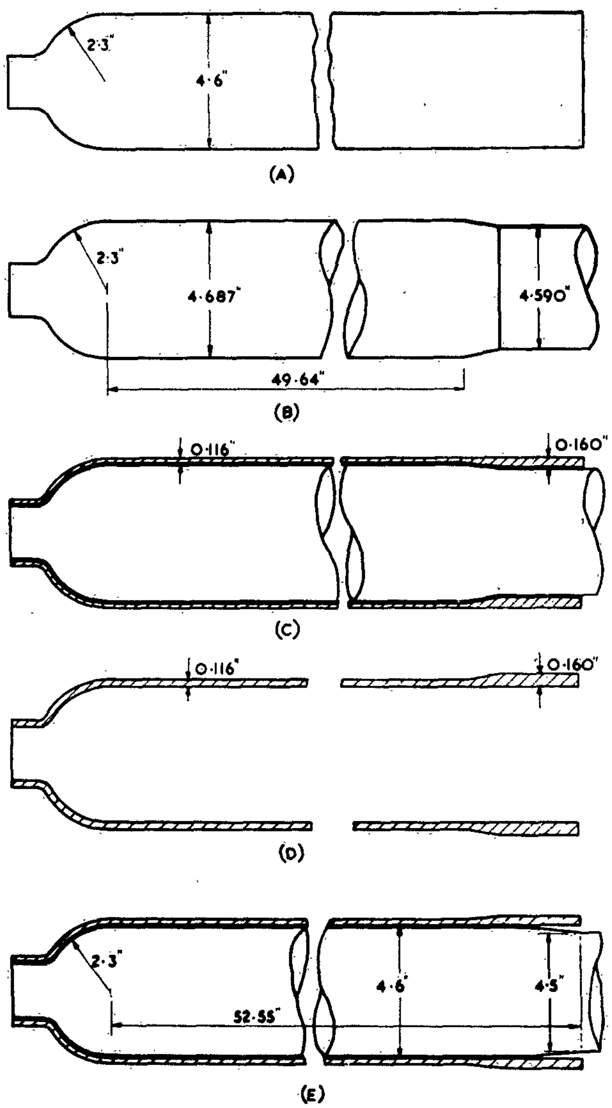


Fig. A28. Manufacture of high strength light-alloy rocket tubes

A82. In the process just described difficulties arise in producing a tube having the correct dimension between the bottled end and the commencement of the thickened portion of the tube at its open end. Nevertheless prototype tubes have been successfully produced and similar work is now proceeding on an 8-in. diameter tube.

PLASTIC TUBES

Introduction

A83. The difficulties and expense of manufacturing light weight rocket motor tubes in high tensile steel led to the examination of the possibilities of using reinforced plastics as an alternative material. In addition to the difficulty of fabricating, high tensile steels have two other objectional features as materials for rocket motor body construction; first, their high specific gravity results in very thin walled tubes since weight saving is often so important, and tubes are thus liable to handling damage (see para. 163); secondly, the necessity for lining the tubes with efficient internal heat insulating coatings adds weight which contributes nothing to the strength of the tubes. The second objection applies also to plastic tubes, since it has now been found necessary to provide an elastic medium which seals and insulates the surface of the tube (see para. A90).

A84. Plastics reinforced with undirectional glass fibres can develop ultimate tensile strengths of 45 tons per sq. in. with a specific gravity of 1·9, a figure which can compete with any known material. When these qualities are coupled with good heat insulating properties and the fact that the strength-giving fibres can be oriented to give a balanced structure, there is no doubt that glass reinforced plastics have great possibilities for the manufacture of efficient rocket motor bodies.

A85. Owing to the prices of glass and resin it seems unlikely that reinforced plastic bodies can be manufactured as cheaply as those made in large numbers from deep-drawing steels with ultimate tensile strengths up to 45 tons per sq. in., but as soon as high tensile steels become necessary the position is reversed by the high cost of the fabrication process. Finally, it is desirable to find an alternative material to high tensile steel, which is always in great demand in times of national emergency.

Choice of reinforcing fibre

A86. There are four main types of reinforcing fibres for plastics, namely, asbestos, natural cellulose, the synthetics (nylon, fortisan, etc.), and glass. It was found that the first three were not suitable for rocket motor bodies, since they do not conform to certain necessary requirements as follows:—

(1) be available in quantity, preferably in this country
(2) possess a high strength/weight ratio
(3) be dimensionally stable
(4) be capable of being highly oriented
(5) possess as high a Young's modulus as possible.

A87. Glass fibres fulfil the first four requirements very adequately. They combine great strength which may lie in the range 110 to 130 tons per sq. in. with a low specific gravity of 2·4. A disadvantage is a low Young's modulus. This will result in fairly large strains in any pressure vessel made from glass fibres; but at some sacrifice in efficiency, these strains can be limited in the circumferential direction and made zero or negative in the axial direction by choosing the appropriate fibre orientation. However, it should be noted that this strain limitation can only be done at the expense of exaggerated strains in other directions.

A88. The high strength of glass/resin combinations and their low specific gravities should enable them to compete easily with mild steel for many rocket motor applications, while from laminates with glass in the filament form, specific hoop strength figures equivalent to 130 to 150-ton steel are attainable. In fact one firm reports a figure which is estimated to be equivalent to 180-ton steel. An additional attraction of these materials is their low coefficient of thermal conductivity which should enable them to maintain their properties under firing conditions.

Method of tube manufacture

A89. The method adopted is to wind the reinforcing material on to a mandrel and a machine has been designed for this purpose. One machine is described and illustrated in ref. 19. The reinforcing material is in the form of woven glass tape (1 to 4 in. wide), glass yarn or rovings, or woven glass cloth—a description of these materials is given in ref. 19. During the early stages of development, tubes were wound on a number of different forms of mandrel by using rubber sleeves and various parting agents; but withdrawal was never easy even where 4-in. tubes were concerned and all were abandoned in favour of a precured Durestos former which is left inside the completed tube and acts as an efficient heat insulator.

A90. The precured former is moulded in Durestos felt by a 'no pressure' process on a parallel cylindrical pressure-moulded Durestos mandrel. A single Durestos felt, moulded to 0·040 in. in thickness, has been used for tubes up to 10 in. in diameter by 3 ft. long; above this size two felts are best. It seems likely that these formers will be quite unsatisfactory for glass fibre tubes operating at high stresses. The most promising lining materials now are natural or synthetic rubbers which are laid on the mandrel before commencing the winding of the glass fibres.

A91. In all winding processes the ultimate aim should be to lay the reinforcing material on to the former under controlled tension in a regular pattern with as few kinks or lumps as possible, and not to damage it in any way while doing so. Glass tape is not easily damaged and can be tensioned quite simply, but considerable ingenuity is required in the design of the final V-guide employed and in adjusting its position relative to the tube being wound to avoid creasing, particularly at the reversal of traverse direction.

A92. Roving, on the other hand, is very easily damaged and cannot be tensioned by gripping. It has a remarkable tendency to wrap round anything revolving and to build itself up in a bunch and ultimately break against any edge presenting itself to the oncoming end of a broken end or filament. It is essential that it be laid on the tubes in a flat ribbon and this demands a rather complicated final guiding system.

A93. It has been the practice to pass the tape or roving through a resin bath, because the lubricating effect during the critical final guiding is beneficial and the resin content of the finished tubes could be kept constant in this way. Another method, which is now preferred, is to apply the resin to the tape or rovings at the point of contact with the mandrel. Most of the work on reinforced plastic tubes reported in ref. 19 has been carried out with polyester resins. Many of the problems associated with this work can be investigated by using those resins which are comparatively cheap. So far, none of the projects has reached the production stage, but when they do, it is likely that the epoxy resin would be used. Broadly speaking, these latter resins when used with suitably treated rovings or fabric result in laminates having a higher performance than those made with polyester resins.

End closures

A94. The production of satisfactory end closures for reinforced plastic tubes has proved the most difficult problem to solve. Various types have been tried out in this country and the reader is again referred to ref. 19 for details. One type which gave satisfactory results in laboratory tests and firing trials is the 'inverted dish-shaped' end closure referred to in para. 167 and illustrated in fig. 32. This type was a most useful and cheap form of closure for development and research purposes, but has now been abandoned in favour of some form of cemented scarf or sleeve joint. This latter form of closure is an American development and information about it will be found in ref. 20.

A95. Briefly, the scarf joint consists of machining the outside ends of the tubes to a taper of between 5° and 7° (for a wall thickness of 0·2 in.) with a finish so rough as to resemble a fine screw thread and to glue on to them metal sleeves with a matching internal taper of equally rough finish. Sleeves used to date include steel, aluminium, and light alloy. This type of glued scarf joint is highly efficient for securing end closures for tubes up to 8 in. in diameter and probably up to 10 in.

Summary

A96. This brief account of the manufacture of plastic tubes for rocket motor bodies is included to indicate the methods being tried out at present. More detailed accounts of winding machines and techniques, end closure problems, etc. will be found in ref. 19 and 20. Performance figures are quoted in these reports, but as new techniques and methods are evolved and more is learned about the problems involved, these figures may well change and should not be taken as final.

STRIP WOUND TUBES

Introduction

A97. During the past two years a novel method of manufacturing rocket motor tubes has been developed which possesses several advantages when compared with other methods. Basically, the process is simple: the tube is formed from several superimposed layers of flat strip material wound helically on a removable mandrel. In order that the structure may be able to carry longitudinal loads, the layers of strip material are bonded together with a synthetic resin adhesive which is capable of withstanding high shear stress. To complete the motor body, end rings to which closures may be attached are similarly bonded to the tube.

A98. This procedure leads to advantages over conventional methods; these advantages may be summarized as follows:—

(1) high strength strip materials which are not amenable to welding can be utilized, for example, spring steel of approximately 140 tons per sq. in. ultimate tensile strength or aluminium alloy of approximately 40 tons per sq. in. U.T.S.

(2) plant requirements for a given production rate are simpler than for conventional motors, particularly where large diameter tubes are required

(3) standard strip sizes can be used for any motor which leads to a corresponding increase in flexibility

(4) dimensional accuracy and reproducibility are greater than for normal methods.

Principles of design

A99. For a given required pressure and diameter the total metal thickness may be determined with suitable safety factors by using simple thin-walled tube theory, assuming that the steel carries the hoop stress; the axial stress is then transmitted by the resin bond. The design consists of determining the number of layers of steel such that the resin shear stress based on the shortest shear path through the laminate does not exceed a nominal value, which is less than 25 per cent of the shear strength of the resin used. Present practice utilizes Araldite type 15 resin with a shear strength of approximately 8,000 lb. per sq. in.; the shear stress in the resin is thus held below 2,000 lb. per sq. in.

A100. For a given width of strip, which is generally less than 3 in. at present, the overlapping of succeeding layers is arranged geometrically so that none of the butt joints in the layers is opposite to another. Analysis has shown that this arrangement is essential to achieve a structure which has maximum hoop strength and yet will sustain a comparable stress in the axial direction.

A101. It will be apparent that for a bonded-on ring, the end pressure load is transmitted through a single layer of adhesive. The choice of overlap length in this case has therefore again been based on an average resin shear stress of 25 per cent of the ultimate shear strength of the adhesive. It must be noted, however, that theoretical analysis of the stress system in a simple lap joint predicts, and experiment has verified, that the load carrying capacity is not linearly related to the overlap length because of the existence of a shear stress concentration factor. This would imply an upper limit to the end load which could be sustained by a joint of this type regardless of the overlap length for a given adhesive and metal components. Present indications are that this limit, which can easily be extended by alterations in joint configuration, is adequately high for current boost motor design, that is, up to 20 in. in diameter.

Principles of manufacture

Materials

A102. Experience has been gained with cold-rolled steel strip material, hardened and tempered to give an ultimate tensile strength of 140 tons per sq. in. with a 0·1% proof stress of 120 tons per sq. in. Epoxy resins such as Araldite type 15 and Epon 828 have been proved to be suitable adhesives.

Strip preparation

A103. The steel strip is delivered in coils containing not less than 200 ft. and at present the preferred dimensions are 2·24 in. wide by 0·007 in. thick. Degreasing of the strip is followed by shot blasting on both sides, after which an even coating of adhesive in solution is continuously applied, the solvent being subsequently removed by infra-red heating before the strip is wound in coils. In this condition the strip may be stored for a considerable time and used as required.

Tube winding

A104. The prepared strip is wound on to a suitable mandrel by means of a winding head, the essential function of which is to provide tension in the strip sufficient to ensure flatness of lay, and also to enable the correct helix angle to be maintained. The strip is attached with a clamp to the end of the mandrel, and as the mandrel is rotated the winding head is traversed along the lead screw at a rate to give the correct helix angle. The mandrel is maintained at a temperature of 105° C which is sufficient to melt the resin while the tension in the strip causes the resin to flow, thus ensuring a uniform bond. At the end of the layer the strip is clamped to the mandrel and cut, the second layer then being wound in the same direction with the appropriate overlap. Successive layers are added until the required thickness has been built up.

Preparation and assembly of tube

A105. Before removal from the mandrel, the tube is part-cured at 150° C to permit safe handling and is then cut to the required length with an abrasive grinding wheel. To facilitate end ring assembly the outside ends of the tube are cleaned with a belt sander to remove excess resin and then shot blasted and degreased. The bore of the end ring is similarly shot blasted and degreased and the tube is inserted into the ring and held concentric by shims. The annular gap between the tube and end ring is then filled with Epon 828, a liquid solvent-free resin, and the whole assembly is cured at 180° C for two or three hours in an air oven.

Properties of strip wound tubes

A106. The criterion adopted for acceptance of completed motor tubes has been a hydraulic test to a specified pressure, together with similar tests to destruction on selected designs. For this purpose it has been found necessary during testing to prevent the water being forced into the laminar structure, since this leads to premature failure by the peeling apart of the layers; the interior of the tube is therefore sealed off with an impervious rubber lining. Hydraulic testing to destruction has shown that the full strength of the steel can be realized without adhesive failure occurring, and in certain cases maximum hoop stresses greater than those expected from the nominal ultimate tensile strength of the steel have been encountered.

A107. Other tubes have been subjected to a range of external loadings involving bending and torsion alone, and in combination with internal pressure. Environmental tests over a range of temperatures and cycles of temperature have also been carried out and the tubes have been found to be unaffected by such conditions. Finally, a considerable number of firings of 6-in. and 11-in. tubes has been successfully accomplished over a range of conditioning temperatures.

A108. The results of all these tests have engendered considerable confidence in these structures, for in every instance the tube has behaved as if it were of a solid unlaminated material. Thus, strip material of the highest strength can be fully utilized without difficulty.

INSPECTION AND TESTING OF ROCKET MOTOR TUBES

Mean diameter, ovality, and bow

A109. In the measurement of these errors during inspection of rocket tubes it is difficult and sometimes impossible to differentiate between errors due to ovality and those due to bow. It is, of course, always possible to determine the exact shape of any section of the tube and this will determine the ovality of that section ; however, bow is not so easy to define (see para. A3). As has been stated, for motor tubes in production the practice has now been standardized of allowing for all these errors in a general statement that the tube must accept a full form cylinder gauge and lie within a cylindrical form, both of which are specified (see fig. A25 and para. A4).

Measurement of wall thickness

A110. In the development and inspection of these long thin-walled tubes, it is necessary to determine the actual wall thickness (to a fairly high degree of accuracy) at any point along the tube. Ordinary calliper gauges are not very satisfactory for these long lengths as it is not usually possible to obtain the required rigidity. One method developed which gives satisfactory results employs an alignment telescope. This is an instrument which can be adjusted so that its line of sight can be raised or lowered *parallel to itself* through a measurable amount up to a maximum of about 0·050 in. (see fig. A29).

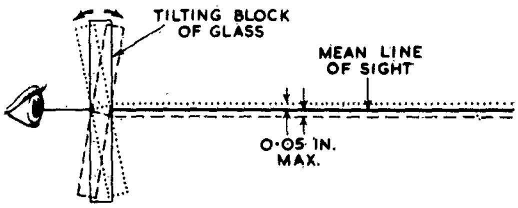


Fig. A29. Principle of alignment telescope

A111. The way in which an alignment telescope is used to measure the wall thickness of a rocket motor tube is shown in fig. A30. The telescope is mounted on its levelling screws on a rigid base. On a similar rigid stand a slip gauge of the nominal thickness of the tube to be measured is laid on hardened steel rollers. An illuminated graticule is mounted on the slip gauge and the alignment telescope is adjusted on its levelling screws so that the mean line of sight passes through the centre of the graticule.

A112. The slip gauge is now removed and replaced by the rocket tube. The line of sight is now adjusted so that it again passes through the centre of the graticule. The amount of adjustment, which can be read off the instrument, is the amount by which the wall thickness at the point in question differs from the nominal thickness of the tube, and hence the actual thickness at the point can be found. The tube can be moved axially along the rollers or rotated as desired and so the wall thickness at any point can be determined.

Pressure testing

A113. In testing rocket motor tubes it is customary to measure the permanent set after pressure testing as a volumetric expansion and to limit this to a certain amount depending on the quality and volume of the tube being tested. One method used for this test is illustrated

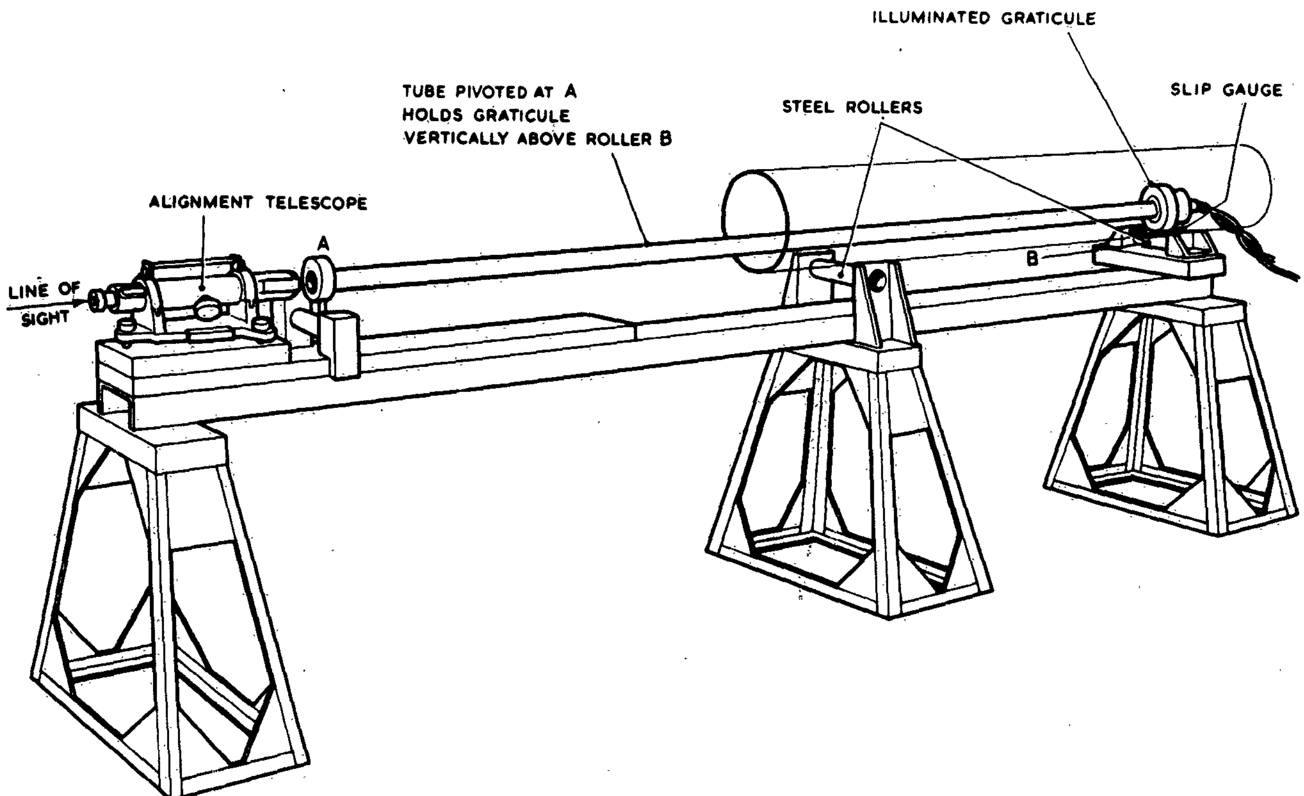


Fig. A30. Measurement of rocket tube wall thickness

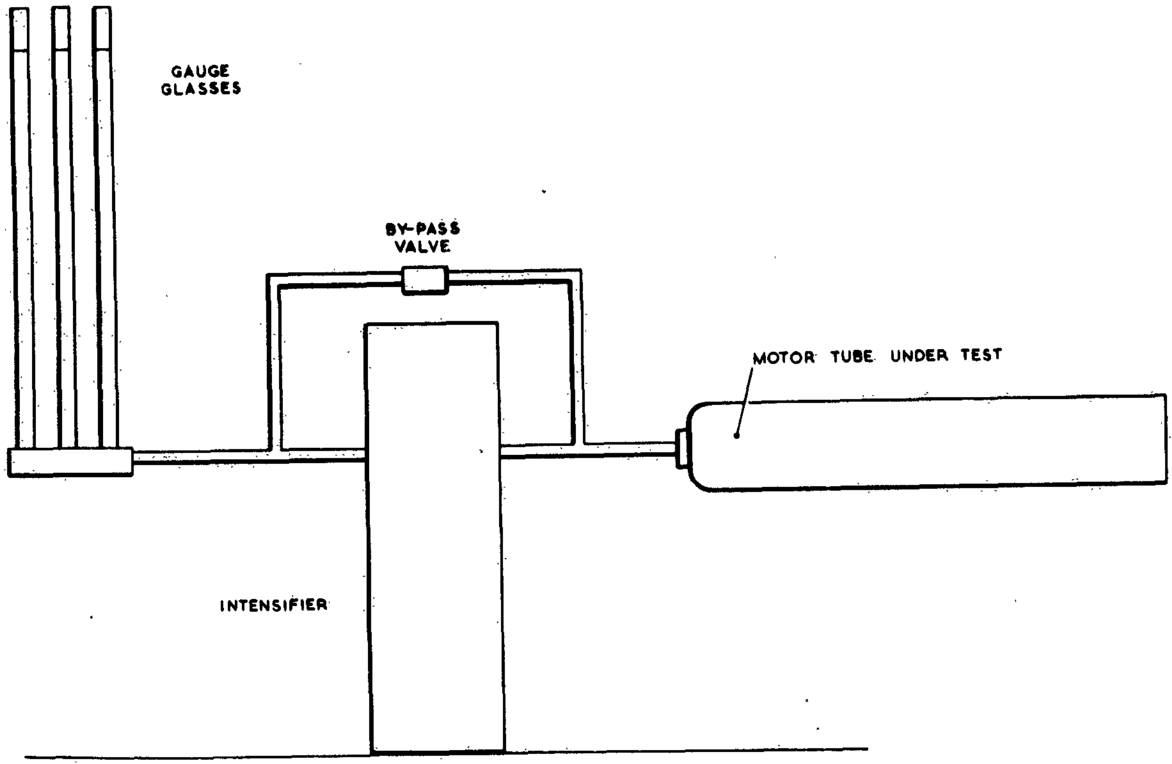


Fig. A31. Pressure testing rocket tubes

diagrammatically in fig. A31. The gauge glasses, the intensifier, and the motor tube under test are filled with water so that the level in the gauge glasses reaches some predetermined mark. This entire water circuit is then isolated from the water supply and the by-pass valve is closed.

A114. In operation, water is drawn from the gauge glasses through the non-return valve of the intensifier and used to pressurize the motor tube under test. After reaching the test pressure and remaining at this pressure for a specified time to see that conditions are steady, the by-pass valve is opened and water is allowed to return up the gauge glasses. The volumetric difference represented by the difference between the initial and final gauge glass readings is regarded as the permanent set in question (see note 4 to fig. A25).

NOZZLES

Introduction

A115. The materials used in nozzle manufacture were considered in Section 5 of the main text, where it was seen that among heat absorbing metals mild steel was one of the most suitable. Of the non-metallic heat resisting materials phenol-formaldehyde resin reinforced by long fibre crysotile asbestos has proved very successful. There are a few special problems associated with nozzle manufacture and these will now be considered.

A116. The variation of the pressure, temperature, and velocity of the combustion gases along a nozzle is shown in fig. A32. From these curves it will be seen that the pressure falls from the operating pressure at the rear end of the combustion chamber to a little over half this value at the throat, and thereafter continues to fall until it becomes approximately atmospheric at the exit end of the nozzle. At the same time the temperature also falls but is still high at the throat, where the velocity of the gases reaches the local velocity of sound.

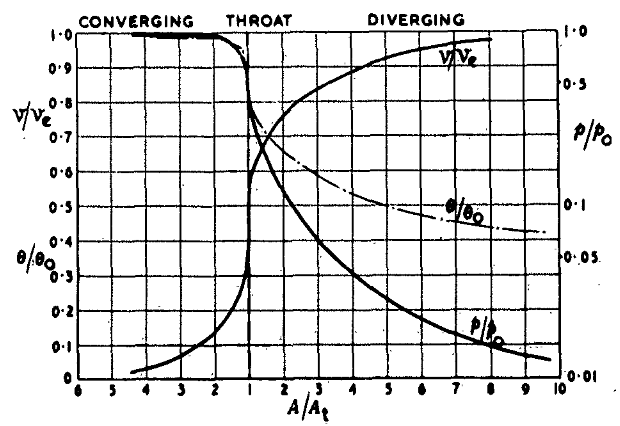


Fig. A32. The conditions of gas flow in a nozzle

A117. Because of the high pressure and temperature of the gases at the entry end of the nozzle, the thickness of the material there has to be adequate to withstand the conditions. At the throat, although the pressure is lower, the temperature is still high while the gas velocity is considerable, and it is found that this area is the most liable to erosion. Hence it is necessary to thicken up the nozzle at the throat. At the exit the pressure is low and this end of the divergent cone can be quite thin, the only limiting factor being the risk of damage in handling. These considerations, together with the overall requirement of keeping the weight of the complete nozzle to a minimum, account for the variations in thickness along a nozzle (see fig. A33).

Problems of nozzle manufacture

A118. Nozzles have been made from steel, light alloy, and plastics, and in some cases from a combination of plastic with steel or light alloy. The majority have been made from mild steel, which has good heat conducting properties combined with adequate mechanical strength and reasonably high melting point (see Table 6). Special heat resisting steels have been tried, but generally they are inferior in heat conducting properties to mild steel and there has been no overall gain from their use.

A119. For nozzles made from steel an obvious possibility is to have them cast in their final form, but efforts to produce them in this way have not been very successful as the shapes required do not fall in line with foundry techniques. In general, cast nozzles have required an excessive amount of subsequent machining which has added considerably to the cost of the completed nozzle. A few nozzles have been cast in ductile iron and in spheroidal graphitic cast iron and some have been fired statically. The results have been most inconsistent; erosion in some cases was negligible and in others very severe. There is some evidence that porosity, particularly near the throat, is responsible for the heavy erosion encountered, but other defects may have contributed. Nevertheless, work is still proceeding to develop a satisfactory cast iron nozzle, but results are not very promising so far.

A120. Nozzles made from mild steel are produced by machining from solid, machining from forgings, and fabrication from machined or unmachined components. The surface finish of the inside of the nozzle is required to be reasonably good and an ordinary machined finish, particularly at the throat, is satisfactory in mild steel.

A121. The majority of boost motors used in this country are disposed in a 'wrap round' formation about the main missile (see fig. 44). It is frequently necessary that the thrusts of each should pass through the same point and that their jets should not impinge on any tail control surface. These requirements can be met conveniently by offsetting or canting the nozzles; a typical canted nozzle with its dimensions is shown in fig. A33.

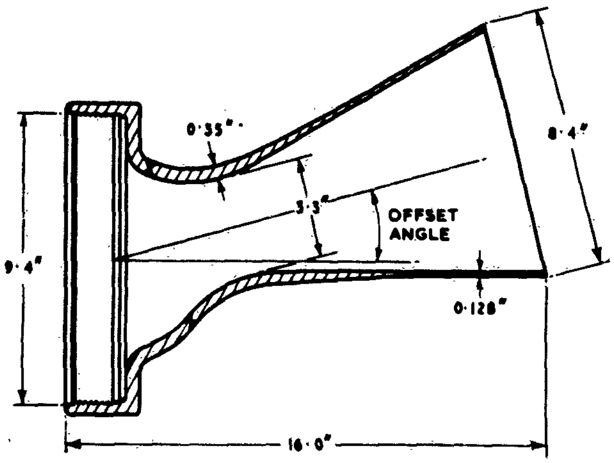


Fig. A33. Typical canted nozzle

A122. The thickness and the cross-section of the nozzle shown in fig. A33 vary from section to section and the nozzle as a whole is not symmetrical about any axis. Where boost motors are used with different vehicles, it sometimes happens that the offset angle also varies and this adds to the complexity of the manufacturing and production problems. Hence to manufacture this nozzle as an integral machined component is a difficult and costly operation. One method which has been extensively employed for the manufacture of canted nozzles will now be considered.

Mild steel canted nozzles

A123. The method used for canted nozzles employs a combination of machining and fabrication. Initially the nozzle is made in three parts as shown in fig. A34. The nozzle end plate (1) and the throat section (2) are machined from mild steel forgings, while the remainder (3) of the divergent cone is fabricated from mild steel sheet. The throat section is first welded circumferentially to part 3 to produce the divergent portion of the nozzle. The nozzle end plate is then bored at a diameter to suit the remainder of the nozzle and at an angle to suit the offset angle required. The two parts are then held in a jig and circumferentially welded to form the complete nozzle as shown in fig. A33. This method is known as the *dome and cone* method.

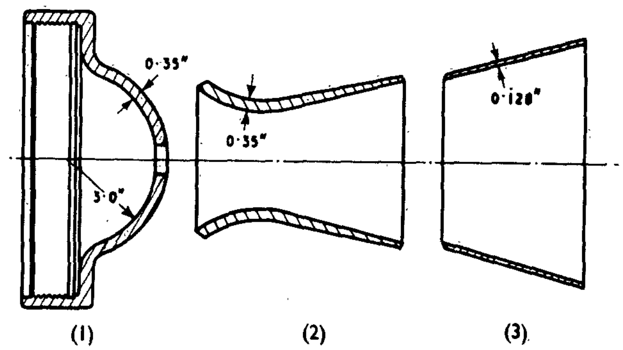


Fig. A34. Dome and cone method of nozzle manufacture

A124. The method permits the manufacture of quantities of components all common to various angles of offset, which are then determined by the final fabrication stage. It is not an ideal shape but is a reasonable compromise which can be produced at a not too excessive cost.

Plastic nozzles

A125. In view of the difficulties inherent in nozzle manufacture in ferrous materials, much effort has been devoted to finding a cheaper alternative material. In the plastic field, an obvious possibility, efforts have been made to develop moulded nozzles using fibrous reinforcements of glass and asbestos in polyester and phenolic resins. Glass as a reinforcing material has not been successful, either in the form of wrapped glass cloth laminates or chopped fibre; erosion is very severe and laminates split. On the other hand a material made from asbestos fibres in phenolic resin moulded as a 'flock' under high pressure has been found to behave as well as mild steel as regards erosion (see para. 232 to 235 and fig. 46).

A126. A disadvantage of the material is that it does not permit much distortion before it cracks (between 0·2 and 0·5 per cent). This limits the application of

steel or other reinforcing material. Efforts to improve the flexibility of the material by the introduction of rubber have caused a noticeable reduction in its resistance to erosion.

A127. The strength of the material is extremely variable (between 2,000 and 5,000 lb. per sq. in.) and this causes further difficulty. In operation the nozzle is required to resist pressures varying from the full operating pressure of the motor at the open end of the combustion chamber to atmospheric pressure at the nozzle exit. In view of the variable strength of the material it is necessary to simulate these pressures during the testing of the completed nozzles. The method used has not been completely developed, but a series of rubber bags inserted in the nozzle and pressurized to the value to be sustained in practice are employed.

A128. The plastic nozzle just described is the only one to be successfully produced in quantity and it has been used on boost motors developing a thrust of 8,000 lb. for 3 sec. However, this is a relatively small nozzle and for larger sizes, in view of the low mechanical strength of the material, it is necessary to consider metal reinforcement. Because of the low resistance to distortion of this plastic material, the design of such metal reinforced nozzles requires careful consideration, since stress concentrations in the plastic can be produced and lead to failure in operation. Efforts to make a larger reinforced nozzle by using a mild steel end plate to which was moulded a Durestos convergent-divergent portion have not been very successful, since the difference in flexibility under pressure of the two components caused cracking of the plastic in operation.

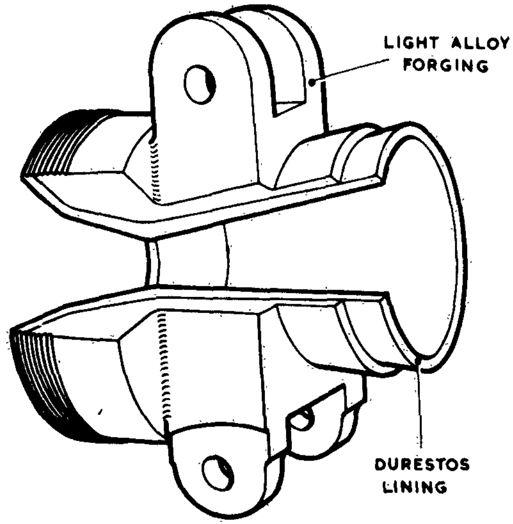


Fig. A35. Combined plastic nozzle and rear end closure

A129. A combined nozzle and rear end closure designed for a Mayfly motor is illustrated in fig. A35, in which a light alloy forging is used to take all the loads due to gas pressure, boost thrust, and fin drag. The inside of the forging is in the form of a convergent-divergent nozzle and is lined with Durestos RA51, moulded in position.

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INDEX

(Numbers refer to paragraphs ; heavy type indicates definition)

Adiabatic flow, 18
Adiabatic relation, 18, 213, 216, 219
Air-to-air rocket, 144, Table 8
Alignment telescope, A110
Alloy steels for nozzles, 230
Angling of nozzles, 225, A121
Anti-resonance rods, 128, **135**
Anti-tank weapons, 2
Araldite resin, A99
Area of burning surface, 15, 39, 71–78
Argon arc welding, A27, A40
Asbestos fibres, 232, A86, A115, Table 5
Assisted take-off motors, 2, 130, 140, 145, 204, 208, 228, Table 8

Backing bar, A26, A41–A43, A52
Bakelite cement, 234
Ballistic theory, 8, 14–23
Barrage weapons, 2
Barrelling of charge, 108
Basic thrust equation, 218
Bazooka, 2
Bernoulli's equation, 17, 213, 219
Blast tube, **236**
Boost motors, 2, 140, 144, 225
Boost motor, design of, 244–254, Table 8
Bow, 164, A6, A109
Brake press, A25
Brittle propellants, 111
Broaching steel tubes, A29
Bronx rolls, A39
Burning by parallel layers, 6, 35
Burning rate, dependence on pressure, 38–41, 148
Burning rate, dependence on temperature, 42–43, 148, 227
Burning rate, mean, 15, 29
Burning time, 6, 29, 82, 148, 227
Buzzard motor tube, A63

Calorimetric value, 41, **51**, Table 3
Canted nozzle, 224, A121
Carbamite, 122
Cast double base propellants, 33, 64, 89, 246
Cast iron nozzle, A119
Casting powder, 128
Cavity-type charge, 263
Cellulose acetate, 91, 101
Ceramics, use of for nozzles, 229, 232
Change in charge shape with burning, 74–77
Charge shape, 70
Choke, **217**
Choking, **215**
Circumferential welding, A30, A51
Cogged charge, 75
Cold drawing, 169, A4
Colloidal propellants, **33**, 38, 50-56, 62-65, 127-128
Colloidal propellants, manufacturing limitations of, 62–65
Combustion chamber, 5
Combustion chamber strength, 71
Combustion pressure, 5
Combustion temperature, 5, 51, Table 3, 138
Composite propellants, **33**, 41, 57–61, 66–69, 130, 246, 259
Composite propellants, manufacture of, 66–69
Composition of igniters, 178–181
Composition of solid propellants, 33, Table 1 and 2
Conservation of energy, 17
Conservation of mass, 15
Constancy of burning surface area, 71, 84
Cool propellants, 41, **52**
Cordite charges, 94–106, 108–111
Cracking of propellants during storage, 117–125
Critical pressure, 206, 214
Cruciform charge, 75, 97

Danger of bursts, 123
Decarburization, A57
Decomposition of propellants, 36, 177
Deep drawing, 169, A4
Deep-drawn tubes, A60–A68
Demon boost motor, A75
Dependence of burning rate on pressure, 38–41, 148
Dependence of burning rate on temperature, 42–43, 148, 227
Design details of solid propellant motors, Table 8
Design of a rocket boost motor, 244–254
Design of a rocket charge, 70–78, 245–247, 257–261
Design of a rocket sustainer motor, 255–266
Design of igniter containers, 186
Design of rocket motors, 3, 8, 24–32
Design of strip wound tubes, A99
Design requirements, 8, 24–32
Development of rocket motors, 2
Diameter/thickness ratio, 169, A2
Differential pressure, 172
Dinitrotoluene, 122
Dish-shaped end closure, 167, A94
Distortion of rocket motor tubes, A33
Divergence angle of nozzle, 222
Dome and cone method of nozzle manufacture, A123
Dummy cordite, **95**, 98
Durestos, Table 5, 232, A90, A116

Effect of flaws in propellant charges, 123
Effect of gas velocity, 20–23, 44–49
Effect of high temperatures on motor body materials, 159–162
Effect of peak pressures on motor tube strength, 148–154
Effect of star design on stress concentration, 111
Effect of stress on properties of propellant, 107–116
Effectiveness of igniter, 178
Effects of heat treatment, A56–A59
Efflux velocity, 141–220
Elimination of secondary peaks, 134, 135
End design, 155–158, 168, A94, A101, A105, A109
Energy conversion in nozzle, 209, 220
Epon resin, A102
Epoxy resin, 166, A93
Equilibrium pressure, 42
Erosion factor, **20**–23, 46
Erosion of plastic nozzle, 233, 234
Erosive burning, 44–49, 72, 152
Ethyl cellulose, 91, 101
Expansion ratio of nozzle, 138, **221**
Exothermic gas reaction, 36
Extruded propellants, 33, 62, 247, 258
Extrusion press, 62
Extrusion process, 63

Fabrication from sheet, 169, A4, A22, A37
Fibre glass, 238, A86
Fizz reaction, 36
Flame reaction, 36, 56
Flash intensity, 129
Flash suppression, 54, 126–128, 182, 183
Flashless ignition, 182, 183
Foam reaction, 36
Friction in nozzle, 222
Functional limitations of solid propellants, 38
Functioning of solid propellants, 33

Gas conduit, 13, 29, 49
Gas density, 15
Gas evolution during storage, 119–125
Gas velocity, 15
Gas velocity, effect of, 20–23, 44–49
German rockets, 224
Glass cloth, 239, A89

Glass fibres, A86
Glass fibre plastic, 160, 161, A83
Glass rovings, A89
Glass tape, 239, A89
Glass yarn, A89
Gosling motor tube, A36
Graphite, use of for nozzles, 229, 235
Grid, **12**
Grinding welds in tubes, A27, A48
Guillotining sheet metal, A37

Hard propellants, 111
Head end closure, **12**
Heat treatable alloys, A78
Heat treatment, A19, A34, A37, A54
Heavy weight tubes, A2, A13, A70
Heliweld welding head, A44
Hemispherical ends, 158
High temperature storage, effect of, 91, 117–125
Hoop stress, 31, 150, A10 A62
Hot moulding process, 98, 139
Hot propellants, **52**
Hot rolling, 169, A4
Hot swaging, A13
Hydraulic testing of tubes, A31, A106, A109
Hydrocarbon binders, 125

Igniter, 9, **12,** 177
Igniter containers, design of, 186
Igniters, design principles, 188–192
Igniter flash, 181
Igniter housings, 199–205
Igniter location, 186, 187
Igniter shock, **184,** 185
Igniters, protection from moisture, 189
Igniters, strength of, 189
Igniters, use of metals for, 197, 198
Igniters, use of plastics for, 196
Igniting compositions, 177–181
Inclined nozzles, 224, A121
Industrial methods of steel tube manufacture, A4
Inhibited charges, 71, 82, 87
Inhibition by bonding, 88, 89, 94
Inhibition of burning of colloidal propellants, 88–106
Inhibitor, **12**
Inspection of rocket tubes, A109
Internal ballistics, 14–23
Interrupted burning technique, 46

Jet separation, 220, 222

Lead salts, 40, 56
Length/diameter ratio, 155-157
Light-alloy motor body tubes, 5, 162, 168, A75
Light weight tubes, A33, A73
Limitations on propellant design, 58–61
Liquid binder, 34, 66, 113
Liquid propellants, 1, 4–7
Liquid propellant motors, 2, 4–7
Loading density, 28, 49, 152, 165
Location of igniter, 186, 187
Longitudinal welding, A26, A40
Luminous gas phase reaction, 36

Magnesium powders, 178–181
Maintainer igniter, 206–208
Mandrel drawing, A4
Manufacture of strip wound tubes, A102
Manufacturing considerations associated with motor bodies, 164–170, App. A
Manufacturing limitations of solid propellants, 62–65
Materials for igniters, 193–198
Materials for motor bodies, 159–163, 248
Materials used for inhibitors, 90–92
Materials used for nozzles, 229–235, A115, A118, A125
Materials used for strip wound tubes, A102

Mayfly motor tube, A14
Meal powder, 183
Mean diameter, A6, A109
Mechanism of burning of solid propellants, 35–37, 177
Medium weight tubes, A14, A71
Metallic-arc welding, A27
Metals used in nozzle construction, 229, A118–A124
Migration of plasticizers, 90–93, 117
Mild steel, use of for nozzles, 229, A120–A124
Molecular weight of combustion gases, 138
Momentum thrust, **218**
Motor body, 4, 9
Motor body design, 137, App. A
Motor body shape, 158
Motor tube, **12**
Motor tube design, 148–154
Multiple nozzles, 224

Nitric esters, 33, 36
Non-luminous gas phase reaction, 36
Notation, **13**
Nozzle, 9, **12,** 209
Nozzle constant, 19
Nozzle construction, materials used in, 229–235, A115, A118
Nozzle discharge coefficient, **19,** 83
Nozzle end plate, **12**
Nozzle erosion, 233, A119
Nozzle expansion ratio, 138, **221**
Nozzle extension tubes, **236**–240
Nozzle manufacture, A115–A129
Nozzle shape, 222, 223
Nozzle theory, 211–217
Nozzle throat area, 15, 19, 27, 72

Obturation, methods of, 171–176
Optimum charge shape, 157
Optimum thrust, 219
Oscillations in pressure, 136
Ovality, 164, A6, A109
Overall design, 9, 241

Paper carton igniter, 199
Parallel layer burning, 6, 35
Peak pressure, 14, **23,** 28, 45–48, 148–152
Perforated charge, 71
Performance data for typical propellants, Table 3
Performance details of solid propellant motors Table 8
Phenolic resin, 166, 232, 239, A115
Phenol-formaldehyde resin, 232
Plastic coating expansion mould, 102
Plastic motor body tubes, A83
Plastic nozzles, 233, 234, A125
Plastic propellants, 33, 89, 107, 112–116, 125, 162, 172
Plastic Q, 95
Plastic tubes, A83–A96
Platonized propellants, 40, 128, 152, 228
Plasticizer migration, 90–93, 117
Plug drawing, A81
Polyester resin, 166, 239, A93
Polyisobutene, 116
Potassium cryolite, 54, 56, 127
Potassium salts, 127–128, 131, 132
Precipitation heat treatment, A81
Preforming sheet metal, A24, A37
Pressed charges, 33, 259
Pressure exponent, 39, 47
Pressure exponent for colloidal propellants, 40
Pressure exponent for composite propellants, 41
Pressure in a rocket, 14, 19, 20–23, 27, 39, 45, 71, 138, 150, 246
Pressure oscillations, 136
Pressure testing of rocket tubes, A106, A113
Pressure thrust, **218**
Principle of conservation of energy, 17
Principle of conservation of mass, 14
Products of combustion, 17
Projection firings, 254

Proof strength, 153, 159
Propellant charge, 9, **12**, 33
Propellants, colloidal, **33**, 38, 50–56, 62–65, 127, 128
Propellants, composite, **33**, 57–61, 66–69, 130, 246, 259
Propellants, liquid, 1, 4–7
Propellants, solid, 1, 4–7, 33

Radio attenuation, 131–132
Radiographic inspection of welds, A31, A48, A50, A53
Rate of burning, 16, 20–23, 29, 39–41, 45, 50
Rate of burning, mean, 15, 29
Rate of gas efflux, 15, 19, 82, 212
Rate of gas production, 15, 26, 39
Regularity of burning, 133–136
Reinforced plastics, 160, 161, 265, A83
Reinforcing fibres for plastic tubes, A86–A88
Relation between length and diameter of charge, 81–85, 250
Requirements for rocket motor tubes, A2
Resin bath for glass fibres, A93
Resin impregnated asbestos, use of for nozzles, 229, A125
Rifle powder, 65
Rocket motor bodies, manufacturing considerations, 164–170, App. A
Rocket motor design, 3, 8, 24–32
Rocket motor performance, 140–142, 152, 157, 245
Rocket motors, development of, 2
Rocket motor tubes, light-alloy, A75
Rocket motor tubes, plastic, A53
Rocket motor tubes, steel, A13
Rocket motor tubes, strip wound, A97

Safety factor, **154**
Salts, 33, 34
Scale, A57
Scarf joint end closure, A94
Secondary peaks, 57, 133–135
Selection of charge design, 81–87
Semi-ellipsoidal end, 158
Sensitivity of igniters, 181
Shock wave in nozzle, 220
Sizing steel tubes, A32
Sliver, **79**
Slotted tubular charge, 261
Smoke suppression, 126, 130
Solid phase decomposition, 36
Solid propellants, 1, 4–7, 33
Solid propellants, functional limitations of, 38
Solid propellant motor, 2, 4–7
Solid propellant motor, components of, 10, **13**
Solution heat treatment, A81
Specific heat, 17
Specific impulse, **18**, 26, 41, 51, Table 3, 83, 130, 138, 247, 259
Specific proof strength, 159
Specific volume, 209
Spontaneous decomposition of propellants, 117–125
Spring nozzles, 224
Stabilizers, use of, 122
Stainless steel for nozzles, 230
Static firings, 253
Steady state, **15**, 36, 85
Steel insert, **240**
Steel motor body tubes, A17
Steel nozzles, A120
Storage temperature, fluctuations of, 88, 117–125
Stresses in propellant charges, 107–116
Stress relief, A25, A39, A48
Stress relief technique, 101
Stretch forming rocket tubes, A37, A49
Strip wound tubes, 166, A1, A97
Strip wound tubes, assembly of, A105
Strip wound tubes, design of, A99
Strip wound tubes, manufacture of, A102
Strip wound tubes, materials used for, A102
Strip wound tubes, properties of, A106
Strip wound tubes, winding technique of, A104
Stripped charge, 97
Submerged arc welding, A32
Subsonic blast tube, **236**
Supersonic blast tube, **236**
Suppression of flash, 54
Surface temperature of nozzles, 231
Sustainer motor, 2, 140, 146, 163, 208
Sustainer motor, design of, 255–266
Symbols, 13

Tabbed charge, **94**
Tailpipe, **236**
Technique of inhibition, 88–106
Temperature cycling, effect of, 94, 107, 113, 115
Tensile strength, 31
Testing of rocket tubes, A106, A109
Textiles used for igniters, 194
Thermal conductivity, 162, 230, A88
Thermal decomposition of propellant, 36, 177
Thermal insulation of motor tube, 74, 81, 88, 171, 237, 253, 264, A83
Thermoplastic material, 88–92, 98, 196
Thermosetting material, 196
Thrust, 25, 218
Thrust in a rocket motor, 218–220, 227
Thrust plug, **12**
Time of burning, 6, 29, 82, 148, 227
Total impulse, **13**, 25, 83
Transient peak pressure, 153
Tropical storage, 117
Tubular charge, 75, 108
Turbulence losses in nozzle, 222

Ultimate tensile strength, 154, A2
Unguided rockets, 140, 144, 157
Units, 13, 21
Unstable burning, 53
Upper temperature limit, 108, 109

V2 missile, 2
Variation in ballistic properties of propellant, 90–92
Velocity at nozzle throat, 18, 216
Velocity of rocket at all-burnt, 140, 141
Velocity of sound, 18
Vicker's pyramid numbers, A42, A55
Viscosity of liquid binder, 114
Vistac, A77

Wall thickness, measurement of, A110
Wall thickness of motor body tube, 31, 150, 164, A9
Web thickness, 29, **79**, 80
Weight of ends, 32, 155
Weight of motor body, 30
Working pressure, 23, 47, 148, 154
Wrap-round boosts, 225, A121

Yield point of plastic propellant, 113
Young's modulus, 109, 117

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