WASC 2333

Solid Rocket Motors
Code of Design Practice

Code of Design
Practice -
(Rocket Motors)

SOLID ROCKET MOTORS

CODE OF DESIGN PRACTICE

TECHNICAL NOTE 79/49

ISSUE 4

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Thermal conductivity CL7225 ~ 0.22 (W/mK)

Density ~ 1.12

CL2759 ~ 0.33

Density ~ 1.57.

Distribution

1	Commercial and Projects Director
2	Technical Director
3	Head of Projects
4	Head of Materials
5	Chief Engineer
6	Projects Department Manager
7	Materials Department Manager
8,9	Projects Section Managers
10	Ballistics/Maths Department Manager
11	Divisional Laboratory Services Manager
12,13	Propellant Technology (Cast double-base, Composite)
14	Casting Powder Technology
15	Igniters Department Manager
16	System GWSO Co-ordinator
17	Divisional Quality Manager
18-24	Projects Department (each office)
25	Design Services Manager
26	Configuration Control Manager

Amendment Record Sheet

This Technical Note will be updated to introduce any changes when approval has been obtained. Changes to the document will be in accordance with 101 711-34/1/HQ, Configuration Control of Quality Management Documentation.

Change No	Issue	Date	Affected Sections
	3	March 1993	
SA 3595	4	October 1993	All

Page	Issue	Page	Issue
1	4	Part 4	3
2	4	Part 5	3
3	4	Part 6	2
4	4	Part 7	3
5	4	Part 8	2
		Part 9	3
Part 1	3	Part 10	3
Part 2	3		
Part 3	3		

This Technical Note comprises 5 pages, plus 10 parts. Its issue is known by the issue of page 1, but the issue of all other pages and the 10 parts are stated above. Control of the pages of each of the 10 parts is covered within the respective part.

Code Of Design Practice

This document specifies the design requirements for solid Rocket Motor Systems within the Commercial/Projects and Technical Directorates of the Rocket Motors Division, Royal Ordnance.

TN 79/49 comprises ten (10) PARTS covering design and development control procedures, with each PART divided into SECTIONS. The 10 PARTS are:

PART 1	Design and Development Co-ordination
PART 2	Design of Solid Rocket Motor Components
PART 3	Processes (Bonding and Surface Treatments)
PART 4	Ancillary Tooling and Equipment
PART 5	Compatability (Chemical and Physical)
PART 6	Safety
PART 7	Testing Procedures
PART 8	Reliability and Maintainability
PART 9	Risk Management
PART 10	Packaging

Each part contains its own appendices, listing relevant experiences/design principles obtained from development project rocket motors.

Additional sections are:

- Inputs awaiting inclusion
- List of important changes

PART 1 - DESIGN AND DEVELOPMENT CO-ORDINATION

Contents

1. Design and Development Co-ordination

The management structure of RO Rocket Motor Division (RMD) is primarily a centralised, functional organisation, with each speciality grouped within its own department or section. Within the structure, the Commercial/Projects and Technical Directorate are jointly responsible for rocket motor design and exercise overall direction to development and qualification programmes. Co-ordinating authority and Design Authority is vested from the Technical Director through to the Projects Department. This co-ordinating function is the RMD policy by which a sole person is responsible for project performance, including overall design, programme achievement in terms of technical performance, timescale and cost.

Overall project control is exercised by the respective Project Manager in accordance with the Code of Project Management Practice (100 905-23/3/HQ).

Day to day co-ordination of project activities is also the responsibility of the Project Manager, who will call on other departments or sections as necessary throughout the project as detailed in Table 1.

The overall design of rocket motors is the responsibility of the Project Manager, while the design details of the individual components is shared with the respective Technical Authority. The basic design methods undertaken at RMD for motor components are described in Part 2 of this document.

An overall programme may be split into two broad phases these being:

(i) the design phase culminating in a development cost plan, i.e. paper studies only, and

(ii) the development and qualification phase, i.e. manufacture and testing of systems.

On occasions there may be some overlap or a feasibility phase may be inserted during which trials may be carried out to investigate 'grey areas'.

The two phases listed above are detailed in 100 905-23/3/HQ (Code of Project Management Practice), and may be discussed in the following sections.

1.1 Design Phase

The aim of this phase is to produce a design to meet the Technical Requirement issued by the Missile Contractor. NB: RMD may also be the missile system DA (Prime Contractor) in this context.

The depth of design may vary considerably. In the initial stage it may only be necessary to carry out a parametric study to give the missile contractor initial guide lines for a new missile.

As the study progresses more detailed designs and development costs plans will be required.

All design will use the general principles laid down in Part 2 of this document.

At some stage a formal design study will be required, the format of which is outlined in section 1.1.1.

The development cost plan requires a formal trials programme. This programme will vary dependent upon the purpose, e.g. feasibility, limited clearance or qualification for service use, and it is not possible to propose trials programmes for all of these within this document. However the principles to be applied for the design of a development and qualification programme for service use have been established in conjunction of knowledge of philosphies held by the Ordnance Board and other bodies and are given in section 1.1.2.

In some instances Reliability and Maintainability programmes are requested (refer to Part 8); for rocket motors the development and qualification programme is often the reliability programme.

Reliability estimates may also be required; these can only be based on experience with similar systems.

1.1.1 Format Of Design Study

Design studies should include the following sections:

Summary
Introduction
Requirements
Design Considerations
Design
Discussion

In addition, a section covering development and qualification is usually included although this may form the basis of a separate document.

The 'Requirements' section will consist of a summary of the main information in the Technical Requirement.

Under 'Design Considerations' the factors leading to the choice of propellant, charge and hardware features are to be detailed. The factors to be considered include the requirement, materials and value engineering considerations. The discussion should emphasise areas where extensive experience is available and highlight 'grey' areas. This means that the design sections can be limited to a description of the design and its performance.

Additional sections may be generated by any special requirements.

1.1.2 Development and Qualification

The Work Breakdown Structure (WBS) or development and qualification plan for a motor for a service application should contain the following activities as a minimum:

i) Project Management
ii) Motor and equipment design
iii) Component and equipment procurement
iv) Motor assembly
v) Performance and component development
vi) Preliminary environmental trials
vii) Prequalification or sequential environmental trials
viii) Qualification
ix) Deliveries
x) Spares

To understand the interaction between, and the necessity for, the different sections it is necessary to appreciate the philosophy and form a qualification programme.

While the qualification programme should be defined by the Missile Contractor, RMD is frequently requested to propose it. The philosophy applied under these circumstances is given in Appendix I. Typical qualification programmes for motors based on this philosophy are given in figures 1 and 2.

The different stages of the development and qualification plan are outlined in the following sub-sections for both the motor design and development phases.

The development and qualification plan is an essential output from the design phase and together form the technical plan from which a cost plan can be prepared. The contents of the basic sections are covered in the following sub-sections:

i) Project Management

This covers the activities of the Project Manager and Ballistician throughout the programme.

ii) Motor and Equipment Design

This covers all aspects of motor design including agreement of interfaces, changes, chilling, freezing and preparation of the MRI, design of plant and equipment.

iii) Component and Equipment Procurement

This section covers procurement of motor components plant and equipment.

iv) Motor Assembly

All motor assembly work is covered in this section.

v) Performance and Component Development

In this phase motors are fired over the temperature range to check the ballistic performance and the motor hardware thus ensuring that the motor performs satisfactorily in the 'fresh' condition.

When motor hardware is a long delivery item it is often advantageous to carry out initial firings in either a heavyweight motor with as representative an internal profile as possible, or an interim lightweight motor which is not fully representative externally of the production version. In either instance the final standard of lightweight components are used as soon as they become available.

Structural tests on motor components will also be carried out.

vi) Preliminary Environmental Trials

The purpose of this phase is to test the motor over the individual environments to which the qualification motors are to be subjected. In this way any adverse effects can be determined before any sequential testing is undertaken. These environmental trials may be started as soon as a satisfactory motor standard has been achieved and need not await completion of the performance and component development. As examples, bump and vibration may commence before the propellant has been finalised provided the anticipated characteristics, or an interim body may be used to commence storage or humidity trials.

The choice of trials to be carried out may be influenced by experience with similar motors or the severity of the environment. For example if a similar motor has successfully completed trials of similar or greater severity then it will not be necessary to subject a new motor to these trials.

vii) Pre-qualification or Sequential Environmental Trials

These trials will usually consist of four motors which will be subjected to the worst sequential environmental testing proposed for the qualification. This will give the necessary confidence to start the formal qualification.

viii) Qualification

This is the formal series of qualification trials required by the missile contractor to clear the motor for 'service' production.

ix) Deliveries

Supply of prototypes at different stages of development are to be itemised.

x) Spares

A number of spare motors are allocated in case additional trials are required at any stage in the programme.

1.1.3 Development Cost Plan (DCP)

The preparation of a DCP is to follow the Cost Estimating Department procedures in the Commercial Department Operating Manual.

When breaking down a programme into:

major tasks
work packages
activities

the following guide lines should be followed:

i) Major Tasks (MT)
These are the main areas in the development and qualification plan as defined in section 1.1.2.

ii) Work Packages (WP)
These are the main areas of work under each major task

iii) Activities (Ac)
These are sub-divisions of work packages and should ideally be, but are not always, restrained to work carried out by a single cost centre. Normally a number of cost centres will contribute to build up the cost of an activity.

As an example of this the following break down could apply:

MT Motor and Equipment Design

WP 1	Casting equipment	Ac 1 bottom plate Ac 2 top plant and pressure head
WP 2	Mould tools	Ac 1 forward closure insulation Ac 2 aft closure insulation Ac 3 nozzle insulation
WP 3	Body manufacture	Ac 1 mandrel Ac 2 bonding jig
WP 4	Body lining	(No sub-division)

In the case of body lining then this would be considered to have one activity.

In addition to being used for cost estimation the MT, WP and Ac numbers should also be used for costs codes against which costs can be collected and monitored. As a cost centre number is also included in the cost codes this will allow costs to be broken down to cost centres.

In the example above the following cost centres could book against an activity.

Drawing Office	Propellant (casting & lining equipment design)
Machine and fitting shops	Manufacturing techniques (mould tool design)
Plant engineers	Hardware inspection

1.2 Development and Qualification Phase

When a contract is awarded for the development and qualification of the rocket motor, the development and qualification plan forms the basis in terms of both trials and timescales for the programme.

Detailed procedures and guidelines are laid down in document 100 905-23/3/HQ, and should be referred to when a contract is awarded.

TABLE 1 - SERVICES/DEPARTMENT AVAILABLE

Services	Department	Section
Hardware Design	Projects	Projects
Charge Design & Performance Analysis	BMD	Ballistics & Maths Services
Stress Analysis	BMD	Ballistics & Maths Services
Drawings, MRI	Design Services	Drawing Office
Design of manufacturing equipment	Engineering Propellant Tech	Drawing Office
Insulation & Choke materials	Projects/Tech	Materials & Hardware Techniques
Inspection techniques	QA	
Environmental trials & specification	Engineering	Trials & Support Services
Igniter Design	Propellant Tech BMD	Igniter Ballistics & Maths Services
Charge & Igniter manuf.	Propellant Tech	Prop. R & D/Igniter
Body insulation	Projects/Tech Propellant Tech	Materials and Hardware Techniques/Materials Section
Insulation mouldings	RMDD Production	Materials & Hardware Techniques
Hardware manufacture	Engineering	Workshops
Motor assembly, test beds and trials	Engineering	Workshops
Firing analysis	BMD	Ballistics & Maths Services
Placing & progressing of external orders	Commercial	Purchasing
Packaging design	Design Services	Drawing Office
Painting & Surface Protection	Projects/Tech Production	Materials & Hardware Techniques
Cost Estimating	Commercial	Cost Estimating
Cost Monitoring	Computer Financial	

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Test Group No.		I								II				III		IV				V											
Quantity of Motors		8								4				2		4				12											
	Test No.	1	2	3	4	5	6	7	8	1	2	3	4	1	2	1	2	3	4	1	2	3	4	5	6	7	8	9	10	11	12
Pre-firing History	Accelerated ageing															X	X	X	X												
	Bump test-High Temp	X	X	X	X											X	X														
	Bump test-Low Temp					X	X	X	X									X	X												
	Vibration test (5h) High Temp	X	X					X	X							X	X														
	Vibration complete Spectrum High Temp									X																					
	Vibration Test (5h) Low Temp			X	X	X	X											X	X												
	Vibration complete Spectrum Low Temp												X																		
	Temp. cycling	X	X	X	X	X	X	X	X							X	X	X	X												
	Humidity Test									X	X	X	X																		
	Safety Drop Test													X	X																
Firing Condition	High Temperature	X		X		X		X		X	X					X		X		X	X	X	X								
	Normal Temperature													(X)	(X)									X	X	X	X				
	Low Temperature		X		X		X		X			X	X															X	X	X	X

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NOTE: The order of testing for bump and vibration may be reversed.
The motors subjected to safety drop will be fired if satisfactory
(NB: Failure on firing does not invalidate these two trials)

Figure 1 Qualification Plan - Typical Programme For Army and Navy Motors

Figure 2

Qualification Trials

Typical Programme For Air Force Motors

Test Group No.	I								II	III	IV	V				VI
No of motors in each test	8								4	2	4	4				12
Pre-firing Conditions																
Accelerated ageing[a]												X	X	X	X	
Bump test high temp	X	X	X	X								X	X			
low temp					X	X	X	X						X	X	
Vibration high temp	X	X			X	X						X	X			
low temp			X	X			X	X						X	X	
Temperature cycling	X	X	X	X	X	X	X	X				X	X	X	X	
Humidity									4							
Transport shock[b]										2						
ring Conditions																
High temp	X		X		X		X		2			X		X		4[c]
Normal temp										(2)						4[c]
Low temp		X		X		X		X	2				X		X	4[c]
Steady Acceleration																
High temp											2					
Low temp											2					

a) 4 months at 60°C (or equivalent)

b) Safety test - Fire if satisfactory

c) Two at each temperature subjected to low external pressure prior to ignition

APPENDIX I

Philosophy For Qualification of Rocket Motors

a) First source Qualification

The aims of a qualification programme are primarily to establish reliability of the design in terms of performance and functioning over the range of environmental conditions that the motor might experience in its lifetime.

The number of trials proposed should make it possible to indicate that the design reliability and performance can be achieved throughout the required life. The numbers can never be high enough to establish a high measure of reliability with a high degree of confidence, nor can the manufacturing quantities during qualification be high enough to establish proper conditions for assessing reliability.

A reasonable measure of reliability can only be accomplished by selection and proof during production. The philosophy in this phase is to test a relatively high percentage of motors from the initial production quantities, reducing the percentage as production proceeds in accordance with a pre-arranged programme.

b) Second Source Qualification (or validation)

In this case the design reliability has been established and confirmation is required that the new supplier can provide equivalent products using his sources of labour and materials. Second source qualification is equally applicable to components, either hardware or charge or complete rocket motors.

Qualification Programmes

a) First Source Qualification

The types of test involved during a motor qualification are listed below. In considering the programme necessary to demonstrate an acceptable product, a balance has to be struck between the desire to obtain reliability from a large number of combined tests and the consequent complexity of such tests within a practical timescale.

Types of Test

i) Performance at various temperatures
ii) Bump and shock
iii) Vibration
iv) Temperature cycling
v) Humidity
vi) Steady acceleration
vii) Ignition at low external pressure (if relevant)
viii) Safety drop
ix) Life

In typical use environments simulated by tests ii), iii), iv) and vi) can always be expected to occur. Because of the difficulty in obtaining data while firing under steady acceleration and since the levels of acceleration are usually unlikely to cause trouble, it is normal that only tests ii), iii) and iv) are done sequentially, and separate tests done for vi). Similarly humidity v) and, where relevant, ignition at low pressure vii), although they must be demonstrated, can also be treated separately. Safety drop viii) is primarily a safety test after which motors may be fired although failure does not invalidate the test or qualification.

Life ix) can usually be approximately predicted in qualification by means of accelerated ageing followed by a sequential test typical of subsequent use. However, care must be taken to select an accelerated trial in terms of temperature(s)/duration which does not create modes of failure which, experience has shown, does not occur in real life cycle, eg propellant gas cracking.

Although data from straightforward motor firings at various temperatures (i.e. not testing other than conditioning) are usually available during development and may therefore be used for comparison with qualification data, these firings are unlikely to be from motors of qualification standard. This is particularly so when the whole development is being aimed at showing that the motor will be capable of passing severe environmental tests. It is therefore usual to include some motors in qualification which are only temperature conditioned i) prior to firing; the purposes of these trials are firstly to give some measure of reliability of the basic motor and secondly to provide standards against which the performance of the remaining qualification trials can be judged.

The detailed test levels will be based on those which will be experienced in service together with an appropriate safety factor.

b) Second Source Qualification

For second source qualification the first task is to identify those new features which can affect the design and/or performance. These factors will determine the type as well as the extent of qualification. As an example, if the supplier has been making the chosen propellant for another purpose, the trials covering this aspect could be limited.

By means of the qualification tests it must be possible to demonstrate that the second source manufacture is adequate and performance levels can be achieved throughout the required life. As in the case of first source qualification the numbers can never be high enough to establish a proper measure of reliability nor can be high enough to establish proper conditions for assessing reliability. Consequently reliability should be assessed during production as mentioned in the section covering philosophy of qualification.

c) Start-Up Qualification

In the event that (i) there is a break in production of greater than 12 months (full manufacturing methods/specifications are available), and on the assumption that during the intermediate period:

ii) like manufacturing processes have been undertaken
iii) no change in source of ingredients/material has taken place

the normal acceptance procedures shall be deemed necessary. If at least one of these assumptions is not valid, then an appropriate Requalification should be undertaken, as agreed with the Design Authority.

PART 2 - DESIGN OF SOLID ROCKET MOTOR COMPONENTS

SECTION 1

Design Of Solid Rocket Motor Components

2.1 DESIGN OF SOLID ROCKET MOTOR COMPONENTS

General Overview

Unless specified to the contrary with-in the contract, solid Rocket Motors shall be designed in accordance with Def Stan 08-5 to meet the performance criteria in a Technical Requirement.

For the purposes of design the components of a motor may be defined as follows:

Structural Components

- Motor body
- End closures
- Blast-pipe (if required)
- Nozzle including seal
- Thrust vector control (TVC) system
- Strakes

Non-Structural Hardware

- Mouldings
    - Body insulation (internal and external)
    - Obturators
    - Hold back rings
- Body lining

Charges

- Propellant (CDB, EMCDB, HTPB, EDB)
- Inhibition
- Grain retention

Igniter/Initiator

- Pyrotechnic
- Pryogenic

although the components cannot be designed in isolation.

Figure 1 illustrates the principal components of a typical solid rocket motor, and detailed design procedures (i.e. design principles, design criteria, processing, manufacturing, historical experience, etc) for each motor component are listed in Sections 2.1 - 2.4 (inclusive). A brief description of a rocket motor follows:

The propellant charge, which may be loose and separately loaded, or bonded to the walls of the motor body by being formed (cast) in situ, can have a cross-section in a variety of different configerations according to the requirements of the thrust-time characteristic (ballistic performance) of the motor by the missile.

The motor body (or case) is usually cylinderical in shape and is most frequently of steel construction, but may also be of light alloy, reinforced plastic or carbon fibre structure. The internal surface of the motor body and the end closures are lined with a thermal insulant whose function is to provide both thermal protection to the pressure member and also to withstand the erosive conditions due to the high velocity gas flowing to the nozzle. It is also employed under the name of charge inhibitor, to protect the outer surface of a loôse charge from igniting so that combustion will occur only in those surfaces where it is required by design.

The "head" end closure, of similar material to the body, usually contains an igniter boss to accomodate the igniter. The rear or aft end closure contains a nozzle throat insert of high heat resistant material and an expansion core, the materials of which depend on the temperature and mass flow rate of the propellant combustion gases. The nozzle may form part of a blast pipe if the location of the motor in the missile makes this necessary. A TVC system is employed if some form of control derived from deflecting the motor exhaust is required, particularly when the missile is moving too slowly for aerodynamic surfaces to be effective.

The design of all relevant components shall conform to good engineering practice for pressure vessels using the safety factors given in Def Stan 08-5. In carrying out the design the following documents may be referred to:

i)	BS1500 fusion welded pressure vessels	
ii)	R Ae S data sheets	
iii)	Standard text books such as:	
	Formulae for stress and strain:	Roark and Young
	Theory of elasticity:	Timoshenko and Goodier

Computer aided design (CAD) techniques, including finite element stress analysis (FEA) shall be undertaken whenever possible to support value engineering and the analysis of complex sections.

When predicting limit pressures for use in hardware design for CDB rocket motors, 12.5% is to be added to the mean maximum pressure predicted at the upper operating temperature in order to allow for within lot and between lot variation, and also the confidence factor required by Def Stan 08-5. This should be 15% for HTPB propellant motors.

A useful book to aid rocket motor design is:

"Solid Rocket Propulsion Technology"
- Alain Davenas (SNPE)
- James Taylor (NEC)
- William Berair & Wang

NOTE: THE AIM OF TN79/49 IS TO PROVIDE A CODE OF PRACTICE (I.E. GENERAL GUIDELINES AND STATEMENTS) FOR THE DESIGN OF SOLID ROCKET MOTORS. THIS DOCUMENT IS NOT INTENDED TO PROVIDE DEFINITIVE/SPECIFIC DATA ON ALL ASPECTS OF DESIGN.

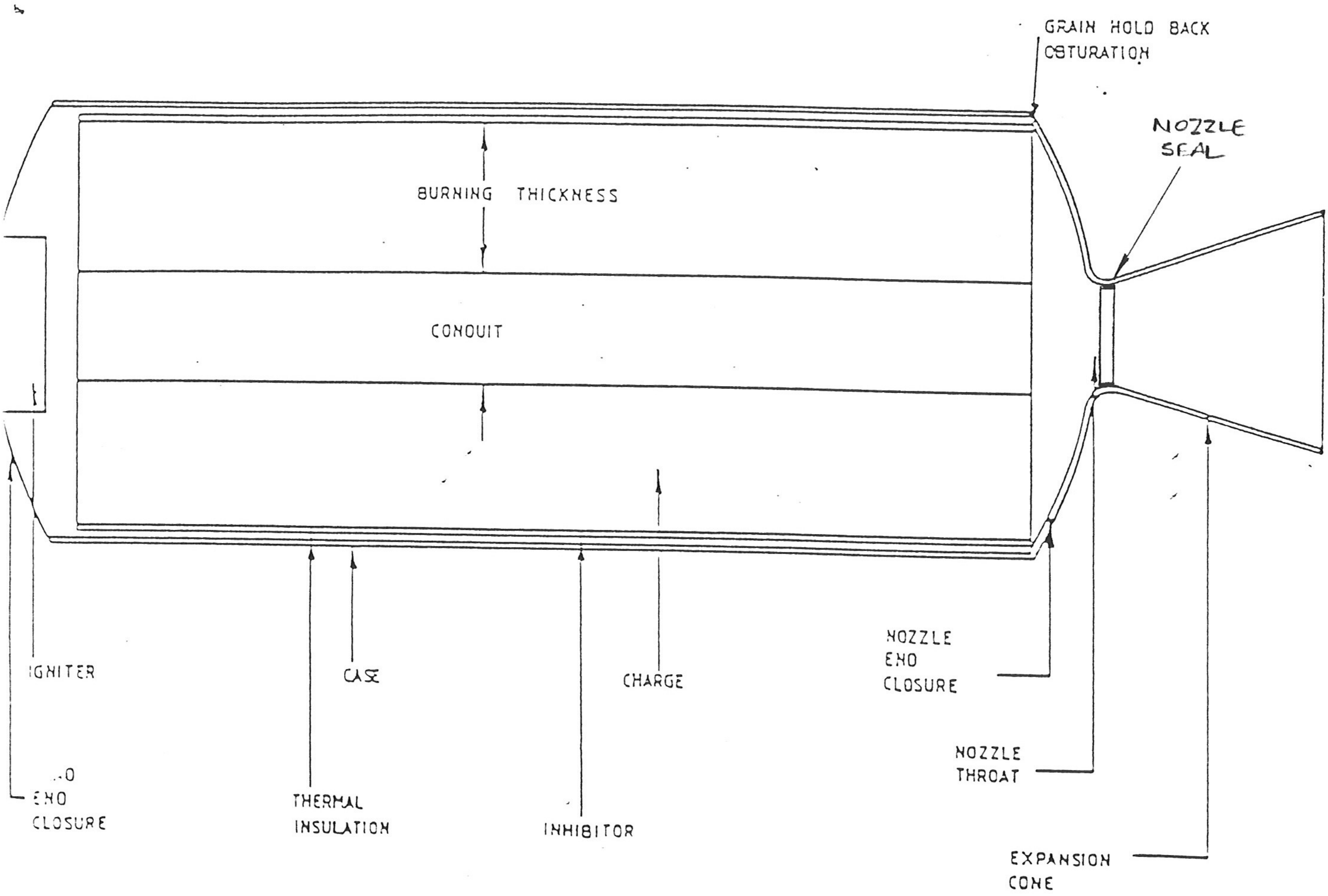


Fig. 1 Solid Propellant Rocket Motor

SECTION 2

Structural Components

2.2 STRUCTURAL COMPONENTS

2.2.1 Motor Body

General

The prime function of the rocket motor body is to provide a combustion chamber for the propellant charge, and for this purpose it must be designed to withstand the pressure and thermal stresses produced. In general the body is designed on the basis that any temperature rise due to heat transfer both from internal and external sources will be limited by the insulation such that the strength of the motor body will not be affected.

Frequently, and particularly in the case of small tactical weapons, the motor body forms an integral part of the missile structure. This results in the body having to withstand bending, shear, shock and vibration loads, due to transport and missile flight conditions. The motor body is often s located in the missile that some or all these loads reach a maximum at some section along the body. Not only will the motor body have to be designed to withstand this type of loading whether the motor is firing or not, in other words, whether the body is under internal pressure or not, but the missile design may impose a requirement for a minimum value of flexural rigidity. It is also a requirement to demonstrate the structural integrity by means of a proof test.

Again, due to the location of the motor body in the missile, it is frequently required to provide attachment points for the fixed control surfaces, for launcher shoes and other linking components ie strakes for wires. Accurate location, both radially and longitudinally, of these features is almost always demanded.

Since missile flight may continue for some time after motor burn-out, designing for the above mentioned flight loads may have to take account of body heating. This is also applicable to air carriage systems.

Materials and manufacture

The normally available materials can be divided into three groups: metallic, non-metallic and hybrid. The metallic materials can be further subdivided into groups according to the method of manufacture; non-metallic materials which take the form of plastic reinforced by glass, Kevlar or carbon fibres, are, in the case of motor bodies, always applied by winding a tube of the required thickness on a mandrel, and winding on, or separately bonding on, the end fittings. Hybrid motors include Kevlar overwrapped aluminium (KOWA) or Kevlar overwrapped steel strip laminate (KOWSL).

Rapier = 125

2.2.1.1 Strip Laminate (SL)

General

The strip laminate process consists of winding a number of layers of adhesively coated metal (usually steel or aluminium) onto a heated mandrel, curing off the same then adhesively attaching end fittings and/or other items to produce a motor case. The process is well-proved, is particularly applicable where the body length/diameter ratio exceeds 4 and offers a construction which is significantly advantageous under fuel fire or RATTAM conditions.

2.2.1.1.1 Design Considerations

The principles of the construction are:

i) the hoop loads are taken by the layers of strip

ii) the longitudinal loads in the tube are transmitted by shear in the resin layers, and

iii) loads are transmitted from the end ring to the tube by shear in the resin layer, Figure 2.

The basic steps used in the design of a strip laminate motor body are given in Figure 3.

Documents to be used in the design process are given under Reference 1.

Material properties are provided in Appendix 1.

Each aspect of the strip laminate construction is considered separately below.

Wound tube

In most respects the mechanical properties of tubes made by the strip-laminate process are identical to those of homogeneous tubes hence for the strength of the tube the usual principles of design may be applied, based on the total metal thickness of the tube wall. The latter is calculated from:-

$$\text{Hoop stress capability of steel} = \frac{\text{Load}}{\text{Area}}$$

$$\text{UTS} = \frac{Pd}{2t}$$

For steel strip a nonogram has been constructed to illustrate the number of layers of 0.25mm thick steel with 2.00 GN/m^2 minimum UTS required for various design pressure, Figure 4. (Note, however, changes introduced in May 1984 require the UTS to be 1.96 GN/m^2 minimum with a thickness of 0.255mm minimum. This, coupled with a reduced thickness tolerance, gives the same design criteria).

The number of layers selected to make up the required thickness must not be less than three to avoid distortion under pressure in the regions where strip edges butt, but may exceed this by any desired amount. However, it is advantageous to make the number of layers as small as possible, consistent with reasonable strip thickness, as the winding time is thus reduced.

For the tensile strength of the steel to be fully utilised it is, of course, necessary to ensure that the shear strength between layers of strip is not the weak point in the design. A suitable strip overlap pattern is chosen to ensure this which, in practice, consists of the longest adhesive shear path with the minimum of repeat patterns. For a three layer tube the pitch is simply one third of the strip width. For tubes of four layers or more various patterns are possible but they are generally chosen to suit a practical number of clamp positions around the circumference of the mandrel, typically 3,4,6 or 8 (Fig 5). It is recommended that at least four layers are wound before a repeat pattern occurs. Current layer requirements are such that repeat patterns are rarely encountered.

The effects of bending stresses on the wound tube are considered using the normal rigidity criteria applicable to homogeneous tubes.

2.2.1.1.2 End ring

a) General

The end fittings, which may be in the form of attachment rings or complete closures, are provided with cylindrical extensions to provide the necessary bonding surface. These extensions may be designed to fit the strip laminate tube internally or externally. Internal bonding has the advantages that a flush external diameter can be provided if required, the fit in the tube is more easily controlled and a saving in mass can be effected by using the end fitting itself to provide a portion of the bonding surface. If a flush internal diameter is required, however, external bonding must be used with a consequent local increase in external diameter (Fig 6).

The resin bond attaching the end fitting to the body tube is of the greatest importance and inexpert design or poor production practice in this feature can lead to failures. The end ring bond must also be protected from heat during firing by careful design of the insulation especially at the closure-to-body joint.

b) Calculation of end ring bond length

The end ring bond is designed on the demonstrated shear stress value of the bond as follows:

i) From the motor designer's requirement for the pressure that the body must stand, the thickness of each layer and the number of layers for the tube are chosen. Since a finite number of layers of an available thickness strip may not precisely correspond to the motor requirements an actual design burst pressure for the tube is calculated on the minimum strength specified for the steel. In practice it has been found that burst strengths vary by up to 15% above the calculated value due to the positive tolerances on both steel strength and thickness. Hence to ensure that the body fails by the tube bursting in hoop rather than the end ring being ejected the pressure utilised for end ring bond design is 15% above that calculated for the tube.

Hence the load on the end ring bond is:

Minimum calculated burst pressure of the tube x 1.15 x area of end closure.

ii) The shear strengths of two end ring adhesives are referred in Appendix 1 and the figure recommended for design use common to both adhesives is given as 30 MN/m^2.

This figure assumes a full cure up to 145°C - if such a cure is not possible, then a reduction of this stress level, in line with values in IMI/SRS/274 should be applied. A value of 35 MN/m^2 is normally achieved on lap shear tests at 20°C, thus providing a further factor of 1.17.

It should be noted that end ring adhesive MS3657, XD4236 requires significantly higher cure temperatures to achieve maximum strength than is afforded by the normal bonded assembly cure of typically 135 min $\pm$ 5 min at 100°C $\pm$ 5°C.

This additional cure is normally provided by the cure of the lining at 145°C (Nominal).

It is imperative that, when designing end ring bond lengths, the application is considered, ie lined or unlined supply, such that the correct cure/resin strength is used. Furthermore '<u>knock-down</u>' factors must be applied to cater for life, high temperature, fatigue or any other adverse environmental effects.

The strength of the bond is:

End ring circumference x end bond length x adhesive shear strength.

iii) Hence the length of the end ring bond can be calculated from i) and ii) above.

c) Peel effects

The relative stiffness of the body tube and the end fitting bond extension is known by experience to have a marked effect on the achievable bond strength.

This is always higher for external end bonds and also for bodies with a comparatively rigid wall, ie for bodies designed to withstand a high internal pressure, since it is easier in such cases to make the effective change in wall thickness caused by the bond extension less abrupt, and thus to minimise the peel effect.

Hence care must be taken when designing an end joint to ensure that stress concentrations at the end of the bond are avoided so that no peeling effect is produced particularly with internally bonded fittings. The tip of the end ring should be feather edged such that it will flex without the adhesive bonding the first layer of strip to the second layer of strip separating in peel. In general this can be achieved by the tip of the end ring being no thicker than 1.5 x the strip thickness and continuing on a 4^{o} taper, but only a detailed analysis will ensure an optimum design.

d) Non-adhesive end ring joints

With the objective of saving mass the possibility of attaching end rings by riveting has been considered. Calculations carried out in typical motors, one of 125mm diameter designed with 250 bar burst pressure wound from three layers of strip and another of 250mm diameter designed with 150 bar burst pressure wound from four layers of strip gave the following results:-

Motor Diameter (mm)	Burst Pressure (b)	Number of Rivets	Proportion of circumference occupied by rivet holes (%)	Length of end ring joint (mm)	
				Riveted/	Bonded
125	250	24	30	39	26
250	150	56	34	54	31

These calculations utilise the recommended design strength for the adhesive and assume 4.8mm diameter rivets of Monel metal which has a strength of 0.75 GN/m^2. They are also for a "balanced" design so that if hoop bursts are to be ensured then both the riveted and the bonded joint lengths would have to be increased.

It will be seen that the length, and hence mass, of riveted end rings is greater than bonded ones and hence cannot be recommended. Other disadvantages of riveting are that the surface of the strip side would no longer be planar and counter-sinking would be required on the end ring side. Care would have to be taken to avoid drilling rivet holes through, or close to, butt joints between strip. A further disadvantage is that a very good fit between end ring and tube would be required for efficient riveting.

2.2.1.1.3 Resistance to Fatigue

In general, as with any other form of construction, a reduction in achievable strength is to be expected upon cycling, depending on the number of stress cycles applied.

165mm strip laminate bodies were manufactured with a view to examining this aspect and these were subjected to pressure cycling at a peak pressure corresponding to half the experimentally determined failing pressure for the particular design involved. Since it was considered that the end bonds would be more susceptible to fatigue than the body tube itself, these were deliberately designed to be highly stressed, so that failure would always take place in this region.

The test was continued up 10 000 cycles, and bodies were withdrawn at intervals and pressure tested to destruction. The failing pressure being noted. Failure always took place, as intended, in the end ring bond. The results showed that 50% ultimate strength was maintained up to 10 000 cycles.

2.2.1.1.4 Accuracy of Construction

One of the advantages of the strip laminate form of construction is that the end fittings are added to the basic tube in the finish machined condition and there is, therefore, no need for machining of the complete body. To obtain the full benefit of this feature it is necessary to establish that bodies can be produced in this way to acceptable standards of accuracy, that is, straightness and roundness of the tubular portion and squareness of the ends.

After passing proof test end out-of-squareness is normally less than 0.1% of diameter and the combined bow and ovality less than 0.01% of length.

2.2.1.1.5 Attachments

Attachments are very specific to individual motors and usually include wing roots, launcher lugs and cable ducts.

These are normally adhesively bonded to the motor body but welding has been investigated as an alternative. This was limited to the laser technique, which gives accuracy of beam without the need for a vacuum environment required by electron-beam welding, and to stainless steel strip as welding to carbon steel, which also contains sulphur and phosphorus, would not be easy. It proved imperative to restrict welding to the outer layer of steel strip since any thermal degradation of adhesive resulted in gas blow holes in the weld.

The resulting necessity to melt no more than half a strip thickness, 0.125mm, required beam alignment of such accuracy that a low-cost production technique could not be envisaged. In addition, the strip steel adjacent to the weld received heat treatment which reduced that layer to half strength. It was concluded that welding was not a practical production method for fixing attachments to strip laminate bodies unless the outer layer of strip was thicker than 0.25mm and some of the initial strength in that layer could be forfeited.

2.2.1.1.6 Aeroheat Considerations

General

The effect of aerodynamic heating of missiles has to be considered in its relation to its effect on both the propellant and the structural materials of rocket motors. Its effect on propellant is common to all rocket motor designs and is not discussed here but on adhesively bonded structures, such as strip laminate, it may prove to be of critical importance since all known adhesives exhibit severely limited performance at high temperatures.

Temperatures

Skin temperatures expected on rocket motors due to aerodynamic heating depend on the velocity of the missile, its height above sea level and the ambient temperature. As a rough guide, recovery temperatures up to 70^{o}C can be expected at Mach 1, 200^{o}C at Mach 2 and 470^{o}C at Mach 3 when at sea level, dropping to - 10^{o}C, 85^{o}C and 250^{o}C respectively at a height of 10km (Table 1). Temperatures within the rocket motor will additionally depend upon the duration of the flight.

Currently used Adhesives

All epoxy adhesives, used exclusively in all UK designs of strip laminate motors up to the time of writing, lose a significant portion of their room temperature strength just above 100^{o}C and are certainly unusable in rocket motor structures above 150^{o}C when they will have lost approximately 80% of their room temperature strength. This is illustrated in Figure A1)Appendix 1) which also shows that at 100^{o}C end ring adhesives fall below the design value of 30MN/m^2 shear strength and strip adhesive drops to 33 MN/m^2. Hence 100^{o}C is considered the critical temperature which must not be exceeded in current strip laminate rocket motor body designs.

Once temperature is reached the loss of strength is instantaneous. However, providing the cure temperature of 180^{o}C is not exceeded, the original strength is recovered on cooling.

2.2.1.1.7 External Insulation

Where the temperatures resulting from aerodynamic heating are too high for the adhesives or the propellant systems then it is possible to utilise external insulation. However, it will be necessary to ensure that such insulation does not significantly impair the performance of the body under fuel fire or fragment attack conditions.

a) Materials

The prime properties of such an external insulant, whilst meeting the usual handling and environmental conditions associated with rocket motors, are low thermal conductivity and diffusivity. Typical examples are given in Table 2.

Materials with the lowest coefficients of thermal conductivity tend to have low densities and are relatively fragile. Hence they have to be applied in practical thicknesses, which are not likely to be less than 1mm, and have to be protected with another material, also not likely to be less than 1mm thick. Materials with slightly higher coefficients of expansion, although tougher are, of course, less efficient and minimum thicknesses in the region of 2mm are still envisaged.

Hence the penalty with this approach will be either an increase in rocket motor diameter of at least 4mm or an equivalent decrease in charge diameter resulting in either a loss in motor performance or an increase in length.

Many of the materials under consideration will be degraded when subjected to high temperatures. For one-off temperature regimes (missile flight) degradation in the form of charring and ablation will be acceptable. For repeated temperature regimes (fast air carriage) the material used for the insulant, or at least its outer layer, will be restricted to those which do not degrade. As a general guide the majority of candidate materials show some signs of charring near 200^{o}C, the main exceptions being silicone based rubbers and polyimide-type foams.

b) Materials tested

Initially tests were carried out on four of the above materials.

The test sample was an internally lined carbon fibre reinforced plastic (CFRP) body covered with the experimental material which was held in placed by hoop wound glass reinforced plastic (GRP).

For convenience an available electrically heated mandrel was used as a heat source, the direction of heat flow thus being the reverse of its direction during aerodynamic heating. Controls were set such that the mandrel heated from room temperature to 200^{o}C and then held steady at that temperature. Temperatures on the inner and outer surfaces of the test sample were recorded against time.

The test arrangement results are given in Ref 2.

Thermal calculations were carried out on the best, Microtherm, and worst, Raychem SRA, of the above materials, both nominally 3mm thick, using an initial soak at 45^{o}C followed by 8 minutes heating at 173^{o}C. Temperature distributions immediately after heating are given in Ref 2.

This culminates in a cork/GRP insulation system which has satisfactorily passed oven and radiant heating thermal tests up to 175^{o}C. It has also performed well when subjected to some environmental trials and fuel fire trials. For temperatures in the range 175-250^{o}C a polyetherimide foam/GRP system should be considered.

2.2.1.1.8 Testing

The structural integrity of bodies which are intended for use as pressure vessels should always be checked by proof pressure testing at a pressure greater by a pre-determined amount than the highest pressure to which it is expected that the vessel will be subjected, but less than the ultimate pressure by a safe margin. The method of testing should be such as to apply circumferential and longitudinal loads in the correct proportion.

It must be remembered that with this method of construction vessels will not be intrinsically pressure-tight and that a sealed lining must therefore be provided for the pressure test operation. This lining may be temporary, and stripped out after the test, or may form part of the test equipment, or may be permanent, forming an essential part of the finished component; the method adopted will depend on the particular circumstances of design and production.

It has been found that failure to provide such a lining will result in leakage of the pressurising fluid through the body and this will, in turn, damage the resin bonds, possibly causing failure either during the test or later.

If a lining is bonded to the inside of the tube it is imperative that this liner overlaps the tube end ring joint sufficiently to form an effective seal.

If a separate rubber bag is used then it is imperative to ensure that

a) there are no cavities into which the pressurised bag could extrude and puncture, and,
b) a bleeder cloth is used between bag and motor body to avoid stiction and obturation which could rupture the bag.

A wealth of testing has been undertaken on strip laminate bodies and these are outlined in Ref 2.

2.2.1.1.9 Behaviour under Fragment Attack and in Fuel Fires

While strip laminate motors perform in a similar way as homogeneous steel motors in relation to mechanical properties, their reaction under fragment attack and fuel fire is significantly reduced. Relevant documents are listed in Ref 2.

2.2.1.1.10 Summary of the process

The basic manufacture of a rocket motor body by the strip laminate process is relatively simple:

Steel strip is degreased, shot blasted and degreased again. It is coated with a solvented adhesive which is then dried and the strip is coiled and stored. The coated strip has a life of at least six months.

The coated steel is helically wound onto a heated mandrel so that there is a small gap between successive turns of the helix. Successive layers of strip are added until the desired thickness is obtained. Each layer is wound in the same direction but the helices are staggered.

After winding is complete the adhesive is partially cured and the tube is removed from the mandrel and cut to length. End fittings, and any other fittings which may be required, are bonded in place using a jig to ensure accuracy. The assembly is then fully cured.

The finished motor may be lined, painted and filled in exactly the same way as a body made by any other process.

Basically, the equipment required consists of strip preparation and coating plant, a winding machine (which may be a converted lathe), cutting equipment, a curing oven and an assembly jig.

2.2.1.1.11 Historical Experience

Appendix 2 outlines motors which have been manufactured using the strip laminate instruction and those qualified and in production are identified.

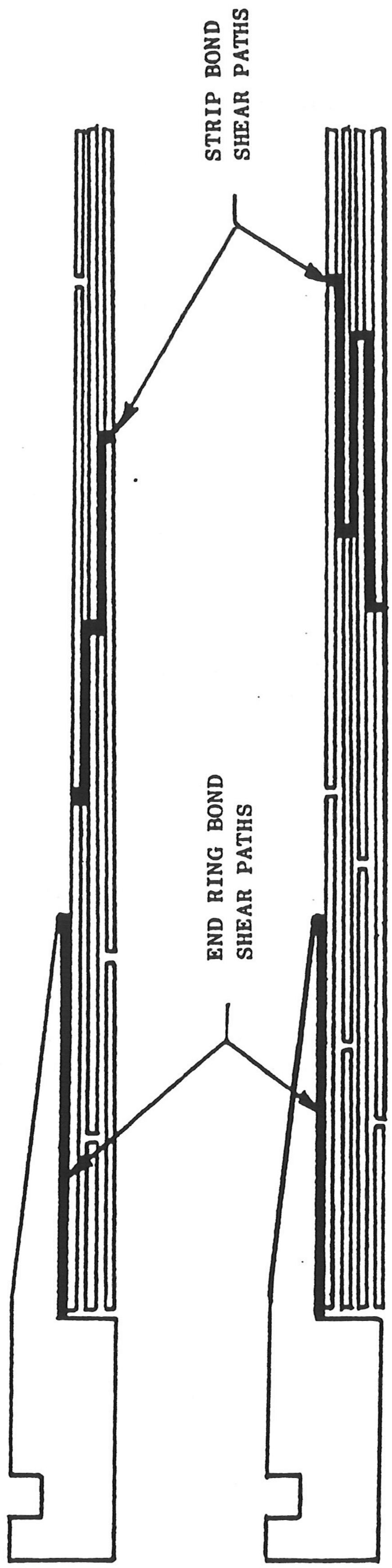


FIG. 2 END RING AND STRIP BOND SHEAR PATHS

Calculate total thickness of ~~steel~~ metal

↓

Decide width and thickness of strip and calculate number of layers

↓

Select strip lay-up pattern

↓

Calculate end ring joint length

↓

Design end rings with respect to peel forces and interfaces

↓

Confirm that the design meets stiffness requirements

↓

Design attachments

↓

Consider effect of Aeroheat

Fig. 3 Basic Design Procedure

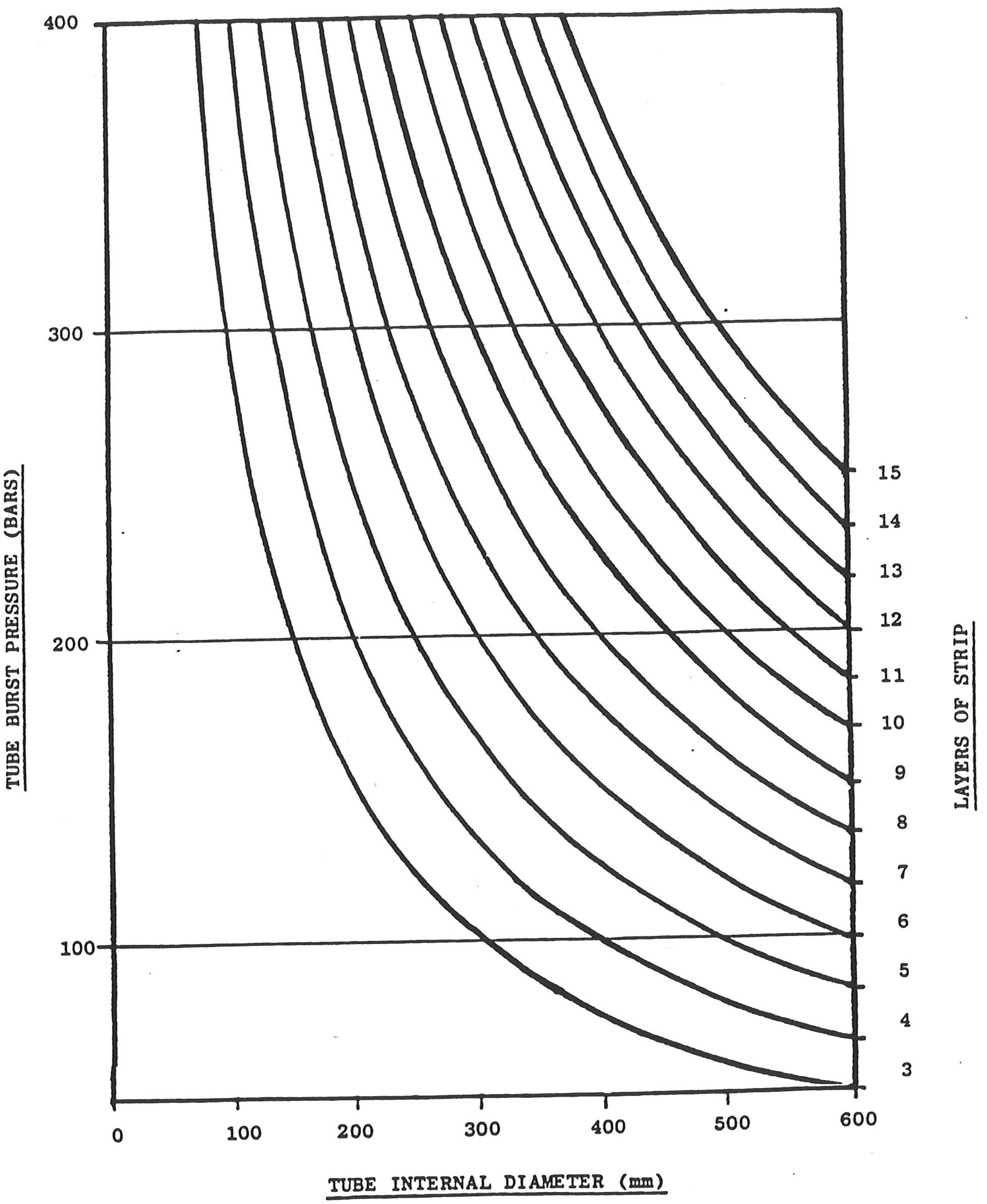
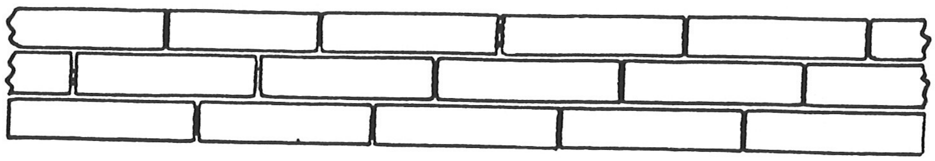
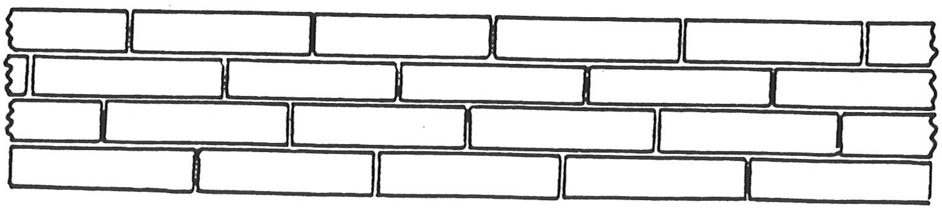


FIG. 4 BURST PRESSURES OF VARIOUS DIAMETER TUBES MADE FROM 0.25 mm THICK STRIP WITH 2.0 GN/m^2 UTS



THREE LAYER TUBE

WOUND ON 3-CLAMP MANDREL



FOUR LAYER TUBE

WOUND ON 8-CLAMP MANDREL

FIG. 5 STRIP OVERLAP PATTERNS

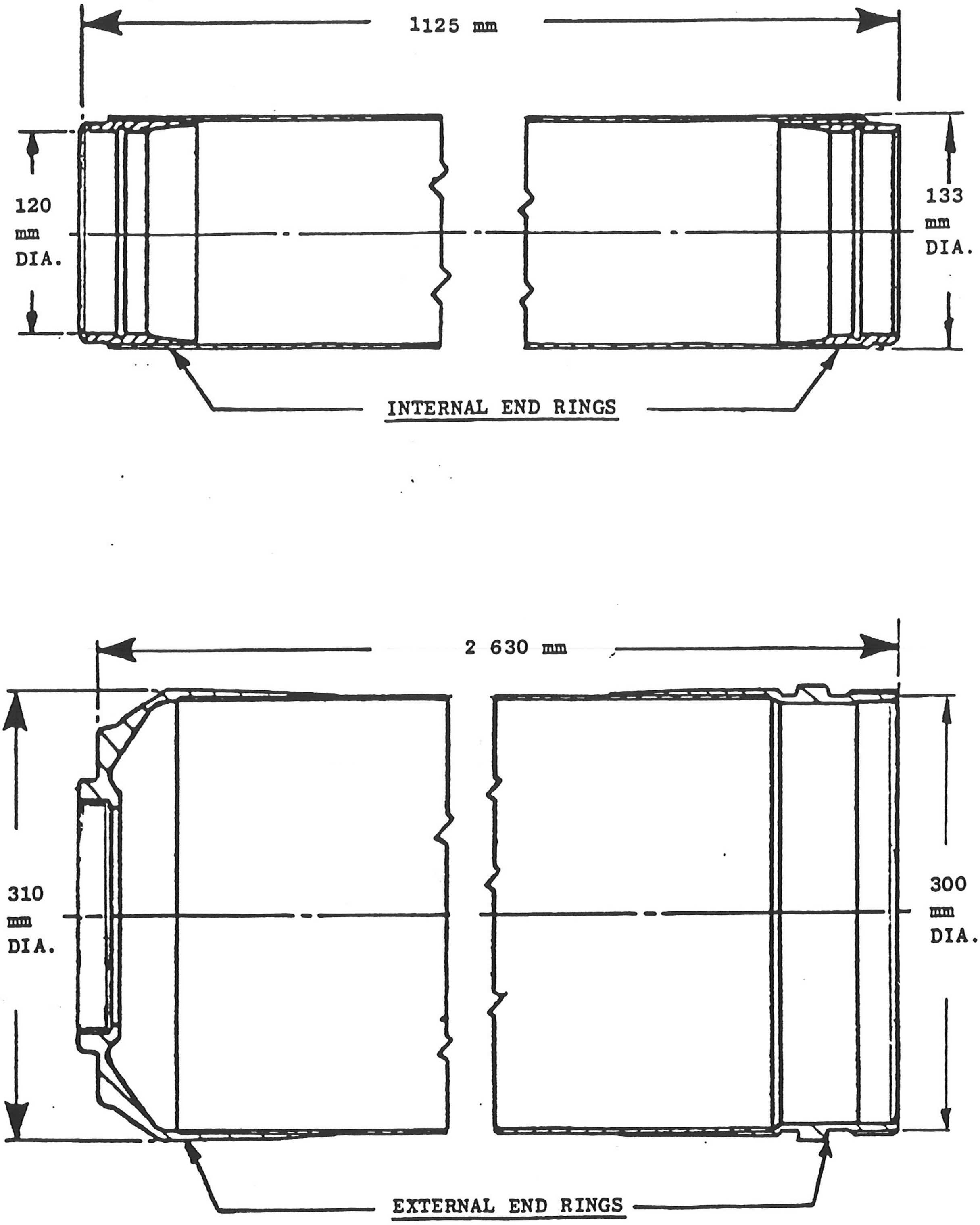


FIG. 6 TYPES OF END RING FITTINGS

Type of Heating	Mach. No.	Height above Sea Level (km)	Recovery Temperature (°C)
Air Carriage	1	0	70
		10	-10
	2	0	200
		10	85
Missile Flight	2.5	0	300
		5	200
		10	170
	3	0	470
		9	300
		10	250

Table 1 Calculated Recovery Temperatures

Material		Coefficient of Thermal conductivity	
Group	Example	Governed mainly by	Typical figure (Jm/m².s.°C)
Light Alloys	Aluminium	Metal	210
Steel	Steel	Properties	45
Carbon	Pyrographite ('C' direction)	Carbon	2-7
"Conducting fibre"/ resin composites	CFRP	Fibre and resin content	1.2
"Non-conducting fibre"/resin composites e.g. glass, silica, Kevlar.	GRP	Resin content	0.2-0.5
Rubbers	EPDM CL 7225	Filler	0.3
	Hypalon CL 2759		0.32
	Raychem SRA		0.22
Filled paints	Adcora-Hypalon paint G 74/1	Filler	0.16
Dry fibres	Glass	Amount of air entrapped	0.4-0.6
	Kevlar		0.4-0.6
	Cork		0.04
	Saffil paper		0.03
Micro-porous materials	Min-K, Microtherm	Pore size approaching MFP of air molecules*	0.022
Gases	Air (for comparison)	—	0.026

*Where pore diameter approaches the size of the mean free path (MFP) of the gas most molecular collisions are with pore walls (not other molecules) hence conduction is low.

NB: Materials entrapping air exhibit reduced conductivity at altitude, air itself approaching 0.017 $Jm/m^2.s.°C$ at 15 km above sea level.

Table 2 Thermal Conductivities of Candidate Materials for External Insulation

Appendix 1

1.1 Materials - Metal Strip

General

Since rocket motor bodies are usually designed on the highest strength-to-weight values under internal pressurisation conditions it will be seen that the choice of metal lies between

a) the latest conventional aluminium alloy
b) steel strip
c) maraging steel, or
d) titanium

Of these only carbon steel strip was available when the strip laminate process was conceived and, for the practical engineering considerations of availability and cost, it still shows considerable advantages over the other materials.

Most of the experience gained to date with the strip laminate technique has been based on the use of carbon steel strip, rolled and polish ground, having a nominal design ultimate tensile strength of 2 GN/m^2. Recently stainless steel strip of equivalent strength has also been qualified.

For cheapness it is desirable to use strip as wide as possible as this reduces the number of turns and hence the winding time. However, if excessively wide strip is used, difficulties due to lateral curvature and malalignment of adjoining turns may arise. A strip width of 100mm has been found practical for tubes of diameter greater than 100mm; below this diameter the strip width should be reduced to a value not greater than the diameter. Similarly it is desirable to use strip as thick as possible, consistent with ease of winding and the requirement for a minimum of three layers, as the use of thicker strip gives reductions in both cost and proportionate variation in thickness due to accumulation of tolerances. In practice most of the bodies produced have been between 100 and 200mm diameter and strip of 100mm wide and 0.25mm minimum thickness has become the standard material.

It is important that the strip be flat, closely toleranced and free from edge defects.

1.1.1 Carbon steel strip

The historical background surrounding the introduction of carbon steel strip material is given in Ref 2.

The existing specification for this material is IMI/SRS/237.

Severe outdoor exposure can have a deleterious effect on the steel strip, even when painted with an approved system.

1.1.2 Stainless steel strip

Stainless steel strip was introduced as an alternative source material to avoid problems associated with single source supply and to offer improved environmental resistance.

Specification IMI/SRS/235 was raised to cover this material. The carbon steel specification in use at the time, IMI/SRS/47, was used as a reference but the UTS was changed arbitrarily from 1.96 - 2.25 GN/m^2 to 2.00 GN/m^2 minimum. The 0.1% proof stress was changed from 1.70 to 1.80 GN/m^2 minimum on the basis of initial test results but was subsequently changed back to 1.70 GN/m^2 minimum when more results had been obtained. The 0.250-0.280mm thickness was retained.

The effect of outdoor exposure on both painted and unpainted 127mm diameter bodies has been investigated over 5 years on sites at Summerfield and Ardeer, Scotland. Corrosion, even on the unpainted bodies, was negligible and burst levels excellent.

1.1.3 Dimensions

Except for development trials in the mid 1950;s and rechecking in the mid 1980's the dimensions of the strip used for the strip laminate process have been 100mm wide x 0.25mm thick. This situation was reviewed early in 1986, Ref 3.9 and is summarised below.

There are three basic reasons for alternative dimensions:

i) to obtain total wall thicknesses which are nearer optimum, particularly for the smaller diameter, thinner bodies.

ii) to allow the winding of smaller diameter tubes for which narrower, and possibly thinner, strip is required, and

iii) to reduce processing time on larger tubes on which thicker and/or wider strip can be used.

Significant changes to strip dimensions would require changes to plant, existing equipment being able to handle strip up to 0.50mm in thickness and up to 100mm in width.

Further information concerning

Width
Thickness
Tolerances

and QA is given in Ref 2.

1.2 Materials - Adhesives

1.2.1 General

All the adhesive joints in strip laminate motors to date have been based on epoxide resin chemistry, this being the strongest practical system available for production use. The original primer and all the resins and hardners used are supplied by Ciba-Geigy. The primer for the improved system is supplied by Union Carbide. They are specified in Table A1.

1.2.2 Strip adhesive

The strip coating adhesive is a two-component solid epoxide resin/dicyandiamide hardener system, the resin having a high molecular weight of approximately 1200. It is known as grade AZ/HZ.15 and manufactured to specification IMI/SRS/22.

Both resin and hardner are dissolved separately in ethyleneglycol monomethylether solvent and a powdered filler is added prior to coating the strip following which the solvent is removed. When cured at 175^{o}C it has an ultimate shear strength at room temperature in excess of 44 MN/m^2 but the stress in the adhesive between layers of strip in the finished tube is usually well below the ultimate. Relatively little cure occurs below 130^{o}C hence the coated strip has a long shelf life at room temperature. Its variation of strength with temperature is given in Figure A1. Whilst there is no significant loss in strength at 60^{o}C, a typical motor operating temperature, compared to that at room temperature it is recommended that a value of 40 MN/m^2 be used for design purposes.

1.2.2 End ring/attachment adhesive

Current adhesive systems

The original end ring/attachment bonding adhesive system is a two component liquid epoxide resin/methyl-amino-phenol based hardner/filler system, the resin having a low molecular weight of approximately 400. The system is known as grade X33/1202 and is cured at 175^{o}C. It is used in conjunction with a polyamide primer, grade DZ.80, which is applied to all metal surfaces.

An alternative adhesive system has recently been qualified, grade XD4236 to specification IMI/SRS/274. The chemistry of this system is confidential to the supplier but is believed to involve a similar but accelerated cure system enabling polymerisation to take place at 120^{o}C. During the polymerisation rubbery blocking groups are formed in the molecular chain which tend to toughen the adhesive and to retard degradation reactions, such as the ingress of moisture, thus giving improved environmental resistance. It is a solvent-free, single component liquid system and is used in conjunction with a silane primer, grade A187.

Both end ring adhesives exhibit ultimate shear strengths at room temperature in excess of 35 MN/m^2. The variation of strength with temperature is given in Figure A1. As with the strip adhesive there is no significant loss in strength at 60^oC but for design purposes it is recommended that a value of 30 MN/m^2 be used.

The original adhesive system is still in use for the bodies which were qualified with that system but the alternative adhesive is used for all new designs.

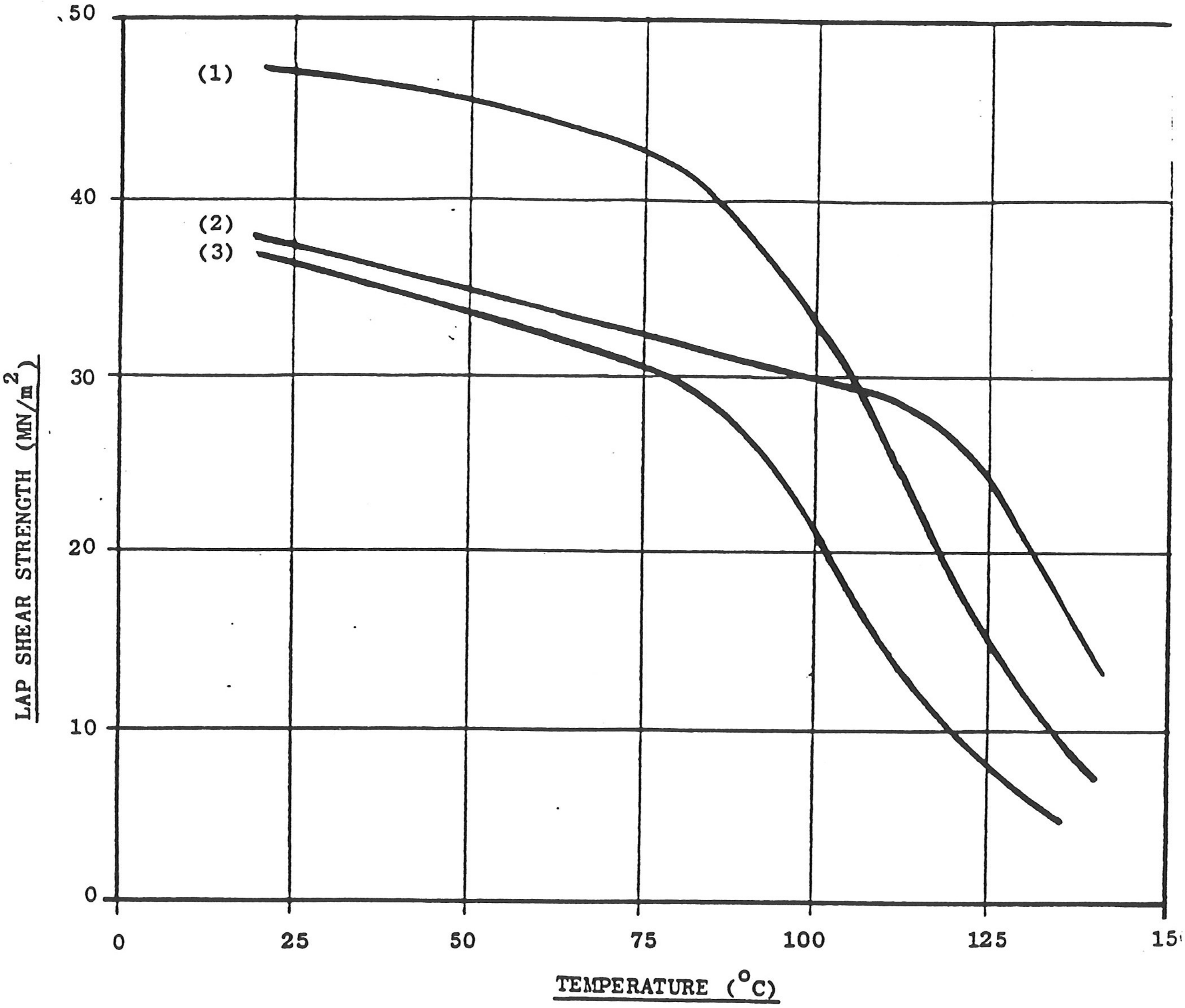
Further information concerning

Primers
Cure Cycles
Effect of storage
Experimental adhesives
Riveted joints

and manufacturing methods is given in Ref 1.

Use	Material		Grade		Buying Spec.	User Test
			Development	Production		
Strip coating	—	Adhesive	AZ/HZ 15	XD.659	TS.466 DTD.861	IMI/SRS/22
End ring & attachment bonding	Original system	Adhesive	X33/1202	XD.637	TS.467	UTR.29
		Primer	DZ.80		AFS.651	UTR.28
	Improved system	Adhesive	MS.3657	XD.4236	IMI/SRS/274	
		Primer	A.187		IMI/SRS/275	

Table A1 Qualified Adhesives



(1) Strip Coating Adhesive AZ/HZ 15
(2) End Ring Adhesive XD.4236
(3) End Ring Adhesive X33/1202

FIG. A1 VARIATION OF ADHESIVE STRENGTH WITH TEMPERATURE

Appendix 2

Motors manufactured in strip laminate

The following motors have been produced with strip laminate bodies:

Reference Number	Name	Diameter (mm)
E513	Bullpup	318
E533	Saluki	600
E561	Troy (p)	127
E579	Magenta	195
E597	Thermopylae (p)	127
E598	Cadiz (p)	195
E600	Taranto (p)	195
-	Micom	127
-	Harm	254
E601	Sparta	
E603	Trajan	
E603	Hadrian	
E606	Scipio (p)	
E613	Remus	
E614	Romulus	
E615	Antony	

(p) denotes qualified and in production

2.2.1.1.12 References

1	Design Documentation	
1.1	Def Stan 05-123	Technical Procedures for the Procurement of Aircraft Weapon and Electronic Systems
1.2	Def Stan 08-5 (also AVP32)	Design Requirements for Weapon Systems
1.3	Def Stan 08-3	Ordnance Board Safety Guidelines for Munitions.
1.4	MIL-A-8591G	Airborne Stores, Associated Suspension Lugs and Aircraft Store Interfaces.
1.5	JF Harvey	Theory and Design of Pressure Vessels - Van Nostr and Reinhold 1985
1.6	Roarke Timoshenko	PV Design Stress Analysis
2	Tech Note 87/38	Strip Laminate Rocket Motor Bodies - Design and Fabrication Considerations, M Chase 10.89.

2.2.1.2 Fibre reinforced plastic rocket motor tubes

Design Principles

The fundamental design principle in designing fibre reinforced plastic (FRP) rocket motor tubes or pressure vessels is to initially assume zero stiffness and strength contribution from the plastic matrix material, and to rely wholly on the structural properties of the fibrous material. This assumption is known as "netting analysis" and is used to define the required lay-up in the rocket motor tube cylindrical section as well as the geometry of the composite end domes.

Once the initial lay-up has been selected the effect of the matrix properties may be included in determining individual layer stresses and strains and overall stiffness by use of a laminate analysis suitability loaded to simulate rocket motor forces during carried and free flight. Laminate analysis is in general use throughout the composite industry for accurately prediction of ply stresses and strains, and details of the analysis technique can be found in any general composites handbook such as (1). An extension of laminate analysis applicable to filament wound axisymmetric structures is found in (2) which gives details of deriving ply stresses and strains under mechanical and thermal loading. For generally orientated fibres in 2-D space by means of the finite element method.

Also included in reference (2) is the netting analysis procedure required so as to produce an isotensoid filament wound head end dome.

Design Criteria

Techniques such as the method of mixtures may be used in determining uni-directional ply mechanical properties from the individual ply and matrix properties. It has been found, however, that these theoretically derived values considerably overestimate the strength and stiffness of the rocket motor tube. This is attributed to processing effects caused during filament winding as the fibres are passed through the resin batch and over rollers. The reduction in strength and stiffness is also more pronounced for high modulus carbon fibres with a relatively low strain to failure. These results are discussed in detail in reference (3) in which experimental pressure and bend test data is compared against derived figures so as to provide design guidelines for FRP rocket motor tubes.

Materials

Netting analysis is generally accurate for materials in which the transverse stiffness is low (<20%) of the longitudinal stiffness along the fibre direction. Using this criterion netting analysis is therefore applicable to most structural fibres (carbon, glass, aramid, metallic) set in a plastics matrix. There is, however, a new family of materials known as metal matrix composites in which the transverse properties offer considerable structural stiffness in which case netting analysis is no longer applicable. These materials are still orthotropic in nature and therefore can quite accurately be modelled using standard laminate analysis or finite element analysis as for the fibrous plastics discussed earlier.

References

(1) Vinson, JR — "Composite Materials and their use in structures", Applied Science Publishers Ltd, 1975.

(2) Dabinett, J — "The design and analysis of filament wound axisymmetric structures", Cranfield Institute of Technology, MSc Thesis, 1990

(3) Dabinett, J — "Stiffness testing on a 140mm diameter CFRP experimental rocket motor case", ROS technical note 92/83, 1992.

2.2.1.3 Kevlar Over Wound Aluminium (KOWA)

This paragraph covers the design considerations and requirements of rocket motor cases constructed using high strength aluminium alloy, dry overwound in the hoop direction with a arimid fibre marketed by Du Pont Ltd under the proprietary material name of Kevlar 49.

The advantage of dry overwinding are the high speed with which the layers of Kevlar can be laid down in comparison to the wet winding method, a typical floor to floor time of approximately 2 to 2½ minutes is quite normal. Also there is no cure cycle required in this process unlike its wet winding counterpart.

2.2.1.3.1 Design Considerations

There are three main considerations when designing a case using this form of construction. The first is its suitability if the bending requirements are higher than the setback/pressure loadings, which may be the case in a agile weapon system; then a conventional case is more suitable as there is little increase in the bending load capability of an aluminium alloy Kevlar overwound case.

Assuming it is suitable, the second consideration is the stressing of the case. Due to the requirements of Def Stan 08-5 on factors of safety and confidence levels, one mode of case failure is beneficial. The failure mode is more predictable in the longitudinal direction as this is dictated by the thickness of the aluminium wall. Degradation, changes in yarn thickness and possible fibre damage would cause significant changes to the hoop strength of the case; therefore, for this reason and to reduce the mass of the case to a minimum, the longitudinal failure mode is preferable. To calculate the thickness of the aluminium alloy and Kevlar see reference 1.

There are two approaches to the stressing of the Kevlar i.e. a continuous winding tension giving a varying strain within the Kevlar layers, or secondly varying the winding tension. The former is the easiest to produce and is suitable when a small number of layers is involved. Varying the winding tension enables a constant fibre strain to be held throughout the layers without fibre relaxation on the inner layers. This latter method is more suitable for the overwinding of steel tubes. To calculate the stress in the Kevlar of either methods see reference 2.

The third consideration (once the case has been designed) is the design of the pressure test equipment. Unlike a conventional case where sealing the ends and applying pressure gives a correct hoop failure strength, cases failing in longitudinal mode have other forces other than pressure acting upon them. These include the setback load of the main body of the missile being accelerated plus any drag effects. The setback loads of the case, propellant, fins, etc, plus the impact of the internal ballistics acting on the case and nozzle where plus and minus effects occur due to the convergent and divergent geometry. Therefore the pressure test equipment must allow the case to expand both diametrically and longitudinally; this is achieved by the introduction of a differential piston, see figure 7.

Reference 1 - Ballistic and Maths Department Design Aid Manual Section 0303 issue 13.

Reference 2 - PERME TR276 "Strain Distribution in Motor Cases Overwound Under Tension" by J Cook, February 1984.

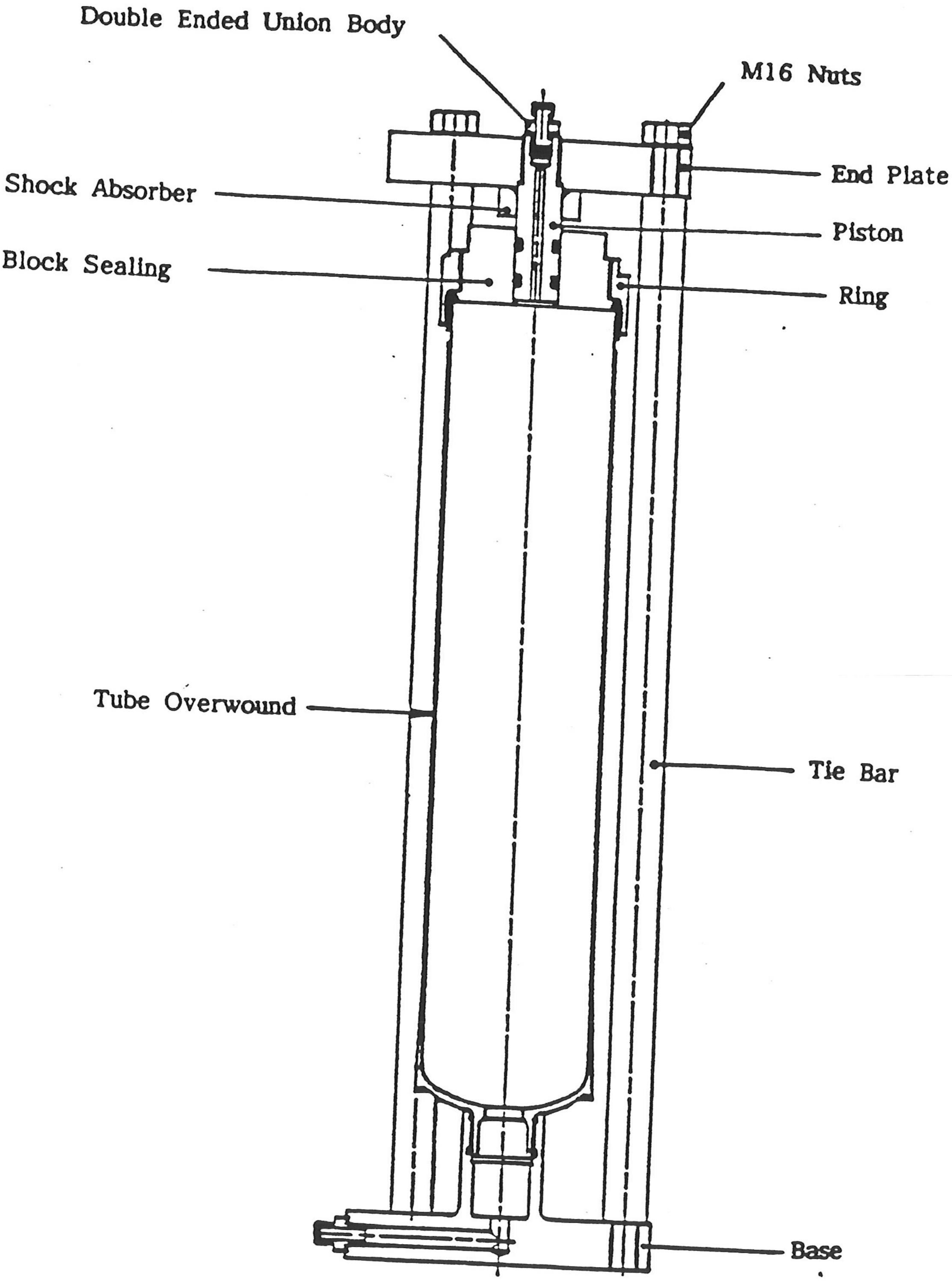


Figure 7 Tube Pressure Test Equipment

2.2.1.4 Hybrid Motor Case

Definition

A motor case manufactured for a homogenious metallic material with longitudinal slots machined part way or completely through, sometimes called a "Chinese lantern". The slots are filled with a resin and the case finally overwound with a fibre.

Use

This form of rocket motor case was derived to allow a way of passing the insensitive munition requirements.

Design

The slots are equally distributed around the perimeter and weaken the case in the hoop direction. The remaining material has to withstand the longitudinal load but the fibre takes on the role of withstanding the hoop loads. As with the Kevlar overwound case the design should fail in the longitudinal direction when normal internal pressure is applied.

2.2.1.5 **Homogeneous Body**

Metallic materials are the only ones used in the production of homogeneous rocket motor bodies at this time. Materials include steel, aluminium alloy and in some instances magnesium alloy although RMD have never used the latter.

The choice of material is dependent on many factors including strength and stiffness, method of manufacture, weight requirements, cost and other less significant but no less important factors such as availability.

2.2.1.5.1 **Steel**

Motor bodies can be made in high strength by the following methods or processes:

1. Wrapping and welding sheet of the desired thickness.

2. Machining from forgings or extrusions.

3. Deep drawings to the required thickness and machining the end.

4. Helically winding strip of the required thickness around a mandrel and welding alon the (helical) butt joint.

5. Flowturning/flowforming.

2.2.1.5.2 **Aluminium**

The above methods are, in general, equally applicable to high strength aluminium alloys, but the following points should be borne in mind when selecting the material and the method of manufacture.

1. Method (1) is now obsolescent and was not successful when applied to aluminium alloys.

2. Method (2) can be very costly in terms of wasted materials unless close tolerance forgings or extrusions are available in addition, if a large amount of material has to be removed, distortion on machining may cause problems.

3. A limited amount of experience of Method (3) is available.

4. Method (4) suffers from the disadvantage that the welds must be radiographed, that specialist equipment is required, and that the Poisson effect on winding a relatively this trip may create an internal channel which can trap solvents when lining the body.

5. Method (5) is in extensive use in the FRG, USA and the UK. The LAW motor tube and others utilise a Kevlar overwrapped, flowformed aluminium body (see para 2.2.1.3) but as yet RMD have not designed a motor body comprising a flowformed homogeneous tube.

2.2.1.5.3 **Other Considerations**

When selecting the material the following further considerations should be noted:

1. A body thickness/diameter ratio of less than 1/200 is undesirable due to the risk of distortion and damage. Consequently it may not be possible to realise the full strength of a high strength material.

2. As already mentioned, the body may have to be designed to withstand missile flight loads or to give a specified value of flexual rigidity. It may be found that these requirements are determinative, so that the internal body pressure is no longer the only design criterion. In such cases, it may be advantageous to use aluminium alloy rather than steel, so as to obtain a thicker body without a high mass penalty.

3. The heat treatment of many aluminium alloys is comleted by an ageing process at a temperature, about 130^{o}C, which is lower than that which may be used during subsequent processes, such as lining, which may be applied to the body. In such cases, care should be taken to restrict the time during which the higher process temperature is applied.

4. Fears are sometimes expressed by certain authorities that motor bodies in high strength aluminium alloy may be liable to stress corrosion. it is relevant to comment that tests carried out on project motor bodies have shown these fears to be without foundation, provided care is taken, particularly in the provision of large fillet radii, to avoid stress-raiser.

5. Finally, it should be borne in mind that ultimate tensile strength, or the strength/density ratio, may not always be the determining factors when selecting a material. Ductility, impact strength, high temperature strength and corrosion resistance, as well as easy machinability, or any of these, may be of equal or even greater importance.

Material properties shall be taken from British Standard Metal Specifications or other agreed documents.

2.2.2 End Closures

The principles of the end closure design are the same as the body design relating to pressure and materials to be used. However since end closures are usually thermally protected on the internal gas exposed faces by rigid insulants which have very low strain capability, end closures are usually designed on a stiffness criteria to support the insulation and prevent cracking of the insulant.

Sealing of the end closure against gas leak between the mating surfaces of the body or nozzle is generally achieved with 'O' seals in internal grooves. Groove dimensions and end closure clearances with body or nozzle should follow the manufacturers' recommendations for static joint seals. Leak testing of joints following final assembly end closures should be carried out.

Pressure monitoring holes should be avoided in aft closures due to gas dynamics being greater than at the forward end.

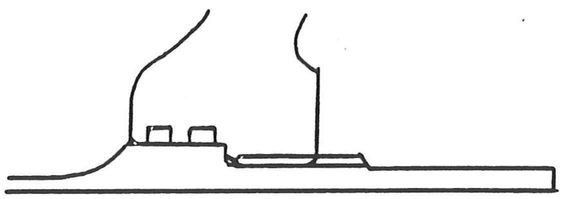
Pressure testing of end closures should be carried out when all manufacturing has been completed, refer to Part 7 of TN79/49.

2.2.2.1 Closure Retention

Forward and aft closure retention forms an extremely important function with regard to the rocket motors structural integrity and safety. Generally speaking, retention of a closure is done by the use of screwing, bolting or ring-and-groove devices. The design must be capable of withstanding at least the maximum motor pressure expected and in some cases the retention device is designed such that it will actually fail before the body bursts. This is a very useful safety consideration.

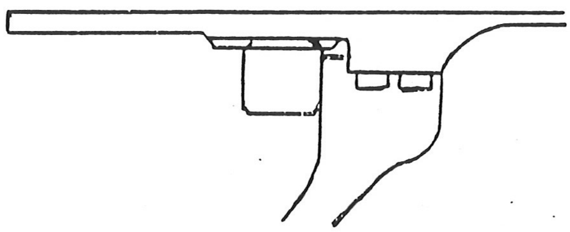
A selection of typical closure retention devices is given below.

(i) Threaded Closure/Body



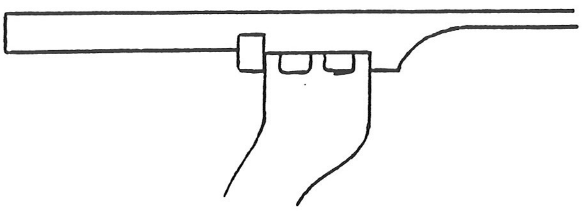
A thread locking adhesive is usually required to protect the screwed joint from the effects of vibration, etc. A buttres thread is very effective in this type of design. Rotational fixing of the closure is difficult to achieve.

(ii) Screwed Ring



Again thread locking adhesive would be required for the screwed retaining ring. Rotational fixing of the closure can be achieved with this method if a radial pin is fitted into the closure slot at A.

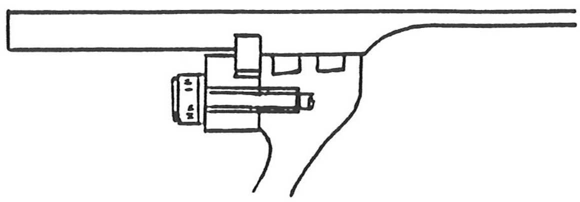
(iii) Retaining Ring



This device allows the closure to be machined very plain on the outside diameter and butts up against a shoulder in the body. The retaining ring is then fitted into a close toleranced groove behing the closure. The thickness of the closure would also have to be tightly toleranced to ensure minimum movement. Rotational fixing of the closure is again difficult although a radial pin/slot device may be designed.

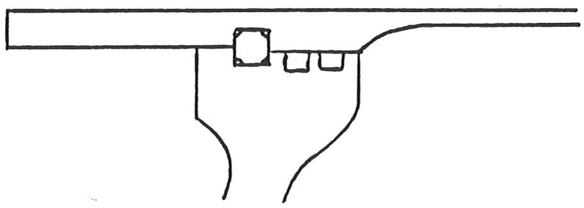
The retaining ring is sometimes known as 'spirolox' or 'circlip' type.

(iv) Retaining Ring Plus Clamp Ring



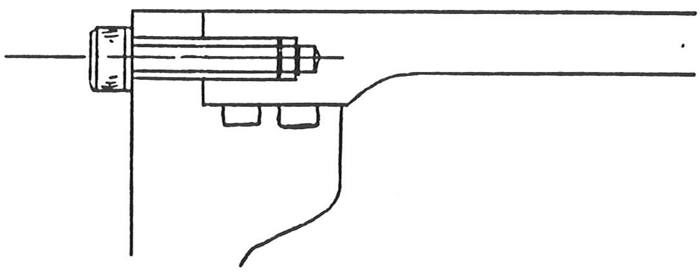
This method of closure allows a very simple internal body diameter to be issued. No step is required for the closure to butt up against although tapping of the closure is required. The retaining ring would be the same as that shown in (iii). Rotational fixing of the closure can be effected by either radial slotting and pinning of the closure itself, or by fixing the clamp ring in position with the closure using a dowel, and subsequently position the clamp ring with a radial pin and slot.

(v) Locking Wire or Autman Key



This device is probably the neatest method of retaining a closure and takes the minimum amount of room. An access hole has to be made in the outside of the motor body to feed the lock wire through. The material for the lock wire is a soft grade of steel which will bend to the diameter of the body. Rotational fixing of the closure is difficult. The present E603 Sidewinder motor has such as retention device.

(vi) Bolts



This method is predominately for heavyweight rocket motors and provides a simple method of closing off the motor body's ends. Also, according to the number of bolts used, the failure pressure for the closure can be varied; this has benefits when research motors, which sometimes rise to unacceptable internal pressure levels, can be saved from total destruction, ie the body does not burst.

(vii) Miscellaneous

There are other retention devices which are equally effective as those described above. It may be desirable to incorporate the closure retention with the fore or aft body joint. This would require detailed interfacing. Bonding closures in with adhesive is another option whic could be considered in future as could winding in the closure to the body with glass or carbon fibre.

2.2.4 Nozzles

2.2.4.1 Design

Nozzle or multi-nozzle shall be carried our in accordance with the MOD(PE) Rocket Motor Design Handbook Part 1 Section 6 Nozzle Design. This document covers the theoretical performance of nozzles and thrust from the internal contour.

Detailed information/data on nozzle and efflux characterisation is described in document 101 941-23/3/SU - BMD Design Aids for Solid Propellant Rocket Motors.

2.2.4.2 Structure

Many nozzles in current use have three main components, these being:

i) the throat insert
ii) the insulation lining
iii) the outer structure and attachment

Although short burn, erosive tolerant motors can have only one piece nozzles with the throat not requiring insulation and containing an attachment to the motor.

For materials selection of the components refer to Materials Department Operating Manual OM90/4 latest issue. Consideration should be given to the

a) bonding-in of the throat insert and lining to the outer structure when they are in the finished form. Alternatively,

b) moulding the insulation into the structure with the throat in-situ, then final machining to interface requirements.

2.2.4.3 Attachment

Nozzles are generally attached to the aft end of the motor at the motor stage assembly, by threads, screws or locking rings. Sometimes the missile contractor requires the nozzles to be assembled after other missile fittings are assembled. In this case provision must be made for transporting the motor with a transport sealing cap or the assigned nozzle assembled.

Sealing of the nozzle against gas leak between the mating surfaces of the body and nozzle is generally achieved by 'O' seals in internal grooves. Groove dimensions and nozzle clearances with the body should follow the manufacturers recommendations for static joint seals. Leak testing of joints following final assembly of nozzles should be carried out.

2.2.3 Blast Pipes

Two types of blast pipe may be used.

i) a supersonic tube
ii) a subsonic tube.

The supersonic tube is subjected to low pressure, high velocity supersonic gas flow, and has higher losses than the subsonic tube which is subjected to high pressure, low velocity subsonic gas flow. The subsonic tube is almost always used because of the very low losses associated with it.

The design should be carried out in accordance with the MOD (PE) Rocket Motor Design Handbook Part 1 Section 5 (latest issue).

A blast tube normally consists of a load bearing outer structure and a thermally protective inner. The basic design criteria for the two components are the same as for the motor body and insulation, but relative strains and stiffness criteria must also be considered.

Missile considerations may limit the blast pipe outside diameter and therefore the bore for gas travel. No steps or changes in direction should be made without consideration of gas dynamics.

The effect of blast tubes on rocket motor performance is detailed in RAE Farnborough Note RPD18, entitled: "Approximate theoretical calculations of the effect of cylinderical tailpipes on the thrust of a rocket motor."

For material selection of blast pipe structure and tube liners (insulation) refer to Materials Department Operating Manual OM90/4 latest issue. Consideration should be given to the bonding-in of insulation or moulding in-situ techniques as described in sections 2.3.1 and 2.3.2.

Pressure monitoring holes should be avoided due to gas dynamics leading to excessive erosion of material.

2.2.4.4 Nozzle Seals

The sealing of the rocket motors' nozzle, hermetically or otherwise, considerably aids the initial ballistic performance of the propulsion system, especially when cold by assisting the motor pressure rise. It also prevents ingres of moisture into the propellant chamber as well as stopping foreign bodies being accidentally or otherwise, pushed through the nozzle throat into the motor. The pre-requisite for the designing of nozzle seals is that they should be light to avoid damage to launcher or personnel, and costs effective. Also any Electro Magnetic Compatibility (EMC) or Electro Magnetic Pulse (EMP) requirement must be taken into consideration at an early stage.

There are three main types of seal used in RMD rocket motor nozzles at present. These are:

i) Aluminium Foil
ii) Rubber Plug
iii) Choke 'Two Piece' Seal

However, there are many other ingenious methods for providing a nozzle seal and these will be mentioned briefly to enlighten the designer of further options which may be open to him. Firstly we will concentrate on the 'standard' methods of nozzle seal design.

2.2.4.4.1 Aluminium Foil

This is by far the most popular method of sealing a rocket motor nozzle and is probably the lightest, cheapest and easiest hermetic seal to produce.

The aluminium foil itself is usually between .025mm (.001") and .125mm (.005") thick, although thicker foil could be used dependent on the burst pressure needed to aid motor performance. This would be determined by discussions with the Ballistic and Maths Department and may be the Igniter Design Authority. A typical grade of aluminium foil in use at present is to BS1470.

Special tooling may be required to form the foil to the shape of the profile it is to be attached to. This normally requires simple press tools to provide 'blanked' or 'formed' foils. A typical formed foild can be seen in position in figure 8.

The adhesive used to 'fix' the foil into position must be compatible with the propellant used in the motor. Again, a typical adhesive used at present is Pliobond 20 to specification AFS 1693. However, the choice of adhesive, and its application, must be discussed with Materials Department prior to use.

It is possible to purchase self-adhesive foils which have been used succesfully in rocket motor applications. Typical material for such foils is described at Scotch self adhesive tape - No 433. - thickness 0.09mm (.0035") with silicone adhesive agent. These type of foils can be ordered to whatever size is required providing they are flat and not formed.

The positioning of the foil nearly always depends on where there is an acceptable 'bond' areas for the adhesive. Various 'typical' positions are shown in figure 8. However, from a motor perforamnce point of view the preferred position would be at 'A' where once the seal has been broken there could be no possibility of the 'foil adhesive' remainders distrubing the gas flow through the nozzle, which in the case of an exacting misalignment requirement, could be critical. Occasionally two foils are used in the nozzle: the first in the throat region as the 'burst' disc and the second at the nozzle exit plane to ensure the nozzles have not been tampered with, ie foil would appear dented on broken.

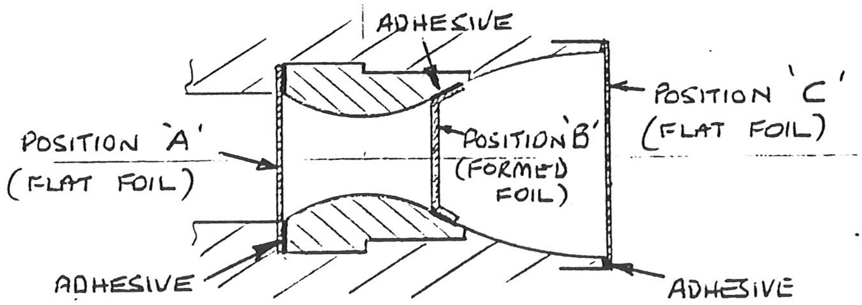


Figure 8

2.2.4.4.2 Rubber Plug

The use of rubber plugs to provide an hermetic seal and ignition aid in rocket motors is well proven over many years in small motors (< 120mm) at RMD. The shape and type of material used for the plug must be carefully designed as a 'too' tighter fitting plug could increase intial motor pressure dramatically and the type of material must be stable from a hardness and composition point of view for much the same reason.

The materials used for such plugs are typically silicone based because of its wide temperature range capabilities. Two materials used in motors at RO are Silicoset 101 and Silastic ERTV. These are both mouldable materials which can be used in such a way by pouring into the required shape mould.

Both these materials are ambient cure materials, however, it may be prudent to introduce a post curing operation to ensure that the material is fully cured. Experience has shown that if the nozzle plug material is not fully cured it may well cure off when in position in the nozzle throat. This again could create unacceptably high initial motor pressure.

Typical shapes of moulded nozzles plugs and their respective positions in the nozzle choke throat region are shown below in Figure 9.

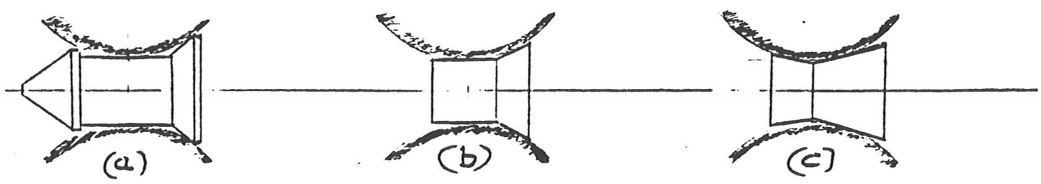


FIGURE 2

FIGURE 9

When the shape of the plug is finalised then some consideration must be given to designing a tool to insert the nozzle plug into the correct depth. This is important from the variability in eject pressure which can be experienced when the plug is pushed in either too far (high pressure) or not far enough (low pressure). The tool itself must be designed in such a way as to not damage the internal profile of the nozzle's expansion cone.

2.2.4.4.3 Choke 'Two-piece' seal

This is probably one of the most complicated seal arrangements presently in use but it does have three major functions. Firstly, it provides an hermetic seal, secondly it is a burster disc for aiding ignition and thirdly it carries the igniter wires through its centre. Figure 10 shows the device in detail and fits around either side of the choke throat diameter. The seal could also be used in a simpler form without the igniter wires.

In designing such a plug care must be taken to ensure that the potting for the wires provides a totally sealed assembly. Also the thickness of the diaphragm can create problems in machining becuare of its necesary thinness. (The diaphragm provides the 'burst pressure' feature of the seal and therefore a 'thick' diaphragm would require a very high pressure to eject the seal).

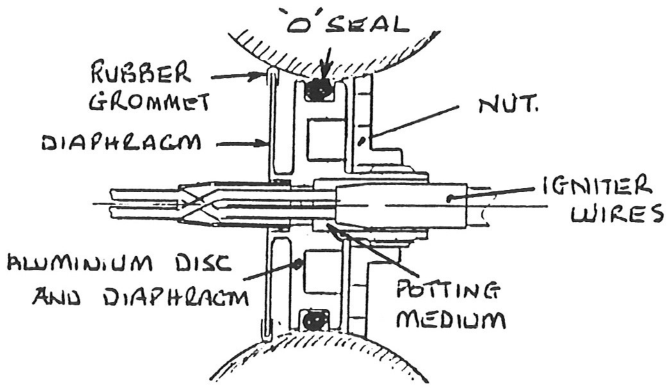


Figure 10

The seal around the choke throat is effected by placing the disc/diaphragm in the subsonic side of the nozzle throat and offering the nylon nut in from the expansion cone end and screwing the two components together.

2.2.4.4.5 Miscellaneous

Other forms of nozzle seal that have been used are mentioned here to assist the designer in offering possible alternatives which may well be more applicable to his requirement.

a) Frangible disc - a disc of mouldable material is sectioned and bonded back together before fitting into the expansion cone of the nozzle. This enables the disc to withstand high pressure from outside the expansion cone but collapses and fragments at low pressure when the motor ignites.

b) Desicant seal - this seal is situated in the nozzle expansion cone and combines a burster disc type seal with a desiccant to control moisture.

c) Polystyrene seal - Various shapes of polystyrene have been used for sealing nozzle expansion cones. However, great care must be taken when using this material because of its vulnerability to damage and chemicals.

2.2.2.4.6 References

1. Technical Note 92/100 Issue 1 Report on the Investigation into Nozzle Plug Ejection. Characteristics Associated with the E596 Dwina Motor as used in the Bofors USA Missile Failures.

2.2.5 TVC

2.2.5.1 Introduction

The development and evaluation of thrust vector control (TVC) systems for tactical missiles has been actively pursued in the United Kingdom for nearly two decades. Initially emphasis was placed upon evolving thrust vectoring techniques appropriate to solid propellant rocket motors aimed essentially at establishing a comprehensive capability in this field. This exploratory work was undertaken by a relatively small number of organisations, principally Summerfield Research Station. The Propellant Explosives & Rocket Motor Establishment Westcott, Strathclyde University and the Royal aircraft Establishment, Farnborough. This particularly active phase of work subsequently resulted in eight TVC systems being taken to a stage of development appropriate for project application. Additionally the jetavator TVC system was adopted for an anti-tank missile, secondary injection was evaluated on the Sinner test vehicle and more recently, further test vehicles have been flown featuring a spoiler and swivel nozzle TVC system. These flight proved systems covered thrust range 1000N to 35000N actioned from the conventional cast double base propellant formulations to highly aluminimised composite modified cast double base mixes.

Recent TVC work in the United Kingdom has been principally undertaken by Royal Ordnance where emphasis has been directed towards specific applications for present developments and future generation missile requirements.

Although all possible TVC techniques are evaluated for any one application, the majority of present developments have featured either a spoiler solution or, more predominently, a ball and socket swivel nozzle device. Where missile roll control is desired a twin swivel nozzle TVC solution has been shown to be particularly suitable.

Future TVC requirements would appear to have a predominance in the short range weapons field, where small size, high agile, tactical missiles would be employed. In this area boost/coast propulsion requirements appear attractive, control initially being achieved by thrust vectoring and finally aerodynamically. To keep abreast of these requirements common actuation systems have been examined capable of powering both control devices.

The following pages review the TVC systems that have been developed to project application level and in doing so give an insight into how designer chooses and designs the TVC system for his particular application. In this context performance and control data are presented for the following systems: Jetavator, axial jet deflector, spoiler, domed deflector, secondary injection systems, flexible nozzles and ball and socket swivel nozzles and jet vanes. Various actuation systems are reviewed appropriate to these TVC devices. Finally, the implications of roll control on TVC systems and an overlook of future development trends are presented.

2.2.5.2 Applications

Thrust vector control has wide application in modern tactical missiles. The following summary indicates where TVC can be used to advantage.

a) Missiles where short range interception is required.

b) Surface to Air missiles where high target crossing rates are possible and rapid initial flight path correction is desirable.

c) High speed missiles where considerable agility is required.

d) Low speed missiles where aerodynamic control would be combersome, particularly for anti-tank weapons with manual control.

e) Vertically launched missiles followed by rapid turnover, thus removing the need for an elaborate launcher.

f) Submarine launched missiles where course correction is required when surfacing in different sea conditions.

g) Missiles where the system benefits from having a wide separation between the launcher and tracker.

h) Separately boosted missiles where dispersion is a problem.

The principal applications listed above cover all types of tactical missiles where solid propellant rocket motors are suitable. The directional control for the rocket motor efflux gives the necessary missile agility to meet the application specified.

2.2.5.3 Classification

Numerous methods of thrust vectoring the efflux of solid propellant rocket motors have been examined in the United Kingdom. In considering these methods it is convenient to arrange them into three principal groups. These groups may be defined as follows:

Group 1

Nozzle Deflection

This group contains all forms of moving nozzle, or expansion cone devices where the entire gas jet is move. Members of this group are:

i) Flexible Nozzle
ii) Ball and Socket Swivel Nozzle

Group 2

Secondary Fluid Injection

In this system, fluid is injected through the nozzle expansion cone into the motor gases. The penetrating fluid causes an oblique shock to occur in the supersonic nozzle gas flow, which gives rise to an uneven pressure distribution and causes the efflux to be deflected. Members of this group are:

i) Liquid Injection
ii) Hot Gas Injection

Group 3

Jet Exhaust Deflection

Systems which employ obstructions in the efflux of the rocket motor come into this category. Members of this group are:

i) Jetavator
ii) Axial Jet Deflector
iii) Spoiler
iv) Domed Deflector
v) Jet Vanes

2.2.5.4 Performance

The performance of the TVC system can basically be divided into four aspects:

a) Jet deflection angle - that is the amount by which the efflux may be deflected.

b) Side thrust coefficient - defined as the side thrust divided by the undisturbed axial thrust.

c) Axial thrust loss - that thrust loss incurred by operating the device.

d) Actuation effort - the total force characteristics required to be applied to the device to achieve a given response.

Jet deflection angle and side force coefficient describe the lateral force capability of any TVC system. For TVC system using shock wave formation it is normal to describe the lateral force capability in terms of side force coefficient and an equivalent jet defection angle.

Actuation effort is a necessary parameter when sizing the driving mechanism. Additionally, for system study purposes it is convenient to describe the maximum closed loop bandwith the total servo system/TVC devices can achieve. In this context the bandwith given for any particular actuation method relates to the total electro-mechanical system.

2.2.5.5 Description of Systems

The systems which are described below have all been evaluated to a level appropriate to project application and in certain cases to actual missile applications.

A summary of the capabilities of the systems described are given in table 3.

2.2.5.5.1 Flexible Nozzle

Figure 11 shows the flexible nozzle concept. It consists of a nozzle mounted directly to the rocket motor aft closure by means of a laminated flexible mounting. The laminations consist of concentric spherical layers of elastomeric and thin metallic shells bonded to form a flexible sandwich. The mounting is stiff in the axial direction but can easily be deflected sideways. This mounting may interface between a conventional motor closure and optimised nozzle.

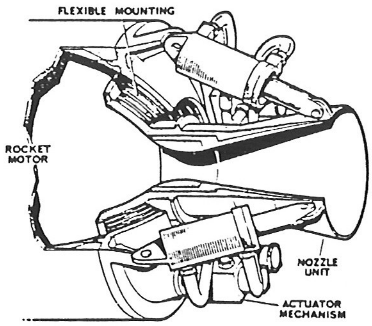


Fig. 11 Flexible Nozzle

Development commenced in the United Kingdom in 1967 using a design concept based originally on an earlier Lockhead Propulsion Company design. Initially work was directed towards producing an efficient flexible lamination by laboratory tests prior to rocket motor firings. In actual firings, flexible nozzle have been tested on motors developing 35,000N thrust for 2.5s duration at maximum jet deflection angle of $\pm$ 20^{o}, but a practical maximum is considered (15%) composite modified, CDB propellants. Actuation torques are high and depend essentially upon the motor operating pressure and lamination section required for the particular application. However a basic design figure for the motor stated is considered to be in the order of 70Nm/^{o}. The high actuation torques exhibited by this system have prevented it from finding missile applications.

However, the ability of the system to utilise optimum nozzle profiles without imposed vectoring losses, other than consine effect, suggests some advantages.

2.2.5.5.2 Ball and Socket Swivel Nozzle

The general design of a ball and socket nozzle is illustrated in figure 12. The choke and expansion cone is supported and located within a gimbal ring and this unit is pivoted about a central point on the nozzle axis. A shroud fixture is attached to a blast-pipe or closure and this provided a socket into which the choke and expansion cone move. A special seal is provided between the spherical surfaces to prevent the escape of high temperature pressurised rocket motor gases. Control is provided by actuators operating via the gimbal ring to give movement in both pitch and yaw planes.

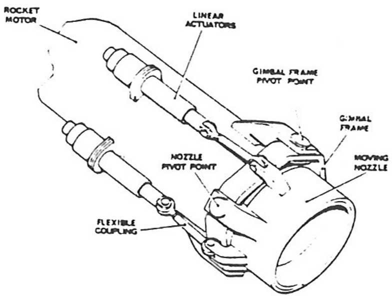


Fig.12 Ball & Socket Nozzle

Development of ball and socket swivel nozzles commenced in the early 1960's. Designs examined at that time bear only slight resemblance to present day devices which are finding extensive application. Development in this areas has, more than anywhere else, been project orientated.

The design standard illustrated was initially directed towards an air to air missile application and many firings have taken place on dual thrust motors. In this application jet deflection angle $\pm 20^{o}$ have been demonstrated on motors exhibiting 10,000 N thrust for 8 seconds, derived from a fairly conventional cast double base propellant have a flame temperature of 2850K.

Other developments have examined twin and quadruple nozzle configurations. The former has been supplied by RMD as part of the propulsion system for a vertical launch test vehicle and a demonstration test vehicle for Kawasaki Heavy Industries of Japan. The latter was for a project, now cancelled, which demanded nozzles to be coupled to external control surfaces. In these particular applications nozzle deflections of $\pm 15^{o}$ were required.

Swivel nozzles of this design, have also been demonstrated with motors having composite modified propellants. In these trials jet deflection angle of ± 8 were demonstrated with a single nozzle delivering high thrust, the flame temperature being 3600K.

Swivel nozzle development is now on a wide base at Summerfield with units being tested up to $\pm 25^{o}$ deflection on a range of motor sizes. These devices are also considered to have the greatest future application potential. Both gimballed and gimballess designs of swivel nozzle have been successfully demonstrated with flight type actuation.

The jet deflection capability of the ball and socket swivel nozzle is governed by the space between the fixed shroud and moving nozzle components. The only axial thrust reduction which occurs is that associated with the consine effect of deflecting the jet stream. Actuation torques are low compared to the flexible nozzle, since deflection occures about the nozzle choke and seal friction is limited to line contact. As with all systems, torque levels depend upon any specific application, but for the 10000 N thrust application described torques were measured at 40 Nm at maximum deflection.

2.2.5.5.3 Secondary Liquid Injection

Figure 13 shows a general view of the secondary liquid injection system. High pressure liquid is injected into the rocket motor expansion cone setting up an oblique shock wave which causes gas deflection.

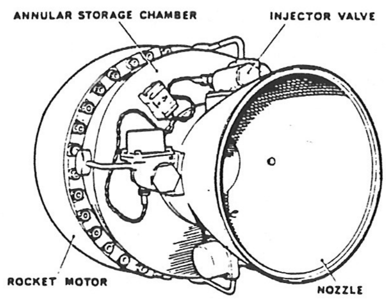


Fig.13 Liquid Injection

Most of the investigations in this field were carried out in the mid 1960's and used motors employing composite modified propellants having thrust levels of up to 35000 N for 2.5 sec duration.

Many firings have been conducted using different fluids suitable for tactical weapon applications. These have ranged from the "inert" fluids of the Freon family up to more energetic fluids such as strontium perchlorate/water solutions.

In addition to static firing trials, liquid injection TVC was successfully applied to the SINNER flight test vehicle.

The maximum jet deflection angle for an inert liquid system is 4^{o}. The formation of a shock wave around the point of fluid injection would suggest the system suffers thrust losses. However, this is not the case, for the added secondary mass causes augmentation of the jet efflux and a marginal net thrust gain is evident.

The use of reactive fluids has demonstrated a slight improvement in side specific impulse performance over the inert liquids, however beyond 4^{o} jet deflection angle both systems exhibit a rapid decrease in efficiency.

The principal attraction of a liquid injection TVC unit is that a simple low mass control system is all that is required to operate it. Consequently where small jet deflection angles are all that are required liquid injection is a strong contender.

2.2.5.5.4 Hot Gas Injection

In this TVC system gas is bled directly from the motor combustion chamber or from a gas generator and redirected into the expansion cone; control is by means of valves mounted on the motor nozzle. Figure 14 shows a typical installation.

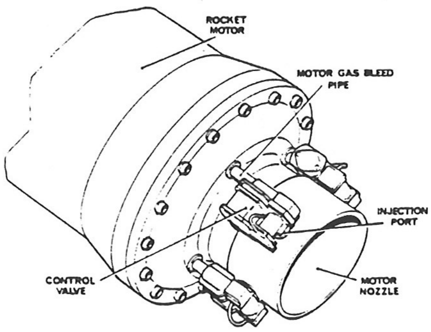


Fig.14 Hot Gas Injection

The majority of development activity occurred during the early part of the present decade but has since declined.

A considerable amount of theorectical work was undertaken at RO (Westcott) supported by practical firing trials at RO (Summerfield).

Firing trials were primarily undertaken with motors delivering 18000 N axial thrust. Jet deflection angles up to 12^{o} were achieved by venting direct from the motor chamber into the nozzle. A significant part of the trial's activity was associated with the development of hot gas valves to control the secondary injectant flow. This was principally undertaken by the Royal Aircraft Establishment, Farnborough.

As with secondary liquid injection hot gas injection has the advantage of requiring only a simple control system but has the added advantage that no secondary fluid is required if motor gas is used. Its advantageous high jet deflection angle is only off-set by the sophisticated hot gas valves which are essential to its success.

2.2.5.5.5 Jetavator

The jetavator system is shown in Figure 15. Basically a tubular extension to the rocket motor nozzle is pivoted about a point on the nozzle axis near to the exit plane. When the jetavator is inclined it interferes with the gas stream and causes jet deflection. The tubular extension or jetavator device is usually supported by a suitable gimbal frame and actuation provides movement in both the pitch and yaw planes.

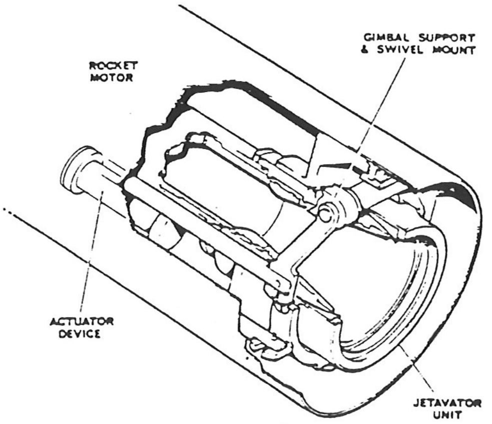


Fig.15 Jetavator

Development of the jetavator commenced at RMD in the later 1950's and work has continued at various levels of effort up to this present time. The initial programme was directed towards providing a new rocket motor and TVC system for a research anti-tank guided weapon system.

The jetavator system is now in quantity production as part of a propulsion unit for a medium range anti-tank missile.

Performance characteristics have been extensively evaluated with motors applicable to anti tank applications. Typical jet deflection angle, and actuator torque curves versus jetavator movement are shown in figures 16, and 17 respectively as obtained from low level dual thrust motor trials.

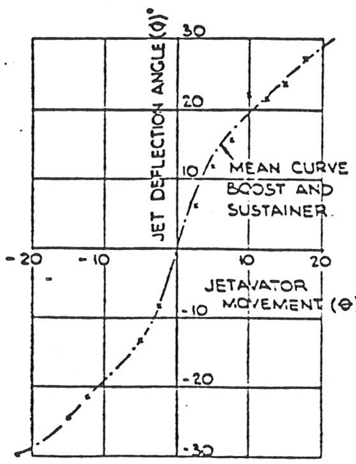


FIG.16

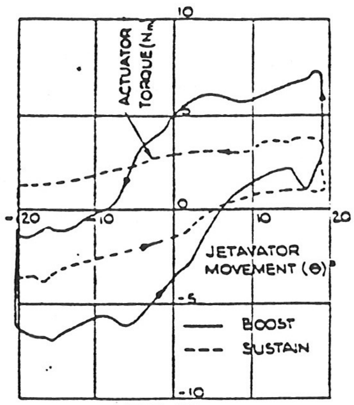


FIG.17

The large jet deflection angles which may be achieved with the jetavator make it an attractive system, but actuation torques demand slightly larger actuators compared with swivel nozzle devices and erosion of the jetavator extension can be a problem.

2.2.5.5.6 Axial Jet Deflector

Figure 18 shows a view of the flight type system developed for a flight test vehicle. It utilises four deflector blades situated around an under-expanded nozzle; the blades move in and out of the efflux in an axial direction to produce shock waves giving jet deflection and are controlled by linear actuators. Support for the blades is given by a roller track onto an outer shroud.

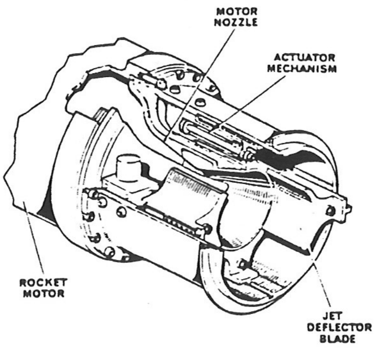


Fig18 Axial Jet Deflector

Initial exploratory work commenced in 1966 with a 10 000 N thrust motor and was later extended towards a flight test vehicle application, featuring a motor generating 35 000N thrust. Much of the interest in this system has waned in recent years primarily because of the availability of more attractive TVC devices.

It was soon realised during the exploratory work that the axial jet deflector had a limited application since the maximum jet deflection angle obtainable is about 7^{o}, and it is necessary to use an under expanded nozzle. However a good linear relationship exists between inserted blade area and jet deflection angle allowing good proportional control. Axial thrust losses, other than those associated with the inefficient nozzle are negligible.

Actuation loads are low if sufficient rear bearing support is available, however inertial loading may be large in high linear acceleration applications.

2.2.5.5.7 Spoiler

Figure 19 illustrates the geometry of a typical semaphore spoiler system. The method uses four blades moving in the exit plane of the rocket motor nozzle to block off part of the exit area. Opposite spoilers from a pair, one pair controlling the pitch plane (referred to launch conditions), the other yaw. When two adjacent spoilers are fully IN, the other two are always OUT and the control power exerted is a maximum.

As the spoiler blade is inserted into the gas stream an oblique shock wave is generated inside the nozzle expansion cone, which produces a non-uniform pressure distribution and gives lateral thrust. The lateral thrust capability is limited by the fact that, as the spoiler insertion is increased, a point is reached when the principal shockwave generated upstream impinges on the opposite wall of the nozzle.

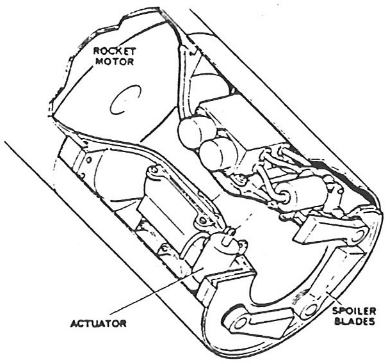


Fig 19 Semaphore Spoiler

A consideration amount of theoretical investigation into the performance of the spoiler system was undertaken by Strathclyde University, Glasgow, and RMD. Scale model testing with air rigs, using Schlieren photography gave a basis for theoretical models. Although it did not prove possible to fully represent the "actual" system, a much greater understanding of the important parameters resulted.

In 1968, work was initiated on the development of a semaphore spoiler system for a flight test vehicle. Spoiler blades have been actuated by rig type drive mechanisms and also flight standard electrical actuators. On the majority of firings instrumentation allowed records to be made of actuator torque levels for single and multi-blade operation.

During this development a dual thrust motor employing conventional cast-double-base propellant was used for firing trials. Approximately 150 firings have taken place with the spoiler TVC system in both project definitions and project development.

Figure 20 give an indication of the capability of the semaphore spoiler system. Side force coefficients of 0.25 ($14^{\circ}C$) have been demonstrated with this system. Its greatest advantage over all other mechanical TVC systems lies with the very low actuation torques observed for its operation. A typical range of actuation torque for various motor thrust levels is shown in figure 21.

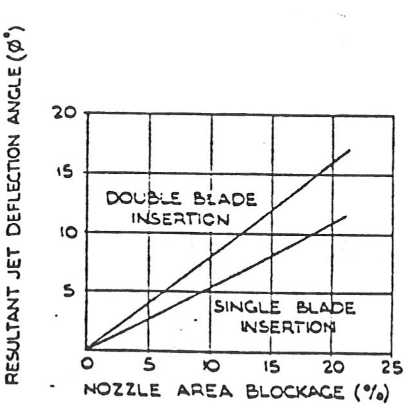


FIG.20

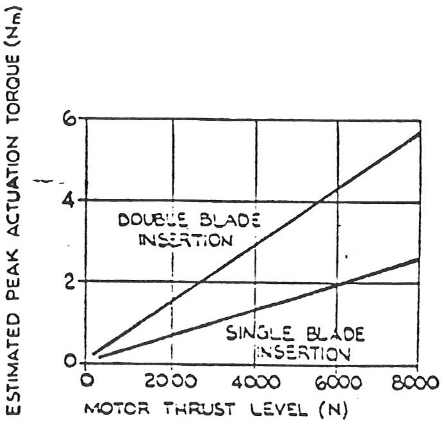


FIG.21

The spoiler system may be applied to any normal rocket motor nozzle thus maximum efficiency. Axial thrust losses occur during blade insertion and are relatively linear at approximately 1% for 1° jet deflection.

The disadvantage of the spoiler system are primarily associated with the blade assembly. Since the spoiler must be housed around the nozzle exit a larger than normal missile base area is necessary, also the blades tend to be heavy and thick in section, since the erosive environment demands high temperature materials. Set against these disadvantages the low actuation torques suggest small actuator packages. The system can be further simplified for roll induced missiles where only a single blade is necessary to achieve pitch and yaw control.

2.2.5.5.8 Domed Deflector

The domed deflector illustrated in figure 22 basically comprises a spherical dome with a circular hole the same size as the exit diameter of the nozzle, which is located at the exit plane of the nozzle. The dome is pivoted about a point on the axis of the nozzle and this is usually upstream of the throat section. The deflector unit may be supported by a special plain bearing or it may be supported in a gimbal frame.

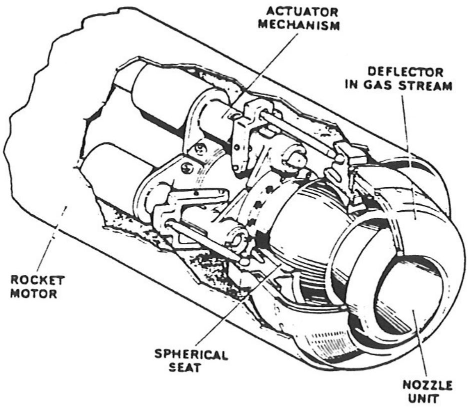


Fig.22 Domed Deflector

The unit functions in a similar manner to the spoiler; as the dome deflector is inserted into the jet efflux a principal shock-wave is produced in the supersonic gas stream and this results in jet deflection. Any gas wash which occurs between the dome and the end of the nozzle on insertion of the deflector into the jet stream is re-directed around the outside of the nozzle in an axial direction. Thus there is a significant improvement with respect to axial thrust losses over the conventional spoiler.

Development of the particular method, was initiated at RO in 1970. A motor generating an average thrust of 8000 N for 6.5 s was employed for the experiments. The propellant used was a conventional cast-double-base formulation having a flame temperature of 2800K.

This work showed that the equivalent jet deflection angle and axial thrust losses are, to a first approximation, proportional to the nozzle exit area blockage. In general 1% area blockage gives 0.52^{o} jet deflection with a corresponding 0.26% axial thrust loss. Therefore the dome deflector only suffers half the axial thrust loss seen with the spoiler but has a similar blockage v jet deflection angle characteristic.

However unlike the spoiler much higher actuation torques are present and approach those of the swivel nozzle device.

2.2.5.5.9 Jet Vanes

Jet vanes are one of the few proven means of TVC whereby roll torque can be obtained from a single nozzle. Furthermore, the small envelope constraint common to most of the tactical missile studies may create packaging problems where 2 axis control is required, e.g. twin swivel nozzle system, and a single nozzle alternative, i.e. jet vanes may be more attractive, even if less efficient.

RH Goddard is said to have been the first person to make use of jet vane TVC in the late 1920's. Since then it has been used on the German V2 missile and also on rocket such as Redstone, Sergeant and Pershing. It is also believed that for a number of current missile studies jet vanes are being actively investigated in both Europe and the USA.

Thrust vectoring is achieved by movement of one or more vanes usually placed at the nozzle exit as shown in figure 23. Side forces are produced by the aerodynamic loads generated on the vane surface by the deflected gas. In other words each vane acts as a wing in a supersonic gas flow.

TYPICAL LAYOUT OF JET VANE TVC SYSTEM

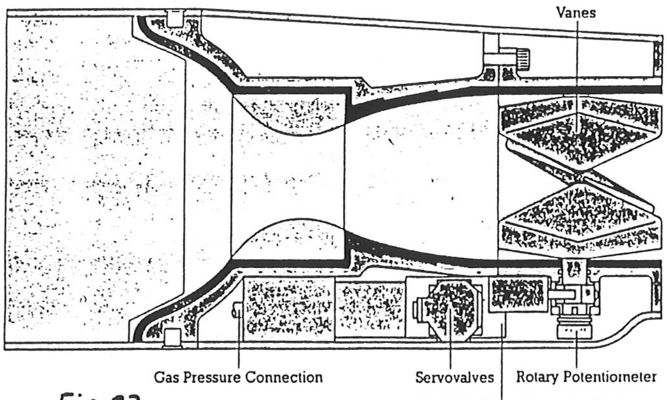


Fig 23

The main advantages of jet vanes are: a single nozzle fitted with three or more vanes will produce pitch yaw and roll moments, mass and inertia of the system are likely to be low, small envelopes can be accomodated and only low actuation forces are required if vane distortion and heat transfer to the bearings can be minimised. In addition it is a relatively simple operation to jettison the blades when the missile has reached sufficient speed for control to be passed to the aerodynamic surfaces.

The major disadvantage of jet vanes is vane erosion which is likely to be severe with high energy aluminimised propellants. This may lead to changes in vane characteristic which in turn may cause control difficulties resulting in instability problems. A further disadvantage is the thrust losses associated with vanes constantly immersed in the motor efflux. These losses increase in magnitude with increasing angles of attack of the vane and can become excessive if any distortion of the vane occurs.

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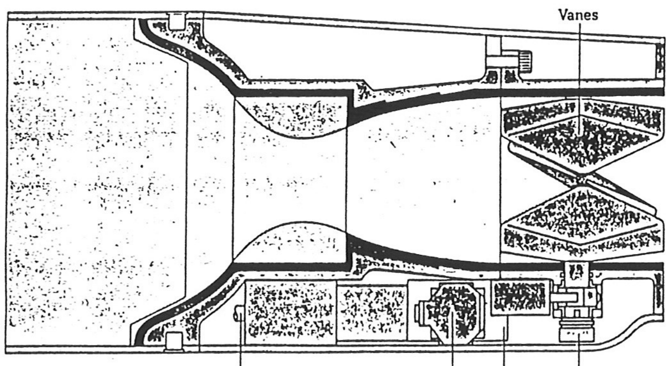

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Vane angles of attack greater than 25^{o} should be avoided, although brief excursions out to 30^{o} may be tolerable in some instances. Once again reducing the expansion ration will reduce the angle of attack required for a given jet deflection.

Material selection will depend primarily on the type of propellant in use. The high energy aluminimised propellants cause more sever erosion problems than others. There is little documented evidence of vane materials performance with these propellants but initial investigation by Bayern Chemie suggests that a tungsten blade coated with a layer of material having a low thermal conductivity may be suitable. Material selection therefore remains the major development area and suitable materials will only be identified when the results of future evaluation firing become available.

2.2.5.6 Actuation

Actuators are essential to any TVC system. The efficient of the total system depends not only on the thrust vectoring device but the combined actuation and TVC function.

During the early phases of TVC development actuation was achieved by ad hoc means. more recently the development of flight standard actuation systems has predmoniated. The present policy of the rocket motor producers in the United Kingdom is to offer the missile manufacture a total propulsion package where rocket motor, TVC device, actuation and signal processing are integrated within a single unit. A typical example of such a package is shown in figure 24.

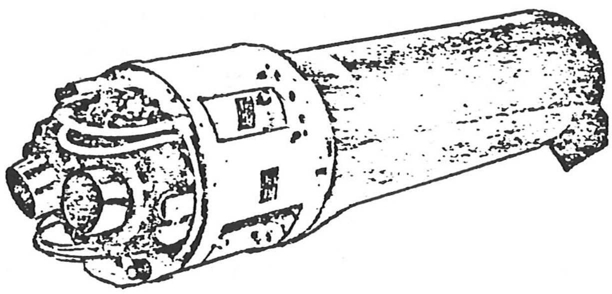


Fig 24 240 mm motor and TVC package

The choice of an actuation unit for any TVC system is peculiar to the actual missile application. However, it is possible to identify certain preferred combinations. The following actuation methods have been studied primarily at RMD, initially in collarboration with the RAE Farnborough and Sperry Gyroscope Limited (BAe Plymouth).

2.2.5.6.1 Electrical

Solenoid

In any TVC application where bang-bang operation is appropriate and relatively low actuator torques and small movements are applicable solenoids have application.

In particular solenoid flight actuation systems have been developed for anti-tank applications with spoiler, jetavator and dome deflector TVC. Typical performance capabilities are:

Actuator pull	30N
Response time	15ms
Total actuation system mass (anti-tank spoiler - 2 blades)	0.4kg

To achieve short response times current shaping techniques have been employed to obtain optimum performance.

Electric Motors

Considerable experience has been gained with electric torque motor devices, particularly those incorporating Samarium Cobalt magnets. Such motor have found application in both bang-bang devices, for medium size spoiler systems, and proportional drives for swivel nozzle applications.

High torques are possible from reasonably low weight motors, typically 100 Nm, from a motor of 1.3 kg mass, but response times are slow since large armature inertias and high gear reductions are usually necessary. Typical system bandwidths are 12Hz and as such have limited the application of electric motor drives.

Hydraulic

Hydraulic servo drives have found extensive application with TVC systems. In general simple single acting pistons have been adopted for actuator drives in push/push configuration. Moderate oil pressures (200bar) enable high force drives to be derived from small size units. Various servo control valves have been evaluated principally by Sperry Gyroscope resulting in a pulse length modulated servo valve being selected for general use. Bandwidths, typically in excess of 30 Hz, are more than adequate for most tactical missile applications. Typical installations, capable of meeting stringent performance requirements, for swivel nozzle units of the type shown in figure 24 have been produced for a total actuation mass of 2kg for 8 piston actuators and servo valves.

Many methods have been examined for producing the fluid oil pressure, including expulsion cylinders driven form motor gases or cold compressed gases and circulating pumped systems. the choice of any unit can only be based upon the required operating time and duty cycle in relation to motor burning time, operating pressure and gas temperature.

2.2.5.6.2 Pneumatic

Pneumatic actuation systems using both hot and cold gas have been used to drive TVC devices. Principally pneumatic actuation has been used for bang-bang servo where high response coupled with medium power drives have been required. Actuator masses are small but a mass penalty is incurred for a cold gas reservoir, hot gas generator or motor gas filler.

Typical open loop bandwidth for bang-bang pneumatic actuator drives are 120 Hz. Proportional drive devices suffer much slower response because of the low bulk modulus of the fluid, in such instances typical closed loop bandwidth of approximately 25 Hz were observed.

Attractive actuation packages have been produced for an anti-tank jetavator system, using hot gas and a spoiler using cold gas. In the first instance the requirement was for a medium speed, proportional drive and the latter, a highly responsive bang-bang drive.

2.2.5.7 Roll Control

2.2.5.7.1 Roll Thrust Vector Control

Roll position or roll rate stabilisation are requirements for most tactical missiles. The considerable agility available from TVC control in the pitch and yaw flight planes may compromise the stability of the roll axis control, consequently roll control must also be available from the TVC or propulsion package when aerodynamic control is not viable.

The amount of roll torque required depends upon the particular missile application but will generally fall into one of four roll thrust vector control systems operating bands. These are:

i) expendable impulse motor
ii) tangential thruster units
iii) twin TVC nozzle motors
iv) jetavators

2.2.5.7.2 Expendable Impulse Motors

These devices cover a considerable thrust range typically 5N to 20 kN with nominal burning times of 0.020 s. Sizes are proportional to impulse, and being one shot devices several units must be packaged within the missile structure on tangential planes if repetitious control is required. These units have not found general applications, primarily because of their limited control capability and volumetric requirements.

2.2.5.7.3 Tangential Thruster Units

Small tangentially mounted nozzles, venting the primary rocket motor gases through hot gas valves have been developed for roll control. Efficient packages have been produced for a four nozzle assembly deriving into 5% of the main motor thrust. These devices are considered adequate for roll correction on single nozzle TVC propulsion systems to compensate for nozzle TVC propulsion systems to compensate for induced roll. Generally tangential thruster units offer a more efficient package in terms of mass, volume and control efficiency over impulsive motors.

2.2.5.7.4 Twin TVC Nozzle Motors

For missile applications where high levels of roll torque are demanded in addition to large TVC efflux jet deflection angles, twin TVC nozzle systems provide an attractive solution. Inevitably, twin ball and socket swivel nozzle units have been adopted for these applications, since they have been shown to offer the optimum package. The amount of roll torque is limited only by the nozzle deflection angle and nozzle separation. Generally a nozzle deflection angle of $\pm 15^{o}$ coupled with a separation distance of approximately one third the missile diameter has been found to cater for all roll moment requirements.

2.2.5.7.5 Jetavators

2.2.5.8 Future Trends

An ever increasing number of new tactical missile developments in the United Kingdom and Europe generally are taking advantage of the presently available TVC technology. Feasibility studies for future generation missiles also feature TVC requirements, but with advances being made in other areas smaller and more responsive missiles will be required. To keep abreast of these future trends considerable effort is being placed on optimisation studies of presently available TVC devices, actuators and power sources.

As an initial conceptual study the twin swivel nozzle assembly shown in figure 25 was developed. Directed at a motor developing 20000 N thrust, such a system offers, within a package of 180mm dia x 400mm long, a complete TVC and actuation system capable of pitch, yaw and roll controls. It also has the advantage of enabling the direct coupling of aerodynamic control surfaces to the same nozzle actuators for any subsequent coasted flight. Similar optimisation studies are presently being undertaken with the semaphore spoiler assembly. In this area the accent in to reduce actuation mass whilst side force coefficients are being increased by improved blade design. Applications for spoilers are seen in the area of low cost missiles, consequently simple bang-bang services are presently being developed for such applications.

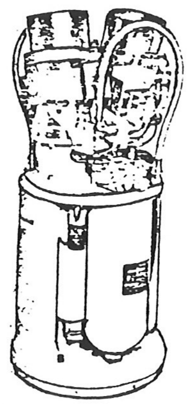


Fig 25 180 mm TVC Package

Interest in hot gas injection is also being revived for applications to short burn high impulse motors. In this area the emphasis is on low inert mass and small diameter, probably associated with hypersonic flight. In such applications only small initial flight path corrections are required with which hot gas injection can adequately cope.

The present feasibility study work is aimed at missile developments which could commence ten years hence. Past experience has shown that propulsion system technology must always be at least ten years in advance of missile requirements if today's propulsion technology is to be incorporated in tomorrow's missiles.

2.2.5.9 References

Useful documents associated with designing a TVC system are listed below:

1. BMD/MDA/08/01 - Jet Vane TVC Performance Prediction

2. Special Report - Jet Vane TVC Part 1 Theoretical Consideration

3. Technical Report 90/14 Issue 2 - Final Report on the Mathematical Model of a Jet Vane System for the BAe Plymouth Jet Vane TVC Demonstration Programme.

4. Rocket Motors Design Manual Part 1 Section 9 - January 1980.

5. Technical Note 91/23 Issue 1 - Technical Requirement Specification for a Thrust Vector Control (TVC) for the Kawasaki TVC System.

6. Technical Note 90/143 Issue 3 - Technical Requirement Specification for the Actuation for the Kawasaki TVC System.

7. Technical Note 90/11 Issue 1 - Design Study for a Thrust Vector Control of Breadboard Actuation System for Kawasaki Heavy Industries, Japan.

8. Technical Note 90/12 Issue 1 - Design Study for Demonstrating a Thrust Vector Control System with Breadboard Actuation for Kawasaki Heavy Industries, Japan.

9. KHI - TVC Data Pack - Volumes 1-7.

Techniques	Method	Jet Deflection Angle	Axial Thrust Loss	Type of Control	Actuator Size
Moving nozzle	Flexible nozzle	± 15°	Cosine effect	Bang-bang or pro portional	Large power No gimbal ring
	Ball and socket	± 25°	Cosine effect	as above	Small power
Secondary fluid injection	Liquid injection (inert)	± 4°	Augmentation	as above	Small-liquid depends upon duty cycle
	Hot gas injection	± 12°	Depends upon duty cycle	Bang-bang using fluid amplifier or on/off mechanical valve	Small
Mechanical Obstructions	Jetavators	± 30°	10% without actua-tion 20-25% during actuation	Bang-bang or pro-portional	Medium gas actuator
	Axial jet deflector	± 7°	Under expanded nozzle	Proportional or bang-bang	Medium size actuator
	Spoiler	± 14° (single blade) ± 22° (double blade)	1% per degree deflection	Bang-bang or pre portional	Small actuator
	Domed deflector	± 18°	½% per degree deflection	as above	Medium size actuator
	Jet vanes	± 10° (Double Vanes)	5% undeflected 18% deflection 10°	as above	Small actua-tion

Table 3 Performance Comparison of the Different TVC Systems

COMMERCIAL IN CONFIDENCE

COMMERCIAL IN CONFIDENCE

2.2.6 Strakes

Strakes are normally metallic channels which are attached to, or are part of the motor and/or missile for one or more reasons which may include:

- to carry wirings or similar
- to support structural items eg fins, launcher feet
- to provide additional strength
- to provide an electrical path for electrical continuity, lightning or EMC/EMP protection.
- to provide a means of handling the motor
- to enhance protection of the motor case

Strakes can be integral with the case or attached by mechanical or adhesive (cold or hot cure, silver loaded electrical) techniques.

The purpose and use of the proposed strake should be considered as early as possible in the design process where clearly the use of such devices may have interfacing implications.

The following factors should be considered in selecting the appropriate strake(s) to suit a particular application:

- purpose/requirement
- dimensional envelope - interface, tolerance
- structural loads imposed
- environment - induced and/or natural
- material and construction
- means of attachment
- handling/vulnerability
- safety aspects
- compatibility - mechanical/electrical/chemical
- quality control/inspection requirements
- cost

Departments which may be affected by the choice of strake(s) and which therefore should be involved in the decision process would include Materials, Production and QA.

Reference to Def Stan 08-5 and AvP32 should be made concerning choice of materials and method of attachment.

2.3 NON-STRUCTURAL HARDWARE

This section includes the design of non-structural components used to complete the assembly of the rocket motor. It includes reference to sub-sections describing mouldings, both rigid and flexible; body lining, for cartridge loaded and case bonded charges; and resonance rods.

2.3.1 Mouldings

This sub-section briefly describes features that could be moulded to shape to make up or form part of a rocket motor. It includes components that are rigid, components that are flexible, and obturators.

2.3.1.1 Insulation

Insulating components that are moulded include both rigid and flexible items. The rigid insulation materials are used to provide mouldings to protect the forward closures, aft closures, blast tubes, the nozzle expansion cone and back of choke. They are also used in areas experiencing severe erosion conditions, or possible to achieve a very low level of smoke, even for the aft end of a body. Flexible insulation materials are commonly known as "rubbers".

2.3.1.1.1 Rigid Insulation

Four main materials that should be considered are:-

1 Asbestos phenolics (eg durestos)
2 Carbon phenolics
3 Glass phenolics
4 Silica phenolics

These materials in the as moulded condition may be considered to be unsuitable for use within the motor chamber due to them being incompatible with propellants. If this is the case then usually a post cure operation will convert these materials to a compatible condition. Incompatible mouldings may be used in the as moulded form in certain applications, for example for insulating the nozzle expansion cone when the motor seal is trapped forward of the nozzle in or by the choke.

Prior to selection of a material discussion with the Technical Authority is recommended to optimise the material, its thickness and particular design features. This will ensure that particular requirements such as erosion, strength, flame and smoke are satisfied.

Useful reference documents are:

Tech Note TN 73/24	Low temperature curing adhesives
Tech Note TN 82/57	Development of computer model for ablation of Lining material
Tech Note TN 83/3	Programme Manual for computer model for ablation of Lining material
Tech Note TN 90/105	Compatibility of materials

Operating Manual OM 90/4 for Materials Department

SECTION 3

Non-Structural Hardware

OM 90/4 refers to the operating and filing system of the department which can be used to provide the technical information and individual material specialists who will advise on the use of material for moulded components for particular applications. In some instances the design of the component will be influenced by the form of the raw moulding material that is available. For example, some materials may not be available as a felt and others may not be suitable for transfer moulding.

For further details of rigid insulants, see para 2.3.2.4 - Body Lining - Blast Pipes.

2.3.1.1.2 Flexible Insulation

2.3.1.1.2.1 General

The flexible insulants are rubbers such as Hypalon and Royalene, names of rubber polymers given by the manufacturers.

The rigid insulant is much more resistant to the erosive effects of high speed gases, whereas the flexible rubbers are more suitable for areas of low gas flow and where the component will dilate under pressure.

Ablation is the mechanism by which organic based insulants function under the conditions met in rocket motors. It is a sacrificial process where the polymers breakdown absorbing heat by endothermic reactions to produce low molecular weight gases which diffuse through the "char" to give a cool boundary layer.

The inorganic fillers, asbestos or silica fibres reinforce the char to form a hard carbon layer. In rigid insulants the chemical structure of the phenol-formaldehyde resin is a rigid three dimensional lattice, and forms a much harder carbon char than rubbers which are linear molecules, which are looped and compressed. This gives good extensibility but also results in a softer, less rigid char, which is easily eroded by high velocity gas flows. Polymers start to decompose at 300-400^{o}C and with rising temperatures they produce hydrocarbon gaseous products having C_5 - C_1 structures. The lower the size of these the better because the "cracking" or decomposition of these gases absorb heat.

The factors controlling the process are:-

1 the high temperature heat source

2 the effusing of the volatile products in direct opposition to the heat flow

3 Endothermic heats of decomposition

4 Thermal conductivity of polymer, char and volatile products

The energy to decompose a polymer such as Hypalon is 53 kcal mole^{-1} and for Royalene 91 kcal mole^{-1}.

The characteristics of an ideal casing insulant are

1 Low thermal diffusivity, ie $\dfrac{\text{Thermal Conductivity}}{\text{Spec Heat x density}}$
2 Heat absorption due to endothermic phase and chemical changes
3 Transpirational cooling of the char structure by the volatile products of degradation
4 A strong residual char structure

2.3.1.1.2.2 Types of flexible insulants and composition

Typical rubbers used in rocket motors are

Red Hypalon	CL2759 (Chlorosulphonated Polyethylene)
Black Hypalon	CL8167
Hycar (nitrile)	MM 4/45 (Acrylonitrile)
	MM 382
Royalene	(Ethyl propylene Terpolymer)
Butyl	
Neoprene	

Red Hypalon is considered to be the optimum flexible insulant, but it does have a high density when compared with compounds based on Royalene which has only slightly worse performance. The rubbers such as Hycar (nitrile) Neoprene or Butyl have not as good performance but have important uses such as Hycar laid over Durestos to prevent "out gassing", or Butyl as boots and obturators where their properties are used to the best advantage.

Grades of rubber used at RMD and some of their properties are shown in Table 4.

2.3.1.1.2.3 Using thermal insulants

The performance of any insulant is effected by motor pressure, burning time, gas velocity and combustion temperature. A rule of thumb for making comparisons of conditions is the factor of pressure and burning time, then relating the selection to erosion and gas velocity.

If there is a high gas velocity as in a blast pipe then a rigid insulant is required. Whereas with low gas velocity a component which can dilate, as in a motor tube, then a flexible insulant should be selected.

2.3.1.1.2.4 Where are insulant required?

With a case bonded propellant charge of a radial burning motor, the body tube only sees the hot gas at the end of burning but the charge ends will require insulating at the nozzle end by Durestos, and head end by rubber. Although the tube only sees the heat at the end of the burning, it is often necessary to ensure the tube is protected because of strength or missile requirements. Also, in air to air missiles they have to survive aeroheating of temperatures up to 172^{O}C. In these cases a tube must be insulated.

With a cigarette burning charge the tube is in contact with the flame for the whole burning time and the insulation needs to be thicker than for a radial burning charge. It can be optimised by tapering the lining so it is thicker at the nozzle end to allow for the greater erosion at that end.

Loose charges need less insulation over the tube because they have charge inhibition and an air gap, but they need head end and rear end protection and also require obturators.

The main use of rubbers is for lining tubes. The rubber is in the form of a sheet 1-2mm thick, usually in the uncured state as this improves bonding and enables the rubber to flow to shape under pressure. The usual insulation used is Hypalon or Royalene. If these are used with a cast rubber propellant such as HTPB the linings need to be dried by heating under vacuum, usually at 100^{o}C at 5mm Hg. The purpose of this is to remove the water in the rubber which reacts with the HTPB polymer binder.

The application method is to apply an adhesive to the inside of the motor tube and lay the rubber sheet into position. This can be difficult as there is only limited room to get into a motor tube through the restricted openings and reach down tubes which may be several feet long. A film of parting agent, such as PFTE, to prevent sticking is laid onto the rubber followed by a layer of cloth. Inside this is put a pressure bag. A vacuum is applied between the bag and lining and then the bag is pressurised. The whole lot is then heated in an oven for a time depending upon size.

There is a second application method involving the use of liquid rubbers. The liquid is put into the tube and the tube is rotated so that the liquid is forced onto the tube wall and forms a uniform layer. It is kept spinning until the rubber has cured. The rubbers are usually a polyurethane polymer with fillers such as silica or alumina fibres. The difficulty with this technique lies in selecting the right mixture to give a liquid of suitable viscosity and cure time but at the same time has a good performance in a motor. They have the advantage that they are easier to put into tubes, less labour intensive, and do not require drying before use with HTPB propellants.

A second major use for flexible insulants is in the manufacture of "boots"; they are loose rubber cups or flaps bonded to the motor tube at one end and to the propellant charge at the other and may be included at either or both of the head and nozzle ends of the filled motor tube. They provide the means whereby the propellant charge is able to expand and contract (which may be a considerable amount over the possible working temperature range, - 55^{o}C to +70^{o}C) without debonding or cracking of the propellant. Whereas all the rubbers previously mentioned will retain their required flexibility characteristics up to and above +70^{o}C some have better low temperature performance. See figure below:

-30^{o}C	Hypalon CL2759 and CL8167 Acrylonite MM 40/45 MM 382
-40^{o}C	
-50^{o}C	
	EPDM (Royalenes)
-60^{o}C	Natural rubber R54 (time dependant flexibility decrease)
-70^{o}C	Butyl rubbers

Flexibility Low Temperature Limitations

2.3.1.1.2.5 Testing materials

The insulation characteristics of flexible insulants need to be tested under conditions similar to their working environment. ie

1) in a hot gas stream 2000-3000^{o}C
2) at high pressure
3) with burning times of up to several seconds.

To produce a league table of results it is not necessary to use a large motor; a motor the size of a K round of 50mm dia is adequate to identify suitable materials for testing in a larger motor or even in a feasibility study.

The other methods use torches such as the plasma arc or the ASTM torch test.

The best known is the ASTM torch test developed by the American Standards bureau. This is a calibrated oxy-acetylene burner, the flame of which plays on the surface of the sample and the back temperature is measured together with the time to burn through. From these results an index of performance is calculate.

Most materials performance are judged on

1) Erosion rate
2) Char rate
3 Thermal conductivity

But erosion and char rate are the most important as a practical requirement in deciding just how much and what insulation to use.

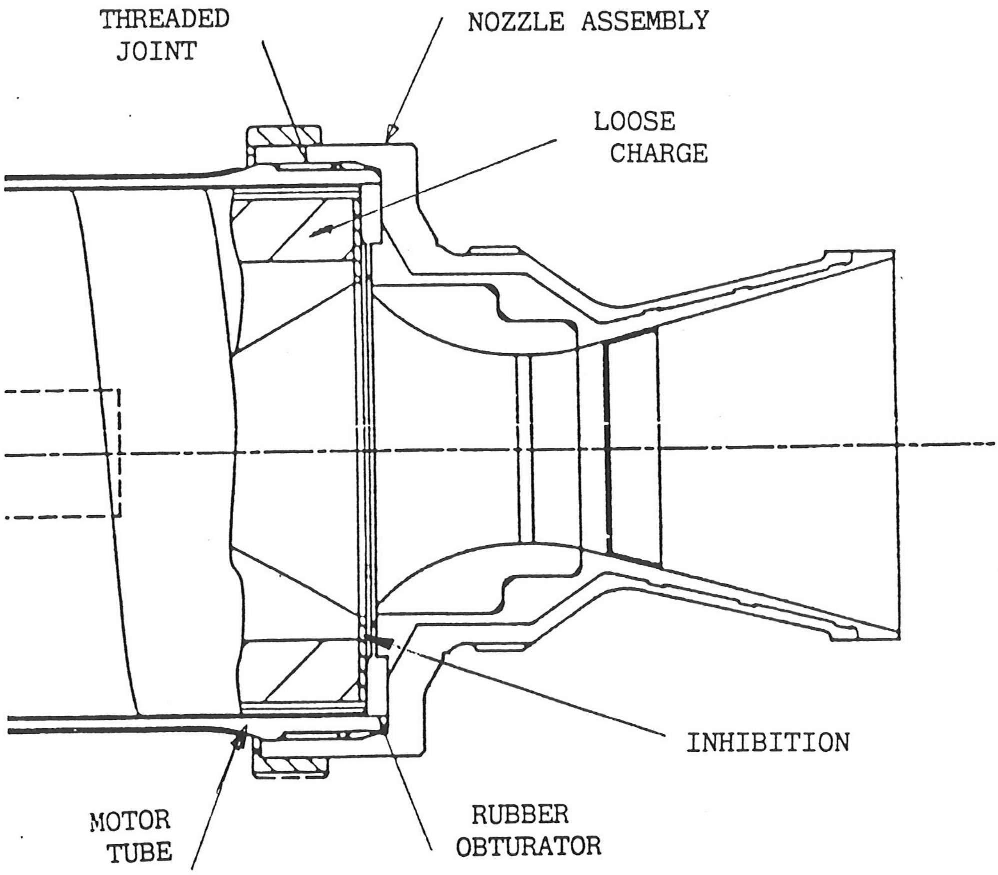
In cigarette burner, Hypalon 2759 at a pressure 3.5 MPa had an erosion rate 1.2 mm/sec.

Because of the temperatures and the complex mechanism of ablation the measurement and calculation are difficult. There are several mathematical models and programmes have been derived but do not necessarily conform to all the available data. Firing trials of proposed systems are the only way to obtain conclusive performance levels.

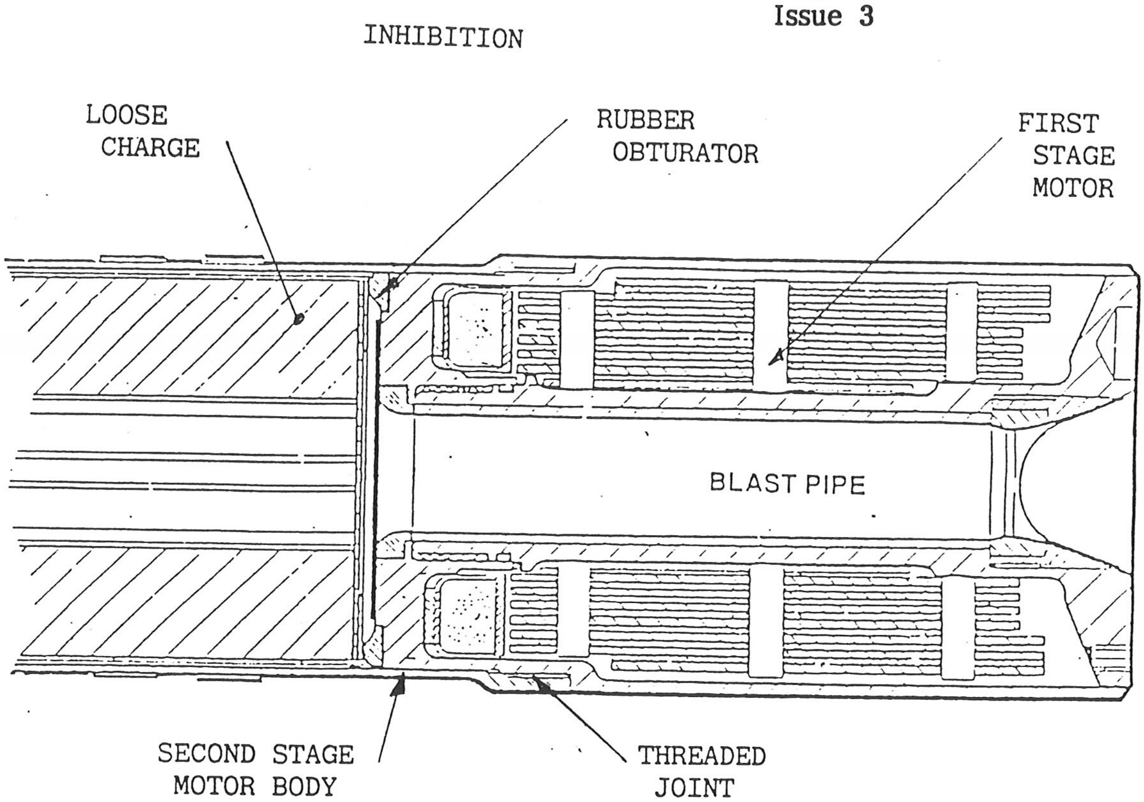
2.3.1.2 Obturators

2.3.1.2.1 General

The word obturator stems from the latin 'obturare' meaning 'to close', and in gunnery and rocketry terms means that which closes or seals apertures preventing the escape or flow of gas. It is specially associated with those seals which interface between the motor tube, the nozzle end closure and the loose charge. Representative examples being shown below:



Whinchat VB



Javelin S15
(Crake)

2.3.1.2.2 Operation

The obturator is normal a rubber item either moulded in situ or moulded and subsequently fixed by adhesive to the motor tube nozzle end closure. Its main objectives are to provide a seal between the end face of a loose charge and either or both the motor body or the nozzle end closure, preventing gas flow down the outside of the charge from the higher pressure head end back into the lower pressure nozzle area, it also supports the charge during motor firing. A secondary objective can be to provide the main seal preventing flow of hot gases to the threaded tube joint, or to assist in this purpose if there is also a separate 'O' seal included in the design, ie. the Blackcap and Redstart motors.

It should be noted that during motor firing the pressure is greater at the head end than at the venturi end, and this forces the charge against the obturator assisting in the formation of a gas tight seal. Drag forces from the high velocity gases in the motor conduit also assist in forcing the charge against the obturator as does the missile acceleration. The design may be such that compression of the obturator by the charge causes transverse bulging of the obturator against the motor tube providing or assisting in the formation of a gas tight seal in that area.

In the absence of adequate obturation, the flow of hot gases around the outside of the charge could lead to erosion and burning of the circumferential and end inhibitory coatings on the charge. This result in the exposure of the propellant material giving a greater burning surface area, higher pressures and leading subsequently to possible failure by overpressure of the motor structure. There is also the possibility that the flow of hot gases along the outside of the charge will burn and erode any heat resistant coating applied to the inside of the tube resulting in heating of the metal tube, lowering the mechanical properties of the material and ultimately failure under normal motor pressures. Failure of the obturator could also allow hot high pressure gases into the region of the threaded joint, again leading to heating and erosion of the structure and ultimately failure at normal motor operating pressures. It is of course likely that any of the above failure modes will occur simultaneously in the event of obturation failure.

2.3.1.2.3 Design consideration

To ensure the minimisation of failures both the design and manufacture of obturation systems need to be undertaken with care. The following aspects should be noted during the design of a suitable safe and reliable obturator. Additionally care should be exercised in the design of the associated loose charge (see Section 2.4.7.1).

Physical considerations:

The material chosen should be:-

a explosively compatible
b chemically compatible
c resiliant over the operating temperature range of the motor, of a hardness compatible with the loads to be supported and compressible to form the necessary charge to nozzle end closure seal and the pressure vessel seal if required. A suitable satisfactory material is Butyl Rubber to Def Stan 93-4.
d The surface finish of the moulded obturator on its mating surfaces should be of 'O' seal standard and free of flash lines.
e It should be free from pitting, crazing, blisters or soft areas. It should also be free of inclusions ie metallic-non-metallic or hard cured rubber.

Dimensional considerations:

The design should be such that

a) The surface, which is to mate with the end face of the charge, should when in position in the assembled motor lie as square as possible to the axis of the motor tube. Thus the geometric squareness of the nozzle/obturator should be closely controlled.

b) The obturator design should cater for the maximum possible misalignment between the loose charge and motor axis over the whole operating temperature range.

Manufacturing considerations:

During the manufacturing and assembly processes the obturator should be kept free of surface contamination.

2.3.2 Body Lining

Rocket motor bodies in the majority of cases need to be protected by lining with an insulating material. In many instances this lining not only provides a heat insulation layer but a layer of material that will protect the case from the very high erosive conditions that can occur within particular the areas of the motor body subject to propellant gases throughout the burning time of the rocket motor. This protection ensures that the motor body components retain adequate strength throughout.

This section includes the body lining for cartridge loaded charges, and case bonded charges for the CDB, EMCDB and composite (HTPB) propellants.

The material used to insulate the structural part of the body that would otherwise be exposed to the propellant gases is usually rubber. However, for blast pipes and other areas of very high erosion (due to high velocity gases), reinforced plastics such as resinated asbestos may be beneficial, or possible a combination of both flexible and rigid materials. Reinforced plastics also tend to give off less smoke than rubbers in high stress areas.

The thickness of the material used is based largely on previous successful designs, the chose size being modified as required during the development stage.

The main advantages that rubbers have over the rigid insulation material are:

1 Lower thermal conductivity
2 Higher heat energy dissipation on degradation
3 Mechanical properties which are a better match for adjacent propellant, but simultaneously allow for structure movement.

Most 'rubbers' consist of a base elastomer to which curing agents, accelerators and fillers have been added to give specific properties to the finished 'rubbers'.

Three base elastomers have been used in rubbers these being:

i) Chloroprene (Neoprene) now superseded by
ii) Chlorosulphonated polyethylene CSPE (Hypalon) and
iii) Ethylene propylene terpolymer, EPDM (Royalene)

The first of these, Neoprene, was used primarily due to its availability and acceptable performance. Hypalon proved to be eminently satisfactory but has a relatively high density. EPDM was chosen after extensive research as the elastomer capable of absorbing most energy on degradation, excluding fluoro-carbons which are often intractable materials.

The latter two materials Hypalon and EPDM are currently used for insulating bodies. These can either be in a sheet or moulded form.

Thicknesses of rubbers are usually based on those used in previous successful designs. The thickness is proved by firing trials during development and modified if necessary.

A 'Heat Transfer Program' for the prediction of rubber thicknesses has been developed. (See TN 82/57 and TN 83/3).

Thickness used on motors are shown in Table 5, and graphically interpreted in figure 26. When using this information particular care should be taken to ascertain the time the rubber is exposed to hot gases considering the protective properties of propellant and inhibitor.

2.3.2.1 Body Lining for a Cartridge Loaded Charge

The insulating material that lines the body is usually bonded to the motor case using adhesive described in Part 3 of TN79/49. Generally the materials are vulcanised into position within the body however for some less severe environments cured material can be adhesively bonded into position using for example Pliobond 20. Spin coating techniques may also be considered for the application of some insulation material.

It may be possible to leave the body unlined and rely on the charge inhibitor to provide sufficient protection during the burn. The motor for the MILAN anti-tank missile using the Sutra E593 charge operates on this principle., A very good fit between charge O.D and body I.D must be ensured to guarantee that there is no gas flow around the outside of the charge.

Some useful reference documents are:

Technical Note TN 85/40 Ablation of Rocket Motor Body Lining Material
TN 87/8 Elastomeric Lining Material (EPDM)
TN 86/5 Body Lining Design Manual

All lining materials used within the motor chamber must be compatible with the propellant being used.

2.3.2.2 Body Lining - Case Bonded CDB/EMCDB

The principles for body lining case bonded charges for (CDB/EMCDB) are the same as that described in 2.3.2.1, except at the vulcanising stage a propellant bonding component is added to the surface before curing the rubber.

In designing the lining a major consideration is the rigidity of the propellant and temperature environment the motor will be subjected to in service. If unacceptable strains will be experience in the propellant relief sections in the lining should be considered.

a) Relief sections generally are in the following form:

i) Peripheral Stress Relief (PSR) is generally used over the length of the radial section of a slotted radial charge design, not exceeding two thirds the length to enable temperature effects in the unslotted section to be minimised on charge contraction. Thickness of lining material must be considered and thickening at the joint of intersection between the relief and case bonding must be considered. Generally a one piece lining sheet over the PSR and case bonded section is advisable.

ii) Flap bellows or boot used at the forward or aft end of the body is used in the same way to give propellant stress relief at the ends to avoid unidirectional stresses in the charge.

When introducing these relief sections the body should still be lined behind the relief and a parting agent introduced between the two layers of rubber to avoid bonding them together.

Body hydrostatic pressure testing of linings with relief sections should be thoroughly dried in an oven afterwards to ensure all water has been driven out from behind the loose linings or when using PSR it is advisable to hyrostatic pressure test with a rubber bladder to prevent water ingress completely.

2.3.2.3 Body Lining - Composite Propellant

The following information outlines the main considerations when choosing a body lining material for use in conjunction with composite propellant. More specific information is available from the Materials Department and is referenced in their Operating Manual OM90/4.

2.3.2.3.1 Cartridge loaded charge

The only material used in the UK to date is Hypalon. However other types have been used in development including EPDM7225 and 7806, (Rowanite 8202) and castable systems such as LR69 (Rowanite 8203) and LPA5 (Rowanite 8201). No examples of cartridge loaded composite motors are in production at this time.

2.3.2.3.2 Case bonded charge

The material used depends upon the design of the charge conduit. Where the charge is designed such that part of the case is exposed relatively early in the burn, insulation and erosion characteristics are required. Suitable materials used to date in this role are Hypalon and LR69.

Where the charge burns out uniformally and the case is only exposed at the end of burn, minimum insulation only is required and materials such as LPA5 have successfully been used as a non erosive insulant.

Examples of motors/insulations in case bonded configuration are:

Hoopoe	Hypalon
Oystercatcher	LR69
VT1	EPDM 7225
Serrin	LPA5

2.3.2.3.3 Reinforced plastics

In areas where heavy erosion protection is required (eg blastpipes and/or nozzles) rigid materials such as resinated asbestos or carbon composites are used.

High erosion areas also exist within the motor tube body (eg vent end of Hoopoe) and again these high erosion materials must be used.

Suitable materials used to date are:

RA51 - resinated asbestos
XM1006 - resinated glass fibre
RA1 felt - asbestos felt
PM173 - carbon composite

2.3.2.3.4 Lining processes

The actual processes used to line the tube is basically dependent upon the material being used.

eg	Hypalon	i) moulded and bonded
		ii) moulded in-situ
		iii) spun or cast
		iv) laid up as sheet and bonded
	Asbestos	i) moulded in-situ
		ii) laid up and bonded

Other lining materials are assembled using techniques similar to those outlined above, depending on the material.

2.3.2.4 Body Lining - Blast Pipes

Blast tube liners are usually plastic reinforced to improve their mechanical properties for use as rocket motor insulants. The plastic constituent is conventionally a phenolic resin reputed to retain its cyclic ring structure even after appreciable head degredation, thus helping retain the charred residue in position.

The reinforcement is usually fibrous. For greatest efficiency the fibres should be orientated in an optimum direction but for cheapness and simplicity of tooling random fibre is very often acceptable.

When reinforced plastics are used around the throat insert it must be strong enough to transmit loads from the insert to the load bearing shell, both radially and axially and must not lose this capability because of charring or thermal expansion. This is discussed in section 2.2.4.

There are two basic methods of manufacturing blast tube insulating liners, these being:

i) the liner is moulded and then assembled into the shell and bonded in position

ii) the liner is moulded directly into the load bearing shell.

The most commonly used liner material is asbestos-phenolic although silica phenolic or carbon phenolic may be used.

Asbestos-phenolic moulding materials are available in the form of felt and flock and there is no significant difference in the performance of the finished moulding under most uses. Felts lend themselves to relatively flat components, where some of the insulation is structurally unsupported and where adhesion to the support is required. Flock and maserated felt are used for intricately shaped or high length to diameter ratio mouldings since the fibre has random properties as well. However, in combination with certain propellants, an incompatibility has been observed with the use of flock containing the "Novolak" resin, with rapid depletion of the prime propellant stabiliser. See reports on E587 and E599.

Care has to be exercised when moulding in-situ to ensure that the plastic material does not shring from the structural support as it cools from the mould temperature. Resinated asbestos can be readily moulded inside aluminium but when moulding inside steel very coarse keying is required to ensure retention of the insulation.

High density material give the best resistance to erosion. The theoretical density depends upon the densities of the resin and fibre and their relative proportions. For example, for Durestos RA51, values over 1.70 Mg/m^3 are satisfactory, whilst values over 1.76 Mg/m^3 are rarely achieved. Matched metal mould tools are required to achieve these densities.

Silica fibre reinforced resin has a higher erosion resistance than asbestos phenolic but also has a higher thermal conductivity, especially along the silica fibres. Thus its attack rate is higher.

Carbon-fibre reinforced phenolic has even higher thermal conductivity and improved resistance to erosion than silica-phenolic.

One problem that has been encountered with asbestos and silica phenolics is that the eroded debris is in the molten state and flows along the blast tube and expansion cone walls. Theis debris can jam moving parts such as those associated with TVC systems. This problem can be overcome by the use of carbon phenolic; propellant changes can also be beneficial in eliminating calcium from the NC and thus the slag, calcium silicate formation.

Grades of reinforced plastics, with some of their properties, are shown in table 6. Blast tube thickness used at Summerfield are given in table 7, the most typical are shown graphically in figure 27.

Table 4. Grades of Insulating Rubbers

Material	Specification	Density (kg/m^3)	Thermal Capacity per unit mass ($J/kg\ ^oC$)	Thermal Conductivity ($Jm/m^2s\ ^oC$)	Thermal Diffusivity (m^2/s)	Tensile Strength (MN/m^2)	Elongation to break (%)	Hardness (^oBS)	Coefficient of Linear Expansion (per ^oC)	Data on Adhesive Bond-ability to metal and itself	Data on Stress-Strain properties +60 to -40°C	Data on Storage Life and General Developmen
eoprene K1468	Admiralty K1468(c)	1850	-	-	-	5.8	400	80	-	-	-	-
yplon CL2759	Vulcanised sheet: Admiralty K1555	1790	2300	0.39	9.5×10^{-8}	9.5	120	85	2×10^{-4}	-	-	-
)	Unvulcanised sheet: IMI/SRS/104	"	"	"	"	"	"	"	"	SRS User Test Manual IMI/SRS/50 UTR 1	IMI Tech Note SRS72/21 "	IMI Tech Note SRS72/32 "
	Unvulcanised Moulding slab IMI/SRS/44	"	"	"	"	"	"	"	"	UTR 2	"	"
ypalon CL8436	AFS623(A)	1430	-	0.26	-	15.0	400	75	-	-	-	-
ypalon CL8980	IMI/SRS/41	2860	-	-	-	10.0	50	-	-	-	IMI Tech Note SRS72/21	-
PDM CL8509	IMI/SRS/45	1380	-	-	-	6.9	500	50	-	IMI Tech Report SRS70/1	-	IMI Tech Report SRS67/11
PDM CL8799	IMI/SRS/46	1400	3000	0.30	7.4×10^{-8}	6.9	500	85	-	IMI Tech Report SRS70/1 IMI Tech Note SRS70/23	IMI Tech Note SRS72/21	IMI Tech Report SRS67/11
PDM CL11184		1290				6.9	500	85	-	-	-	-
PDM CL1187	IMI/SRS/51	-	-	-	-	-	-	-	-	-	-	-
PDM CL11248	IMI/SRS/110	-	-	-	-	-	-	-	-	-	-	-
PDM CL7170	IMI/SRS/182	1300	-	-	-	-	-	-	-	-	-	-
PDM CL7225	IMI/SRS/231	All data IMI/ROS/TR 87/8										
PDM CL7806	IMI/SRS/317	All data RO/RMD/TR 82/2										

FIG: 26

BODY LINING THICKNESSES V BURNING TIME.

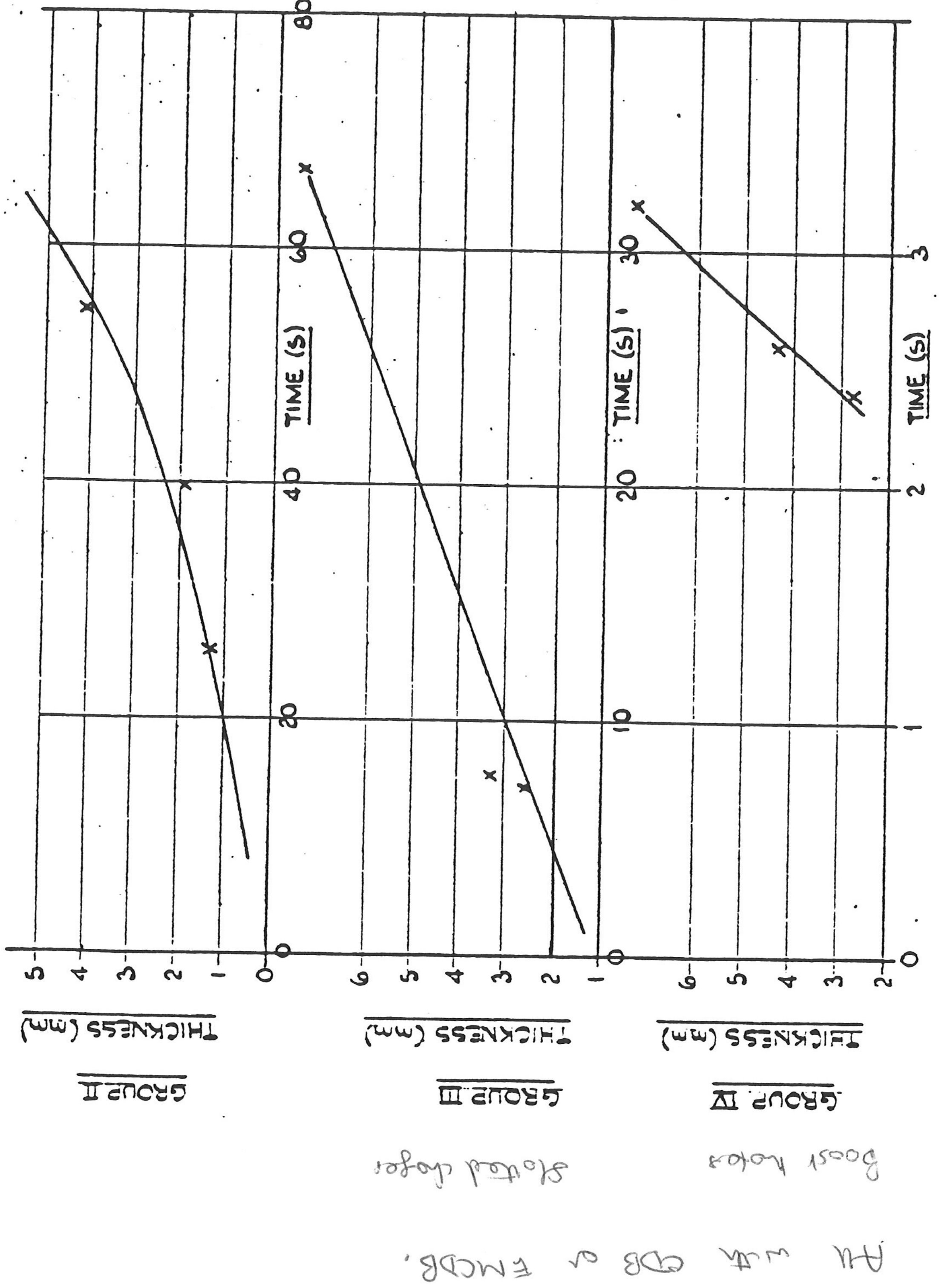


Table 7. Reinforced Plastics Blast Tube Thicknesses Used

Motor	GA Drg.No.	Blast Tube Drg.No.	Av.Pressure (b)	Burning Time (s)	Reinforced Plastic: Grade	Reinforced Plastic: Thickness (mm)	Comments
E532 Sealyham	WD70800	WB70529	89	1.1	Asbestos string E532/13 (ICM)	1.3	Boost
		WB70526	92	14.9	Asbestos string E532/12 (ICM)	3.8	Sustain
E556 Vigilant	WC45000	WB45034	154 + 34	2.3 + 9.8	Asbestos string Railko 7/305	2.5	
E561 Troy	WD50360	WB50231	104 + 28	1.1 + 6.1	Durestos RA 51	4.2	
E597 Thermopylae	OW120578	2W120257	135 + 45	1.1 + 4.8	Durestos RA 51	4.2	
E552 Pointer	WD62400	WD62395	94 + 29	5.5 + 20.4	Durestos RA 51	5.3	
E515 Wolfhound	WD17890	WC17992	50	39.7	Asbestos string Mintex	8.6	
E528 Foxhound	WD150500	WB150516	50	35.9	Asbestos string Mintex E528/7	9.5	
E547 Deerhound	WD151500	WD151515	39	33.5	Asbestos string Railko 7/305	10.8	
E587 Matapan	MWD220010	MWB220272	30	55.1	Durestos RA 1	13.5	
AJ168 (330 mm)	MWD330000	MWB330020	42	92	Durestos RA 51	17.7	
E598 Cadiz	OW 191799	1W191517	120	2.5	Carbon phenolic PM173	6.5	Non-asbestos mtl
E580 Jena	MWD160705	MWD160519	50 + 31	4.7 + 3.3	Carbon phenolic PM173	6.4	Non-asbestos material
E533 Saluki	WD230000	WD230309	136 + 31	6.3 + 20.1	Asbestos string Mintex	12.7	Early design
E573 Narva	MWD171343	MWC171268	112	65.6	Durestos RA 51	19.7	High pressure, long burn time
E593 Milan	1W2281	BAe893191	170 + 7	1.0 + 11.0	Silica phenolic MMS 894585	3.5	Non-asbestos mtl.

NB: Last five motors non-typical for reasons shown. Not graphed in Fig. 2.5.1

2.3.3 Resonance Rods

These items are used to mechanically suppress unstable burning that would otherwise occur within the conduit of a charge. A resonance rod simply acts as a baffle to any suppress unstable flow conditions that would occur. The rod is normally attached at the forward end of the motor, off the forward closure, igniter or supporting spider. The length and shape of the rod will depend upon the severity of the instability.

Many different shapes have been used in the past from round rods to cruciform sections in various materials from steel to carbon fibre pultrusions.

A better method that should be given first consideration is the use of particulate damping that is refractory particles that are incorporated into the propellant.

For advice on the best method of suppressing instability for a particular motor contact the performance and propellant Technical Authories.

COMMERCIAL- IN- CONFIDENCE

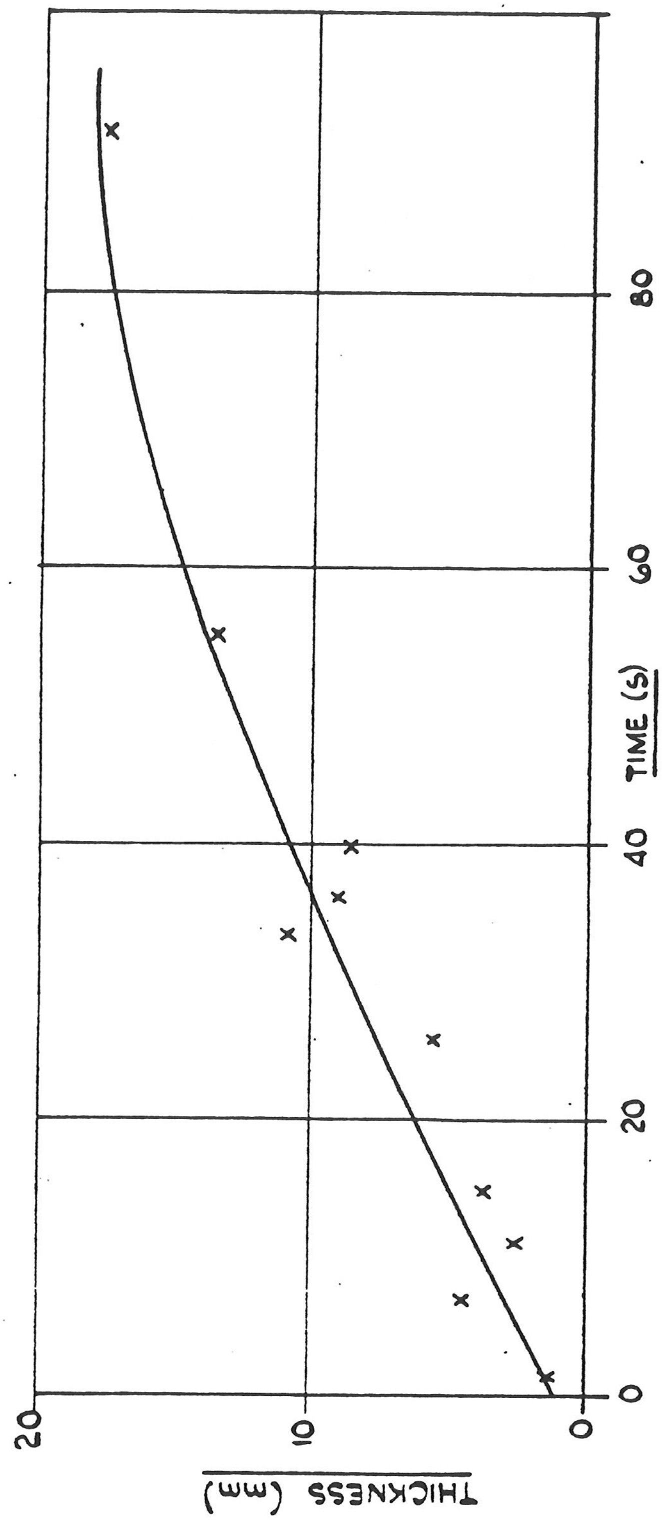


FIG 27

BLAST TUBE LINING THICKNESSES
v BURNING TIME.

COMMERCIAL- IN- CONFIDENCE

Table 6. Grades of Reinforced Plastics

Material	Specification	Density (kg/m^3)	Thermal Capacity per unit mass ($J/kg\ ^\circ C$)	Thermal Diffusivity (m^2/s)	Young's Modulus (GN/m^2)	Tensile Strength (GN/m^2)	Extension to break (%)	Coeff. of linear expansion (10^{-6} per $^\circ C$)
Asbestos string - phenolic ex Railko Mintex or ICM	7/305 E528/7 E532/12,13	1630	-	-	-	-	-	-
Asbestos flock - phenolic grade Durestos RA51/57	DTD5539 or AFS1242	1700	1400	2.7×10^{-7}	-	0.04	0.4(flat sample)	15
Asbestos felt - phenolic grade Durestos RA1	DTD5511(A) or AFS1241	1680	-	-	23 (A direction) 14 (B direction)	0.17 (A direction) 0.12 (B direction)	0.8(flat sample)	9 (A direction) 15 (B direction)
Silica cloth - phenolic	MJC - RC2	1700	900	2.5×10^{-7}	17	0.09	-	4
	MMS894585	-	-	-	-	-	-	-
Glass cloth - phenolic	MJC - RC2	1800	850	2.8×10^{-7}	23	0.41	-	-
Carbon flock - phenolic grade PM173	RS 1016	1500	-	-	-	0.032	0.8(flat sample)	6
Glass flock - phenolic grade XM.884	IMI/SRS/278	1700	-	-	-	0.04	0.35(flat sample)	-

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Table 5. Rubber (Except Group 1) Thicknesses Used

Nominal Motor Characteristic	Motor	GA Drg.No.	Body Insulation Drg.No.	Average Pressure (b)	Burning Time (s)	Rubber (except Group 1)		Comments
						Grade	Thickness (mm)	
Group I: Non-rubber insulation	E556 Vigilant	WC45000	WB45013	154+34	2.3+9.8	Polythene	1.5	Body parallel section
	E596 Dwina	2W101179	3W101179	120	2.2	Durestos	0.4	" " "
	E599 Riga III	2W101250	2W101063	100	6.0	Durestos	1.6	" " "
Group II: SCB Charges	E552 Pointer	WD62400	WC62409	94+29	5.5+20.4	CL8980	1.3	" " "
	E515 Wolfhnd	WD17890	WD17979	50	39.7	K1468	1.9	" " "
	E587 Matapan	MWD220010	MW220012	30	55.1	CL2759	4.1	" " "
	E573 Narva	MWD171343	MWB171212	112	65.6	CL8799	6.0	" " "
Group III: Slotted regions	E561 Troy	WD50360	WD50399	104+28	1.1+6.1	CL2759	2.6	Slotted regn.& burnbk.
	E597 Th/pylae	OW120578	OW120524	135+45	1.1+4.8	CL2759	2.2	Slotted regn & burnbk.
	E580 Jena	MWD160706	MWD160412	50+31	4.7+3.1	CL2759	3.4	" " "
	E547 Deerhnd	WD151501	WD151507	39	33.5	CL2759	7.5	" " "
Group IV: Boost motors	E579 Magenta	MWD191072	MWD190948	117	2.4	CL2759	2.8	" " "
	E557 Chow	WD190550	WC190418	110	2.6	CL2759	4.3	Aft body insulation
	E554 Retriever	WD100610	WB100250	102	3.2	CL2759	7.5	Aft clos.insulation
	E598 Cadiz	OW191799	1W191423	120	2.5	CL7225	3.1	Slotted regn.& burnbk.
	E600 Taranto	OW191800	OW191794	130	2.5	CL2759	2.8	Slotted regn.

SECTION 4

Charges

2.4 CHARGES

2.4.1 Charge Design

The Ballistics and Maths Department (BMD) is responsible for the charge design of solid rocket motors, and the charge design is carried out generally in accordance with the following Documents:

i) 101 924-23/2/HQ - BMD Manual
ii) 101 941-23/3/SU - BMD Design Aids for Solid Propellant Rocket Motors

iii) RMD various computer programs used in motor design. (Index of titles maintained by BMD).

The responsibilities of the BMD include, but are not limited to:

o Charge, and where necessary, nozzle contour design in accordance with the relevant technical requirements.

o Ballistic performance, including performance of internal hardware affecting ballistics of motor grain and pyrogen igniter.

o Ballistic acceptability of casting powder, casting liquid, powder blends, EDB propellants and composite propellants.

o Acting as Technical Authority for performance (advising the Project Manager accordingly).

A full definition of the BMD's personnel's terms of reference are available in ref (i) above. BMD personnel are responsible for the retention, checking, approving and storage of the design calculations in accordance with the precedures laid down.

Other useful references include:

i) Solid Rocket Propulsion Technology
(Alain Davenas - SNPE)

2.4.2 Erosive Burning

The BMD tables guides to the design of charges to minimise the onset of erosive burning in 101 941-23/3/SU.

However, if this criteria cannot be met, the BMd predict the effects of erosive burning by running the Lenior Robillard Prediction Program (LRPP). This program produces pressure/time and thrust/time profiles and associated ballistic analysis for multiple charge motors, and allows for the effect of erosive burning applying the theory developed by Lenior and Robillard.

Further details available through the BMD Manager.

2.4.2.1 References

1. 101 941-23/3/SU - BMD Design Aids
2. LRPP - Software Program
3. BD15 - Investigation on the erosive burning of CDB propellants
4. TR68/10 - Erosive burning of solid propellant.

2.4.3 Instability

Methods that the BMD use to eliminate unstable burning are detailed in the following reports:

101 941-23/3/SU - BMD Design Aids

BD32/36 - Practical Aspects of Unstable Burning with CDB Propellants

TR64/9 - Combustion Instability in CDB Solid Propellant Rocket Motors

TR77/5 - Interim Report into the Suppression of Combustion Instability

SSP/D - BMD Computer Program

TR81/1 - The Use of Silicone Carbide as a Combustion Instability Suppressant in Radial Burning Solid Propellant Charges.

2.4.4 Structural Integrity

The BMD is responsible for analysing the thermally induced and pressure-induced stresses and strains in the charge. The BMD personnel work in conjunction with the Project Manager in order to achieve a design which is structurally sound.

2.4.4.1 Stress Relief

There is a general tendency for tactical weapons to have high length to diameter ratios, primarily to keet aerodynamic drag loads down as low as possible. This results in the propulsion motor also having a high L/D. Case bonded motors with high L/D ratios are subject to hoop strains, stresses imposed by longtitudinal expansion/contraction, peripheral stresses, etc, and thus may require stress relief in such key areas: techniques employed in order to facilitate relief are detailed below, and further information on analysis carried out by BMD for bond-line stresses at termination points, stress concentration areas, transition regions, etc. is available in document 101 941-23/3/SU.

2.4.4.1.1 Stress Relief at Ends (needs and techniques)

Case bonded motors with high L/D ratios may require relief at one or both ends depending on design to alleviate stresses imposed by longitudinal expansion/contraction due to the thermal environment with the periphery bonded to a stiff case.

End flaps or "boots" are provided to give end relief and take the form of split thickness of body insulation over a burn-back distance from the end. The outer layer is bonded to the motor case, the inner layer is bonded to the propellant and a separating medium is included between the two layers. These flaps may be essentially parallel with the motor body or form part of all of a "bottle end".

Depending on the shape, they may be moulded or vacuum formed. in some instances it is necessary to seal the flap so that propellant components cannot be introduced during casting.

2.4.4.1.2 **Longitudinal Stress Relief (need and techniques)**

For high L/D ratios, case bonded charges in radial configurations are subjected to hoop strains which will eventually, as the temperature decreases, cause radial cracking. The high loading densities required in most designs mean that longitudinal stress relief is necessary.

The relief takes the form of 2 or more inhibited slots running longitudinally through the propellant web. The inhibiting units are held in place in the casting equipment and subjected to case bond adhesives in the same manner as the body lining. The units are "V" shaped with some reinforcement at the base of the "V" which is adjacent to the motor body.

An advantage of this system is that as the units protrude into the conduit to allow them to be supported in the core, they act as resonance suppressants, and are more effective than the resonance rod (see para 2.3.3).

In the case of slotted radial configurations, these longitudinal stress relief units are only in the radial portion of the charge as the slots provide sufficient relief in themselves. For other designs i.e. star centres, clover leaf etc, the relief is provided over the total length.

2.4.4.1.3 **Peripheral Stress Relief (need and techniques)**

Longitudinal stress relief units have been shown adequate for, in particular, case bonded slotted radial charges down to -35^{o}C. However, there are very large bonding areas involved for each unit and thus the application is specialised and requires high levels of inspection to produce a consistent product. Peripheral stress relief for slotted radial charges has been developed to overcome the above problems. This method allows the radial portion of the charge to act as a loose charge, and the slotted portion to remain case bonded. In effect, the end flap system (para 2.4.4.1.1) has been extended at one end for the whole of the radial portion.

Charges with this relief can tolerate lower temperatures than with longitudinal units and the volume lost to propellant is reduced. There is no more extra bonding area and the only essential design criteria is to ensure that the unslotted end of the charge cannot obturate the gap behind the charge causing large differentials.

Unstable burning is not suppressed by this system, and thus in the case of non aluminised propellants some other method has to be employed.

2.4.4.1.4 Choice of Systems and Design Considerations

Much of this has already been covered but some of the essential design considerations are listed below. All comments are applicable to conventional and composite modified cast double base case bonded charges.

(1) Full soak temperatures below -10^{o}C with high loading density and high L/D ratio will almost certainly require stress relief.

(2) Stress relief may be necessary at temperatures above -10^{o}C where high L/D ratios are involved.

(3) Longitudinal stress relief is applicable down to -35^{o}C for all radial burning configurations.

(4) Peripheral stress relief is superior to (3) for slotted radial designs and may be of use on stepped star centre charges.

(5) Case bonding will generally produce a lighter all up mass, but economically loose charges may in some instances be better - particularly where charges can be cast in multiples.

6) These stress relief systems are utilised in case bond motors employing conventional unfilled and filled (CMCDB) propellants where the operational conditions induce strains in excess of the capability of these propellants. In the case of elastomer modified propellants (EMCDB), such devices are in practice not required for designs employing a volume loading factor of 96%, and induced strains in excess of 70% at -40^{o}C.

2.4.4.1.5 Stress Relief Devices - Material and Manufacture

The materials used for the manufacture of stress relief devices or concepts are essentially those employed for motor body lining operations.

As defined earlier, three systems employed to relieve stresses in case bonded motors are:

1) End flaps or boots
2) Longitudinal stress relief devices or slot inhibitors
3) Peripheral stress relief designs.

1. **End Flaps**

These are usually manufactured from Hypalon CL2759 rubber. Depending on the complexity of the end flap arrangements, a laying-up process from rubber sheet, or mouldings manufactured by compression moulding or vacuum forming can be utilised. The end flap is usually sealed during the casting operation to prevent (a) ingress of casting liquid, or (b) expansion of air into the propellant. The flapseal is cut open after propellant cure to effect the necessary relief.

The rubber to rubber bonds can be effected by Redux 775 adhesive or CL8980 solution, the rubber to metal bonds by Redux 775 adhesive and rubber to propellant by Redux Formvar adhesive system.

2. Slot Inhibitors

These devices effectively segment the radial part of the charge propellant, so length and shape will be dictated by the propellant and lined motor geometry. Generally specially designed jigs are constructed to form the slot inhibitors to size and shape.

The material used to produce these items is generally Hypalon CL2759 rubber, although other materials such as Hypalon CL8980 or ethylene propylene rubbers could be considered for smoke emission or weight reasons.

The normal techniques is to build up the shape and thickness of the slot inhibitor from various thicknesses of rubber sheet cut to size and placed in the jig. The whole assembly is cured at a predetermined time and temperature. Again rubber to rubber bonding is obtained by the use of Redux 775 solution or Hypalon CL8980 paint. The surfaces in contact with the propellant are coated with Redux Formvar adhesive.

Considerable care must be maintained when fitting slot inhibitors into lined motor tubes to ensure no gaps are evident between the motor wall and spline of the slot inhibitors.

The lining of tubes can be modified to ensure a good fit during assembly.

3. Peripheral Stress Relief Concept

The normal lining procedures and materials described earlier are used for the manufacture of peripheral stress relief motors. The essential innovation is a peripheral gap between the motor tube and propellant which has to be maintained over the radial part of the charge. This is achieved by establishing the correct rubber lining thicknesses to (a) insulate the propellant, and (b) protect the motor tube during firing. This will depend on charge configuration and propellant combustion characteristics such as burning time and flame temperature.

The peripheral gap is maintained during lining and casting by inserting a sheet of parting agent between the motor tube lining and the propellant insulation to prevent bonding or stiction in this area. Materials such as Tygaflor sheet, PTFE and polythene sheet can be used. These remain in position during the life of cast motors.

If the relief gap has to be extended in the burn-back region of the lining, then additional lining must be introduced to prevent burning through via the peripheral gap during firing.

One of the big advantages of the peripheral stress relief concept is that a higher temperature, e.g. 65^{O}C can be applied during propellant consolidation, giving considerable improvements in the propellant to rubber bonding characteristics.

2.4.4.2 Radii On Cores

Cores were originally manufactured with sharp corners on star points and slots. While the design information and formulae are based on such assumptions, in practice all corners should have generous radii in order to reduce stress concentrations. It is essential that when giving details of core sizes, appropriate radii are specified for such stress raising corners.

Changes to manufacturing equipment necessitated by the omission of such radii and later introduction can in certain circumstances by very costly. Hence a further reason for introducing these radii initially.

2.4.4.3 References

References that the BMD use are, but not limited to:

1. 101 924-23/2/HQ - BMD Manual
2. Tech Report No 8 - Structural Integrity of Composite Propellant Charges.
3. Handbook of the Engineering Structural Analysis of Solid Propellants (Fitzgerald, JE and Hufferd, WL)

2.4.5 Propellants

Solid propellant is a generic term for a substance which burns in a rapid, controlled manner. Conventionally, it is one of two types, either involving a mixture of separate fuel (binder) and oxidiser, or consisting of chemical components, the molecules of which contain fuel and oxidiser. A typical propellant of the latter type is comprised of nitroglycerine (NG) and nitrocellulose (NC) with the addition of chemical stabilisers and burning rate modifiers: this is known as a DOUBLE BASE propellant, manufacture being normally by casting or extrusion. The propellant of the former type is known as a COMPOSITE propellant.

The choice of a propellant for a particular application can depend on several factors, the most obvious one being the need for the selected propellant to posses suitable burning characteristics so that when used in a particular charge configeration the required internal ballistic performance is realised. Other factors are:

- o Charge to be mechanically strong enough to withstand large temperature variations without fracture or bonding failure
- o Ability to withstand and function satisfactorily under high axial and lateral accelerations.
- o Exhaust to be compatible with the requirements of guidance radiation, optical tracking and disclosure aspects.
- o Burning instability must be controllable
- o Service life must be adequate, and any drift in ballistic performance must be with-in limits.

2.4.5.1 Cast Double Base Propellant

2.4.5.1.1 Nomenclature

CDB: Cast-double-base, the "double base" being NG and NC.

CMCDB: Composite modified cast-double-base: cast double base propellant have the addition of fuel (normally aluminium) and oxidiser (normally ammonium perchlorate).

EMCDB: Elastomer modified cast-double-base: cast double base propellant matrix modified to include an elastomer system.

2.4.5.1.2 General

Two major classes of propellants are manufactured, these are the conventional unfilled and filled cast double base (CDB) and unfilled and filled elastomer modified cast double base (EMCDB) propellants. The nitrogen content of the nitrocellulose used is 12.6% based on mechanically nitrated cotton.

Unfilled CDB Propellants

The main features of unfilled CDB propellants are given below:

1. Good chemical stability with long service life of up to 20 years.

2. Wide range of burning rates available 2.5 - 36mm/s on plateau pressure ranges of 20/35 - 90/200 bar with excellent reproducible performance.

3. Very low levels of smoke emission, when fired with smokeless inhibition system, axial smoke levels of 0.25 dB for 150mm diameter motors are achieved.

4. Propellant formulations for cartridged loaded charges or case bonding applications are available.

5. Large proofed batches up to 20 tonnes of casting powder can be supplied, ensuring consistent and reproducible performance for ballistic parameters.

6. Casting powder lots can be blended together to give propellants with a wide range of ballistic properties.

7. Process flexibility means no practical limits to charge length and diameter, high loading density with duplicated charge configurations, dual or multi-thrust performances from one charge are available.

Main Performance Parameters

Burning rate	mm/s	2.5-36 on plateau
Plateau pressure range	bar	20/35 - 90/200
Density	kg/m^3	1560 - 1610
Flame temperature	K	1500 - 3000
Temperature Coefficient	$\pi_k (\%/^{o}C)$	0 - 0.3
Achieved specific impulse	Ns/kg	1800 - 2300

Filled CDB Propellants

The development of filled CDB propellants has resulted in much higher energy and density characteristics than the unfilled types. Relatively high filler loading level, in the order of 50% of metal fuel and oxidisers, such as ammonium perchlorate and nitramines are introduced in the propellant via the casting powder. These propellants retain all the essential features described for the unfilled propellants.

The ballistic properties of typical ammonium perchlorate/metal fuel filled propellant is given.

Filled CDB propellants, which retain the low smoke emission typical of unfilled propellants have been developed. These propellants with filler loading levels up to 50% nitramine exhibit excellent plateau characteristics with burning rates of 6mm/s to 21mm/s over 30 - 150 bar pressure range specific impulse figures of 2320.

Main Performance Parameters for CMCDB

Burning Rate	mm/s	10-35 at 70 bar
Plateau Pressure Range	bar	Pressure exponent 0.35
Density	kg/m^3	1750
Flame Temperature	K	3800
Temperature Coefficient	π_k(%/^oC)	0.5
Achieved Specific Impulse	Ns/kg	2450

Unfilled EMCDB Propellants

A recent major advance in propellant technology has been achieved by the development of a new class of propellants known as elastomer modified cast double base propellants. The propellant matrix has been modified to include an elastomer system which gives the propellant a low temperature strain capability comparable to that of the HTPB and CTPB propellant types. Elongations of 20% at -40^{o}C are attained for JANNAF tensile specimens.

All the desirable features, such as plateaunisation, smokelessness, flexible processing, case bonding, good service life, etc., of the unfilled CDB propellants are retained.

Main Performance Parameters

Burning Rate	mm/s	5-25 on plateau
Plateau Pressure Range	bar	20/35 - 90/200
Density	kg/m^3	1550 - 1600
Flame Temperature	K	2600 - 2900
Temperature Coefficient	$\pi K (\%/^oC)$	0.1 - 0.3
Achieved Specific Impulse	Ns/kg	2000 - 2300

Filled EMCDB Propellants

EMCDB propellants can be formulated to include fillers such as metal fuels, perchlorates and nitramines to give specific impulse levels comparable to filled CDB propellants. These fillers do not significantly affect the inherent low temperature strain capability. A low smoke version, containing nitramines, is available.

Recent Developments In Propellant Technology

Combustion instability is a recurring problem in rocket motors, particularly with higher energy systems. Propellant formulations, containing additives which suppress instability more effectively than mechanical devices such as resonance rods and yet give only marginal increases in smoke emission, have been characterised. These additives are effective in both CDB and EMCDB propellant formulations.

Full investigation and development programmes into the type and level of suitable additives for boost and sustainer propellants to fully suppress secondary motor combustion have greatly reduced flash and infra-red emissions from rocket motor exhausts. The additives were selected to have the minimum effect on smoke emission.

Burning Adjustment By Liquid

The following may be used as burning rate adjusters:

NG content
SOA - 0.1 mm/s per 1% addition to AS liquids have typically been obtained in combination with OIO type type powders (E585 Riga or E599 Riga III).

2.4.5.1.3 Design

The design of CDB propellant charges is carried out accordingly to the Ballistic and Mathematics Department, Design Aids for Solid Propellant Rocket Motors. This document covers the following design references:

BMD/MDA/01	Gas Dynamics
BMD/MDA/02	General Mathematical Statistical and Gas Dynamic Functions
BMD/MDA/03	Assessment and Performance Data and Design Methods
BMD/MDA/04	Charge Design
BMD/MDA/05	Propellants
BMD/MDA/09	Motor Performance Data

Other useful reference documents which can aid the charge designer are listed below:

1. TN BD 26 "Systematic design of charges for solid propellant rocket motors Part 1 Method of Design" by H M Darwell.

2. TN BD 27 "Systematic design of charges for solid propellant rocket motors Part II Configurations" by H M Darwell and M W Oaks.

3. TN BD 28 Issue 2 "Tabulated functions of gas glow in solid propellant rocket motors" Volumes 1, 2 and 3 by H M Darwell and M J Allen.

4. TN BD 23 "Two chamber dual thrust motors with a single external nozzle Part 1", H M Darwell.

5. "Approximate theoretical calculations of the effect of cylindrical tailpipes on the thrust of a rocket motor" by DM Clemmow PERME Westcott. Pub by RAE Farnborough No RPD18.

6. TN BD 19 "Investigation of the erosive burning of CDB propellants" G F P Trubridge and H M Darwell.

7. AVP 30 (DEF STAN 05-13) Technical Procedure Requirements.

8. AVP 32 (DEF STAN 08-5) Design Requirements for Guided Weapons.

9. RO Summerfield Technical Reports and Technical Notes.

10. "Solid Rocket Propulsion Technology" by Alain Davenas (SNPE).

Some of the texts used by a Mathematician in designing double base charges.

1. Elements of Gas Dynamics by Liepmann and Roshko, Pub John Wiley and Sons.

2. Formulae for Stress and Strain 5th edition by Roark and Yound, Pub Mc Graw-Hill.

3. Stress analysis techniques in rocket motor design, Summerfield Technical Note 85/6 by Dr F R Wallis.

4. Conduction of Heat in Solids 2nd edition by Carslaw and Jaeger, Pb Oxford at the Clarendon Press.

5. Tables of Physical and Chemical Constants 14th edition by Kaye and Laby, Pub Longman.

6. Theory of Elasticity 2nd edition by Timoshenko and Goodier, Pb McGraw-Hill.

7. TN BD 28 Issue 2 "Tabulated functions of gas flow in solid propellant rocket motors" Volumes 1, 2 and 3 by H M Darwell and M J Allen.

8. Rocket Motor Design Handbook Section 6 Nozzle Design by H M Darwell and M J Chase.

9. RO Summerfield Technical Reports and Technical Notes.

2.4.5.2 Extruded Double Base Propellants

2.4.5.2.1 General

Extruded double base propellant was originally developed for guns and known as cordite, before being employed as a rocket propellant in the 1930's. Double base propellant is so called because it consists of two main ingredients, nitrocellulose and a nitric ester, generally nitrogylcerin. The cellulose used for the manufacture of nitrocellulose for EDB propellant is either nitrated bleached wood pulp or mechanically nitrated cotton linters such that the final nitrogen content is of the order of 12.2%, this being the most suitable level for ease of gelatinisation by the rolling process. This nitrocellulose is plasticised or gelatinised by use of nitrogylcerin although esters based on ethylene glycol and other materials have occasionally found usage. Incorporated into this mixture are a variety of ingredients, some examples of which are contained in the following table:

2.4.5.2.2 Typical EDB Propellant Ingredients

Material	Function
Triacetin/Phthalates	Liquid Plasticisers/ Coolants
Cellulose Acetate/Sucrose Octa Acetate	Solid Coolants
Carbamite/2 Nitro Diphenylamine	Stabilisers
Lead and Copper Compounds	Ballistic Modifiers
Potassium Salts/Refractories	Exhaust Modifiers
Candelilla Wax	Extrusion Aid

In addition, RDX has been added as a propellant constituent to provide an increase in impulse (Rowanite 102). Replacement charges in Blackcap and Redstart motors have produced a 7 to 10% increase in impulse. Current UK methods of manufacture rely on a wet mix process in which NG is sprayed onto an aqueous slurry of NC and other ingredients; much of the water removed; and the dewatered sheet passed through heated rollers to give a colloidal sheet. The tightly coiled sheet is then passed through an extrusion die to provide the basic internal charge profile. The final dimension of the charge is achieved by machining and the external surfaces inhibited, as required. Alternative methods of manufacture will result in replacement of wood pulp by cotton linters as a source of nitrocellulose in conjunction with gelatinisation and drying of propellent base material using a shear mill.

Details of charge inhibition using Ethly Cellulose are contained in section 2.4.6. Alternative methods of inhibition are necessary for small charges where stress relief coating is impracticable i.e. The Dox II system has been successfully employed for the inhibition of gas generator charges for Rapier 2000.

The propellant charges as manufactured have a long safe life under normal storage conditions though the relaxation of extrusion stresses and consequent change in charge dimensions has proved life limiting in the case of the VU propellant charge for Blackcap and caused problems in other project motors. An enhanced charge annealing programme has been proposed in an effort to alleviate extrusion stresses but this has never been universally adopted.

EDB propellants can be produced to exhibit a wide range of ballistic performances with burning rates ranging from 2.5mm/second to 50mm/second. Further details of design information are contained in Casting powder/EDB Facility Manual OM92/24. Charge design programmes are described in the Solid Motor Design and Assessment User Guide to Programs (100 211-06/1/WE and 100 213-06/1/WE).

Extruded double base propellants have the normal advantages associated with double base propellants in their low smoke capability. They have particular application in the production of thin webs for short burning time motors. In addition cartridge loaded charges offer the possibility of charge replacement to increase the life of an in-service store.

2.4.5.3 **Composite Propellant**

Currently there are two main groupings of composite propellant, and they are i) rubbery ii) plastic. The major difference between the two is that rubbery composites are cured after motor filling, whereas the plastic type does not require curing.

2.4.5.3.1 **Plastic Composites**

This propellant type is becoming obsolete although it is still manufactured for use in the Pendine sled motor (RD2552) and until recently was used in the Gosling motor (RD2421).

Further details are available in documents listed in the Composite Department Operaring Manual OM90/2.

2.4.5.3.2 **Rubbery Composite**

Rubbery propellant is known to RMD in two forms

i) Carboxyl-terminated-polybutadiene (CTPB) and
ii) Hydroxyl-terminated-polybutadiene (HTPB.

CTPB is not used for any motors in the UK although the USA have used it for the Sparrow and Sidewinder rocket motors.

Hydroxyl terminated polybutadiene (HTPB) propellant is a rubbery composite propellant based on Ammonium Perchlorate (AP) and a rubbery binder. It is a widely used propellant being suitable for both casting and extrusions although the latter process is not particularly common.

Its main advantages are:

a) ease of processing/filling
b) high energy levels
c) relatively cheap
d) capable of operation over wide temp. range
e) capable of achieving wide and varied charge designs
f) capable of being used in dual thrust/one body charges either by charge design or multiple casting
g) fast burning rates available

Main disadvantages

a) smokey - signature
b) unpleasant bi-products of combustion (HCL acid)

Further information on HTPB can be found in the Composite Propellant Department Operating Manual OM90/2.

Thus HTPB is a versatile, relatively cheap propellant but possesses properties which make it less desirable when signature and/or post firing environment are important.

2.4.5.3.2.1 **Cast HTPB**

RO have considerable experience in case bonded HTPB and have used it in motors such as Hoopoe (HT627) Oystercatcher (HT342) and Nuthatch (Rowanite 601).

Cast HTPB is almost always used in a case bonded configuration although RMD does have some experience in casting into beakers for subsequent cartridge loading (Nuthatch).

2.4.5.3.2.2 **Extrudable HTPB**

It is possible to formulate HTPB to have properties which allow it to be extruded through dies to produce a given charge design.

The LAW rocket motor used this technology to produce a sheet of propellant (Rowanite 501) which was extruded, cured then stuck to backing paper and subsequently bonded to the motor tube.

Another possibility with extrudable HTPB is to fill a motor around a former and then remove the former prior to curing although RMD do not have a great deal of experience in this method.

2.4.5.3.2.3 **HTPB Additives**

To allow for variations in HTPB propellant properties, various additives can be introduced into the formulations. Some examples of additives are given below, with more in depth information being provided in documents referenced in OM90/2:-

Molybdenum Trioxide	radar attenuation suppression
Titanium Dioxide	burn rate catalyst/instability suppressant
Zirconium Carbide	instability suppressant
Ferric Oxide	burn rate catalyst
Butacene	burn rate catalyst

2.4.6 Inhibition

There are a number of materials that can be used to inhibit the surface of a charge. These are described in detail in the following sub-sections. For a particular application the various properties and characteristics that a material posseses needs to be considered to ensure that the correct inhibition is chosen for that application.

The relevant Technical Authority should be involved should there be any doubt about an application or choice of material

In addition to chosing a material based on its technical characteristics and performance, some consideration should be given to the ease of processing and cost of the material. The objective being to choose an inhibition system that is cost effective with regard to processing during development and production while being functional to satisfy the design requiremenets.

For a material to function as an inhibitor it is required to have a low rate of heat transfer through it and prevent the propellant temperature, protected by it, from reaching the auto-ignition point (160-180^{o}C).

The inhibitor requires a sufficiently low thermal conductivity, low rate of combustion and/or erosion consumption under the rocket motor combustion chamber conditions.

In practice, this is not as severe a restriction as commonly supposed since a number of low softening temperature thermoplastics have functioned satisfactorily, eg ethyl cellulose, cellulose acetate, polythene. These properties can be compensated within limits by increasing the inhibitor wall thickness. Typical properties of a number of materials are :

Material	Thermal Conductivity cal/cm/s/°C x 10^{-4}	Min. Thickness Inhibitor Wall (mm)*
Polystyrene	2-3	
PVC (Plasticised/unplasticised)	3-4	2-2.5
Phenol Formaldehyde	3.5	
Polymethyl Methcrylate	3.5-5.0	
Polyvinyl Acetate	4.0	2.5
Acetals	4.0	
Ethyl Cellulose	4-6.5	2.5
Cellulose Acetate	4.5-7.5	2.5
Polyesters	5.0	2.5
Polyethylene	2.5	1.5
Hypalon CL 2759	9.5	1.0
Royalene CL 8799	7.2	1.0
Hypalon CL 8980 (iron oxide filled)	6-9? 12	1.0

Material	Thermal Conductivity col/cm/s/°C x 10^{-4}	Min. Thickness Inhibitor Wall (mm)*
Hypalon CL 4851	6-9?	1.0
Neoprene Unfilled	5.0	1.0
Butadiene Styrene	4.5-5.5	
Acrylon Nitrile	4.5-5.5	2.5
Organo-Silicones	3.5-3.7	1.0-2.5
Dox II		1.0
PB40K		1.0

* - These figures vary a little depending on combustion chamber conditions, upper firing temperature, storage life required, propellant plasticiser level etc.

Chemical compatibility with propellant is an essential property of any material and well established standard tests are available for measuring this property. In general most basic polymers if carefully formulated with the necessary ingredients can yield compatible materials with some exceptions, eg polysulphide polymers.

The usual restrictions on the use of materials for inhibition are bondability, mechanical properties and resistance to plasticiser migration from the propellant as well as secondary aspects such as availability, processability and cost.

Many polymers have an inert low energy surface to which it is extremely difficult to bond. Apart from the distinct class of potting/sealant materials the CDB process involves casting the propellant directly into the preformed inhibitor. The propellant bond is formed by diffusion of nitroglycerine into receptive resins such as polyvinyl formal (Formvar). One or more resins/or primers are required to form a bridge between the Formvar and the polymer surface. This bridging resin is required to sufficiently cross-link the Formvar to achieve a bond and render adequate cohesive strength to the plasticised Formvar. Too great a degree of cross-linking of the Formvar would inhibit the propellant diffusion bond process. The bridging resin itself should not absorb nitroglycerine to the point where its cohesive strength is destroyed or its links to the polymer broken. Thus various polymers have specific specialised areas of adhesion which do not lend themselves readily to the process involved.

It is frequently the case that very strong joints are formed when evaluated under tensile or shear conditions. Only a minority show good strength in peel. This is particularly the case with rigid substrates and adhesives. Similarly very tenacious joints may be the case in relatively low rates of loading but high rate of energy input/high impact rates can destroy the bond. Again rigid substrates/adhesive are the most prone to this character.

Distinct from most load bearing adhesive joints the typical inhibition systems can involve solid cylindrical blocks of propellant with an external surface coated with adhesively bonded inhibitor. Differential shrinkage imposes a peeling mode on any bond flaw and if the peel strength is low then unbond propagation can be extensive. The effect is accentuated in solid charges and as the diameter decreases and as the temperature is lowered towards the brittle point of the propellant and inhibitor.

Flexibility, particularly at low temperatures, is therefore an important property of the inhibitor. Stress at the adhesive interfaces is more readily dispersed in elongation of the inhibitor and in so doing part of the peeling mode is converted to a tensile mode. Rigid materials tend to concentrate the stresses at the adhesive interfaces and promote peeling modes.

For similar reasons thermal expansion/contraction mis-match with the propellant is more important with rigid as compared to flexible materials. Where the bond in peel is very tenacious with rigid materials then the mis-match of mechanical and expansion properties frequently lead to cracking/fracture of the inhibitor coating on temperature cycling.

Some typical material properties are given :

	Material	**Coefficient of Linear Expansion x 10^4 per ^oC**	**Elastic Modulus kg/mm^2 at 65%RH***
1.	Phenol Formaldehyde resin -		
	Filled 0.2	up to 2000	
	Unfilled	1.0	600
2.	Hard vulc.eborite rubber	0.7	350
3.	PVC - Unplasticised	0.7	150 - 300
	Plasticised	2.5	
4.	Polystyrene	0.85	250 - 400
5.	Formvar	0.7-0.8	150+
6.	Polyvinyl Acetate	0.7-0.8	150+
7.	Polymethyl Methacrylate	0.7-0.8	350
8.	Nylon 1.0	750	
9.	Cellulose Acetate	1.0-1.5	200 - 500
10.	Ethyl Cellulose	1.0-1.5	350
11.	Hypalon CL 2759	2.0	
12.	Hypalon CL 5980	2.0	
13.	Dox II		
14.	PB40k		
15.	Neoprene Rubber	2.0	
16.	Most Synthetic Rubbers	2.0-2.4	Soft < 10 Hard
17.	Polyisobutylene	2.1	
18.	Polyethylene	2.5	20+
19.	Polyesters (Cross-Linked)	1.0	200 - 500
	Typical Propellant	2.1	

* - These figures are a guide extracted from various sources. The modulus is time dependant and the result is dependent on the exact conditions of the test, sample size, strain rate etc.

As mentioned low temperature properties of polymers are important. Linear polymers will pass through a second order change of state at low temperatures. That is flexible rubber like materials will pass into a relatively inextensible hard state at a temperature commonly referred to as the brittle point. Compounding with ingredients, particularly plasticisers can modify the brittle point within limits. The brittle point is a time-dependent property. Under rapid loading conditions the brittle point is stiffening/loss of extensibility well above the brittle temperature due to progressive crystallinity.

Typical properties are :

Material	**Brittle Point °C**
Natural Rubber	-56
Polyisobutylene Polymer	-54
Butyl Rubber	-50
Polysulphides	-16 to-48 according to type
Neoprene	-33
Butadiene-Acrylonitrile (Hycar)	-12 to -21
Silicone rubber	-80
Hypalon CL2759	-20
Hypalon CL8980	-20
Filled Polyisobutylene CL 5555	-20
Natural rubber CL X 2826	below -35
Natural rubber (Titanium dioxide filled)	below -35
GRS (Styrene/butadiene) filled X 3687	below -35
CL8509 Royalene	-40
CL8799 Royalene	-40
CL8986 Royalene - Iron oxide filled	-20
CL8985 Royalene - Calcium hydroxide filled	-25
Dox II	
PB40K	

As an illustration of the effect of low temperature, a natural rubber compound of brittle point -56°C shows a hardness (BS short index) of 57 at -30°C, 74 at - 40°C, 84/90 at -55°C.

The resistance of the inhibitor material to plasticiser migration from or into the propellant is most important. Where the absorption is high marked degredation of properties can occur i.e. increasing softness, tackiness and in extreme cases complete solution can occur. In other cases chemical stability is impaired followed by chain scission giving fisuring/cracking of the inhibitor coat.

Moreover diffusion of nitroglycerine plasticiser into the inhibitor renders it more combustible, and this process can proceed to the point where the inhibitor ceases to function. The materials most prone are non crystalline linear polymers. Crystalline polymers and cross-linked materials are difficult to plasticise. Certain ester and nitrile groups in polymers show an affinity for plasticiser, e.g. cellulose acetate, polyvinyl acetate, acrylonitrile rubbers and some polyesters, polyurethanes.

2.4.6.1 Specific Inhibitors

For the purposes of this document only those inhibitor systems which have been fully evaluated for project application or are in gernal use at RMD are described.

These systems are cellulose acetate (CA), ethyl cellulose elastomeric inhibitors, composite CA/Hypalon, polythene, Silcoset 105 and 101, Dox II, PB40K, and Flexcrete, and are described in detail in the following subsections.

2.4.6.1.1 Cellulose Acetate to TS263

Inhibitors can be formed by wrapping sheet material on a mandrel with acetone as a binder or by moulding from flake. Moulded components of high length/diameter ratio are usually highly stressed and subject to brittle fracture. Problems of yield occurred in moulding Pointer and Vigilant inhibitors due to this cause. Fully moulded inhibitors were abandoned for Vigilant production in favour of manufacture of the tube by winding. Therefore some manufacturing development would be necessary to provide fully moulded components in certain shapes and sizes.

Manufacture from sheet by convolute winding is a well established and very reliable method. Moreover thick-walled 'blanks' formed by convolute winding can be conveniently machined to a variety of shapes. Bonding of CDB propellant to cellulose acetate is extemently good when the joint is formed during casting. This is because the casting liquid readily plasticises the cellulose acetate forming a diffusion bond. There is usually no specific adhesive interface but rather a blurred diffusion of plasticised nirtrocellulose merging into nitroglycerine plasticised CA.

The bond therefore can be expected to survive all the extremes of temperature likely to be met in a tactical requirement. A variety of charge systems have been proved over the temperature cycling and firing range - 40/+60^{o}C. The mechanical properties are a good match for the typical propellant properties in the convolute wound stage. The latter show a much improved ductility compared to the harder moulded component.

The mechanism promoting good adhesion is also that which is the source of the inhibitors most serious limitations. The diffusion of nitrogylcerine plasticiser into the cellulose acetate continues with storage. Levels as high as 60% NG in CA have been recorded with Pointer and Sealyham boost under extreme accelerated storage conditions. Submersion of cellulose acetate in casting liquid results in complete solution.

Nitrogylcerine absorption in the cellulose acetate increases its combustibility to the point where it ceases to function. Therefore this imposes a storage life limitation on the charge and its upper firing limit. The combustion rate of nitroglycerine rich cellulose acetate is very temperature dependent. Storage trials have shown that life can be extended by 50% + for a given system when the upper firing condition is reduced from 60 to 20^{o}C.

The principal factors influencing the diffusion of nitroglycerine into a given cellulose acetate are temperature, time and propellant plasticiser level. Factors affecting charge functioning are inhibitor thickness, burning time, annular gap between charge and combustion chamber, gas flow condition over the cellulose acetate.

Propellant plasticiser content is a dominating influence. Propellant nitrogylcerine contents of 35 to 41%+ (as occur in Sealyham boost, Pointer) would generally rule out cellulose acetate as an inhibitor. On the other hand a high NC propellant such as OIO would be expected to give an acceptable service life for a Naval technical requirement.

An illustration of the storage life obtained with highly plasticiser CDB is given in the following tabulation:

Motor	Storage History	Firing Temp ^{o}C	Firing Result
Pointer (41% NG in propellant)	3 weeks at 60^{o}C	60	Failed at 5 sec
	7 weeks at 60^{o}C	20	Failed at 6 sec
Vigilant (35% NC in propellant	12 weeks at 60^{o}C	60	Failed in boost 3 sec
Sealyham sust. (27% NG in propellant)	16 weeks at 60^{o}C	60	Failed after 11 sec

In the case of Pointer, for example, if the storage period of the trial had been limited to 1-2 weeks at 60°C or firing temperature reduced, then failure would be expected later in the burning period (motor burning time 26 sec) in accordance with the reduced inhibitor combustion rate.

The level of nitrogylcerine in the inhibitor which determines a malfunction varies with the motor design e.g. burning time, gas flow condition.

Temperature coefficients of nitrogylcerine diffusion into cellulose acetate have been determined. This factor varies over the temperature range but to a good approximation 1.4/5°C can be taken.

Cellulose acetate also has limitations when employed in thin web charges of relatively soft propellant where differential pressures tend to lead to charge collapse e.g. Sealyham boost. This is referred to again under composite inhibitors.

2.4.6.1.2 Ethyl Cellulose

This material is currently used on many UK EDB cartridge loaded production motors to limit the exposed burning surface of the charge. The basic material is to specification 100 796-03/1/WE to the composition shown in Table 1 from bought-in ethyl cellulose flake and is prepared by processes called up in the Materials Department Design Guide for Plastics and Rubber.

Table 1 products shall be manufactured from ethyl cellulose flake plasticised and stabilised with approved additives.

INGREDIENT	SPECIFICATION
Ethyl cellulose, high viscosity	CS 2724
Diethyl phthalate	BS 574
Di-n-butyl phtalate	BS 573
p-Octyl phenol	AFS 403
Carbamite	Def Stan 07-105
Dye, CI solvent yellow 14	Def Stan 68-58

Tubes and sheet are manufactured by processes applicable to specific projects; moulding and tape can also be manufactured using this product. Each motor type will require a different thickness of inhibition dependant on burning time, configuration and other factors. Typical inhibition thickness is from 1 to 6mm and any major reduction in the optimum thickness has been shown to cause a performance malfunction.

The process of application of the inhibition to the propellant cylindrical surface is by stress relief. End washers are bonded onto the charge as necessary using an appropriate adhesive and this is allowed to cure. Steam moulding of the end washers to fit the charge contour is sometimes carried out at the bonding stage, as necesary. The ethyl cellulose coating is then expanded by steam pressure and rapidly water cooled so that it is 'frozen' in the expanded state. Adhesive is applied to the expanded coating interior and this is then swaged onto the charge using steam pressure. Finally, after a period of cooling and solvent evaporation of the order of 12 hours the excess inhibition is trimmed. This is an important process to avoid damage to the charge obturator when assembled in the motor.

Other methods of application of the inhibition have involved the winding of multiple layers of EC tape using an adhesive to bond to the charge and to bond together the layers of tape. UK experience to date has shown this process to be somewhat labour intensive in the selection of the optimum conditions for successful inhibition. However it does have the advantage that a single winding machine can cope with a wide variety of charge diameters.

Ethyl cellulose has for practical purposes been found to be unsuitable for CDB charge inhibition due to different processing parameters and the difficulty in achieving a suitable bond at the propellant to ethyl cellulose interface within a reasonable process timescale.

2.4.6.1.3 Elastomeric Inhibitors

With a few exceptions elastomeric inhibitors have the important property of resisting nitroglycerine migration from the propellant. Properly compounded they also have very good stability of properties under the extreme conditions of temperature/humidity to be encountered in tactical environments. Therefore service life limitations of the motor/charge due to inhibitor causes can be eliminated.

The mechanical properties can be readily matched to any inhibitor requirement. There is little reason to discriminate between the various rubber materials as inhibitors. Components can be manufactured from sheet by vulcanising the joints. Moulding of components of high length/diameter ratios is difficult in most cases especially when highly filled for certain applications e.g. smoke.

Many of the synthetic rubbers have inert difficult surfaces for bonding and specific adhesives/surface treatments are usually necessary. For this reason Hypalon compounds are no more and no less suitable in general then other synthetic rubbers. However the processing/adhesive technology with Hypalon inhibitors would be standardised with the similar technology for case-bonding where Hypalon polymers were chosen for their superior endothermicity as thermal insulants.

A range of polymers have been evaluated in a wide range of filler compounding to specific purposes. These included Hypalon, ethylene/propylene terpolymers, natural rubber, butyl, silicone and Neoprene. Many of these were evaluated for smoke comparison (some 60 compounds).

Of those which have had extensive evaluation the following compounds can be listed. Hypalon CL 8436, Hypalon CL 4581, Hypalon CL 8980, Hypalon CL2759, Royalene CL 8509, Royalene CL8799, Natural Rubber CL 8967.

Those inhibitors which have seen extensive project evaluation/acceptance are Hypalon CL 8436, CL 4851, CL 8980.

The bond system is the Redux/Formvar system and the same principles apply as that described under case bonding. The density of the rubber inhibitors is usually higher than that for CA and is affected by the type and amount of filler. However the thickness required is 1mm compared to 2.5mm which makes the inhibitor weight more comparable and volumetrically more efficient.

The elastromeric materials form ideal inhibitors and could be universally applied to CDB propellant charges except possibly in 2 areas i.e. (a) occasionally the inhibitor is required to give additional support or rigidity to the propellant charge. This occurs with thin web soft propellants which can be subject to either slump on hot storage or collapse due to differential pressure during firing, e.g. Hypalon was found unsuitable for Sealyham boost: (b) there has been some evidence with an SCB charge design of inhibitor bond failure or peeling during motor functioning. This has been attributed to conditions of differential pressure from aft to forward end of the motor chamber coupled with obturation by the inhibitor of the annular space between the charge and motor wall. The Sealyham sustainer with reverse gas flow to the forward end oil bottle guidance system provided conditions unsuitable for Hypalon inhibitors. Similarly where the forward end volume is relatively large compared to the motor free volume. Gas cooling at the forward end coupled with inhibitor obturation of the annular gap can lead to a similar situation.

Hypalon inhibitors have shown suitable functioning in 25mm diameter gas generator charge, 100mm dia. Vigilants and Bofor applications, 150mm dia. Pointer and miscellaneous SCB and radial buring configurations.

For low smoke applications the specifically compounded elastromeric inhibitors are significantly the best elastromeric inhibition currently available. Of these Hypalon CL 8980 was used for the production of the E552 Pointer charge for the Swingfire missile.

2.4.6.1.4 Composite Inhibitors

These inhibitors utilise conventional cellulose acetate inhibitors with a thin layer of Hypalon sheet interposed between the propellant and the cellulose acetate. The Hypalon sheet is bonded to the cellulose acetate with phenolic R775 adhesive and to the propellant with Redux/Formvar film adhesive. The Hypalon sheet acts as a nitroglycerine migration barrier to protect the cellulose acetate.

The Hypalon sheet thickness requires to be a minimum of 0.015in (0.4mm) to avoid pinhole effects permitting nitroglycerine passage. To control the Hypalon sheet thickness within close tolerances of 0.15-0.20in (0.4-0.5mm) the sheet width has to be restricted for calendering reasons to 24in (601mm). The sheet also has to be calendered at a higher temperature which imposes a more highly vulcanised gloss finish making bonding more difficult. For composite inhibitors above 7.0in (175mm dia) the thickness range has to be extended, because of the greater sheet widths needed.

The inhibitor is formed at 150°C and as a result of partial degradation the cellulose acetate is rendered harder, stiffer and more brittle. Therefore loading bearing designs should not be based on data relevant only to the more ductile cellulose acetate traditionally used.

The composite inhibitor has particular attractions for thin web, soft propellant designs where slump or charge collapse under differential pressures, present in motor functioning, tend to occur. The Sealyham boost motor is typical of this case and the composite inhibitor was conceived for this project. An elastomeric inhibitor leads to charge collapse in Sealyham boost when fired at 60°C. Cellulose acetate inhibited versions function satisfactorily initially but softening/loss of rigidity of the inhibitor results from nitroglycerine absorption by the cellulose acetate. This mechanism occurred in motors, stored 2½ years in HMS Barrosa followed by 3 months at 40°C, when fired hot.

Composite inhibitors CA/Hypalon (2.0/0.5mm thickness) have greater rigidity than 2.5mm thick CA and is essentially unimpaired by storage. As a guide the load required to give an equivalent deflection on the tensometer is given for equivalent strips of inhibitor removed from Sealyham boost charges:

Composite inhibitor	Charge stored 10 months at 52°C	Load 15 lb
CA "	" " " "	Load 4 lb
CA "	Charge unstored	Load 10-11 lb

Composite inhibitors have been introduced more generally as an alternative to elastomeric inhibitors. The Sealyham sustainer charge was the first SCB to be fully evaluated. In a system where obturation of the annular space between charge and motor lining results from the unconsumed inhibitor wall, a possibility exists of inhibitor peeling from the remainder of the propellant charge. This possibility exists if a pressure differential of sufficient magnitude occurs across this obturation. This presupposes (a) total obturation of the annular gap and (b) pressure loss at the forward end. In Sealyham sustainer gas consumption at the forward end oil bottle/guidance system fulfils (b). Thus, Hypalon inhibitors did not perform satisfactorily in this motor due to the total obturation of the annular gap.

In the case of composite inhibitors a thickness combination for CA/Hypalon of 2.5/0.5 and 2.0/0.5mm resulted in total obturation but no peeling (due to inhibitor stiffness). A thickness combination of 1.0/0.5mm gave obturation and peeling analogue to Hypalon inhibitors.

A successful design evolved from a thickness combination of 1.5/0.5mm for CA/Hypalon. It is considered that this gives sufficient rigidity to avoid peeling combined with a thickness resulting in sufficient inhibitor consumption/softening to avoid initial obturation. Specific motor designs may require manipulation of these combinations to achieve a satisfactory result.

The AJ168 (325mm dia) motor development showed Hypalon to be unsatisfactory due to a similar obturation/peeling mechanism. It was considered that this was either (a) obturation combined with a large forward end free volume in which gas cooling gave the required pressure differential or (b) Formvar/propellant bond strength was not fully developed on the motors tested. Composite inhibitor of thickness combination 1.5/0.5mm proved successful in this instance.

Composite inhibited Sealyham sustainer charges have a life at 60^{o}C of 11-12 months limited by gas cracking of the propellant. Sealyham boost has a life of 12 months at 60^{o}C (18 months at 60^{o}C on non-project motors) limited by burning rate considerations. Saab E573 charges have a life at 52^{o}C of 12 months limited by gas cracking. SCB charges have been and would be expected to temperature cycle - 40/+60^{o}C and function correctly on firing.

A composite inhibitor (1.5/0.5mm) has been successfully fired in E552 Pointer motors including flight trials.

The principle disadvantages of composite inhibitors are cost and increased sophistication of manufacture. Labour costs compare unfavourably with elastomeric inhibitors and even more so with potting resin systems. They are not suitable for multiple charge column cast to chape processes. Clearly end cup inhibitors cannot be powder filled in multiple charge columns. If simple composite tubes are used then end face inhibition has to be eventually accomplished, by for example potting systems at a total labour cost in itself essentially the same for a total potting resin inhibitor.

The method of manufacture is more sophisticated, than for example elastomeric inhibitors due to the additional CA/Hypalon interface. The bond at this interface by the existing techniques ranges from acceptable to marginally so dependent on control of process variables. A bonding technique, using the same resins, has been shown in development work to be much superior in strength and application ease. This system has not been utilised, however in project systems to date.

The inhibitors are stiffer than Hypalons or silicones, so that stresses on thermal cycling or rough handling are concentrated to a greater extent at the adhesive interface. In Saab E573 the charge was cantilevered at the forward end of the motor. Bump and vibration in the horizontal position at -20^{o}C resulted in propellant inhibitor separation, presumably due to flexing of the charge. A higher charge cure temperature effected a sufficient increase in bond strength. However, similar bump/vibration at high temperature resulted in inhibitor fracture. Cushioning of the entire charge in Silcoset was adopted to protect the charge from this damage.

Where grain hold back devices are required with a capability for high stress then present techniques demand composite inhibitors in order to obtain a thick wall relatively high strength region for bolt attachment.

Alternative techniques have been evaluated with the higher strength polyurethane potting resins which eliminate the thick walled composite/bolted plate design but not to the rigour of the E573 Saab requirement.

Such thick walled composite grain hold back regions do impose a higher propellant/inhibitor unbond risk. The propellant is softer at the end face tending to induce unbonds up to 6mm in depth. The greater shrinkage stresses involved in the stiff thick walled zone tends to occasional separations up to 20mm in length. In the absence of repair procedures these effects tend to a 5 to 10% charge rejection rate in large scale production.

In respect of low smoke requirements the composite inhibitors are inferior to the best elastomer systems. The discrepancy is markedly enhanced as the degree of induced after burning in the motor exhaust is reduced.

2.4.6.1.5 Polythene Inhibition

Low to medium molecular weight polyethylene has been evaluated in R and D to the Vigilant environment technical requirement. The material does not absorb nitroglycerine and gives a storage life at elevated temperatures equivalent to Hypalon and composite systems. Vigilant charges function satisfactorily after temperature cycling between - 40/+60^{o}C.

On cost grounds these systems are significantly cheaper than composite inhibitors, but only slightly so compared to Hypalon inhibitors. They are of lower density than Hypalon systems.

Their principle disadvantage is to the high degree of smoke produced when used in rocket motors. The bond system developed utilised a chromic acid etch to oxidise the surface polythene. This process dictates that the inhibitors be manufactured remote from a propellant area. The system was developed in the mid 1960's. Since the technical advantages are matched by Hypalon or composite systems and cost advantages markedly exceeded by potted resin systems, Polythene has had no strong impetus for formal project use.

2.4.6.1.6 Silcoset inhibition systems

The Silcoset 101 IMI/SRS/70 and 105 IMI/SRS/69 systems to AFS190 are based on polymethyl siloxanes usually with inorganic fillers which are liquid polymers. These can be cross-linked with 0.2% of a variety of catalysts to give solid elastomers. Although the fuler and base polymer of Silcoset 101 and Silcoset 105 differ, the chemistry, use and application of the two products in the same. These systems and their associated adhesive systems were developed as potting compounds specifically aimed at low cost/large output manufacture of CDB charges. In particular the potting process is the most suitable for the multiple charge column casting to shape process.

Silcoset is a pourable material and is thus suitable for potting around or onto propellant to form an inhibitor. An adhesive system is essential to ensure a good bond to the propellant this is applied by brush coating the propellant surface and curing/drying prior to application of Silcoset. IMI/SRS/194 and 314 refers to this adhesive system.

Apart from the cost/labour advantages involved with such systems they have a number of other advantages. Nitroglycerine absorption is essentially nil (0.2%NG absorption after immersion in casting liquid at high temperature). Thus no service life limitations due to inhibitor degradation can be expected. The permeability to gases is very high eg (CO_2 permeability for Silcoset 105/CA/Hypalon systems are in the ratio 300/5/1.4 respectively). This is of importance in large web propellant charges where propellant gas cracking is a limitation on storage life.

These inhibitors are very flexible and shrinkage or thermal contraction/expansion stresses do not arise out of their use. Silicones also have the best low temperature properties of all polymers with brittle points of about -80°C.

Propellant/inhibitor bonds are extremely reliable, moreso than Formvar/propellant systems. This is at the penalty of a higher degree of sophistication in manufacture, than is preferred for workshop practice. The bond strength exceeds the rubber strength and greater than 90% break in the rubber is expected consistently from all such joints as a specification level.

Peeling modes such as those described under elastomeric inhibitors would not be expected from the nature of the adhesive joint and the tear strength of the rubber eg Silcoset 105 inhibition functions in the Sealyham sustainer case whereas Hypalon does not.

These materials are not suitable for use with thin web soft propellant charges where rigidity of design is required as in Sealyham boost. Silcoset 105 and 101 are not suitable for low smoke applications. These materials are amongst the smokiest tested, although certain applications of a radial burning configuration (eg FFV HEAT shell) are acceptable with Silcoset 105.

Silcoset 105 has been fully evaluated to the Vigilant technical requirement, FFV HEAT shell and firings in both heavyweight and lightweight Pointer motors.

Following its development as a loose charge inhibitor system, Silcoset has been increasingly applied to finished motors for end face inhibition due to its ease of application and flexibility of use with a pourable material, for further details see section 2.4.6.2 and 2.4.6.3.

Silcosets are also used for end inhibition of ballistic rounds for powder proof. The material is not designed for high load bearing joints because of its low strength. If this is compensated for in the design of joint it can be used for grain hold back joints. In this case the application is convenient and of low cost but an accurate knowledge of the load to be imposed and the joint strength is required. For such applications Siloset 101 is used in preference to Silcoset 105 because of the higher strength of the former. See section 2.4.7 for further details of this method of charge retention. For non load bearing inhibition systems eg potting loose charges then Silcoset 105 is preferred because it has significantly lower viscosity than Silcoset 101 and is hence more conveniently pourable.

Some physical properties are given:

	Silcoset 105	Silcoset 101
Specific gravity	1.18	1.45
Hardness BS	45	60
Tensile strength psi*	350	650
% elongation	200	110
Tear strength lb	2	5
Brookfield viscosity poise	120	700
Colour White	Red	

* These figures are obtained by testing flat dumbells of thick gauge. In thin sections of 0.1in (2.5mm) lower strengths are obtained of 100-150 psi for 105 and 200-300 psi for 101 possibly due to the increased significance of flaws in this sections combined with the lower tear strength.

Finally although the labour content of the Silcoset process is low the process cycle time is long, ie 3 days for adhesives treatment + 5 days for Silcoset cross-linking/bonding maturity. This latter maturing period varies with the batch of primer and Silcoset and is also influenced by humidity. In some cases 1 day is adequate but in others 5 days is required and the process has been standardised to this latter worst case.

2.4.6.1.7 Dox II Inhibition

The Dox II inhibition material is a filled resin system that is pourable, low in viscosity and therefore can be easily applied to difficult shapes in thicknesses of 1mm or above. It can be used to provide the complete inhibition or to cover specific areas for example the forward end face of a case bonded or cartridge loaded charge. Dox II will bond direct to propellant but the bond created is unsuitable for most project applications. To achieves a satisfactory bond to propellant it is necessary to treat the particular propellant surface with barrier coat and primer. These are brushed onto the surface and cured/dried prior to the application of the Dox II.

Migration of NG from the propellant into the inhibitor is well known. It can cause a loss in mechanical properties of the polymer and eventual failure of the inhibition system if the NG absorbed becomes excessive. This is particularly true with Dox II. The application of the barrier coat and primer overcomes this problem.

In certain applications, for instance when it would be impossible to correctly apply the barrier coat and where the area or feature is not highly stressed, for instance in the small conduit of the E593, Sutra charge, then it may be possible to omit the preparation of the propellant surface.

The preparation treatment can essentially be completed in 24 hours. The barrier coat is applied after suitable degreasing of the propellant and left overnight for a minimum of 16 hours before the primer is applied. The primer is cured for 1 to 4 hours at 40^{o}C prior to the application of the Dox II resin which is cured sufficiently to handle after 12 to 16 hours at ambient or shorter if cured at 45^{o}C.

This relatively short preparation application and cure time is advantageous when compared with the Silcoset system the other pourable/pottable process available for charge inhibition which can take 8 days to complete.

There are 2 barrier coats that may be used IMI/SRS/288 and IMI/SRS/163, The latter is usually used for project applications for processing simplicity and is slightly better from the amount of smoke that is generated.

The Dox II inhibition system was developed at RMD primarily to produce a very low smoke inhibition system that could be applied to a bare charge. It has been used very successfully on the E593 Sutra charge for the Milan anti-tank missile and the E596 Dwina charge for the Bofors BILL anti- tank missile where minimum smoke signatures were a major requirement. Both of these charges are relatively small in size and are of a cartridge loaded configuration.

Dox II has also been used successfully to provide partial inhibition in conjunction with another inhibitor eg PB40K or to inhibit an end face of a case bonded charge.

The gas permeability of Dox II is poor when compared with some of the other inhibition materials. This may cause problems with certain propellants and charge configurations where gas generated within the propellant during storage may not be able to escape. The gas, locked in by the Dox II inhibitor, causes cracking of the propellant adjacent to the inhibitor and separation of the bond at the Dox II to propellant interface. Careful consideration at the initial design stage should eliminate this problem.

A tabulation of the permeability coefficient of the main inhibitor materials at 23 and 60^{o}C are presented in the Table 8.

As the Dox II resin is pourable and low in viscosity it can be poured over the charge or poured into a mould into which the charge is placed thus displacing the resin around the charge. Both methods of application may cause bubbles to be trapped within the wall of the cured Dox II inhibitor. The size and location of these bubbles should be found by non destructive testing, either radiographic or ultrasonic has been used, to establish if they are critical to the function of the charge.

Design of the potting mould should be given careful consideration to ensure easy release from the mould when the Dox II has been cured and thus avoid straining the initial bond to the propellant. Unbonds at this interface will result if due consideration is not given to this very important requirement.

Dox II is a relatively stiff material. This may be a disadvantage when used to inhibit the forward face of a flexible EMCDB propellant charge. Flexing of the propellant, particularly at the cold extremes may result in cracking of the Dox II inhibitor. The stiffness of the material may be used to advantage to provide support to a soft/flexible propellant. Care at the design stage to optimise the design to obtain the best of Dox II properties should avoid problems. An illustration of tensile properties over temperature range of -40^{o}C to +60^{o}C is presented in figure 28.

Although not originally intended for use as an insulation material Dox II has been used successfully to insulate aft closures for research and development work. This provides a quick and cheap layer of insulation using a simple, cast Silcoset, former to provide the profile and thickness of insulation that is required. A nominal 4mm was used for the E604 Zama development heavyweight motor aft closure and the 150mm research heavyweight motor closure.

Inhibitor Material	Test Piece	1 GTR	t mm	2 GTR	t mm	3 GTR	t mm	Temp ^{o}C
Silcoset 105	2060	1.27	4080	1.15	2100	1.26	60	
	1180	1.23	1230	1.14	-	1.15	23	
Silcoset 101	1790	1.26	1610	1.18	2110	1.21	60	
	912	1.34	850	1.45	989	1.27	23	
Silcoset 105 + barrier coat/primer		329	1.36	261	1.30	377	1.32	60
	258	1.24	339	1.02		193	1.16	23
Silcoset 101 + barrier coat/primer		315	1.03	343	1.04	297	0.99	60
	194	1.10	262	0.99		222	1.00	23
CL7225	115	1.12	107	1.08	101	1.15	60	
	15.0	1.11	17.2	1.16	21.7	1.11	23	
CL2759	20.8	0.98	16.1	1.00	15.4	1.06	60	
	0.348	1.05	0.409	1.09	0.658	1.06	23	
Cellulose acetate		14.2	1.03	10.5	1.03	9.94	1.08	60
	0.263	1.01	0.314	1.03	0.452	1.01	23	
PB40K	8.77	1.76	5.64	1.76	5.69	1.73	60	
	0.222	1.69	0.242	1.62	0.132	1.64	23	
CL8980	6.34	1.00	5.12	1.08	5.32	1.11	60	
	0.210	0.98	0.399	0.98	0.254	1.00	23	
CL8980 + Redux/Formvar system		1.99	1.16	1.27	1.19	1.08	1.20	60
	0.221	1.21	0.105	1.04	0.131	1.18	23	
Dox 2	2.39	1.09	1.91	1.10	2.14	1.04	60	
	0.0103	1.04	0.0308	1.05	-	1.03	23	
Dox 2 + barrier coat		2.84	1.13	1.77	1.12	1.98	1.06	60
	0.0201	1.15	0.0409	1.05	0.0334	1.04	23	

GTR - is gas transmission rate in units x 10^{-15} m^3 (STP). $m^{-2}.s^{-1}.Pa^{-1}$
t - is specimen thickness
Test gas - Nitrogen

Table 8
Results of gas permeability determinations
of inhibitior material at $23^{o}C$ and $60^{o}C$

2.4.6.1.8 PB40K Inhibition

The PB40K inhibition system has been developed at RMD to provide a minimum smoke inhibitor that can be prefabricated prior to charge manufacture to enable the charge to be cast/formed within it. It may be used in thicknesses of 1mm and above and if necessary can be reinforced with fine nylon cloth to provide a stronger inhibitor. Reinforcing can at times provide a "dry" surface to the inhibitor which may, depending on the charge configuration, lead to ultrasonic inspection problems and therefore if possible unreinforced PB40K should be made thick enough to withstand handling and processing. A 2 to 3mm wall thickness should be sufficient for most charges.

The PB40K inhibitor is produced from an extrudate. This is normally tubular but inhibitors can be fabricated from flat sheet to form a beaker/inhibitor during the early phase of development while an extrusion die is being manufactured. MM655 refers to the process for beaker/inhibitor manufacture and IMI/SRS/61,85,95 are appropriate specifications.

Small changes in shape, for example a step in the outside diameter of a beaker, may be moulded in. Care should be taken to avoid where possible sudden changes in shape and sharp corners that would result in cracking, local thinning and cutting through the wall of the inhibitor/beaker.

The bond system used to ensure that the PB40K is bonded to the propellant is the Redux/Formvar system and the same principles apply as that described under case bonding with Hypalon in Section ?

The PB40K inhibition system could be universally applied to CDB cartridge loaded charges but for practical reasons may be considered unsuitable for very small charges. The processing required would not make the system cost effective. As the length to diameter ratio increases the system becomes more viable and worthy of consideration. Gas generator charges of 50mm diameter have been manufactured successfully however the smallest charge diameter in production currently is about 100mm. These are the Riga derivatives E599 which uses 1mm thick PB40K reinforced and the CDB Whinchat E612 which has a 2mm thick inhibitor that is unreinforced.

The largest charge diameter currently using PB40K is the Giant Viper charge E which has an unreinforced 2mm thick inhibitor. Previously charges up to 440mm diameter have been inhibited with PB40K and only the practical problems of forming a beaker limits the maximum size that could be produced. This of course applies to other inhibition materials as well in some case even more so.

2.4.6.1.9 Flexcrete ST Inhibition

The Flexcrete inhibition system is currently used for powder proof charges and research and development charges where the end face needs to be inhibited and where the bond produced is not strained. This limits the use to charges that are to be fired within a few days of the application of the Flexcrete and where charges are not subjected to temperature cycling, storage and mechanical testing.

The main advantage of this material is that the process time for application is very short, the process is simple and the material is cheap. It is a two part resin system

This material is unsuitable for normal project charges and motors.

2.4.6.1.10 EPDM Inhibition

The EPDM inhibition system has been used for inhibiting the outside diameter and end faces of HTPB propellant cartridge loaded charges. This material can be fabricated as for Hypalon and be hand laid up to provide a profiled varying thickness inhibitor into which the charge is cast. This material is quite flexible and will not provide much support to the charge if a softer propellant is required.

It could be used for CDB cartridge loaded charges but as yet has been considered unsuitable. The Redux Formvar adhesive system would need to be used for any CDB applications as for Hypalon.

2.4.6.2 Inhibition for Cartridge Loaded Charges

For cartridge loaded designs due consideration should be given to the interface to the propellant surface and the most suitable material should be chosen to ensure satisfactory performance considering the:

customers requirements
the environment
material properties
bond strength
compatibility (chemical)
processibility
cost

For details of available materials that are suitable for particular applications and the adhesive systems that should be used refer to Section 2.4.6 and 2.4.6.1.

2.4.6.3 Case bonded inhibition

For case bonded designs due consideration of both the propellant/inhibitor interface and the liner/inhibitor interface. The choice of material and bonding medium should consider:-

the environment
material properties
bond strength requirement
compatibility (chemical)
processibility
cost

2.4.6.3.1 CDB and EMCDB propellants inhibition

For case bonded considerations pourable/pottable inhibitor systems are the most suitable for the inhibition of exposed propellant surfaces, namely Silcoset 101, 105 or Dox II. The latter is less suitable for extreme low temperature operation (below - 20^{o}C) and consequently is more suited to CDB propellant types. Bonding mediums and details of materials to be used in each instance are referred to in Sections 2.4.6.1.

2.4.6.3.2 Composite Inhibition

Inhibition materials can be common between various propellant types. The following briefly discusses inhibition with composite propellant but more detail is available in section 2.4.6 and by reference to the Materials Department Operating Manual OM90/4.

No current composite motors use inhibition. However cartridge loaded charges would require inhibition of the outside of the charge which could if required double as the motor insulation (eg Nuthatch EPDM 7225).

End inhibition of charges is used where end burnback is not desirable. This can be applied to either case bonded or cartridge loaded charges although it is not currently used on any UK composite motors. LPA5 has been successfully used for end inhibition in the past.

Ethyl cellulose has also been successfully used as inhibition in 50mm diameter test motors although the EC must be fully dried before use.

A thermoplastic inhibition has been used for base bleed units on extended range artillery shells.

Generally inhibitors are not particularly erosion proof and as such are not successful insulants but when used in conjunction with other materials they can be very effective.

2.4.7 Charge (Grain) Retention

2.4.7.1 Introduction

A rocket motor designed for service use must employ features which will enable the motor system as a whole to withstand the total environment specified. This environment will include climatic, mechanical and flight conditions. A case bonded charge is firmly restrained during its life, whereas a cartridge loaded charges must use pecial devices to stop it moving under transport, handling, firings and flight induced loads. Thee devices are known as grain hold-bak or grain retention systems. it is imperative that in a loose charge system pressure differentials are not present between the central or internal conduit(s) and the annular gap between the charge and the motor case, and that gas flow is prevented in this gap to obviate erosion of the lining and/or inhibition. loads due to external sources such as handling, transport, flight etc may be in any place, thus support of the charge must be adequate for both axial and lateral loadings. Charges within conduits, ie end burning grains, also require to be restrained and these are covered within the sub-sections below.

Transportation loads include all those produced by movement of the store both crated and uncrated before flight. This may comprise bump and vibration from road, rail, aircraft take off and aircraft landing, and storage in ships magazines. Handling loads can produce high shock levels and flight induced loads may well include high axial and lateral acceleration loads due to launch and motor burning and aerodynamic induced vibratio modes.

The geometric envelope and peformance requirements may well dictate that the charge design results in a pressure drop along the inernal conduit(s). This results in a longitudinal load being imparted to the charge at ignition which, if retention was not used, could cause the charge to break up or deforce into the rear closure.

2.4.7.2 Position of Charge Retention

Grain retention systems may be fitted at the head or aft end of the charge and in some instances both. Maximum load on the system should be compressive. The choice for position is generally determined by the type of charge. An example would be a slotted radial designed to have the slots at the aft end. Fitting a GHB at the rear of this charge could mean that the retention system is subjected to full gas flow for the total firing whereas at the head end it would be protected by propellant until the end of burning. With end burning charges, it may be sufficient to hold the charge at the forward end but load may dictate that some lateral support is required and possibly some aft end device as well.

2.4.7.3 Methods Available for End Burning and Radial Burning Charges

2.4.7.3.1 End Burning Charges

There are several different methods that can be used for end burners.

a) Enlarging the beaker thickness to take tapped holes so that a plate can be positively located at the head end. The plate is then attached to the forward closure. A cushioning material may be used in the free volume at the head end. This is useful where it is economic to have an integral forward closure.

b) A variation of type a) arrangement is to place a slit metal ring in the thickened section of the grain hold-back material.

c) Bonding the forward end to the motor. This is acceptable for relatively small charges and where the forward closure is separate. The charge is loaded from the forward end. Note radial burning charges can also be retained by this method.

d) A further system is to bond the forward end of the charge to the plate ie similar to a) but without extra inhibitor and bolts.

e) The claw type GHB is applicable to end burners but is mainly used with radial burning grains - see below.

f) A simple method of retaining the charge under longitudinal loads is to employ a castellated rubber ring at the aft end. This ring must take up the expansion/conraction of the charge across the full temperature range and is thus more applicable to short charges. The charge is pushed against the forward end but gas is allowed around the periphery by the castellations. It is possible that system c) and this system may be used together. When burning of the charge commences, the presure developed on the aft face is adequate to hold the charge forward, so that this system is not for firing restraint.

g) Lateral support against vibration and side loads can be increased if methods (a) is not sufficient laterally by potting the charge into the body such that the potting material is inserted up the side of the charge in the annular gap - care must be taken to allow for radial expansion.

2.4.7.3.2 Radial Burning Charges

For a radial charge it is usual to fit the igniter at the head end; this precludes the use of a) above, but c) can be adopted by having a simple plug in the conduit.

Claw type - this system was favoured for many years, although is now considered uneconomic in terms of mass and volume. The inhibitor (either head end or aft end) is thickened and machined out to take a split ring and an obturating ring. The split ring is held into the forward closure by bolts.

General Notes

There are other types of retention besides those contained here. The spring type of system can be used at either end any may take the form of a helicoil or leaf type metallic spring to hold the charge at the forward end or against a castellated ring at the aft end. Rubber foam can also be used at the head end as an effective spring. These systems rely on the stiffness of the beaker and gas pressure during firing.

2.4.7.4 Materials and Design Techniques

The earlier system - claw type - relied upon the obturating ring functioning during firing. The ring would be in a fitted rubber type of material and unless fitted correctly, would quickly erode producing possible failure conditions. With the advent of better adhesive and elastomer formulations, coupled with generally small charges, the tendency is to use the forward bonding system either to a plate or to the forward closure depending on design requirements.

Larger charges can e physically held onto a plate, but problems can arise if the attachment is too rigid for the low temperature requirement.

Where mechanical systems eg claw of bolted plate types are used, then the inhibitor for the propellant charge has to be a high strength, high modulus material capable of machining to accept the mechanical attachment and such materials are cellulose acetate, composite elastomer-cellulose acetate or specially filled PB40 systems whose properties are given in later sub-sections.

For the bonded systems, then the castable liquid polymer systems are used based on silicones eg silcoset 101 or polyurethanes such as Dox Mix. These provide low cost efficient systems for the majority of applications but where a stringent very high strength system is required then a thermoplastic arylate type material such as unfilled PB40K is utilised in a pre-formed end cup inhibitor where the end cup is bonded to a metal plate for attachment to the forward closure. This latter takes advantage of the high strength adhesion formed between the acrylate rubber and metal when processed at 150^{o}C. The acrylate rubber forms a high strength, strain absorbing adhesive joint. This system is generally more efficient and lower cost than the purely mechanical systems.

2.4.7.5 Basic Choice of Design, Materials and Dimensions

The design chosen depends on the type of body being used, size of charge, induced loads and the type of charge configuration. Generally inert mass must be held to a minimum and thus heavy systems such as the bolted or bonded-on plate and the "claw" split ring devices are unlikely to be chosen for current designs. If simple bonding (or poting) into the forward closure is acceptable then this is probably the cheapest system. The potting material also acts as an insulator for the forward closure. For long end burning charges up to 200mm diameter the bolted end plate is acceptable, above this diameter, either flexible mounts at the circumference are necessary, or bonding with physical attachment at an intermediate diameter into case-in inserts.

2.4.7.6 Materials and Manufacturing Techniques

The materials fall into two groups for use with grain retention systems. The first group includes materials used with mechanical retention devices and the second group of materials are pourable, cold curing elastomers used to bond grain retention attachments to the charge. Sometimes a combination of mechanical and bonded retention system are utilised to achieve optimum strength and performance.

The materials recommended for mechanically attached grain hold-back systems are those based on the methacrylic copolymer PB40 and its variatns and cellulose acetate. It must be noted that cellulose acetate systems have to be overlaid with a layer of Hypalon CL2759 sheet to prevent nitroglycerine migration in the cellulose acetate.

PB40 is a versatile material, capable of incorporating various fillers to modify the physical properties to meet the various demands of grain retention devices.

The following table gives the properties of PB40 variants and cellulose acetate.

Material	Nominal Tensile Strength MN/m^2	Nominal Elongation %
Cellulose Acetate	50	30
PB40 - basic polymer	24	850
PB40K/170 PB40 filled with 75% Kemetal & processed to 170°C	25	10
PB40G/20 PB40 filled with 20% glass fibre (6mm strands) processed at 150°C	20	25
PB40G/75 PB40 filled with 75% glass fibre and processed at 150°C	20	3
PB40 OX/50 PB40 filled with 50% oxamide and processed at 150°C	8	270

The following table gives the failure loads for various materials when tested with a 175mm diameter motor design system.

Material	Grain Hold-Back Design	Method of GHB Material Man.	Failure Load (KN)
PB40K/170	Bolted/Helicoil	Sheet lay up	12
PB40K/170	Bolted/Helicoil	Injection moulded	34
PB40K/170	Split Ring	Sheet lay up	25
PB40K/170	Split Ring	Compression Moulded	18
C/A	Bolted/Helicoil	Sheet lay up	27
C/A	Split Ring	Sheet lay up	25
PB40G/20	Split Ring	Compression Moulded	28
PB40G/75	Split Ring	Compression Moulded	30
PB40	End cup inhibitor bonded to metal plate with spigot to fwd closure	Pressure bag/150^{o}C during inhibitor manufacture	>40

The PB40 variants can be processed and fabricated by various procedures to grain hold types.

a) All Pb40 variants can be laid up by coiling sheets of the material and curing under 5 bar pressure at 150^{o}C or 170^{o}C to give cylindrical grain hold-back blanks which are machined to required configuration. The basic PB40 polymer is difficult because of its elasticity to machine accurately but all the filled versions are readily machined.

b) All PB40 variants can be compression moulded at 150^{o}C or 170^{o}C to give blanks which are machined to shape.

c) PB40K can be injected moulded at 170^{o}C to give blanks which may be moulded to shape or machined to shape.

d) Cellulose acetate sheet is wound to give the necessary blank. Acetone is used to promote the intersheet bonding and long stoving times are required to remove the solvent from thick sections.

All the machined or moulded grain hold-back sections have to be mated with the cylindrical section of the inhibitor. The PB40 variants processed at 150^{o}C will readily bond to each other, the only exception is PB40K processed at 170^{o}C which required an interlayer of basic PB40 sheet to effect a good bond to the inhibitor tube.

The pourable, cold curing elastomer systems recommended for bonding operations in grain retention devices are given below:

Material	**Nominal Tensile Strength (MN/m^2)**	**Nominal Elongation at 20°C (%)**
Silcoset 105 Cold curing silastomer Specification AFS 190A	0.8	150
Silcoset 101 Cold curing silstomer Stonger than 105 but more vicious Specification AFS190A	1.5	100
Dox 2 8.0 Filled polyurethane elastomer Specification IMI/SRS/116	120	

Both the Dox 2 and Silcoset potting/bonding systems include the use of barrier coats and primers to promote good bonding to the various rubber, plastic metal and propellant substrates.

The Dox 2 procedure is simpler and less time consuming and is generally recommended for potting/bonding operations involved in grain retention. However, the silcoset rubbers posses excellent very low temperature properties, which may be important in certain grain retention designs.

The available designs of grain retention systems, referred to earlier, include the following:

a) Closures bolted directly to the charge grain hold-back into which helicoil inserts have been fixed to secure the bolts. The recommended materials for this design are the injection moulded PB40K and cellulose acetate.

b) Claw type arrangements - these devices have been used with cellulose acetate but the split ring or helicoil designs are recommended because of lower weight penalties.

c) Split ring devices - the recommended materials are PB40G/20, PB40G/75 and injection moulded PB5\40K/170.

d) Elastomer bonded attachments - Dox 2 polymer system is recommended with the Silcoset 101 system as an alternative

e) Castellated rubber rings - hot cure silicone rubbers, compression moulded to required configuration can be utilised with differing hardness and physical properties available to meet particular motor design parameters.

f) Charges can be potted directly into motor bodies for support purposes but enough free volume must be retained between the charge and body wall to allow for expansion purposes. This free volume can be achieved by placing a number of longitudinal strips of plastics or metal between and motor wall and the charge. The elastomer is poured into the remaining free space. After elastomer is poured into the remaining free space. After elastomer cure, the strips are removed.

Dox 2 or Silcoset 105 elastomers are recommended for this purpose.

2.4.8 Charge Obturation

2.4.8.1 General Description

In rocket motors with loose charges which have a central conduit and an external inhibitory coating it is necessary to ensure that gas flows only down the central conduit and not down the gap between the outside diameter of the inhibited charge and the inside of the motor ube. This is normally accomplished by the introduction of a seal between the end face (nozzle end) of the charge and the nozzle end closure. A schematic diagram (Figure 29) below shows gas flow without obturation and Figure 30 shows gas flow with obturation.

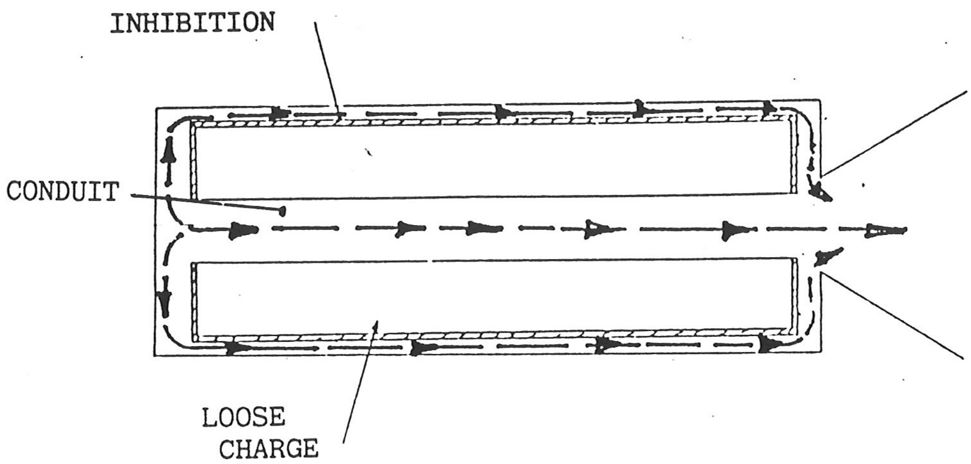


Figure 29 Gas Flow Without Obturation

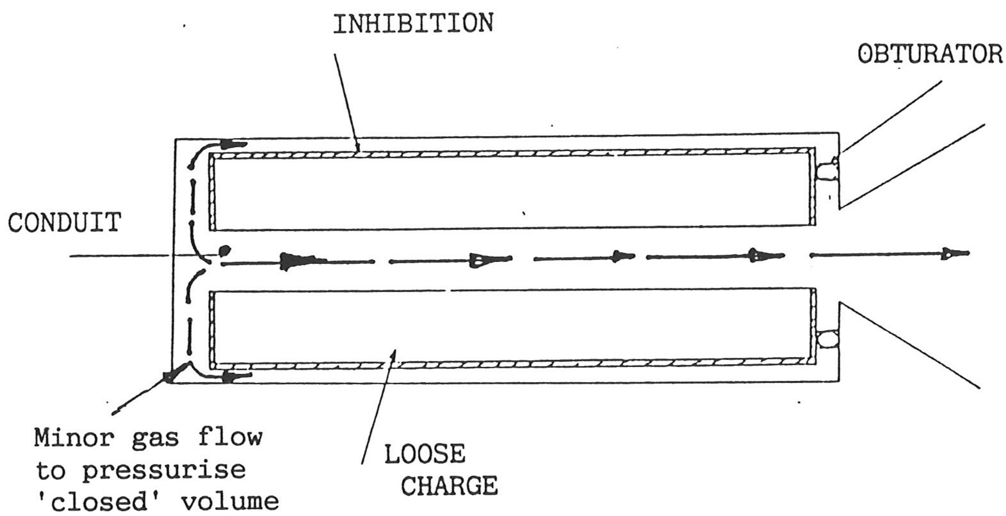


Figure 30 Gas Flow with Obturation

In the case shown at Figure 29 the continuous gas flow between the motor wall and charge causes heating of the motor tube walls and erosion and burning of the inhibitory coating of the charge. Both effects can lead to possible failure of the motor either by weakening of the motor case and a subsequent burst at normal operating pressures or by erosion of the inhibition leading to burning of the outside diameter or end surfaces of the charge rise to high pressures, or by a combination of these failure modes.

Figure 30 illustrates the effect of introducing nozzle end obturation into the motor. The higher pressure at the head end and the effect of drag from the gas flow down the conduit plus acceleration loads forces the charge against the obturation effectively sealing at the point and making the space between the charge and the inside of the tube a 'closed' volume. This volume is quickly pressurised by a small gas flow from the head end afer which the gas becomes stagnant in this region, eliminating heating of the motor tube and erosion/burning of the external inhibitory coating on the charge.

2.4.8.2 Types of Obturator for Loose Charges

Obturation can be achieved in a number of ways, the most widely used are the rubber obturating ring moulded or adhered onto the nozzle end closure, and the use of an inhibitory flexible coating on the end face of the charge which abutts against a rigid annular feature on the nozzle end closure. Examples of the first type are the Whinchat, Crake, Blackcap and Redstart motors whilst the Stall Recovery motor for Fokker (E586 MkIII) is an example of the second type.

It should be noted that cast-in-situ or charges which are fixed or mechanically held in motor tubes by their very nature have either no extenrnal gap or the gap is sealed by the fixing system and therefore have no external gas flow.

2.4.8.3 Design Consideration

With the introduction of an obturator the static pressure on teh outside of the loose charge rapidly rises to the head end stagnation pressure. This is high than the pressure in the conduit at the nozzle end, where the gas velocity is high. Therefore there is a differential pressure tending to cuase the charge to collapse inward at the nozzle end. The effects of this loading can be exacerbated by high charge temperature and increased conduit cross section at the nozzle end introduced to relieve erosive burning of the charge. Collapse of the charge due to the differential pressure will of course result in a changed burning regime, but from the obturation point of view it may also effect the obturator seal leading to failure to obturate.

During the motor phase the charge in the region of the obturator seal must support the longitudinal forces involved. The obturator/charge interface may well also have to transmit the angular accelerations from structure to charge in the cse of "rotating" or "spun" missiles. Thus charge materials (propellant) mechanical strength, the inhibitory, material on the end face and the bond between them have to be specially investigated and selected to provide an adequate mechanical load bearing structure over the required operating temperature range.

The surface of the inhibitory coating on the end of the charge mating with the obturators must be such as to provide a good gas tight seal during motor firing. Materials found suitable include Ethyl Cellulose (EC), Silastomer and DOX. The mating surface is required to be

a) Flat and even.

b) Have minimal upstand of the circumferential coating, if this is a feature of the design.

c) Free from pitting, crazing grooves or sharp edges.

d) Free from contamination, and particles including propellant or EC swarf.

e) Square to the longitudinal axis of the charge.

The coated charge dimensions must be such that all temperatures the loose charge will when within the assembled motor, have full correspondence bewteen the obturator sealing surface and th mating surface on the inhibitory surface of the charge end ring.

2.4.8.4 Radial Clearance and Expansion Allowance

2.4.8.4.1 Thermal Coefficients of Expansion of Various Propellants

The thermal coefficient of linear expansion for cast double base propellant is normally taken as 2.1 x 10^{-4}mm/mm/^{o}C; however, the coefficient varies with cure temperature, conditioning temperature and also with stiffness of propellant. The total variation is over the range 1.5 x 10^{-4}mm/mm/^{o}C to 2.5 x 10^{-4}mm/mm/^{o}C.

2.4.8.4.2 **Radial Gaps for Loading, Accounting For Bow, Ovality and Expansion for Various Length/Diameter Ranges**

Inhibitors used for loosely loaded charges have similar thermal expansion coefficients to propellant and also in many cases similar mechanical properties, thus for radial gaps the charge diameter is used to assess the thermal expansion. The gap allowed for thermal expansion is to allow the charge to expand within the chamber when subjected to a hot soak without causing possible obturation problems. If there are no other considerations, the outside diameter of the charge at the upper operating temperture is the same as the internal diameter of the insulated motor body tube. Allowance for bow and ovality is partly dependent on the method of body manufacture as well as that of the propellant charge. Generally a charge dimensioned to suit the upper operating limit, as mentioned above, can be loaded into a motor at ambient temperature. However, special allowances may be necessary with high L/D charges. Charge bow can be influenced by the manner in which the charge is held prior to loading; in such instances the relative stiffness of the inhibitor can be important. In extreme cases the charge may be loaded when in a cooled condition to allow optimum use of body internal volume yet complying with restrictions at the ends.

Although this section is primarily concerned with loose charge system, it should be noted that case bonded motors can have significant ovality movements across the temperature range due to the imposed stresses within the propellant. This can be an important factor when considering either tube or rail launch where launcher feet are attached to the motor body.

2.4.8.4.3 **Gaps Necessary for Adequate Pressurisation at Low Temperature**

The charge contracts when cold thus opening up the gap between the inhibitor and the body insulation. In the case of case bonded motors, the peripheral stress relief or end relief flaps open. It is imperative, in either instance, that gas pressure is allowed into the gap so that the propellant charge is fully supported around its periphery at ignition. In general the thermal coefficient of linear expansion is sufficient to ensure that this gap is sufficiently wide. In general terms, if the grain retention device and obturation is at the aft end, then relatively small gaps are adequate at the head end. In the reverse case where retention and obturation are at the head end, then radial gaps at the aft end are required to be wider to allow faster pressurisation around the periphery and because pressure in the gap is aft end pressure which could well be lower than the head end pressure. For this reason the majority of loose, radial burning charges have aft end retention and obturation. Typical radial gaps are ½ to 1% of the charge diameter. This depends on the low temperature requirement. For a low temperature of -40^{o}C the radial contraction is between 0.45% and 0.63%.

2.4.8.4.4 Special Consideration for Gas Bleeds Around the Periphery

In many cases, it is necessary to use the motor gas at the head end of the charge for operation of pressure switches, gain change switches etc. This is not a problem in radial burning charges where the conduit runs the length of the charge. However, in the instance of end burning grains where retention, by potting would be a primary choice of retention special arrangements must be made. Various methods are available to the designer.

i) Retain the charge by a bonded plate or leaf spring system so that the peripheral gap allows gas to feed through to the forward end, with due regard to the high temperaure condition.

ii) Embed tubes within the potting material to duct the gas to the forward end.

iii) Pot the charge in the body but leave strips along the length to allow a gas path to the head end.

Alternatively, the gas can be bled through a central inhibited conduit thus allowing complete potting around the periphery.

iv) Special problems can arise with solid SCB proellant charges with certain inhibitors. As the propellant burning front recedes, the inhibitor wall may stand proud from the propellant surface. In such cases the inhibitor material tends to soften and the tube is expanded against the combustion chamber wall, so sealing the annular gap at the charge periphery. As a result of gas cooling in the forward end free space or gas offtake from the forward end, a pressure differential occurs forward-aft which can result in peeling of the inhibitor from the propellant charge. Thus increased propellant burning surface can arise with malfunction of the motor.

Such a mechanism does not arise with low melting thermoplastic matrials e.g. cellulose acetate or PB40K or where pyrolysis consumption of the inhibitor keeps pace with the receding propellant surface. It may arise with the use of thermally resistance materials used as inhibitors such as Hypalon or composite elastomer/cellulose acetate systems. In such instances, the peripheral/annular gap has to be increased to the point where the material properties and the hot gas pressure conditions in the motor render such a sealing mode ineffective. The clearest example of this is the Seacat Sealyham sustainer motor peripheral gap requirement for cellulose acetate as compared to composite inhibitor material.

2.4.8.4.5 Supporting Mechanisms and Design of Such to Cater for Lateral Loads

By definition a guided missile will be subjected to lateral loads during flight. If this occurs during the motor burn, and particularly if a loose charge is employed, then some lateral support may be required. Length to diameter ratios may also be such that vibration could cause lateral movement of the charge within the body. Generally the radial gap is small enough to allow the charge to move onto the body wall without imposing too great a strain on the retention system. If this is not the case, then potted strips between the charge and the body can be employed, or simple strips bonded to the outside of the charge prior to loading. These strips will allow expansion of the charge to occur between the strips radially, at the high temperature, but still give lateral support at low temperature.

For small motors, up to 50mm in diameter with relatively low length/diameter, sufficiently flexible inhibitors are available for potting the entire gap both peripherally and at the head end. In other instances, isolated strips may be necessary to support the charge laterally and esnure that pressure obturation does not ocur. Gas bleeds around the periphery (see 2.4.8.4.4) may also be assisted by such strips. In general the material used is either an elastomeric potting material or a synthetic rubber. The design in terms of thickness and material is generally dictated by the type of grain retention and the length/diameter ratio of the charge coupled with the magnitude of the radial gap.

2.4.9 Effects of Moisture

Water

Most explosives have an affinity for water.

Unless there is evidence to the contrary, it must be assumed that propellant pyrotechnics will be affected in some way by the presence of moisture. This may affect:

a) Burning rate

b) Ballistic stability

c) Mechanical properties

d) Ignitability

e) Calorimetric value

dependent upon the propellant type. Known adverse affects are as follows:

Double Base Propellants

Higher NC propellants have a higher equilibrium moisture content. The following projects have required protection from moisture for the specified reasons:

Project	Parameter	Control	Reference
E554 Retriever	Ballistic Drift	Powder < % Liquid <	
E561 Troy	Ballistic Drift	Powder < Liquid <	
E573 Narva	Ballistic Drift (moisture uptake from cascophen)		
E596 Dwina	Ballistic Drift	Powder < Liquid < Sealed polybag for charges	
E598 Cadiz	Ballistic Drift	Powder < + motor sealant Liquid < + motor sealant	

Project	Parameter	Control	Reference
E600 Taranto	Ballistic Drift	Powder < Liquid <	
E599 Riga III	Burning Rate @ -30^{o}C High π k	Powder <0.4%	
E593 Sutra	Ignitability	Powder < Liquid < Humidity controlled buildings. Sealed polybag	
E604 Zama	Burning Rate @ -30^{o}C High π k	Powder < % Liquid < %	
E597 Thermopylae	Ballistic Drift	Powder < Liquid <	
E532 Sealyham	Boost Sensitive to moisture/ affect on burning rate	Controlled }each moisture }lot	

HTPB

The HTPB family of propellants, no matter the grade or source of polymer, is affected by both oxygen from the air, as well as moistures. Oxygen creates further cross-linking (higher strength lower elongation) whilst moistures affects the bonding of the filler such that both strength and elongation are reduced, it is therfore essential to protect HTPB from moisture throughout the whole of its life. (See TN92/205 with respect to the Scipio investigation programme). Dry environments and/or dessication are essential!

Particular experiences are as follows:

	Propellant	**Polymer**	**Protection**	**Ref**
Hoopoe*	HT (RD2552)	R45M	Dessication+ N_2 purging	OB
Law 80	HT (RD2503)	R45M		OB42599
Scipio	HT 449	Liquiflex H		
E613 Remus	HT	R45M	Dessication	

* Hoopoe is particularly sensitive to O_2 as a result of the radar suppressant, MO_3, content which reacts to give surface hardening, and ultimately surface cracking or low temperature cumulative damage.

Propellant samples must be double bagged and dessicated. The grade of bag material must be also compatible with HTPB.

Pyrotechnics

Chow moisture ingress - distended foils.

2.4.9.1 Manufacturing Methods

To protect from moisture, order of priority should be:

a) Use humidity controlled buildings
b) Protect from moisture uptake by

   i) Store in humidity sealed bags with dessication
   ii) Minimise exposure to atmosphere where relative humidity exceeds %. Specify durations/RH's in process buildings, where humidity is uncontrolled.

c) Protect deliberate water ingress i.e. to lining materials

   e.g. (1) pressure test with water bag to prevent direct contact with water.

   e.g. (2) NDT-without water contact.

d) If water contact has occurred

   i) use water erodication i.e. ovens/vacuum to draw out moisture.

SECTION 5

Igniters

2.5 Igniters

Ignition systems fro rocket motors generally fall into three categories, these are:

a) Pyrotechnic
b) Pyrogenic
c) Hypergolic

Pyrotechnic and Pyrogenic igniters have been developed over many years in RMD and are both very reliable methods of ignition. Hypergolic igniters were developed in the USA and involve spraying the propellant surface of the rocket motor with a highly reactive liquid. This method of ignition is not used in RMD and little is known of its use with CDB propellants.

Igniters of both types a) and b) above are similar in design with the main components being:

i) The initiator, this converts either electrical energy or mechanical movement into a momentary localised source of heat.

ii) The ignition media, this is where the difference occurs in that either pyrotechnic pellets or material is used or a pyrogenic charge is used.

iii) The hardware, this houses i) and ii) above and possible safety arming mechanisms, switch breaks or delay mechanisms.

The Design Authority and Technical Authority for igniters is the Manager of the igniter Section, and must be consulted during the design of ignition systems.

2.5.1 Pyrotechnic Igniters

The design of Pyrotechnic Igniters for solid propellant rocket motors requires an analogous approach as a pure theoretical method is not always possible. Many factors affect satisfactory operation, like propellant type, charge interior shape, igniter location, initial free volume and motor mass discharge rate. The actual ignition process is not completely understood therefore igniters are "developed" from previous experience rather than a clean sheet method.

Initial ignition of the pyrotechnic material can be by either Electrically Initiated Explosive Devices (EIED) or by Percussion Cap or Stab Primer.

Pyrotechnic igniters generate ignition of the rocket motor by radiation, conduction and convection. Conduction and convection being the main modes, the radiative mode being a supportive function. Conduction which is via hot particles and condensing vapours contacting the rocket motor propellant surface. Also with this type of igniter the hot particles in the gas stream above the propellant surface increase the density of gas and therefore part of the convection mode.

The rocket motor propellant must be heated to a certain amount before the ignition process can begin. The time period to this event is referred to as the Thermal Induction Period (T.I.P.). Provided information of the propellant characteristics and the rate of heat transfer is known the T.I.P may be calculated by standard formulae.

Once the process of ignition of the rocket motor propellant has started support from the igniter is still required to aid the process by supplying thermal energy. When a steady state condition is achieved another process is complete which is referred to as the Chemical Induction Period (C.I.P.). Generally motor propellants with a short C.I.P. requirement are satisfactorily ignited by powdercan type 1 pyrotechnic igniters. Long C.I.P requirements are better served by controlled efflux type igniters.

The igniter may only ignite a portion of the rocket motor propellant surface.

Pressure is generated via the ignition process. If insufficient pressure is generated either hangfire, chuffing or misfire will result. This necessitates a nozzle seal, this also serves to prevent excessive over pressure.

The pyrotechnic materials available for use in igniter are as follows. Black powder to CSS110 in G20, G12, G7 and G4 grist sizes. Cordite WM17 and WMT8/Z. Ballistite A16(M) SR 800, SR 371, SR 371a, SR 371c to spec' CS5363 and SR 44 to spec' TS594(B). Materials are used in loose and pelleted form.

Design Considerations

The following items require consideration when developing igniters. Physical dimensions, charge configuration, propellant type and characteristics motor body/closure design, free volume within the rocket motor, initial propellant burning surface area, inert surface area exposed to igniter flux, maximum mass discharge rate from the motor, smoke/signature characteristics and nozzle seal.

PYROTECHNIC IGNITERS REFERENCES

DOCUMENT REF	TITLE
S/R AH TRAPP JULY 72	IGNITION OF SOLID PROPELLANT ROCKET MOTORS
S/R AH TRAPP JUNE 75	IGNITION OF CDB SOLID PROPELLANT ROCKET MOTORS BY PYROTECHNIC IGNITERS
TTCP PAPER/68	IGNITION OF CDB PROPELLANT ROCKET MOTORS
T/R 73/14	THE PROBLEM OF IGNITION OF SOLID PROPELLANT ROCKET MOTORS FOR AN EXPERIMENTAL INVESTIGATION AT SRS
AGARD CONFERENCE PREPRINT 259 SECTION II REF 4	IGNITION AND EXTINCTION OF SOLID ROCKET PROPELLANTS
AS ABOVE BUT REF 8	PROBLEMS ARISING WHEN DEVELOPING PROPELLANT CHARGE IGNITERS
AS ABOVE BUT REF 9	SOME MEASUREMENT OF IGNITION DELAY AND HEAT TRANSFER WITH PYROGEN IGNITERS
PERME MEMO 130	SOME COMBUSTION CHARACTERISTICS OF PYROTECHNIC IGNITER COMPOSITIONS, SR371C AND SR44
DESIGN PRACTICES AT PERME(PE)	ROCKET MOTOR DESIGN MANUAL PART 1 SECT 7 THE IGNITER
RARDE PYROTECHNIC COMPOSITION INFORMATION SHEET NO 1	THE MANUFACTURE AND PROPERTIES OF SR 44
RAE TECH MEMO RDP119	IGNITION OF SOLID PROPELLANT ROCKET MOTORS FOR GUIDED WEAPONS
REP TECHNICAL MEMO NO 592	ASSESSMENT OF PYROTECHNIC COMPOSITION SR 44 PART 1
RPE TECH NOTE NO 191	THE DESIGN AND FILLING OF IGNITERS FOR SOLID PROPELLANT ROCKET MOTORS

2.5.2 **Pyrogen**

For the pyrogenic ignition system the selection of the ignition charge material, its form and total mass must be such that when it functions it produces acceptable motor ignition free form pressure oscillation and thrust shock over the required operating conditions.

A pure theoretical method for determination of the ignition charge is not possible as it is affected by so many factors, ie propellant type, charge interior shape, igniter location, initial free volume motor mass discharge rate. The ignition charge is not affected by propellant mass, burning time, or total impulse.

Due to the complex and transient nature of the ignition process the mass of the ignition charge will be based more upon previous experience and where possible scaling up or down from a previous design, rather than a pure theoretical approach.

The decision to use either a simply can or a controlled efflux pelleted type of pyrotechnic igniter depends mainly upon the Chemical Induction Period (CIP) of the motor propellant charge. Those propellants with a short CIP are generally satisfactorily ignited by a powder can igniter (pyrotechnic) whilst propellants with a long CIP require the more protracted output from a controlled efflux design (Pyrogenic).

A similar approach to that employed for the pyrotechnic system is used to determine the size and orm of the pyrogen ignition charge. Normal propellant/ballistic design principles are applied to design the pyrogen charge, its body and throat sizes.

Generally when using a pyrogen system the propellant ignition charge consists of the same propellant formulation as that used in the first stage of the motor to be ignited.

Igniter Hardware

Hardware is designed using conventional engineering principles within the confines of Def Stan 08-5 and PILLAR Proceeding 101.

Igniter circuitry and associated components must comply with the requirements of Def Stan 08-5.

Ignition Aids

To assist motor ignition a nozzle seal is often provided which is designed to withstand a pressure approximately 10% of the motor steady state pressure.

Packaging

The design of packs to contain igniters and igniter primer assemblies must comply generally with Def Stan 08-5.

Compatibility

All components and materials used in the ignition system must be compatible with CDB propellants and pyrotechnic compositions.

Electrical Test Equipment

All electrical test equipment used during manufacture and for in-service use must comply with Def Stan 085.

References

Documents which the designer can refer to for assistance in designing a pyrogenic igniter are listed below:

1. Rocket Motor Design Manual Part 1, Section 7, The Igniter (see para 7.1.8.5).
2. Def Stan 08-5
3. Def Stan 08-5 Part 5 Strength and Stiffness Requirements
4. Def Stan 08-3 Part 5 Materials Specifications
5. Def Stan 08-5 Part 5 Process and Working of Materials
6. AvP Section 6 Chapter 609/1 Potted Circuits
7. AvP 32 Section 6 Chapter 609/4 Wiring Techniques
   AvP 32 Section 6 Chapter 609/8 Solderless Joints and Terminations
8. Def Stan 08-5 Part 4 Safety Aspects of Packaged Explosives Items
9. Def Stan 08-5 Part 4 Tests for GW Packages
10. Def Stan 08-5 Part 6 Safety test Instruments
11. Def Stan 08-5 Part 6 Safety and Reliability of Systems Containing EED
12. Def Stan 08-5 Part 6 Section 7 Compatibility
13. Enclosure to OB Proc 41273 Principles of Design and Use for Electrical Circuits Incorporating Explosive Components.
14. RARDE Design Handbook for S and A Mechanisms FEA/110/028.
15. Properties of SR Pyrotechnic Compositions RARDE report 1/71

16. Guidance Standards for R & M
Def Stan 00-41 MOD Practices and Procedures for R & M
Def Stan 00-5 Design Criteria for Reliability, Maintainability and Maintenance of Land Service Material

17. Technical Report 74/6
Ignition of Solid Propellant Rocket Motors by Means of a Pyrogen Igniter.

18. Technical Note 87/33
E602 Pyrogen Ignition Development

2.5.3 Initators

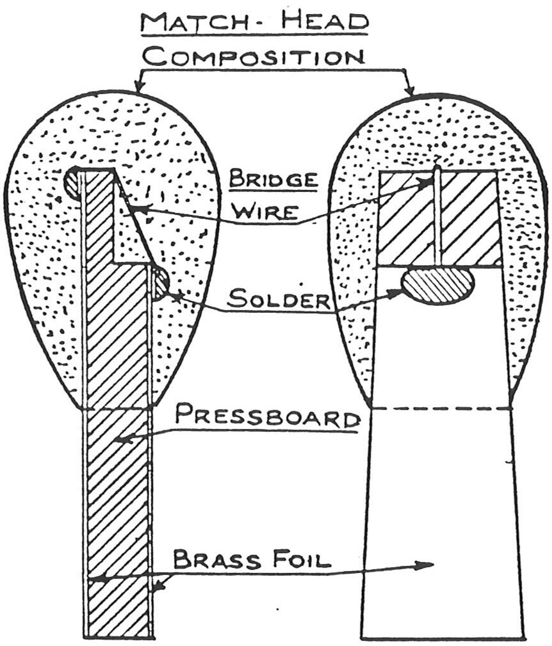
Initiators fall into one of two categories as far as rocket motors are concerned, these being:

1. Electricity Initiated Explosive Devices (EIED)
2. Percussion Cap or Stab Primer

2.5.3.1 Electrically Initiated Explosives Device (EIED)

This takes the form commonly referred to as an Incandescent Bridgewire, match head igniter or low tension fusehead (see sketch below).

Sketch of a typical EIED



The EIED's used within RMD are generally E type fuzes supplied by Nobel Explosives (or NEC) to specification AIR1447. Also IEBW293 to specification GW322 and DR9008 types are used, the latter initiator now being considered preferential on safety grounds.

The E type fuze or match head type of EIED take the form of a stepped strip of cardboard coated with foil on either side. A bridgewire is soldered at the tip of the stalk of cardboard, passes over the step and again soldered to the foil forming the "bridge". This is then dipped into the explosive media forming the "match head". The explosive media surrounds the bridge wire at the step.

On this type of EIED the bridgewire can be made of various materials including nichrome, platinium, tin, lead and copper. Various diameters of these materials give a range of performances. The rate of heat from the bridgewire is controlled by the magnitude of current passed through the wire. The quantity of heat depends on the duration.

The explosive media or match head composition can also vary, all being bonded together with a small quantity of nitro-cellulose. The materials are copper/Acetylide Charcoal/Chlorate and Lead mononitoresorcinate (L.M.N.R)/Chlorate.

The advantages of using the EIED within an igniter are its high reliability low cost and small size. The explosive media also gives a uni-directional reaction.

The IEBW293 type fuze is housed in a metal body. The fuzewire is suspended between two poles and surrounded by explosive media, similar to the match head type. This type of fuze gives a directional reaction.

The DRA008 type fuze is a recent addition to the initiators used and is generally used for pyrogenic type igniters. Again a metal housing is used and a directional reaction is given.

2.5.3.2 **Percussion Cap of Stab Primer**

This type of initiator is rarely used on rocket motors due largely to the size and simplicity of the EIED type iniators. However these devices are fired by a mechanical striker or firing pin, the level of strike energy available is critical to the satisfactory operation of this type of device. The physical size is generally larger than comparative EIED types.

2.5.3.3 **Selection of Initiator Types**

Generally initiator type is dictated by the following :

Reaction required
Reaction type (Directional or Unidirectional)
Availability of electrical power
Amount of electrical power available
Safety levels required
Operating environment
EMC and EMP requirements
RF characteristics
Availability of mechanical striker or similar
R & M requirements
Risk analysis requirements

2.5.3.4 **Initiators - References**

Document Reference	Title
Science of Explosives Part II Chapter IX Appendix	Ignition of Solid Explosive Media by Hot Wires (Elwin Jones)

2.5.4 **Electromagnetic Compatibility (EMC)**

2.5.4.1 The motor section shall meet the EMC requirements specified in AvP32, DEF-STAN 08-5 and DEF STAN 59-41, reference 2.2(1), 2.2(m) and 2.2(n) respectively, except as amended below. The DEF STAN 59-41 notation is used.

Condition	Applicable Level
DCEO 1	Level in Figure 8 applies
DCEO 2	Level in Figure 8 applies
DCEO 3	Not Applicable
DREO 1	DEF STAN 59-41 level applies
DREO 2	Not Applicable
DREO 3	Not Applicable
DCSO 2	DEF STAN 59-41 level B applies
DCSO 3	DEF SAN 59-41 level applies
DCSO 4	Not Applicable
DCSO 5	Not Applicable
DRSO 1	DEF STAN 59-41 level applies
DRSO 2	Level in Figure 10 applies

The EMC requirements specified in PILLAR Proceeding 101 must also be addressed.

The motor section shall be designed to preclude the emission of spurious electromagnetic radiation which may result in the detection of the missile either by the target or by other hostile forces prior to launch, or which may affect the launch aircraft, adjacent stores or other missile units.

2.5.4.2 **Name Plates and Product Marking**

The motor section shall be clearly marked in accordance with the requirements specified in the Physical Requirements Drawing, Figure 2 sheet 5.

The Safe/Arm indicators in the MSI shall be green background with white lettering for safe condition, and red background with black lettering for the armed condition. The transition between safe and arm condition shall be marked such that it is ready identifiable.

2.5.4.2 **Workmanship**

The workmanship employed in the manufacture of the motor section shall be of the highest quality. Particular attention shall be given to neatness and thoroughness of the marking parts and assembles, painting, plating riveting being, welding, crimping, wiring and freedom of parts from burrs and sharp edges.

2.5.4.4 **Motor Section Profile**

The motor section outer profile shall be as smooth as practicable, with discontinuities not exceeding 0.15mm.

2.5.4.5 **Interchangeability**

All motor sections having the same part number shall be completely interchangeable.

2.5.4.6 **Safety**

The design of the motor section shall comply with the appropriate safety regulation called up in the Mandatory Standards document. In particular the relevant parts of the safety specifications called in Section 6.

No single fault shall cause an inadvertent motor firing.

The probability of an inadvertent motor firing shall be less than 1 in 10 during the life of the motors.

2.5.4.7 **No Fire**

The initiator shall not operate when subjected to an electrical current of 1A and power up to 1W in accordance with MIL-1-23659C Notice 1 reference 2.2(o).

2.5.4.8 **Motor Safety Ignition Unit**

The MSI shall be a remotely operated, one shot, shuttered device containing passive electrical and visual status indication systems. It shall provide for the following conditions of the ignition system in an assembled missile.

SAFE:

The initiator shall be positively mechanically isolated from the igniter charge and electrically isolated from the initiator wiring. The initiator shall be shorted and grounded in accordance with MIL-STD-1512, reference 2.2(p). The electrical status indicator and the visual indicator shall both show the safe condition.

ARMED:

The igniter pyrotechnic train shall be aligned prior to, or at the same time as, completion of the electrical circuit to the initiator. The electrical path between the firing supply and the initiator shall be continuous. The electrical status indicator and the visual indicator shall not show the armed status.

The MSI shall give a visual indication of the Safe/Arm position of the shutter system when it is fitted to the motor. It shall also be possible to see the indicator when the motor section is assembled to the missile.

2.5.4.9 **Auto-Return to Safe**

In the event of the motor not being ignited after 1 second from receipt of the arm commance signal the MSI shall automatically return to the safe condition from the armed condition as soon as possible but shall not exceed 14 seconds. The status indicators shall then both show the safe status.

2.5.4.10 **Health and Safety**

The motor section, when treated in accordance with the requirements of this specification, shall be capable of operation, maintenance, transportation and storage without posing health or safety hazard to personnel.

The prime contractor shall not be deemed by virtue of any of the instructions in this specification to have assumed the responsibilities of the contractor under the Safety at Work Act or any other enactment.

2.5.4.11 **Packaging**

If the motor section is dangerous within any of the definitions set out in United Nations Recommnedations for the Transport of Dangerous Goods, reference 2.2(h), then its packaging shall comply, be tested and be marked in accordance with these recommendations.

2.5.4.12 **Grounding**

The motor section shall incorporate the following grounding requirements.

2.5.4.13 **Ground Loops**

Ground loops shall be avoided. Where loops are unavoidable their areas shall be minimised.

Any currents caused to flow in ground loops unavoidable in the design shall not degrade the operation of the unit.

2.5.4.14 **Single Point Grounding**

Single point grounding should be used at all levels. The section power rails shall have their own zero volt returns, these shall be made available for connection to the missile star point.

2.5.4.15 **Hybrid Grounding**

Hybrid grounding may be required in both low at high frequencies must be accomodated by the same circuits.

2.5.4.16 **General Requirements**

The following general grounding requirements shall be met to minimise EMI pick-up and common impedance coupling.

a) Cable screens shall be 360 degree grounded at every connector and interface and at every termination.

b) Signal wiring screens shall be single point grounded, preferably at the sending end.

c) The internal circuitry of the MSI shall be electrically isolated from its case.

d) Circuit power, control and signal returns shall be brought out on seperate leads for return to the missile common reference point.

e) Power, control and signal line filter shall be referenced to the motor structure.

f) Care shall be taken not to introduce ground loops through the use of filter capacitors.

g) An insulation test shall be performed on the unit to ensure that signal wiring is only grounded at the units reference point.

2.5.4.17 **Bonding**

The motor section shall incorporate the following bonding requirements.

2.5.4.18 **Bonding Resistance Limits**

The motor section shall be designed such that the bonding resistances do not exceed the limits shown in Table 2. The blast pipe and nozzle are not considered part of the motor outer case and may not meet these limits. The mechanical design shall be such that these requirements are achieved and maintained throughout the life of the missile.

2.5.4.19 **Bonding Surface Preparation**

All anodic film grease, paint, oxide or other high resistance finishes shall be removed from the imediate area of the bond. Care shall be taken to minimise the material removed from the surface. The use of abrasives which may cause corrosion from abrading material embedded in the surface shall be avoided. The bond shall be made, and then protected where appropriate, immediately after preparation of bonding surfaces.

2.5.4.20 **General Requirements**

Bonding connections shall be such that vibration, expansion or contraction shall not break, loosen or weaken the bond such as to permit an increase in the bonding resistance above the acceptable limits.

2.5.4.21 **MSI Case**

The MSI case shall be bonded directly to the missile motor structure by its normal fixings. All components parts of the MSI case shall be bonded together.

2.5.4.22 **Refinishing**

After bonding any exposed metals shall be immediately refinished with the original or other suitable protective coating.

2.5.4.23 **Documentation**

Documentation in the form of a Design Definition shall be supplied by the contractor for each variant and design standard. The Design Definition shall contain a written description and a specification of the item. The contractor shall slo supply the following documentation, for each variant and design standard, in accordance with the programme timescales:

a) Certificate of Design
b) Certificate of Conformance
c) Production Acceptance Specification

2.5.4.24 **Environmental Test Documentation**

The Contractor shall provide the following documentation relating to environmental test activity.

a) Test programme at least six weeks in advance of the test series, detailing:

   i) Objectives
   ii) Environmental test procedures
   iii) Test unit (Serial Numbers, Build Standard)
   iv) Function test procedure

b) Test Reports detailing:

   i) Deviations from test programme
   ii) Condition and performance of equipment before, during and after each environmental test
   iii) Test unit (Serial Numbers, Build Standards)
   iv) Post test inspection report
   v) Conclusions

The International System of Units (SI) shall be used for reporting motor section measurements and parameters.

Regular statements on mass, centre of gravity and moments of inertia shall be provided to the Prime Contractor.

2.5.4.25 **Models**

The motor models, together with their format, programming language, documentation and validation, which are required by BAe are identified in the Mathematical Modelling Requirements for the Motor Section, reference 2.2(g). These models shall include:

a) a thermal model of the motor section
b) a structural finite element analysis model

These models shall be provided in accordance with the programme timescales.

For modelling purposes the following information shall be supplied, this shall be updated as development proceeds.

i) nominal thrust profile
ii) nominal total impulse
iii) nominal impulse change with respect to time
iv) change in these values with change in environmental conditions
v) electrical power consumption with respect to time
vi) plume characteristics and composition

2.5.4.26 **Logistics**

Reference shall be made to the integrated Logistics Support Requirements for Contractors, reference 2.2(i).

2.5.5 Nuclear Hardening

2.5.5.1 Introduction

The ability to withstand the nuclear effects environment is one of the main requirements for UK service equipment, and the capacity to satisfy nuclear survivability criteria has to be built into the system at the design stage. The nuclear survivability requirements for the design will be integrated fully within the design drawings and manufacturing specifications.

This nuclear hardness assurance plan (NHAP) reviews the nuclear survivability requirements, and lays down how these requirements will be integrated into the project my means of a nuclear survivability programme. The major elements kof the programme are incorporated into the network. A flow chart showing how the activities link to produce a satisfactory product in Figure 31. Observance of the NHAP is mandatory for all staff involved in the project.

2.5.5.2 Nuclear Survivability Requirements

Thoughout this documents, a number of statements are made about the nuclear survivability requirements.

Firstly, the contract states that "It is highly desirable that when a design is deployed at the start line, the rocket motor does not ignite, and the explosive hose does not detonate as a result of exposure to the nuclear effects environment specified for equipment associated with men in main battle tanks (case 4).

In STANAG 4145, the design will be capable of fulfilling its peformance criteria within one minute of the event. Attention will also be paid to Def Stan 08-4."

The STANAG 4145 does not give an EMP environment, but references AEP-4. This document is proving difficult to obtain. However, it is expected that it contains the same exo-atmospheric EMO environment as quoted in the RMCS Guide.

In practical terms the above can be summarised:

Blast:	Safety considerations at start line
Thermal:	Safety considerations at start line
Tree:	Safety considerations at start line
Endo-EMP:	Safety considerations at start line
Exo-EMP:	Survival and operable witin 1 minute

This statement is re-enforced by a number of comments in the Royal Ordnance proposal.

A further document (Ref 3) is called up by the safety requirements of the contract. The OB42413 document has been replaced by Pillar Proc 101, and contains a requirement for EEDs to remain safe in an EMP environment.

2.5.5.2.1 System Design

The system is fundamentally simple in concept, and contains relatively few components vulnerable to nuclear effects. In planning to meet the nuclear survivability requirements, a short threat analysis was carried out to assess which parts of the system were likely to be affected by the nuclear weapon environment.

Taking into account the requirements and applying them to the outline designs, the results of the analysis are given in Table 9.

In essence,

Blast is likely to be significant on the rocket launcher and charge hose assembly (CHA) box, but will translate into a shock loading on other components. MOD have been advices that Royal Ordnance will not harden components against the secondary effect os trailer overturn.

Thermal is likely to be significant on the rocket (propellant), and CHA box.

TREE is likely to be significant on the control box.

EMP is likely to be significant on the control box, EEDs, rocket motor igniter and launcher actuators, a well as on items beyond RO control - such as the blow-out pin.

The first critical assessment of the above will be reported in Design Review 1.

2.5.5.3 Nuclear Survivability Philosophy

The nuclear hardening philosphy for the GVMLI system will ensure that new components will be hardened to a level consistent with achieving the required performance.

The design philosophy will commence by selecting where possible components with a known and acceptable performance. They will be assembled into a system using accepted techniques that will ensure that the intrinsic component performance is not degraded, and that the system performance is acceptable. For example, in the electrical system intrinsically hard components (eg electromechanical relays) willbe assembled into a system using techniques to minimise EMP effects.

Problems arising from the use of GFE, (such as blow-out-pin and hose box) will be addressed, but as no modifications will be ade to GFE by Royal Ordnance (other than to modify them to fit new items) a fully hardened system may not be achieveable. Attention to these GFE items would achieve a fully hardened system.

As installation of the system is not fully under Royal Ordnance control - indeed the host vehicles are not fully defined with respect to individual build standard - hardening for EMP is not straight forward.

Royal Ordnance will ensure that the new GVMLI equipment is fully EMP hardened when installed in accordance with their instructions. Responsibility for ensuring compliance with GVMLI nuclear hardening requirements in Chieftain AVRE rests with Vickers plc.

It is the intention to carry out a EMP hardness demonstration trial, (T905B) probably in PETS 2 at AWE, Aldermaston on a suitable installation when connected to Chieftain AVRE.

No further demonstration trials will be carried out, though limited engineering trials will be undertaken during the development.

2.5.5.4 **System Nuclear Survivability Design Analysis**

Design assessments will be carried out to examine the nuclear survivability requirements fkor the GVMLI system (RO parts) and to ensure integration of these requirements within the design, development, culminating in an assessment report at design chill showing the levels of hardness achieved.

2.5.5.4.1 **Vulnerability and Threat**

Referance has already been made to Annex C which contains the results of a threat analysis. The actions identified will be implemented as appropriate. The recommendations of DEF STAN 08-4 will be used.

Blast

The control box will normally be inside the towing vehicle and not subject to the full effects of blast. The rocket motor igniter will similarly be protected by the motor casing. The rocket/launcher will be designed to withstand the full blast pressure. Wiring harnesses however will be subject to blast effects and it is intended to give these added protection by running them through the trailer box sections where possible.

The hose box will protect the explosive hose, tear webbing, SAFU, etc from the direct blast effects but will be subject to shock loadings. However, the force on the hose box may cause it to overtune, with subsequent damage to the rocket motor/launcher. MOD have been advised that RO will not harden components against such secondary effects.

Thermal Effects

The only items directly affected by the thermal pulse are rocket motor/launcher, harness and charge hose box.

The harness will be constructed with a Tefzel conduit, with some legs (such as that to the rocket motor connector), constructed within a PTFE conduit.

Tefzel and PTFE conduits are temperature rated up to 155^{O}C and 260^{O}C respectively. Nuclear thermal effects may cause charring to the harness conduit, but the harness is likely to survive and remain functional.

The rocket motor design will take cognizance of the thermal pulse and protect against it if necessary.

The likelihood of the hose box, trailer tyres, etc, catching fire and burning when exposed to the thermal pulse is not known. However there is no intention of hardening existing GFE against nuclear thermal pulse, and any secondary effect emanating as a consequence will not be considered.

Improved protection against the standard envrionmental conditions will be afforded by the new CHA cover however, no guarantee can be given that it will afford the necessary protection to the explosive hose from the nuclear thermal pulse. No evidence has been made available by MOD to RO on the likely response characteristics of the explosive hose to the nuclear thermal pulse.

Nuclear Electromagnetic Pulse (NEMP)

The nuclear electromagnetic pulse (NEMP) is an intense electromagnetic field of short duration, less than one microsecond at the receiving point for the exo-atmospheric pulse and a few milliseconds for the endo-atmospheric pulse. Unless systems or equipments are suitably protected damage can occur due to EMP coupling, eg the absorption of energy from the EMP into the harness lines. This will cause a fast rising voltage pulse to be transmitted down the lines and into the control box causing damage to semiconductors and other components unless suitably protected.

RO proposes to minimise the effects of EMP by techniques such as the use of transient protection units (TPUs) at the couplings between harness sections and also between control box and harness, along with screening of all harness lengths. The rocket motor igniter will be fitted in a small Faraday shield, and protected by filters, a procedure well tried with the Rapier system. The launcher sensors will be totally enclosed. Effective shielding and adequate protection for the cable runs, together with a good earthing and bonding system, are also essential for satisfactory NEMP protection, and will be designed into the system. The earthing system will tie the structural members and components of the GV system to a common ground. The detailed design will be dependent kon structural factors such as the fixing points on the trailer, but these can be integrated within the whole system at the design stage.

Particular attention will be paid to the firing circuits to ensure that any high voltages generated do not cause inadvertant firing. The system components will be tested by bulk current injection (BCI) methods.

A potential problem area may exist in that the blow-out pin (which is GFE, and is not to be modified) may fire on receipt of NEMP, despite any measures that could be undertaken by Royal Ordnance in the design of GVMLI components.

Transient Radiation Effects (TREE)

Transient radiation effects will occur in both materials and electronics. No effects are known to RO on the materials to be used, but RO request that additional information is provided via the project manager from MOD exerts.

Electronics can be significantly affected by radiation (generally called TREE, transient radiation effects on electronics). The basic design will choose components that are intrinsically hard, selected from components and technology information contained in the MOD data base on radiation effects SIRE.

The components will be designed into circuits that have further hardening techniques incorporated to ensure that the whole electronic package is satisfactorily hard.

2.5.5.4.2 **Method Adopted**

Annex A shows the general flow of information and decision process through the project. The major milestones in the nuclear hardness assessment reports at periodic intervals to MOD. These will contain information on the state of the nuclear hardening programme and should reveal the status of all the items in the system.

A hardened design should be achieved by sysem design chi. This design will then be monitored for continuation of nuclear hardness as part of the standard configuration management procedure. Activities are proceeding within the various sub systems to meet these requirements.

Nuclear Hardness Assessment Report

A nuclear hardness assessment report is to be submitted to the customer as part of the MOD design review package. Separate reports may be submitted for each environment. Of necessity, these reports will be required at arbitrary dates in the nuclear hardening activities and therefore may be 'snapshots' of milestones, etc. The reports will contain:

a) Brief description of the hardware/software, the build standard of the hardware which is being assessed, plus a list of the relevant drawings, etc.

b) Itemisation of the equipment in sufficient detail to allow a nuclear hardening assessment. It may be necessary to itemise the equipment to different degrees for each environment, eg. For thermal effects, the equipment itemisation may only be necessary for units with surfaces likely to be exposed to the thermal pulse. However, for gamma effects, the same unit will need to be itemised in more detail, ie to individual electronic component level.

c) An assessment of the effects of each of the nuclear environments on the equipment at the level of breakdown given at (b), and also at more assembled levels.

The assessment report will include a simple table showing the results. (Note: It is the intention to monitor the progress by the increase in 'Acceptable Performance' entries). This table will be backed up by information verifying the hardness statements.

Later assessments should show full nuclear hardness has been achieved.

2.5.5.5 Systems Nuclear Survivability Testing

A significant part of the whole nuclear hardening plan is the programe of test and evaluation. This will be done as appropriate throughout the development process, and the trials required are being incorporated in the master trials plan and schedule as appropriate.

Trials are planned only for EMP effect on the electrical items and system. These trials will back up good design practices and theoretical predictions, which will give the basic level of assurance needed.

Testing is not currently thought to be necessary for the rocket motor igniter, due to its close similarity in design and mechanical arrangements to its equivalent in the well-tried Rapier system and current work on ASRAAM.

The igniter will however be considered during BCI evaluation of the harness, by means of an inert/dummy arrangement. In addition, a free field NEMP demonstration trial (T905B) is planned to be carried out, probably at one of the PETS facilities at AWE Aldermaston. Details of this have still to be agreed with MOD but it must be recognised that the whole system (including AVRE plus two trailers) could be too large to fit satisfactorily into this facility.

All trials will have the necessary trials requirements and specifications agreed with MOD, and trials assessment reports will be issued.

The Company has sufficient experience derived from previous projects to optimise the component designs against blast, thermal and transient radiation effects (TREE). Significant component testing under these environments is therefore not anticipated.

2.5.5.5.1 **Component Testing - NEWP**

A NEMP field sets up transient currents within metallic structures (including wires and cables) and provided the amplitudes and waveforms of these transients can be predicted, NEMP susceptibility can be part determined by injecting a simulated current at eh input of interface under consideration. Bulk current injection (BCI) trials, may be considered a practical and economical method of testing subsystem susceptibility. However, RO recognises the limitations of the test in that the short rise times associated with NEMP will not be simulated and as such the validity of BCI testing is under review within RO.

The Company currently intends to conduct a BCI test on the harness system to determine the susceptibility of the GVMLI electrical system to NEMP (Project week 72). This is shown in the electrical system hardening plan at Annex D.

2.5.5.5.2 **Component Testing - Other Nuclear Environments**

By selecting appropriate components and using recognised assembly techniques, it is anticipated that little testing will need to be done.

2.5.5.5.3 **Test Plan**

At system level, all nuclear hardending trials have been incorporated in the trials programme. At subcomponent level, if BCI testing is selected the Company intends to submit a detailed BCI test plan to MOD for approval prior to the actual testing (see Table 16). When these tests are complete and documented, the electrical system will go forward for inclusion in the total system tests at Aldermaston.

2.5.5.6 **Nuclear Survivability Management**

Management of the GVMLI nuclear survivability design and testing will be part of the normal technical function, and be the overall responsibility of the Technical Manager. Technical Management will however be assisted by the appointment of a nuclear hardness engineer NHE). He will also monitor the progress of nuclear hardening measures, and carry out nuclear hardening reviews, and any nuclear hardening audits required during the course of the programme on behalf of systems and sub-systems DA's.

2.5.5.6.1 **Nuclear Hardness Control Board**

Prior to system chill and freeze, the NHE will be required to convene a nuclear hardness control board, to ensure that sub-component assessments are approved and integrated into the overall nuclear hardening requirement. Project Management will be responsible for coordinating the activities of the NHE with other project staff. MOD will be invited to attend the board.

2.5.5.6.2 **Reporting**

Progress reports on nuclear survivability will be reviewed at all six weekly and quarterly review meetings with the MOD, and reviewed at all internal technical progress meetings and design review. The NHE may be called to attend these as appropriate.

At each design review a nuclear hardening assessment report will br presented, giving the latest information on the design status. It is the intention to have a hardened design for each of the sub-systems and the system at its relevant design chill date. Further examination of the design and achieving full compliance will follow between chill and freeze dates.

2.5.5.6.3 **Post-Chill**

After design chill, the maintenance of nuclear hardness will be achieved via the Configuration Control Board.

Instructions necessary for theh maintenance of nuclear hardness of RO equipment after manufacture will be included in the Technical Publications issue to MOD.

Figure 31

HARDNESS ACCEPTANCE FLOW CHART

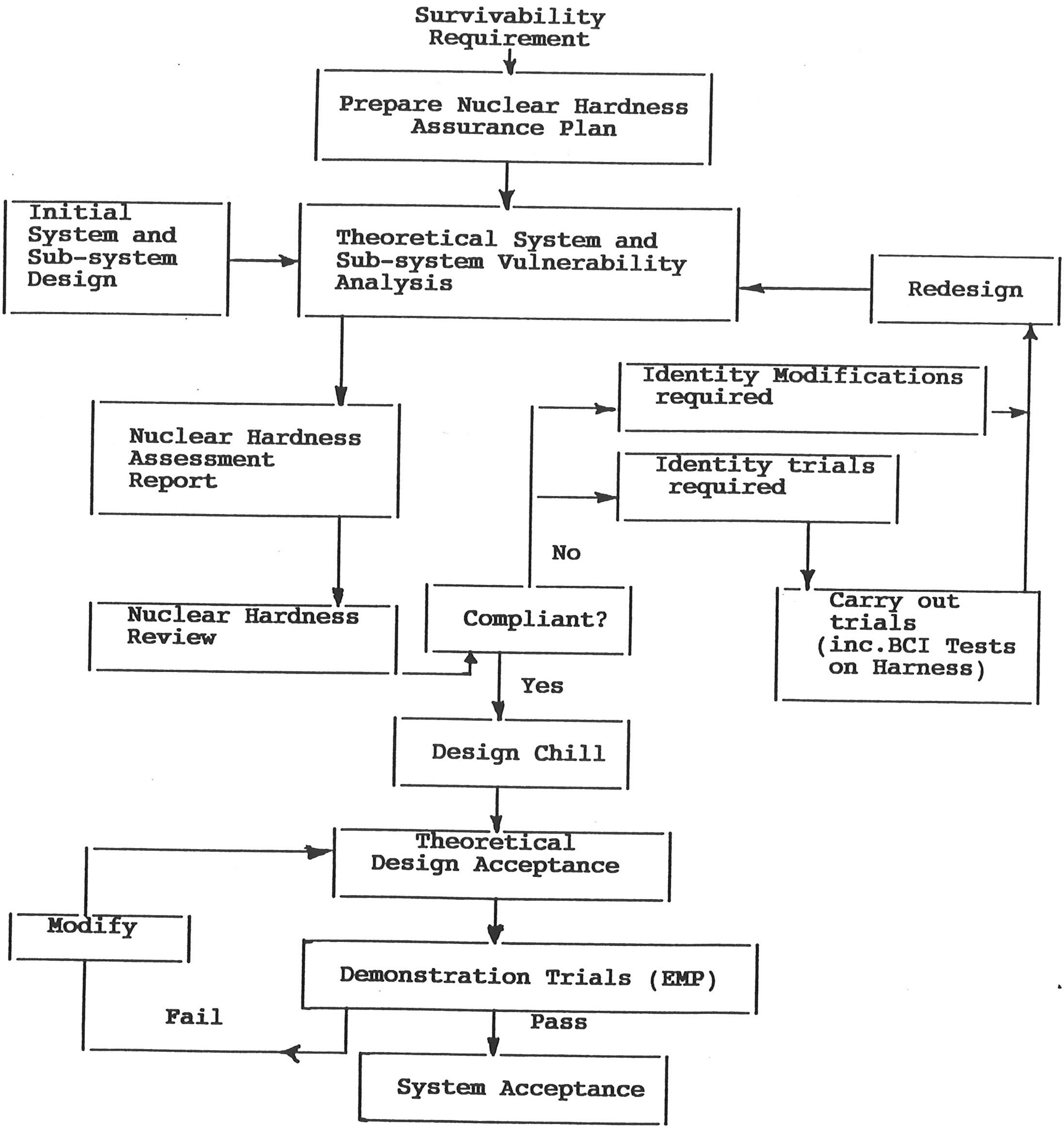


Table 9

PRELIMINARY THREAT ANALYSIS AND ACTION TABLE

THREAT	BLAST	THERMAL	EMP	TREE
SAFU	None	Minor	None	None
HARNESS	Minor. Design Study needed	Minor. Design Study needed	Possible damage to electronic components. BCI test, System Trial	Minor. Some design work needed
CONTROL BOX	None	None	Possible damage thro harness. BCI test, System Trial Installation dependent	Minor. Some design work needed
ROCKET MOTOR	Minor. Design study of case needed.	Propellant heating study needed.	Minor. Igniter doubly protected. System Trial	None
LAUNCHER	Some risk to actuators and hornbeam.	Minor	Sensors, filters, shielded. BCI test, System Trial	Minor
CHARGE HOSE	None	None	None	None
HOSE BOX	GFE	GFE	GFE	GFE
TRAILER	GFE	GFE	GFE	GFE

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Table 10

WEAPON EFFECT		UNITS		OPEN CASE 1 SET A	OPEN CASE 1 SET B	WHEELED VEHICLES CASE 2 SET A	WHEELED VEHICLES CASE 2 SET B	LIGHT AFVs CASE 3 SET A	LIGHT AFVs CASE 3 SET B	MBTs CASE 4 SET A	MBTs CASE 4 SET B	SUPPLY DUMPS CASE 5 SET A	SUPPLY DUMPS CASE 5 SET B
				EQUIPMENT ASSOCIATED WITH MEN IN									
1. AIR BLAST													
Incident Peak Static Overpressure	$\hat{p}$	(psi)	kNm²	(7.5) 52	(6) 41	(7.5) 52	(5.5) 38	(12.5) 86	(11) 76	(16.5) 115	(14) 96	(18) 125	(11) 76
Static Overpressure Duration	tp	sec	ss	0.9	2.5	0.9	2.5	1.2	1.9	1.0	1.7	0.4	1.9
Static Overpressure Impulse	Ip	(psi/sec)	kNm²/s	(2.4) 17	(5.2) 36	(2.3) 16	(5.0) 35	(5.5) 38	(7.0) 48	(5.7) 40	(7.9) 55	(2.4) 17	(7.1) 50
Peak Dynamic Pressure	q	(psi)	kNm²	(1.3) 9	(0.7) 5	(1.5) 10	(0.7) 5	(3.8) 26	(2.6) 18	(6.4) 44	(4.5) 31	(7) 48	(2.8) 20
Dynamic Pressure Positive Duration	tq	sec	s	1.2	3.2	1.2	3.2	1.9	2.8	1.8	2.7	0.7	2.8
Dynamic Pressure Impulse	Iq	(psi/sec)	kNm²/s	(0.3) 2	(0.5) 3	(0.3) 2	(0.4) 3	(1.1) 8	(1.3) 9	(1.7) 12	(1.9) 13	(0.8) 6	(1.4) 10
Peak Underpressure	$\hat{p}_{neg}$	(psi	kNm²	(1.4) 10	(1.2) 8	(1.4) 10	(1.1) 8	(2.0) 14	(1.7) 12	(2.1) 15	(2) 14	(2.2) 15	(1.7) 12
Arrival Time	ta	sec)	s	2.1	6.5	2.0	7.0	2.5	3.8	1.8	3.1	0.7	3.7
2. THERMAL RADIATION													
Total Thermal Energy	Q	(cal/cm²)	MJ/m²	(30) 1.3	(30) 1.3	(75) 3.1	(95) 4	(240) 10	(270) 11	(330) 14	(400) 17	(125) 5	(240) 10
Maximum Irradiance	Qmax	(cal/cm²/sec)	MW/m²	(110) 4.6	(20) 0.8	(160) 6.7	(60) 2.5	(230) 10	(160) 7	(330) 14	(240) 10	(410) 17	(140) 6
Time to Maximum Irradiance	Tmax	sec	s	0.1	0.64	0.18	0.64	0.39	0.64	0.38	0.64	0.11	0.64
80% Energy Delivered in		sec	s	1.0	6.4	1.8	6.4	3.9	6.4	3.8	6.4	1.1	6.4
Pulse Width at Half Qmax		sec	s	0.13	0.83	0.23	0.83	0.51	0.83	0.49	0.83	0.15	0.83

3. INITIAL NUCLEAR RADIATION		UNITS		OPEN CASE 1	WHEELED VEHICLES CASE 2	LIGHT AFVs CASE 3	MBTs CASE 4 INTERIOR	MBTs CASE 4 EXTERIOR	SUPPLY DUMPS CASE 5
Assumed Transmission Factors				TFn = TFy = 1	TFn = TFy = 1	TFn = TFy = 1	TF n = TFy = 0 3		TFn = TFy = 1
Total Dose (Neutron + Gamma)	Dt	Rad(tissue)	cGy(tissue)	2600	2600	2600	2600	8700	75000
Maximum Gamma Contribution	Dy	Rad(tissue)	cGy(tissue)	1350	1300	2000	1770	5900	15000
Maximum Neutron Contribution	Dn	Rad(tissue)	cGy(tissue)	2100	2100	2100	2220	7400	60000
Maximum Combined n and y Ionising Dose	Di	Rad(Si)	cGy(Si)	1700	:700	2550	2250	7500	23000
Maximum Neutron Fluence	Fn	(n/cm²)	~~[illegible]~~ n/mm²	(1×10^{12}) 1×10^{10}	(1×10^{12}) 1×10^{10}	(1×10^{12}) 1×10^{10}	(1×10^{12}) 1×10^{10}	(3×10^{12}) 3×10^{10}	(3×10^{13}) 3×10^{11}
Peak Gamma Dose Rate	γ	Rad(Si)/sec	cGy(Si)/s	3×10^9	3×10^9	3×10^9	3×10^9	1×10^{10}	1×10^{11}

4. COMMENTS		OPEN CASE 1	WHEELED VEHICLES CASE 2	LIGHT AFVs CASE 3 / MBTs CASE 4	SUPPLY DUMPS CASE 5
	Where 2 sets of figures are given they are to be survived independently.	Blast incapacitates 50% of prone men randomly orientated. Thermal and INR incapacitates 50% of men wearing full NBC kit.	Blast overturns 50% of randomly orientated vehicles thereby incapacitating crews.	Vehicle protects crew from thermal radiation.	10% chance of severe damage to contents of dump. 50% chance of moderate damage. Blast is the ruling effect.
For TREE (Transient Radiation Effects on Electronics) INR data to be used are Di, Fn and γ.	All figures are rounded.		Wheeled vehicles Blast levels also supply to equipment in field storage conditions.	Internal fittings protected from direct blast but subject to shock and other secondary effects caused by vehicle overturn. Assumes vehicles are closed down.	

5. ELECTROMAGNETIC PULSE

For Pulse Shape refer to NATO Standard Pulse (STANAG 4145)

a. Exo-Atmospheric Burst.	E Field	H Field
Field Strength at Peak	50 kV/m	130 A/m
Pulse Rise Time (0.1 - 0.9 peak)	5 ns	5 ns
Time to Peak	10 ns	10 ns
Pulse Width (0.1 peak)	600 ns	600 ns
Pulse Width (0.5 peak)	200 ns	200 ns

b. Endo-Atmospheric Burst	E Field	H Field
Field Strength at Peak	40 kV/m	200 A/s
Pulse Rise Time (0.1 - 0.9 psi)	5 ns	5 ns
Time to Peak	10 ns	10 ns
Field Strength at Plateau	30 kV/m	150 A/s
Pulse Length to Plateau	50 ns	50 ns
Pulse Length to End of Plateau	200 μs	200 μs
Pulse Width	2000 μs	2000 μs

COMMERCIAL IN CONFIDENCE

ANNEX A

Database Of Historical Experience For Solid Motors

Developed at Royal Ordnance (Summerfield)

SOLID PROPELLANT ROCKET MOTORS

MOTOR: E612 TITUS - FOR STARSTREAK

AREA OR COMPONENT	DESCRIPTION (mat'l, construction)	COMMENTS (problems, advantages)
Motor Body	KEVLAR OVERWRAPPED ALUMINIUM	Care must be taken on reduction in diameter AND INCREASE IN BODY LENGTH DUE TO OVERWIND.
Igniter	PYROGENIC TYPE. KU PYROGEN CHARGE SR 44 GAINE CHARGE	
Lining	SPUN COATED HYPALON	
Charge/Inhibition	ϕ 99.6 x 530 long CARTRIDGE LOADED STAR CENTRED DESIGN PB 40 INHIBITION DOX END INHIBITION	
Charge Retention/ Obturation	BUTYL RUBBER OBTURATOR RING	
Nozzle	ALUMINIUM ALLOY 7049HC WITH GLASS PHENOLIC XM1006 INSULATION.	MAY BE MOULDED FROM DURESTOS MOULD TOOL.
Blast Pipe	N/A	
Adhesives/Bonding (explosive)	FORMVAR FILM	
Adhesives/Bonding (non-explosive)	CHARGE SUPPORT TO MOTOR BODY – Aluminium Alloy to Glass Phenolic = AMBERSIL OP1 PRIMER SILCOSET 105 CHARGE SUPPORT TO CHARGE SUPPORT PAD – GLASS PHENOLIC TO ETHYLENE PROPYLENE = AMBERSIL OP1 PRIMER SILCOSET 105 NOZZLE CHOKE TO NOZZLE BURST DISC – CARBON GRAPHITE TO ALUMINIUM ALLOY = DOW CORNING 1200 PRIMER RTV 3145	
Surfaces Treatments	CHROMIC ACID ANODISING CHROMATE CONVERSION COATING.	
Other Areas:		

Compiled by: M C ROBINSON

Date: 13-5-93

SOLID PROPELLANT ROCKET MOTORS

MOTOR: E 536 Mk 3 - STALL RECOVERY ROCKET MOTOR FOR FOKKER BV FOR FOKKER F 70.

AREA OR COMPONENT	DESCRIPTION (mat'l, construction)	COMMENTS (problems, advantages)
Motor Body	ALUM. ALLOY	MEDIUM WEIGHT DESIGN WITH HIGH FACTOR OF SAFETY. MOTORS MOUNTED WITHIN AFT PART OF AIRCRAFT FUSELAGE TO PROVIDE A CORRECTIVE THRUST SHOULD CRITICAL STALL OCCUR DURING AIRCRAFT TESTING.
Igniter	PYROGEN	
Lining	CURED HYPALON (2759)	
Charge/Inhibition	COMPOSITE (2mm C.A. / 0.5mm Hypalon)	
Charge Retention/ Obturation	STEEL SPRING PUSHES CHARGE AGAINST AFT CLOSURE OBTURATING AGAINST SILCOSET.	
Nozzle	STEEL CONICAL - UNLINED INCORPORATING SAFETY BLOW OFF DEVICE IF OVER PRESSURISED.	
Blast Pipe	NONE	
Adhesives/Bonding (explosive)	FORMVAR FILM HYPALON/PROP INTERFACE B.C. (ALUMINIUM) FOR AFT END SILCOSET INHIBITION.	
Adhesives/Bonding (non-explosive)	PLIOBOND - HYPALON/BODY	
Surfaces Treatments	SHOT BLAST & DEGREASE BODY	
Other Areas:	SLOTTED RADIAL CHARGE 4 EQUI-SPACED SLOTS.	

Compiled by: G. S. OWEN

Date: 28 MAY '93

19 MAY 1993

SOLID PROPELLANT ROCKET MOTORS

MOTOR: E 596 DWINA.-

AREA OR COMPONENT	DESCRIPTION (mat'l, construction)	COMMENTS (problems, advantages)
Motor Body		
Igniter		
Lining	NOZZLE PLUG MOULDED SILCOSET 101 3W 100879	PROBLEM No 1. NOZZLE PLUGS CURED OFF WHILST IN-SITU IN THE CHOKE THROAT. RESULT: VERY HIGH EJECT PRESSURE REQUIRED TO REMOVE THE PLUG ON IGNITION. SOLUTION: CARRY OUT A HIGH TEMPERATURE POST CURE ON THE MOULDED NOZZLE PLUG.
Charge/Inhibition		
Charge Retention/ Obturation		
Nozzle		
Blast Pipe	CHOKE SINTERED BAR/MACHINED T.Z.M. 3W 101057	PROBLEM No 2 CONSIDERABLY GREATER THAN NORMAL SHRINKAGE OF CHOKE THROAT DIA. (FOUND ON MEASUREMENT AFTER FIRING.) RESULT: MISALIGNMENT (PITCH & YAW) LEVELS OUTSIDE TECHNICAL REQUIREMENT. SOLUTION: ENSURE TZM HARDNESS REQUIREMENT IS GREATER THAN 250 HV10
Adhesives/Bonding (explosive)		
Adhesives/Bonding (non-explosive)		
Surfaces Treatments		
Other Areas:		

Compiled by: M.P. HACKETT

Date: 18:5:93.

SOLID PROPELLANT ROCKET MOTORS

MOTOR: E 596 DWINA -

AREA OR COMPONENT	DESCRIPTION (mat'l, construction)	COMMENTS (problems, advantages)
Motor Body		
Igniter	IGNITER CAP BONDED ASSEMBLY 3W 100866	PROBLEM DURESTOS INSULATION FOR THE IGNITER END CAP BECAME DETACHED (UNBONDED) DURING MOTOR IGNITION. RESULT: BLOCKAGE OF ONE OF THE FOUR NOZZLES COULD OCCOUR. THIS WOULD LEAD TO MASSIVE MISSILE MISALIGNMENT AND POSSIBLE MOTOR BLOW UP. SOLUTION: MANUFACTURE A 'ONE-PIECE' STAINLESS STEEL IGNITER CAP TO 3W 101263. ALSO SEE TECHNICAL NOTE 88/55
Lining		
Charge/Inhibition		
Charge Retention/ Obturation		
Nozzle		
Blast Pipe		
Adhesives/Bonding (explosive)		
Adhesives/Bonding (non-explosive)		
Surfaces Treatments		
Other Areas:		

Compiled by: M.P. HACKETT

Date: 27:5:93.

SOLID PROPELLANT ROCKET MOTORS

MOTOR: E 603 TRAJAN

AREA OR COMPONENT	DESCRIPTION (mat'l, construction)	COMMENTS (problems, advantages)
Motor Body	S.S.L (4 LAYERS + 1mm GRP & 1mm CORK	
Igniter	SIDE-VENTING WITH RES. ROD ATTACHED PYROGEN CHARGE ROWANITE 102 STEEL BODY.	
Lining	HYPALON / DURESTOS	BLISTERING, DUE TO CURE OF DURESTOS. LEAKING DUE TO SHARP EDGES.
Charge/Inhibition	N/A	
Charge Retention/ Obturation	CASE BONDED	
Nozzle	TRIPLE NOZZLE CONFIG DURESTOS / MOLY SUPPORTED BY STEEL SHELL	
Blast Pipe	N/A	
Adhesives/Bonding (explosive)	FORMVAR FILM. FE RESIN IMI/SRS/73	
Adhesives/Bonding (non-explosive)	RC RESIN IMI/SRS/71	
Surfaces Treatments	BODY - EC 90.	
Other Areas:	EMCDB CHARGE	MODULUS OF PROPELLANT DUE TO AGE OF NC IN PASTE MANUFACTURE.

Compiled by:

Date:

SOLID PROPELLANT ROCKET MOTORS

MOTOR: E 604, Zama – FOR TRIGAT M.R.
CHARGE ONLY.

AREA OR COMPONENT	DESCRIPTION (mat'l, construction)	COMMENTS (problems, advantages)
Motor Body	N.A. CHARGE ONLY. AEROSPATIALE COMPOSITE BODY	NO FLAME, LOW SMOKE MOTOR DESIGNED & MANUFACTURED BY AEROSPATIALE, FRANCE. MOTOR DEVELOPMENT & QUALIFICATION PROG. 1988 to 1994 MAY LEAD TO INDUSTIALISATION & SUBSEQUENT PRODUCTION.
Igniter	AEROSPATIALE IGNITER	
Lining	A.S. SILICON RUBBER	
Charge/Inhibition	BOOST/SUSTAINER PSCB INHIBITED WITH PB40K & DOX 2.	
Charge Retention/ Obturation	BONDED TO FWD. END OF MOTOR WITH RTV BY AEROSPATIALE (A.S.)	
Nozzle	TZM NOZZLE & CHOKE A.S. DESIGN & MAN.	
Blast Pipe	CFRP AS DES. & MAN.	
Adhesives/Bonding (explosive)	FORMVAR FILM - PB40K/PROP. Mo BAR. COAT DOX /PROP.	
Adhesives/Bonding (non-explosive)	DOX II to SILICON RUBBER LINER – RHODORSIL CAF 1 PLUS PRIMER DONE BY AS.	
Surfaces Treatments	B/C etc for DOX II Degrease & prepare F/film & PB40 K to Spec.	
Other Areas:	SPECIAL PROFILED AFT END TO PRODUCE HUMP IN PRESSURE PROFILE INITIALLY.	

Compiled by: G.S. OWEN

Date: 28 May '93

SOLID PROPELLANT ROCKET MOTORS

MOTOR: ~~E~~ WHINCHAT VB. RKT MTR.

AREA OR COMPONENT	DESCRIPTION (mat'l, construction)	COMMENTS (problems, advantages)
Motor Body	DRY KEVLAR OVERWIND ONTO ALUMINIUM BODY	DUE TO WINDING PROCESS KEVLAR UNDER TENSION TUBE GROWS IN LENGTH AND DIAMETERS VARY - SOME INCREASE / SOME DECREASE.
Igniter	ALUMINIUM BODY (2 SECTIONS) BONDED TOGETHER WITH BONDED ON DURESTOS SLEEVE.	CONTINUITY PROBLEMS THRO' BOND JOINT. + JOINT CAN BREAK DUE TO THERMAL CHANGES DURING TRIALS.
Lining	HYPALON PAINT SPUN INTO BODY.	PROVIDE VISUAL STANDARD OF ALL ACCEPTABLE STD.
Charge/Inhibition	EDB WITH DENDRITIC CONDUIT. + EC COATING HEAT SHRUNK + BONDED ON	AS ABOVE
Charge Retention/ Obturation	MOULDED RUBBER OBT. ONTO NOZZLE	AS ABOVE
Nozzle	ALUMINIUM WITH DURESTOS MOULDED LINING + BONDED IN CARBON CHOKE + BONDED IN FOIL SEAL.	AS ABOVE
Blast Pipe	N.A.	N.A.
Adhesives/Bonding (explosive)	E.C. COATING AND E.C. WASHERS TO CHARGE OUTSIDE DIAMETER + ENDS.	STRIP TEST OF COATED CHARGE DELETED, DUE TO PROOF BEING CARRIED OUT BY MANUFACTURER. ALTERNATIVE PULL TEST OR OTHER TYPES OF MATERIAL/BOND TESTS SHOULD BE STIPULATED.
Adhesives/Bonding (non-explosive)	NORYL BORE RIDING RINGS ONTO ALUMINIUM TUBE OR NOZZLE. DURESTOS CHARGE SUPPORT & RUBBER PADS INTO TUBE.	OPERATING LOADS MUST BE DEFINED BY CUSTOMER AND APPROPRIATE PRODUCTION TEST INCORPORATED.
Surfaces Treatments	ANODISING VERSES ALOCHROMATING.	FINALISE CORRECT SELECTION AS EARLY AS POSSIBLE. REMEMBER CONTINUITY!
Other Areas:	PAINTING OF MOTOR COMPONENTS. PACKAGING.	ENSURE IT IS REQUIRED AND WHERE! PROVIDE VISUAL STANDARD. ENSURE REQUIREMENTS FOR SHUNT PLUGS, CAPS ETC STATIC DISCHARGE PROBLEM USE ANTI-STATIC POLY BAG.

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Date: 18:5:93.

SOLID PROPELLANT ROCKET MOTORS

MOTOR: ~~E~~ BRAMBLING RKT MTR.

AREA OR COMPONENT	DESCRIPTION (mat'l, construction)	COMMENTS (problems, advantages)
Motor Body	SEE WHINCHAT	———
Igniter	ALUMINIUM BODY c/w PCB + FILTERS + PLUG.	FULLY DEFINE ALL DIMENSION + TESTING OF SUB-CONTRACTED PARTS
Lining	N.A.	N.A.
Charge/~~Inhibition~~	EDB TUBULAR SECTION STICKS.	FULLY DEFINE DIMENSIONS FORM, MASS ETC.
Charge Retention/ ~~Obturation~~	STICK TO CHARGE + SUPPORT PAD TO BODY.	VISUAL STANDARD OFF MOULDED PAD
Nozzle PLATE.	ALUMINIUM WITH HARD ANODIZING COAT.	ENSURE THE MINIMIUM THK. OF COAT REQUIRED IS WELL BELOW WHAT CAN EASILY BE MANUFACTURED.
Blast Pipe	N.A.	N.A.
Adhesives/Bonding (explosive)	STICKS TO CHARGE SUPPORT PAD.	FULLY DEFINE ADHESIVE MASS REQUIRED.
Adhesives/Bonding (non-explosive)	CHARGE SUPPORT PAD TO MOTOR BODY.	AS ABOVE.
Surfaces Treatments	ANODISING VERSES ALCHROMATING.	SEE WHINCHAT.
Other Areas:	PAINTING OF MOTOR COMPONENTS. PACKAGING	SEE WHINCHAT.

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Date: 18:5:93.

PART 3 - PROCESSES (BONDING AND SURFACE TREATMENT)

3. **Processes**

Part 3 of TN79/49 describes the processes (ie Bonding and Surface Treatment) associated with the components used in the development and manufacture of Rocket Motors.

Bonding

The Materials Department is responsible for selection of all adhesives (ie Technical Authority and Design Authority), and procedures are tabled in the Material Department's Operating and Design Manuals.

The bonding processes, controls and design practices shall be in accordance with Def Stan 08-5/1-Design Requirements for Weapon Systems (ref 1) and approved by MOD(PE). Information on MOD(PE) approved procedures for adherent surface preparation, application and bonding of adhesives, process control and production facilities is contained in Leaflets 5-701/2, 5-701/3 and 5-701/4 of Def Stan 08-5/1.

3.1 Adhesives - an Introduction

3.1.1 Design principles

3.1.1.1 The function of adhesives

The major function of an adhesive is to fasten materials together by surface attachment so that stresses can be transmitted from one member of the joint to another, and thus provide a more uniform distribution of these stresses than might otherwise be achieved by most other methods for mechanical attachment.

There are three important basic facts about adhesive materials; they are:-

i) An adhesive does not perform its function independently of the environment to which the bond is exposed and, particularly, when temperature is a constraint.

ii) An adhesive does not exist which will bond anything to anything strongly with equal ability.

iii) The development of consistently high strength bonds can be largely dependent on the surface layers present on the adherends; the use of a suitable pretreatment immediately prior to bonding is usually vital.

The mechanism of the setting or curing process involves at least one of the following processes:-

a) A loss any evaporation or adsorption of solvent from the adhesive

b) Solidification on cooling from above the melting point of the adhesive

c) Chemical reaction within the adhesive

Irrespective of which mechanism is involved in its cure, the adhesive must be fluid at some stage in its application to the adherends and in this condition it must wet the mating surfaces of each material being joined; it must then set or cure to provide the resistance to displacement that is needed in an adhesive bond without leaving high stress residues which might disrupt the bond.

Initially a decision will have to be made about the strength of bond that is needed whenever an adhesive bonding technique is to be used to join two materials together. If, for example, the loading on the joint occurs only from the deadweight of the parts or may not exist in final assembly, then the main design requirement is to select a suitable adhesive against any environmental requirement the bond will have to withstand in service such as its sealing and/or electrical insulating characteristics.

If, at the other extreme, a completely structural type of bond is required, a number of factors will have to be considered if a well designed and reliable bond is to be achieved since it must be appreciated that although the actual joint may be quite a small fraction of the structural weight, it can often contain the severest concentration of stresses.

The design of an adhesive joint will not only involve the customary design considerations but will also involve the selection of the correct pretreatment and adhesive for the particular application and may, in addition, need to take into account the size of the assembly and the availability of plant for its production.

One further factor to be considered with rocket motors is a possible need to use an adhesive which, when cured, will have an acceptable degree of compatibility with any propellant or explosive with which it might come into contact either in storage or in service.

Generally, the design requirements for adhesive bonding differ from those needed for mechanical fastening or welding. Adhesive bonding can seldom be interchanged with either of these two latter techniques but mechanical fastenings can often be combined with it, advantageously, and may make assembly easier by requiring less jigging and tooling. It must, however, be appreciated that adhesive bonding is not of necessity a panacea for al jointing problems because there are many applications where a mechanical or welded joint may be superior.

The main requirements for a good design for structural bonding can be summarised in the following way:-

1) As much as possible of the area bonded should contribute to the joint strength so that loading stresses will be distributed as uniformally as possible.

Localised stress concentrations should be avoided, especially at the edges of the bond.

2) The area bonded together should be as large as practicable with regard to component size and weight restrictions and ideally should be well in excess of any theoretical value (confirmation by laboratory tests may often be desirable and in some cases essential).

3) Peeling and/or cleavage stresses should be kept at a minimum, and, ideally, should be non-existent when the bonded joint is loaded under service conditions.

4) An ideal design will ensure that all stresses on the adhesive will be in shear rather than in tension.

3.1.1.2 Design criteria

The adhesive selected will obviously depend on the function of the bond but it must, nevertheless, be capable of holding the bonded parts together reliably throughout the expected life under the expected service environments.

In the past there has been a tendency to select an adhesive on the basis of its suitability for production processes rather than on its performance. In reported development work there has therefore been much emphasis on the optimisation of the bonding process and its associated quality assurance and this, in turn, has resulted in a considerable lack of data on properties such as creep, fatigue endurance, elastic modulus etc. In making a selection the following considerations apply:-

i) The nature and surface condition of the materials that have to be bonded.

ii) Any special requirement for compatibility with materials such as propellants and explosives which could be in contact or in close proximity with the cured adhesive.

iii) The type of bond required, it can be rigid or flexible in addition to being either non structural or structural in the latter instance the integrity of the component may be entirely dependent on its behaviour.

iv) The environment of its storage and service life with special reference to heat and/or humidity and/or sub zero temperatures.

v) The minimum level (and occasionally the maximum as well) of bond strength that is required within the expected life of the component under the environment it is likely to meet.

vi) Whether loading is expected to be constant or cyclic, and if the latter, what frequencies and levels are expected.

vii) The variability within the strength of bond achieved for any given adhesive and substrate it will seldom be better than that achieved if the substrates are weldable.

viii) Any limitation placed on the bonding process that an be used, by reason of size or the facility to apply the preferred pretreatment and bonding process.

xi) Any unavoidable restraints of availability of tooling, jigs and other equipment, and the 'lead time' that can be accepted.

x) Material and labour costs.

xi) Any factor of health and safety that might be involved with any particular adhesive.

It is also possible to make a number of generalisations about the type of adhesive that can be selected they are:

a) Thermoplastic adhesives may be unsuitable for many structural applications because they not only soften on heating but they also have a tendency to fail under quite low sustained loads and cannot sustain vibratory stresses for a long duration.

b) Although elastomeric based adhesives have low tensile and shear strength, any have a good resistance to peel; they also have particular advantage when materials of differing stiffness and/or thermal expansions have to be joined. This type of adhesive is often used when dynamic conditions at low temperatures are expected where they may replace thermoplastic adhesives which embrittle more than most thermosets under such conditions.

c) Thermosetting adhesives are the most widely used adhesives for structural bonding because most of them not only have a good resistance to fatigue but usually have the best resistance to elevated temperature. Many of them give quite high strength bonds with an acceptable resistance to peeling for most structural applications and also retain an appreciable amount of their room temperature strength at elevated temperature. Although the degree of this retention is dependent on the particular adhesive used, an upper limit of between 70 - 100^{o}C, according to the adhesive, is generally the recommended maximum for continuous exposure for many of those in current use. (There are a few more specialised adhesives that have better resistance).

Apart from these basic differences, adhesives are supplied in many forms; they can be low or high viscosity liquids or pastes and many hot met and thermosetting adhesives are also supplied as films sometimes containing a fibrous mat or woven reinforcement.

Many are supplied fully compounded ready for use, but others have two or more components which have to be mixed before they can be used; (most room temperature adhesives are the latter type).

In general, however, the choice will depend primarily ion the application and then on which would be the most convenient one to use to produce the component. Other factors are the ability to use a system which has been used previously in a similar application and one for which a specification already exists so as to reduce the inventory of materials on site.

3.1.2 Materials/compatibility

There are two facets to compatibility

a) the interaction of adhesives with other materials

b) the specific interaction with explosives and propellants

Under category (a) most manufacturers indicate materials which have a detrimental effect on adhesive systems ie. hot wet environments, certain solvents. Alternatively trials can be undertaken to determine the effect of environments on the joint strengths.

In category (b) this can be divided into

i) the effect of explosives and propellant on the adhesive and adhesive joint and this can be treated as any other system in (a) above

ii) more important is the effect of the adhesive system on explosives and propellant where decomposition of the explosive or propellant can occur together with the production of gases and heat. Standard procedures of test are documented in OM89/4 - Propellant General Systems and Procedures Manual.

3.2 Bonded Joints - Non Explosive

3.2.1 General Guide

A general guide to the choice of an adhesive for the bonding of any two inert engineering materials is detailed in Appendix I.

Appendix II tables the most widely incorporated bonded joints, and describes the relative merits of each. Qualified systems are illustrated in Appendix III.

3.2.2 Processing/Manufacturing

The range of adhesive systems is vast, and each system has specific requirements for processing and manufacturing; there are therefore no general rules, and it is essential and mandatory that the advice of the Technical Authority (Materials Department) be sought.

An illustration of the types of adhesion systems available are given in figure 1.

3.2.3 Systems and Properties

Typical properties, characteristics, advantages and limitations of the most widely used structural adhesives are tabled in Figure 2.

FIGURE 1 - STRUCTURAL ADHESIVES CLASSIFICATION

Structural-adhesives classification

Chemically reactive

- Moisture cure
  - Polyurethanes
  - Silicones
  - Cyanoacrylates
- Heat-activated cure
  - Epoxies
  - Polyurethanes
  - Phenolics
  - Polyimides
  - Polybenzimidazoles
- No-oxygen cure
  - Anaerobics
- Mix-in
  - Epoxies
  - Polyurethanes
  - Modified acrylics
  - Silicones
  - Phenolics
- No-mix
  - Modified acrylics

Evaporation or diffusion

- Organic-solvent base
  - Natural rubber
  - Reclaimed rubber
  - Synthetic rubbers
  - Polyurethanes
  - Phenolics
  - Vinyls
  - Acrylics
- Water base
  - Natural rubber
  - Reclaimed rubber
  - Synthetic rubbers
  - Vinyls
  - Acrylics

Hot melt

- General purpose
  - Ethylene-vinyl acetate copolymers
  - Polyolefins
  - Thermoplastic elastomers
- High performance
  - Polyamides
  - Polyesters

Delayed tack

- Styrene-butadiene copolymers
- Polyvinyl acetates
- Polystyrene
- Polyamides

Film and tape
(One and two sided — supported and unsupported)

- Nylon-epoxies
- Elastomer-epoxies
- Nitrile-epoxies
- Vinyl phenolics
- Epoxy phenolics
- Polyimides
- Polybenzimidazoles

Pressure-sensitive film and tape
(One and two sided — supported and unsupported)

- Natural rubber
- Styrene-butadiene rubber (SBR)
- Reclaimed rubber
- Butyl rubber
- Nitrile rubber
- Polyacrylates
- Polyvinylalkyethers

Electrically and thermally conductive

- Epoxies
- Polyurethanes
- Silicones
- Polyimides

FIGURE 2 - SYSTEMS AND PROPERTIES (BONDED JOINTS - NON EXPLOSIVE)

Advantages and limitations of most widely used chemically reactive structural adhesives

Epoxy	Polyurethane	Modified Acrylic	Cyanoacrylate	Anaerobic
High strength Good solvent resistance Good gap-filling capabilities Good elevated temperature resistance Wide range of formulations	Varying cure times Tough Excellent flexibility even at low temperatures One or two component, room or elevated temperature cure	Good flexiblity Good peel and shear strengths No mixing required Will bond dirty (oily) surfaces Room temperature cure	Rapid room-temperature cure One component High tensile strengths Long pot life Good adhesion to metal Dispenses easily from package	Rapid room-temperature cure Good solvent resistance Good elevated temperature resistance No mixing Indefinite pot life Non toxic High strength on some substrates
		Limitations		
Exothermic reaction Exact proportions needed for optimum properties Two component formulations require exact measuring and mixing One component formuations often require refrigerated storage and elevated temperature cure Short pot life (more waste)	Both uncured and cured are moisture sensitive Poor elevated temperature resistance May revert with heat and moisture Short pot life Special mixing and dispensing equipment required	Low hot temperature strength Slower cure than with anaerobics or cyanoacrylates Toxic Flammable Odor Limited open time Dispensing equipment required	High cost Poor durability on some surfaces Limited solvent resistance Limited elevated temperature resistance Bonds skin	Not recommended for permeable surfaces Will not cure in air as a wet fillet Limited gap cure

Typical properties and characteristics of structural-adhesives

	Epoxy	Polyurethane	Modified acrylic	Cyanoacrylate	Anaerobic
Impact resistance	Poor	Excellent	Good	Poor	Fair
Tensile shear strength MPa(10^1 psi)	15.4 (2.2)	15.4 (2.2)	25.9 (3.7)	18.9 (2.7)	17.5 (2.5)
T-peel strength, N/m(lbf/in)	<525 (3)	14 000 (80)	5 250 (30)	<525 (3)	1 750 (10)
Substrates bonded	Most	Most smooth, nonporous	Most smooth, nonporous	Most nonporous metals or plastics	Metals, glass, thermosets
Service temperature range, °C (°F)	-55 to 120 (-70 to 250)	-160 to 80 (-250 to 175)	-70 to 120 (-100 to 250)	-55 to 80 -70 to 175)	-55 to 150 (-70 to 300)
Heat cure or mixing required	Yes	Yes	No	No	No
Solvent resistance	Excellent	Good	Good	Good	Excellent
Moisture resistance	Excellant	Fair	Good	Poor	Good
Gap limitation, mm(in)	None	None	0.75 (0.03)	0.25 (0.01)	0.60 (0.025)
Odor	Mild	Mild	Strong	Moderate	Mild
Toxicity	Moderate	Moderate	Moderate	Low	Low
Flammability	Low	Low	High	Low	Low

3.3 Case Bonded Charges

3.3.1 Requirements of Case Bonded Systems

The bonding of a propellant charge (grain) to the rocket motor body, possibly via a layer of insulation, allows the rocket motor designer to achieve high loading densities. This is particularly evident where the end attachments have to be within the body diameter which would reduce the available orifice for loading a loose charge. The body insulation and propellant inhibition are integral and thus inert mass can be reduced. Such a system requires a relatively soft propellant and is only applicable to internally, radially burning charge configuration. The majority of tactical weapon systems are required to be operational over a wide range of temperatures and unless the propellant is extremely flexible at low temperatures (-40^{o}C), then stress relieving devices are necessary to ensure the integrity of the charge in these environments. High confidence in the case bond media is also required so that separations between propellant and body lining do not occur. The lined motor body acts as the casting corset and thus the equipment required for manufacture of a case bonded charge is less than that for a loose cartridge loaded grain. However, it is necessary to be able to inspect the finished charge to give a least the same degree of assurance as for a loose charge. Gains are also apparent in terms of grain hold-back devices usually necessary for loose charges.

3.3.2 Methods Used for Various Propellant Types

The methods used for case bonding rocket motors vary depending on the type of propellant being used, but there is no real difference between casting cartridge loaded charges and charges bonded to the motor case. To maximise the elasticity of the propellant, the nitrocellulose content is reduced to the minimum compatible with high temperature modulus and slump. In practice this limit is found at NC:NG ratios of 2:3 for unfilled CDB. In the case of CMCDB the high temperature modulus is benefited by the filler loading, but filler binder de-bonding under high stress-strain is a limiting factor. In practice filler loading levels of 40% with NC:NG of 1:1.7 represent the optimum.

The adhesive systems used for case bonding are exclusively those based on the Redux range of materials produced by Ciba-Geigy Limited. The system for the entire family of CDB propellants is identical in all cases, and based on a formvar-phenolic resin (Redux 302DB film). The main case bonding limitations of this system derives from the mechanical properties of the bonded propellant rather than the Redux 302DB itself. The motor charge design in combination with the predicted thermal environment of the system primarily dictate the mechanical properties required of a case bonded propellant.

In the case of EMCDB propellants the strain capability of the propellant for unfilled and filled compositions is substantially increased over the previously described CDB, and is no longer a restricting factor in practical case bond systems. Again Redux 302DB provides a satisfactory bonding medium for the full range of EMCDB propellants.

A selection of CDB and EMCDB propellant is given below.

Propellant Type	Casting Powder Nitrocellulose	Elongation[+] -40	-20	Remarks
OIO(S6)/A76	91%	<1%	<4%	Not case bondable
ATN(D35)/A76	61.1%	<2%	>8%	Restricted case bonded applications
B25(D1)/N58(D2)	35.1%	>15%	~40%	Case bondable

[+] Janaf C 50mm/min

The extensibility of OIO(S6)/A76 is too low for case bond application under all but the most restricted temperature range. ATN(D35)/A76 can find case bond application but this will generally require the use of mechanical stress relief such as slot inhibition or peripheral stress relief (see Part 2 of TN79/49, Section 2.4.4.1). The EMCDB propellant B35(D1)/N58(D2) is an EMCDB type whose low temperature strain capability is such that it finds application in case bonded motors without the need for mechanical stress relief.

Case Bondable Propellants

A range of more extendable propellants is available for case bonded motors. Case bondable propellants have a nitrocellulose to plasticiser ratio in the region of 2:3 or lower, in order to combat the extra strains induced by the differential thermal expansion characteristics of the motor case material and the propellant. The use of stress relief systems, particularly the peripheral stress relief concept, may enable harder propellants to be utilised but generally this is not desireable. Further details are provided in Part 2 of TN79/49, Section 2.4.4.1.

A typical selection of case bondable propellants is given below:

Propellant Type	Burning Rate at 20°C (mm/s)	Plateau Pressure (bar)	Remarks
ATN(D2 8) - CP19	23	86-146	Contain 5% aluminium - high smoke efflux
ATN(D23) - CP27	22.5	90-145	Smokeless boost
NCP 216 - CP30	18.5	70-110	Smokeless
NCP 302 - CP102	20.5 (70 bar)	-	Composite modified propellant
BDI(D1) - CP20	4.5	20-33	Smokeless Sustainer

Redux 302DB Bonding to EMCDB Propellant

EMCDB propellants contain an elastomeric binder in conjunction with the nitrocellose binder in CDB propellants. The binder is formed in-situ during propellant cure by the reaction of an isocyanate based cross linking agent (Part B liquid) with the Polyol contained in Part A casting liquid. Thus the propellant cure consists of two processes, chemical bond forming as well as nitrocellulose gelation. While the latter provides the mechanism by which Redux 302DB bonds to all propellants it is likely that in EMCDB propellants a degree of chemical reaction with free hydroxyl groups in the adhesive takes place. Experiences to date have not provided quantitive data on the significance of this bonding mode as the effect is masked by the strong diffusion bond produced by nitrocellulose/nitroglycerine diffusion.

Propellant Cure Temperature

It is normal practice for case bonded CDB and EMCDB motors to be cured at 43°C, ie the lower of the two standard temperatures, as this brings the nominal zero strain condition closer to the motor low temperature operating limit.

3.3.3 Case Bonding Considerations, Methods and Materials

The choice of a case bond system for a rocket motor will depend on the design consideration of that motor. The size and shape of the rocket motor will normally be imposed on the designer by the overall missile concept and thus will dictate the coice of propellants and charge geometry.

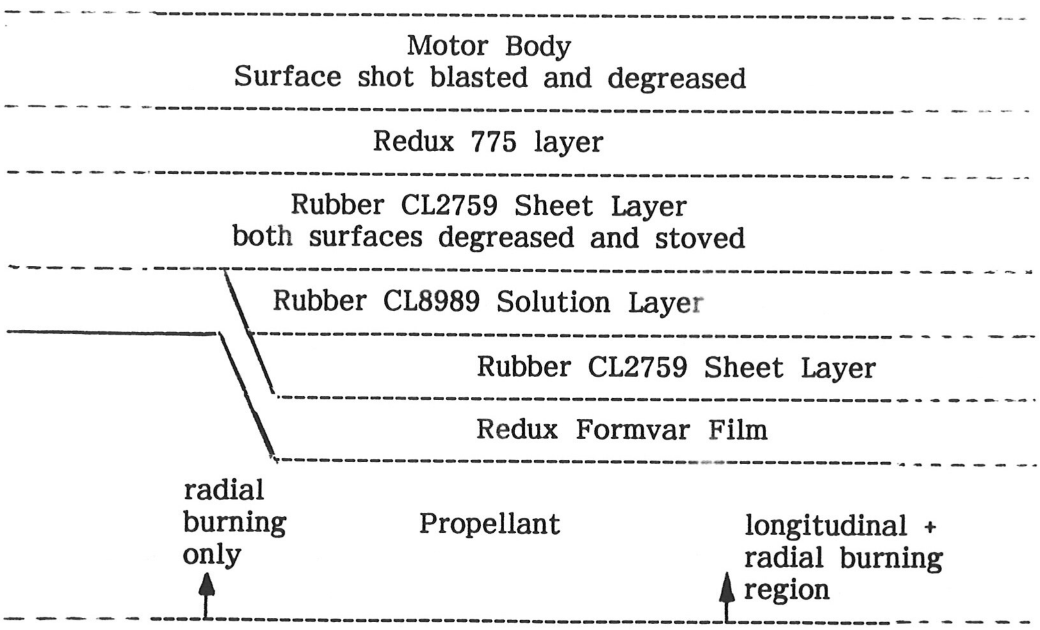
Generally the powder filling, casting and propellant consolidation operations are consistent with those applied to all types of propellant charge manufacture. The consolidation temperature is usually limited to 43^{o}C to prevent extra stress occurring in the propellant web during cold temperature conditioning. Casting equipment has to be specifically designed to accomodate the lined motor tube during the assembly of total casting arrangement.

Consideration of the body insulation requirements to fully protect the motor tube during firing, is necessary because charge designs dictate that the propellant will burn in the slotted regions and longitudinally to expose the lining material to severe erosive conditions. The insulation thickness must be increased to give the necessary body protection in these regions referred to as burn-back regions. This required increase in insulation thickness depends on charge geometry and propellant properties such as burning tie and flame temperature. A typical example is the Troy motor where Hypalon CL2759 rubber thickness over the burn-back region is 2.5mm nominal compared with 0.6mm over the radially burning section of the charge.

Practical consideration of the type of stress relief mechanism to be used in a charge is dictated by the environmental conditions under which the charge must function. Futher details are provided in Part 2 of TN79/49 Section 2.4.4.1.

3.3.3.1 Typical Case Bond System

A typical case bond lining and cast motor arrangement is shown below:



3.3.3.2 **Motor Body Materials and Preparation**

The motor tubes can be produced from the following materials:

a) Steel
b) Aluminium
c) Laminated Steel Strip Construction
d) Glass Fibre Reinforced Plastic
e) Carbon Fibre Reinforced Plastic

The metal bodies require non-contaminated surfaces where lining materials have to be bonded. This is achieved by shot blasting with an abrasive grit such as 4XP Blastyte grit and vapour degreasing the surfaces with trichlorethylene or other approved solvents. The glass and carbon fibre tubes may be wound onto a rubber backing piece. This surface requires abraiding with steel wool, abrasive cloth or possibly by aquablasting followed by a manual degrease using Genklene or other approved solvents.

3.3.3.3 **Materials Employed in Case Bonding of CDB Propellants**

Item	Material	Specification
Thermal insulation chamber liner/ stress relief device	Hypalon CL2759	IMI/SRS/104(AFS1383)
	or Hypalon CL8990	IMI/SRS/41(AFS1385)
	or Ethylene-Propylene Terpolymers	
	CL 11184	IMI/SRS/51
	CL 8509	IMI/SRS/45
Liner adhesive	CL8980 Primer solution	IMI/STS/94(AFS1397)
	Redux 775	TS 640
	or Redux 120	TS 642
Propellant Adhesive	Redux - Formvar film	TS641
	or Duplex Layer Redux 775 solution followed by Formvar powder embedment	TS640 and TS624
Parting Agents	Cellulose Acetate	TS263
	or Propylex Polypropylene	-
		-
	or Tygaflor sheet	-
	or Fluorinated Etyhlene Propylene	-
Pressure Sleeve Bag	Natural Rubber CL 9495	
	or Hypalon CL 6871	IMI/SRS/159

3.3.3.4 Lining Materials and Preparation

The motor body lining material must possess a good ablative and insulating properties, be chemically compatible with propellants, form adequate bonds with revelant adhesive systems, have physical and mechanical properties to meet environmental demands, have long shelf life and good handling propertie in lining facilities.

Hypalon rubber CL2759 to specification AFS meets these demands and is the material generally used for lining case bonded motors. However, other materials such as Hypalon rubber CL8990 and ethylene-propylene rubbers can be considered if weight and smoke penalties are particularly evident. All these rubber grades can be obtained in sheet thicknesses varying from 0.3mm to 5mm to enable the designer to select the required lining thickness to meet motor functioning requirements.

All rubber sheet surfaces must be degreased with a solvent such as Genklene prior to further lining opertions. With Hypalon grades it is recommended that the material is stored overnight at 60°C to remove volatiles, particularly water, which cause some undesired reactions at the metal/adhesive/rubber interface.

3.3.3.5 **Adhesive Materials**

The adhesive systems used for case bonding are exclusively those based on the Redux range of materials produced by Ciba Geigy Limited.

3.3.3.5.1 **Redux 775 - Phenol Formaldehyde Solution to Specification TS640**

Redux 775 is used for metal to rubber bonding operations and certain rubber to rubber bonding requirements. Redux 775 is diluted with methylated spirits (1:3 to 1:6 Redux:meths v/v) and applied by brush coating to prepared rubber surfaces or by roll coating the metal tubes. An overnight store at 60°C is recommended for solvent removal. The glue line cure condition is 30 minutes at 150°C at a pressure of 5-7 bar.

3.3.3.5.2 Redux Formvar Film - Phenolformaldehyde/Polyvinyl Formal Film, Hot Curing to Specification TS641

The Redux Formvar (302DB) adhesive system consists of phenolformaldehyde resin (Redux 775) into which polyvinyl formal granules (Formvar) which have been powder embedded. This system is used exclusively to bond the propellant to the various rubber insulants. The method of application is to lay the Redux film into position on the rubber sheet external to the motor tube using methylated spirits as the tacking medium or to lay on the rubber sheet previously placed in the motor tube, either in the dry state or using methylated spirits, to tack into position. After allowing the solvent to evaporate, a glue line cure cycle of 30 minutes at 150^{o}C under a pressure of 5-7 bar is required during the lining operation. This forms the bond via the phenolformladehyde resin to the rubber sheet and after casting the propellant into the prepared tube, the propellant to rubber bond is established by diffusion of the nitrocellulose/nitroglycerine into the polyvinyl formal resin of the adhesive system.

3.3.3.5.3 Hypalon CL8990 Rubber Solution to Specification IMI/SRS/94

To ensure optimum bonding between two Hypalon CL2759 or CL8980 sheet surfaces, Hypalon CL8980 solution is applied to the required surfaces by brush coating before rubber stoving operations. This procedure generally gives stronger and more reliable bonding than the use of Redux 775 solution.

The rubber solution is prepared from freshly milled CL8980 rubber dissolved in toluene to give a solids contents of 42%.

3.3.3.5.4 Silcoset Primer - SR80M

Silcoset primer SR80Mconsists of a number of components, the primary being SR80Mresin.

This resin is a silanol formed by hydrolysis of a mixture of di and trichlorosilanes dissolved in a blen of toluene and isopropanol.

Converions of the partially polymerised soluable primer into a cross linked product is carried out in-situ on the propellant surface.

3.4 Quality Assurance

3.4.1 The Adhesive

A number of the adhesives that may be considered for use in rocket motor applications can be obtained released to DTD specifications Defence Standards, to a CS or TS specification, to a British Standard or sometimes under an AFS procedure.

Apart from certain specific tests concerned mainly with requirements for composition, the other tests usually required in these specifications involve the preparation and testing of laboratory test specimens such as single or double overlap joints, tested in shear, or a climbing drum or 90^{o}C peeling strength test. In some instances lap shear tests may be carried out either at an elevated temperature or after being held for specified times at such temperature, to determine whether they have the degree of retention of room temperature strength required. In addition there are requirements for the degree of strength retention for adhesive test specimens after they have been immersed in various aircraft fuels and oils.

Procedures exist for obtaining essential adhesives from non UK sources so that they can be certified as complying with specifications relevant to the country of origin; and can include MIL specifications in the instance of materials produced in the USA.

In some instances additional testing is carried out on materials on receipt by the user. These tests are therefore referred to as 'user tests' and may be additional to those already made by the producer to form part of the overall quality control or may have to be made as an interim measure when the materials being used cannot be released against any suitable existing approved specification or an approved alternative is not available.

The Pretreatment and Bonding Process

When structural bonds have to be made, an effective control of this process ideally requires a 'patrol' type of inspection whereby key points in the complete schedule are identified and regular checks made to establish that they have been carried out correctly. These checks should then be recorded at the time on a history sheet accompanying the work. Apart from these inspections the condition of the pretreatment process should be checked regularly together with the composition of any pretreatment solutions employed so that the composition of these solutions can be maintained within predetermined limits and replenished or replaced whenever necessary.

3.4.2 The Completed Bond

At the present time there is not any completely satisfactory non destructive method for assessing the bond strength of a cured joint. At their best, ultrasonic inspection techniques demonstrate the integrity of the cured adhesive, by providing a measure of its void content and they have often been used for this purpose when inspection insulating linings of the main body and head and rear ends of rocket motor cases. Similarly it has been possible to use X-ray examinations for bond integrity when the adhesive used had an appreciable level of antimony oxide fillers.

Apart from these inspections the quality assurance checks that have been used for adhesively bonded joints in rocket motors differ appreciably from those used by most airframe manufacturers. Thus rocket motor manufacturers refer to test the bonded component, or even the finished motor case, whereas airframe manufacturers have relied on tests made on witness specimens that have accompanied the work through its pretreatment and bonding stages (in some instances these specimens have actually formed part of the work before being cut off for test after the completion of bonding). 90^{o} peel and single overlap specimens made from aluminium alloy have been used mainly as test controls and although they are representative of the materials being bonded for airframe construction they seldom simulate a rocket motor part adequately; they have therefore not been used extensively in such applications.

A variety of tests of completed bonds are specified instead by designers of rocket motors and have included the following:-

i) The application of high vacuum to motor cases which have been lined with an elastomeric insulant; freedom from bubbles should ensure that the lining will not lift during any predrying under vacuum prior to filling or during the filling operation.

ii) Static proof loading of entry cones and/or throats which have been bonded into exit cones and venturis.

iii) Pressure checks, for bond impermeability, of blanking discs and closures and rear end linings using compressed air and an aqueous detecting fluid. Alternatively the loss of pressure or vacuum has been measured especially when the use of the detecting fluid is unacceptable.

iv) Loading bonded-on conduit pads, wing strakes and bonded-on studs to check that they do not fail below a predeterimed proof value, usually within a given time.

In the instance of a strip laminate motor case burst and pressure tests are conducted to prove strip laminate construction the bonded end ring joints.

In future rocket motor designs incorporating structural bonding techniques, consideration might be given to the possibility of using witness specimens if only as a quality assurance that the pretreatment was adequate and that the adhesive was satisfactory; to be an effective control these specimens must of course be processed in simulation of the work as closely as possible.

There are also a few, but limited instances, when a test specimen might be produced with the work or be made from a cut out or cut off from it. (This procedure has often been used by airframe manufacturers as confirmation or refutation of doubtful results for witness specimens).

3.4.3 Durability of the Bonded Structure

Durability is usually assessed by exposing motor cases to selected conditions and then subjecting them to proof and burst tests. The condition applied depends largely on the intended applications and are usually specified by Ordnance Board trial requirements; they can include drop tests, vibration and tropical testing in Australia under hot/dry and hot/wet tropical conditions, as well as other storage under simulated service conditions.

Apart from tests on motor cases or simulations of them, a determination of the tensile strength of laboratory test specimens after a prolonged immersion in hot water at 60°C has been showing some considerable promise for making reasonably accurate predictions of the resistance a selected cured adhesive has against a hot/wet tropical environment.

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3.5 References

Useful references for adhesives and bonding processes are:

1. Def Stan 08-5/1

2. Material Department's documentation

3. "Adhesives Handbook" - J.Shields, Ministry of Technology

GENERAL GUIDE

The choice of an adhesive for bonding any two engineering materials must take the following main factors into account:-

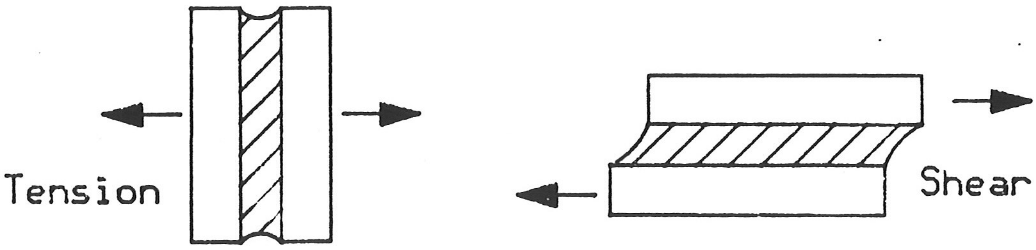
(i) the adhesive must be suitable for use with both the materials to be bonded
(ii) type & magnitude of stress
(iii) service temperature range
(iv) moisture resistance/absorbtion
(v) resistance to chemical attack

Other lesser factors which may be considered are the form of the adhesive, method of application, shelf & pot life, drying time, curing temperature, comparative cost with other methods of joining & labour requirements.

All structural joints must be designed so that the loads that they carry are evenly distributed over thje bonded area. This condition is only satisfied if the bond is in shear or tension. If cleavage or peel stresses are present, the design is bad & the joint is weak.

TENSILE LOADING

The forces are perpendicular to the plane of the joint & the stress is uniformly distributed.

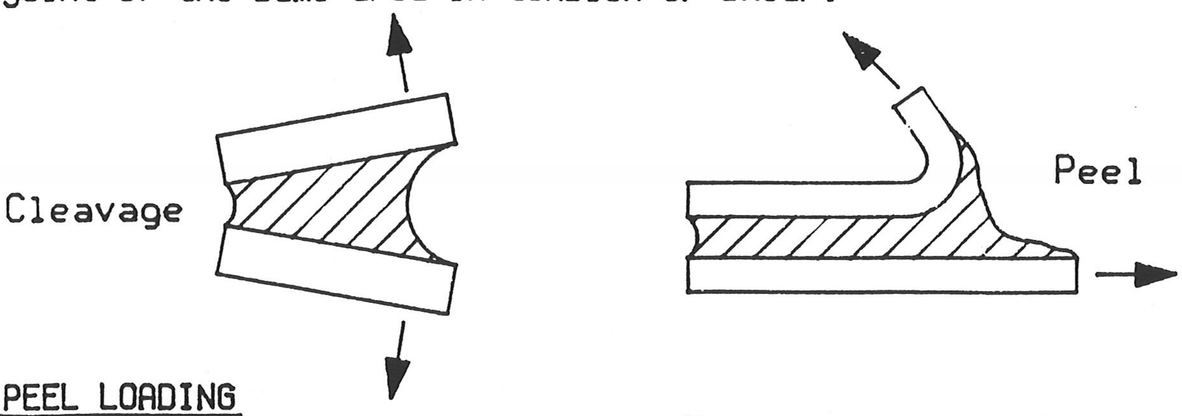


SHEAR LOADING

The forces are parallel to the plane of the joint & the stress is uniform over the bonded area.

CLEAVAGE LOADING

The stress is concentrated on only a small portion of the adhesive which means that the joint can never be as strong as a joint of the same area in tension or shear.



PEEL LOADING

This is the weakest joint of all. The stress is confined to a very thin line of adhesive at the edge of the bond. This type of stress should always be avoided.

MATERIAL/ADHESIVE GUIDE

Material to be joined / Adhesive type	Acrylics (e.g. Perspex)	Cellulose acetate	Cellulose nitrate	Melamine	Non-structural metals	Phenolics	Polyamides (e.g. Nylon)	Polyesters	Polyethylene (PTFE)	Polystyrene	PVC	Rubbers	Structural metals	Urea
Acrylics														
Cellulose acetate														
Cellulose nitrate														
Chlorinated rubber														
Cyanoacrylate														
Epoxy														
Epoxy-phenolic														
Epoxy-polyamide														
Epoxy-polysulphide														
Epoxy-silicone														
Furane														
Natural rubber/latex solution														
Neoprene rubber														
Nitrile rubber														
Phenol formaldehyde														
Phenolic-neoprene														
Phenolic-nitrile														
Phenolic-polyamide														
Phenolic-vinyl														
Polyamides														
Polyester														
Polyurethanes														
Polyvinyl acetate														
Resin-rubber formulations														
Resorcinol formaldehyde														
Rubber based-natural														
Rubber based-synthetic														
Silicone														
Urea formaldehyde														

To find the most suitable adhesive type for bonding two materials find a shaded area that aligns with both adhesive & adherend.

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Cyanoacrylate

General purpose, transparent adhesive which will bond most materials producing high strength joints that are resistant to oils & some solvents, which, although reasonably resistant to water, are broken down by the action of steam. The adhesive sets by polymerization, brought about by pressure on a thin film between the two surfaces to be bonded. It is a rapid set adhesive, usually a matter of seconds. Maximum continuous service temperature is about 80°C, but for short exposure 100°C.

Epoxy

Epoxy resin adhesives are available as two-part room temperature-curing adhesives with amine type hardeners or as one-part systems which must be cured at elevated temperatures. They are primarily metal/metal structural adhesives, but can also be used to bond glass, ceramics, wood, some rubbers & many plastics, but are unsuitable for bonding polyethylene & PTFE.

Unmodified epoxy systems give a high strength bond (shear strengths up to 34.5 MPa) but they have poor flexibilty & impact strength. They have excellent resistance to oils & mould growth, & good resistance to water & various solvents. The thickness of the glue line may be from about 0.025mm to 0.3mm.

Epoxy-phenolic

Combinations of epoxy & phenolic resins give structural adhesives for bonding metals for extended periods of service at temperatures of up to 260°C. Although the resulting bond is brittle & has low peel strength, the good shear strength of an unmodified epoxy with the good heat resistance of phenolic is retained. Shear strengths of up to 20.7MPa are normal, which drop off to about 7-14MPa at about 260°C. Good resistance to water , oils & chemicals is obtained.

Epoxy-phenolics are particularly suitable for bonding stainless steel , titanium, beryllium & other high temperature alloys.

Epoxy-polyamide

Polyamide resins, when combined with epoxies, function as room-temperature curing agents, resulting in a more flexible bond than with an unmodified epoxy. Typical shear strength values are 20.7MPa to 27.6MPa at room temperature dropping to 2-3MPa at 100°C. They have a good resistance to water, oils & chemicals & they are suitable for bonding a wide range of rigid & flexible materials including metals, rubbers, glass, ceramics & most plastics, particlarly nylon, but not suitable for polyethylene or PTFE.

Epoxy-polysulphide

Polysulphide rubber is used to improve the elasticity & peel strength of the epoxy bond. The system has typical shear strengths of 20.7MPa to 27.6MPa & can be used up to about 90°C. They are used mainly for bonding metal tiles, steel plates & beams to concrete.

Epoxy-silicone

Combining silicone resin with epoxy resin results in a system with a greater heat resistance than is possible with other modifiers The adhesive has a typical bond strength of 10.3MPa to 13.8MPa with a continuous service temperature of up to 300°C & an intermittent temperature of 550°C. It is used in the form of asbestos-fabric tape in airframe bonding & other applications where resisitance to heat & oxidation is necessary.

Natural rubber

Natural rubber based adhesives are set by solvent or water evaporation and/or vulcanization. Un-vulcanized bonds lose much of of their strength at about 65°C, whereas, vulcaization allows it to be used to about 90°C. Low strength & the thermoplastic nature of natural rubber based adhesives makes them unsuitable for structural use. Natural rubber has good resistance to water & mould growth, but is adversely affected by oils, solvents & many chemicals.

Neoprene and nitrile rubber

Setting of synthetic rubber based adhesives is by solvent release or by vulcanization, the latter producing the strongest & heat resistant bonds.

Nitrile based adhesive bonds have shear strengths of about 7MPa but are not recommended for structural applications. They may be used between -50°C & +150°C.

Neoprene based adhesive bonds are generallyt suitable where the service temperature does not exceed 90°C. Good resistance to water, certain oils & most chemicals & solvents, with the exception of aromatic hydro-carbons & strong oxidising agents.

These adhesives can be used for bonding natural & synthetic rubbers, some plastics & leather to themselves & to metal & wood. They are not suitable for structural applications.

Phenol formaldehyde

Used as an adhesive for plywood, phenolic, melamine, urea & metal/wood joints providing the metal has been suitably primed. Maximum service temperature is 100°C & it has excellent resistance to water, oils, solvents, etc.

Phenolic-neoprene

This combination of rubber & resin is used for bonding metal/metal & metal/wood where resistance to vibration & low temperatures is of importance. Heat curing is necessary and produces shear strengths at ambient of 17MPa to 20.5MPa, maintaining this strength between -55°C & +120°C. They have excellent resistance to water , certain oils & solvents.

Phenolic-nitrile

These adhesive systems have a superior heat & chemical resistance to those of phenolic-neoprene & phenolic-vinyl. They have a shear strength at ambient of 27.5MPa & may be used on continuous duty up to 175°C, at which temperature the shear strength is down to 14MPa. Minimum service temperature is -50°C. These adhesives may be used to bond metals, plastics, rubbers & certain friction materials such as brake linings to brake shoes in motor vehicles.

Phenolic-polyamide

Combinations of thermosetting phenolic resin & thermoplastic polyamide resin have been developed for metal/metal bonding for high temperature service, particularly aluminium in aircraft structures. The adhesive, which is generally in the form a polyamide film & phenolic resin solution, has a shear strength at ambient of 34.5MPa which falls to 20.7MPa at +150°C & to 17.2MPa at -55°C.

Phenolic-vinyl

Polyvinyl formal resin powder is normally dusted onto liquid phenolic resin. One component systems & films are also available. Shear strengths at ambient are about 34.5MPa & are maintained up about 80°C with a rapid falling off above 100°C. This type of adhesive is suitable for honeycomb-sandwich construction, for bonding cyclized rubbers to metals, & for metal/plastic applications.

Polyamides

Thermoplastic resins are used as hot melt adhesives as well as modifiers with epoxy resin systems. Heat sealing at between 100°C & 170°C, this range of adhesives set immediately on cooling. They give high strength bonds on metals, many plastics, leather, etc.. Their resistance to water, oil, mould & certain solvents is good.

Polyurethanes

This type of adhesive is formed by the reaction of polyisocyanates with certain polyesters. Bonds made with polyurethane are flexible, have good peel strength & good resistance to shock & vibration. The resistance to acids, alkalis, oils & fuels is good but the adhesive is moisture sensitive. These adhesives can be used for bonding most metals, rubbers, foams, plastics, glass, etc. Exposure to temperatures above 95°C is not recommended.

Polyvinyl acetate

Used as a non-structural adhesive for bonding metals, wood, leather, glass, ceramics & many plastics but not including PVC, polyethylene & rubbers. The bond strength metal/metal is 21MPa with heat cured bonds but cold flow can take place at very low stresses. The adhesive has a poor heat resistance (below 50°C) but good resistance to oils & mould growth. However, water & freezing conditions can damage the bond.

Resorcinol formaldehyde

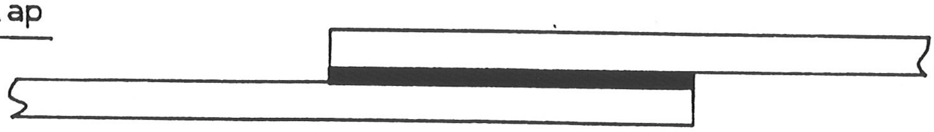
Resorcinol adhesives are mainly used for bonding wood, but some plastics (e.g. acrylics, nylon, phenolics, ureas) can be bonded. They have good resistance to boiling water & excellent resistance to oils, many solvents & mould growth. Service temperature limits are from -175°C to +175°C.

Urea formaldehyde

This is a thermosetting resin used primarily in plywood manufacture, but which is suitable for bonding phenolic, urea & melamine plastics. It has good resistance to water (not boiling), oils, solvents & mould growth. The maximum service temperature is 60°C.

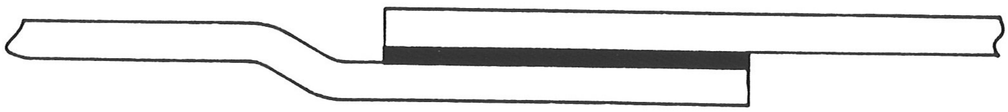
Lap joints

Simple lap



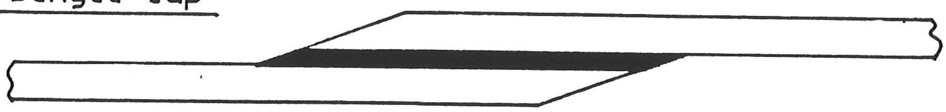
This is not the best design because the shear forces are not in line. Under load the adherends will distort to bring the shear forces into line & the bond area will pivot, introducing a cleavage stress. Under heavy load a soft material will bend at edges of the bond, introducing a peel stress.

Joggle lap



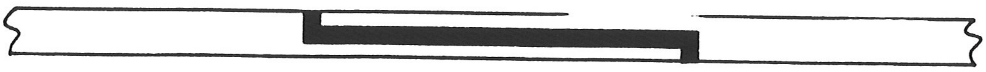
This joint is stronger than the simple lap since it places the entire load bearing area in the same plane as the shear stress on the adherends.

Tapered single lap



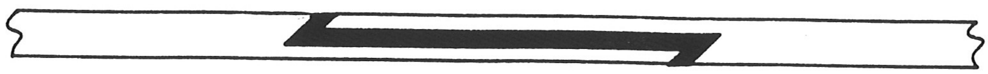
The tapered single lap joint is another more efficient alternative to the simple lap joint. When the adherends distort under load the tapered edge allows bending of the joint edge.

Double butt lap



This joint is very strong because the principle load bearing area is in the same plane as the shear stress.

Double scarf lap



Probably the best joint of all lap joints . It has better resistance to bending than the double butt lap but is expensive to produce.

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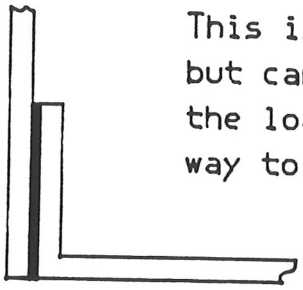
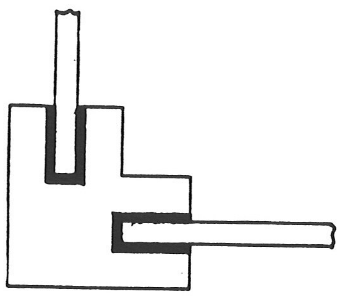
Corner joints in sheet metal

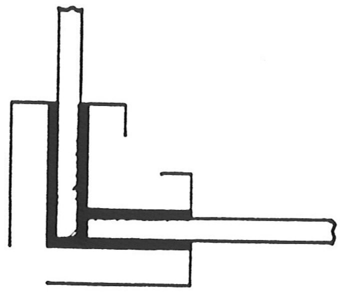
Right angle butt



This is the simplest corner joint but care must be taken to ensure that the loads are applied in the correct way to avoid cleavage.

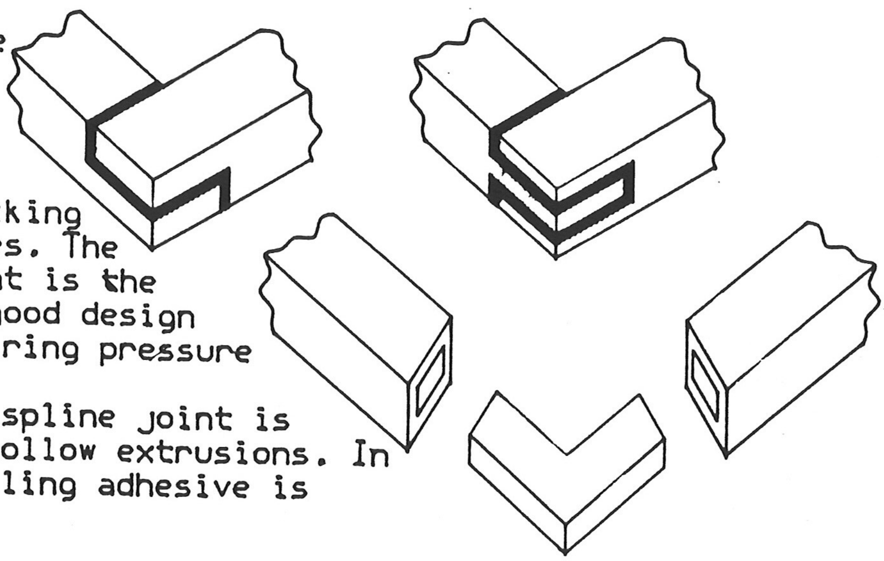
Slip joint & Right angle support joint





Simple supplementary attachments are used to increase the structural rigidity of the joint. Gap filling adhesives are the most commonly used.

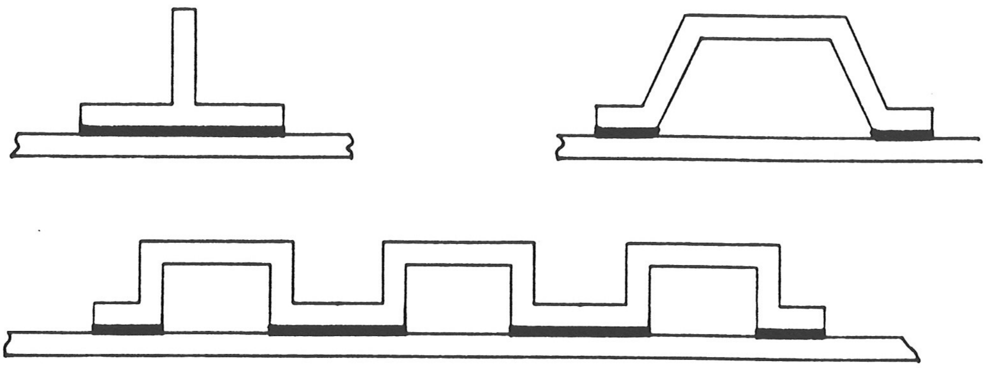
Corner joints in rigid members



Halved end lap joint, open mortise and tenon joint and mitre with spline joint all give good bonding areas to resist racking or twisting stresses. The halved end lap joint is the simplest and is a good design for adhesives requiring pressure during cure.

The mitre with spline joint is usually used with hollow extrusions. In this case a gap filling adhesive is recommended.

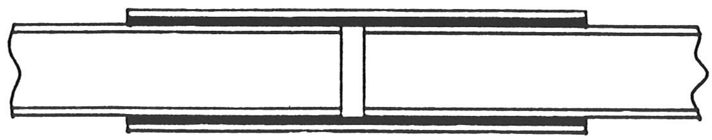
Stiffener joints



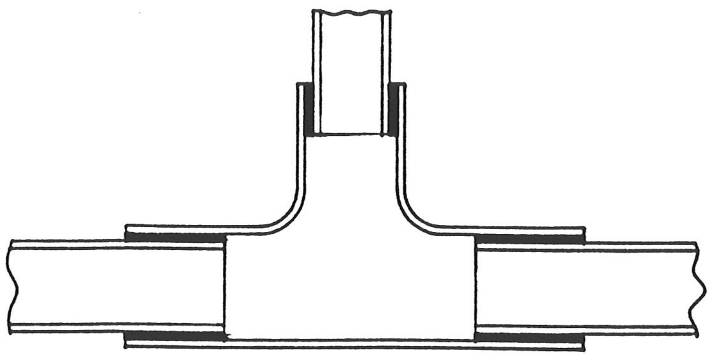
Stiffeners adhesively bonded to thin metal sheets give increased rigidity. The important point to note here is that the thickness of the sheet and stiffening member must be matched. This is because flexure of the assembly will introduce peel stresses in the adhesive unless the stiffener can also bend. It may be necessary to increase the sheet thickness or reduce the stiffener gauge to avoid these stresses.

The choice of stiffener shape, generally 'T' section, hat section or corrugated backing, as shown above, depends on the rigidity required.

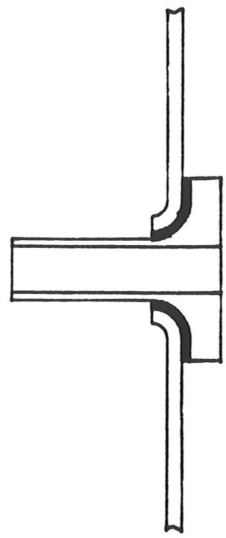
Cylindrical joints



Slip joint



Tee joint

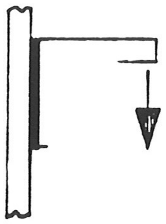


Bush to sheet joint

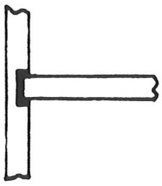
The overlap slip joint is recommended for bonding cylindrical parts such as tubing, bushings and shafts. With adhesive bonding the whole contact area contributes towards carrying the load. A simple variation makes the Tee joint.

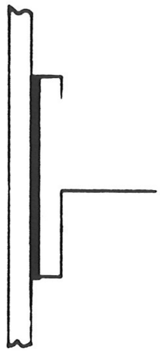
In the Bushing to sheet joint note that the sheet is formed around the hole to minimize cleavage stresses and to increase bond area.

Angle joints

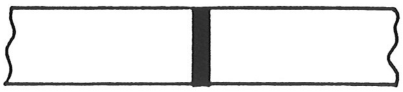


This joint has only fair strength when loaded as shown although the strength is good in the other two directions.
The two designs shown below reduce the cleavage stress level.



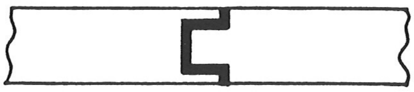


Butt joints

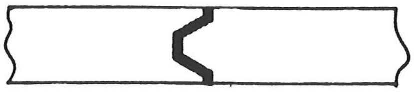


Plain butt joint

Scarf tongue and groove joint



Tongue and groove joint



Landed scarf tongue and groove

The plain butt joint is very weak in bending due to high cleavage stresses. Recessed joints such as tongue and groove, scarf tongue and groove, and landed scarf tongue and groove are stronger and are self-aligning hence making assembly easier. The landed scarf tongue and groove also has its own stops to control adhesive line thickness.

APPENDIX III

Qualified Systems (Bonded Joints Non-Explosives)

APPENDIX IV

Redux 302DB Propellant/Rubber Adhesive System

Since its development as a replacement for the roll coating process for motor bodies Redux 302DB has been used in every case bonded or inhibitor case CDB or EMCDB motor/charge. The table below lists most significant procedures, although is by no means exhaustive.

Motor	Status	Inhibitor
E578 Deerhound	Production	CL2759
E532 Sealyham	Production	Composite CL2759/CA
E552 Pointer	Production	CL8980
E561 Troy	Production	CL2759
E587 Matapan	Production	PB40K
E597 Thermopylae	Production	CL2759
E598 Cadiz	Production	CL7225

3.6 Surface Treatment

Components may require surface treatment to:

- increase wear resistance
- enhance corrosion protection
- improve fatique resistance
- achieve desired appearance

The factors which should be considered in selecting the appropriate surface treatment include:

- purpose/requirement
- environment - induced and/or natural
- processibility/component design
- compatibility - mechanical/electrical/chemical
- dimensional control required
- quality control inspection
- cost

Note: the latter must be considered in conjunction with other motor and missile system items.

Generally each surface treatment requirement should be considered on its individual merits and departments which may be affected and which therefore should be involved in the decision process would include materials, production and QA.

Reference to the following documents should be made in the first instance:

Def Stan 08-5	Chapter 5-706 protective treatments
AvP32	Chapter 606 (suggested metal A/metal B galvanic preference)

Specific documents include:

Def Stan 03-20	Chromate passivated to Def 130
Def Stan 03-5	Electroless Nickel
DTD911	Protection of Magnesium rich alloys
Spec TS10278	Powder coating
Def Stan 03-11	Phosphate treatment
Def Stan 03-19	Cadmium plate
Def Stan 03-24	Anodising
BS1706 & BS3382 parts 1 & 2	Zinc plate and cadmium plate
BS1224 & BS3382 parts 3 and 4	Nickel plate
DTD5588& DTD5555	Paint systems

Note: Where possible, for Environmental Health and Safety reasons, the use of cadmium plating should be avoided.

Further specialist advice is available through:

RAPRAand PERAreference libraries
Paint Research Croyden
British Metal Treatments Ltd, Birmingham.

PART 4 - ANCILLARY TOOLING AND EQUIPMENT

4.1 Introduction

Part 4 of TN 79/49 is concerned with the design of plant and equipment required for the manufacture of Rocket Motor components. The responsibility of all designs lies with the Engineering Department Manager (Production Directorate), and OM89/16 - Design Code of Practice for Engineering Department (Ref 1) details the relevant design procedure adopted.

A listing of the documents used by the Engineering Department's plant engineer during the design phase is provided in Section 3.6: all plant and equipment must be designed to meet both mechancial and explosive chemical safety standards.

4.2 Mould Tools

During the initial conception stage of the design of moulded rocket motor components, the Design Office involves representatives from Engineering, Materials, Projects, and Production Departments. Upon completion, the finished moulded component drawings are passed to the Engineering Department in order for the latter to arrange for tooling manufacture.

The Engineering Department is tasked to compile a Technical Specification outlining the type of tool construction, method of heating, press platen details, etc. The Technical Specification includes information supplied by the Materials Department, viz material properties, shrinkage factors, etc.

The Engineering Department forwards components drawings and corresponding Technical Specification - together with recommendation on possible suppliers - to the Purchase Department, who then go out to tender in the normal manner (as defined in 100 839-23/1/HQ - Commercial Directorate Manual Part 2 RMD Divisional Purchasing Procedure).

OM 89/16 details the Code Of Practice for the Engineering Department, and a typical check list is outlined below for a guideline technical specification for the design and manufacture of a mould tool.

4.2.1 Check List Of Technical Specification

A mould tool is required to produce components which conform to the dimensional requirements of drawing number <   >.

i) Specify type of tool required: compression, transfer, injection mould, vac-form etc.
ii) Specify press platen or moulding machine back plate details
iii) Specify method of tool heating, eg electrical or steam
iv) Specify tool material, surface finish details
v) Specify moulding material, material shrinkage factor, material compatability properties, etc.
vi) Specify Engineering and Materials Departments' contacts to outline design principles of the tooling.
vii) All drawings to be in accordance with Design Office procedures laid down in 101 254-31/3/HQ - Design Service Procedures Manual.
viii) Specify whether the layout drawings/detailed drawings produced by the supplier should be submitted to the Engineering Department RMD, prior to the commencement of manufacture/machining.

4.3 Extrusion Dies

The design and development of extrusion dies is the responsibility of the Engineering Department and all queries are to be directed accordingly. The Engineering Department does not currently lay down a Code Of Design Practice for extrusion die design, and design activity is carried out using the in-house expertise developed over many years, in addition to empirically derived experience from previous activity and manufacture.

Since the late 1980's relatively few extrusion dies have been produced at RMD, these including Titus (CDB Whinchat) and GVMLI project. Both of these dies were developed generally in accordance with the principles of two previous dies, viz Riga III and Matapan.

In summary, die size was calculated by working back from the finished charge size after casting on several existing charges, and comparing this to respective beaker pressure sleeve size. In order to determine the size of pressure sleeve for the new finished charge required, this factor was applied. A similar comparison was made between the existing beaker pressure sleeves and extrusion dies, this factor again being applied to the new beaker size in order to calculate the dimensions of the extrusion die. The Project Manager checks the complete finished extrusion die design scheme prior to manufacture, but Design (and Technical) Authorityship remains with the Engineering Department/Materials Department.

4.4 Casting Equipment

The development and design of casting equipment is the responsibility of the Engineering Department, and all queries are to be directed accordingly, As in the case of section 4.3 (Extrusion Dies), the design of casting equipment is based significantly on a sound knowledge of past developments and designs. Any innovative design will be implemented only after due consideration and approval by the Engineering, Projects and Materials Department.

It is a mandatory requirement that casting equipment must primarily be designed to meet both mechanical and explosive chemical safety standards. The design procedures must comply with OM89/16, and will adopt and include (but will not be restricted to) the Codes of Practice and Design Information tabled in section 4.6.

4.5 Potting Equipment

The development and design of potting equipment is the responsibility of the Engineering Department, and all queries are to be directed accordingly. As in the case of Section 4.3 (Extrusion Dies), the design of casting equipment is based significantly on a sound knowledge of past developments and designs. Any innovative design will be implemented only after due consideration and approval by the Engineering, Projects and Materials Department.

The design of potting equipment will include (but will not be restricted to) the Codes of Practice and design information tables in section 4.6.

4.6 References

Documents used by the Engineering Department and Design Office during the design phase.

1. OM89/16 - Design Code Of Practice for Engineering Department
2. 101 254-31/3/HQ - Design Services Procedures Manual
3. TN92/12 - Assessment Scheme For The Chemical Compatibility Of Materials With Composite Propellants.
4. TN90/95 - Assessment Scheme For The Chemical Compatibility Of Materials With Double Base Propellants.
5. BS5500 - Unfired Fusion Welded Pressure Vessels.
6. BS970 - Part 1, 2, 3 and 4 Materials: Steel
7. BS1470 to BS1475 Materials: Aluminium
8. BS2853 - Design Of Runway Beams
9. BS449 - Design Of Steelwork In Buildings
10. Health and Safety At Work Act 1974
11. Explosives Regulations AvP 42
12. Text Book - Stress and Strain - Raymond J Roark
13. Text Book - Dangerous Properties of Industrial Materials - N Sax
14. Text Book - Institution of Heating and Ventilation Engineers Guide Books A, B, and C.
15. Text Book - Woods Practical Guide to Fan Engineering
16. Text Book - Industrial Ventilation, a Manual of Recommended Practice, American Conference of Government Industrial Hygienists
17. Text Book - Mechanical Engineers Handbook - Marks
18. For compatibility of materials with casting liquid refer to the Laboratory Services Manager, RMD.

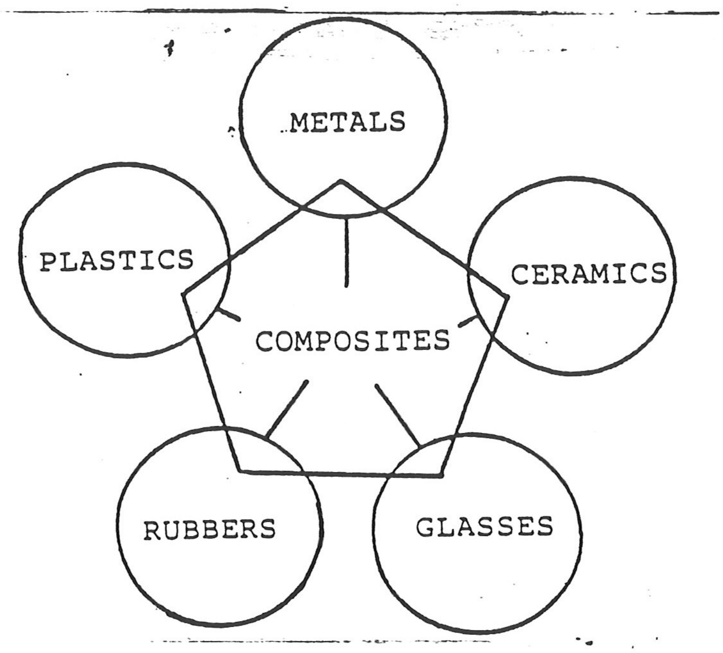
29. Code of Practice 21 Control of Asbestos at Work

20. Tech Guide No 7 - Controlling Airborne Contaminants In The Workplace
21. OM89/4 - Propellant General Systems and Procedures (includes COSHH)

PART 5 - COMPATIBILITY

5.1 **Introduction**

Materials used in the construction of rocket motors cover the full range from flexible rubbers to reinforced metals. The menu of engineering materials is illustrated below: each class of material has properties which occupy parts of a spectrum of stiffness, strength, density, chemical stability, ballistic properties and other thermal properties, and these often overlap.



The procedures for selection and design are dependant on the material class, but all materials contained in explosive compositions have to be compatible, both chemically and physically, with each other and with explosive constituents. The requirement for materials to be compatible applies also to materials which are in contact with, or could come in contact with, explosives during production transport and processing.

5.2 **Compatibility Requirements**

The sentencing of materials in respect of compatability requires to take into account the nature of the material application. In particular whether the contact with explosives involves propellant, casting liquid or powder (for cast double base), or propellant, binder liquid or ingredients (for composite HTPB); whether the contract is intimate; whether the materials is intended to be a reactant to form a finished material, and if so the maximum time of contact with explosives in the intermediate reactant state.

There are essentially two main areas of safety involving compatability clearance of materials. There are, first, on-site safety requirements, e.g. initial R & D trials, process aids, etc. and, second, the DEF STAN 08-5 aspects of safety which are concerned with project safety matters and the long term reliability of a store. These conditions are supported by materials being defined as compatible for certain categories of application and useage.

These categories are defined below:

5.2.1 **Materials Categories**

All prospective materials to be used in rocket motors and associated products and processes are sub-divided into four categories. These are given below with typical examples.

Category 1

Materials in direct contact with propellant or propellant vapours, e.g. all materials located inside a rocket motor or applied to a propellant charge. This category is sub-divided further as follows:

(i) Materials, cured, crosslinked, polymerised or formed prior to propellant application, i.e. lining rubbers, stress relief devices, PB40K.

(ii) Materials crosslinked or polymerised in situ on the propellant, ie. DOX inhibition, Silcosets, liners, other inhibitors.

(ii) Materials used inside the motor but where contact is only by means of a vapour path. These materials will normally be tested in the fully formed state unless any liquids such as varnishes, paints etc., were to be applied to the filled rocket motor such that accidental spillage would result in direct contact occurring.

Category 2

Materials with not continuous direct contact with propellant or propellant vapours, but may have short term contract during processing/filling/casting operations, e.g. materials located on external surfaces of rocket motors such as paints, adhesives, attachments, etc.

Category 3

Process aids with short term contact but will not intentionally form part of a rocket motor or charge, e.g. process propellant formers, parting agents, casting equipment, etc.

Category 4

Casting liquid, casting powder and propellant ingredients (for CDB propellants), and binder liquids and solid propellant ingredients (for HTPB propellants), e.g. ballistic modifiers, liquid polymer systems etc.

5.2.2 Testing Schemes

The schemes illustrated in TN90/95 and TN92/12 (ref 1 & 2 and for CDB propellants and HTPB composite propellants respectively) describe the compatibility tests to be applied to each material category.

Rigid application of the scheme is necessary in that:

(i) Category 3 cleared materials cannot be used for category 1 and 2 uses, and

(ii) Category 1, 2, or 3 cleared materials cannot be used for category 4 applications.

The Laboratory Services Manager or the GWSO are to be consulted if there is any doubt about the interpretation of the categories and items uses.

5.2.3 Test Methods

In addition to TN90/95 and TN92/12 (refs 1 & 2), the compatibility test methods and procedures are given in specification IMI/SRS/103 (ref 3). The sentencing criteria for each individual test is also laid down in IMI/SRS/103.

5.2.4 Physical Compatibility

This compatibility area is more difficult to precisely define. In the case of many rubbers, adhesives, etc. used in rocket motors, the migration of plasticisers (NG, TA) may affect the performance of the material and the adjoining propellant. Usually the NG uptake figure will indicate a possible problem. Other areas to be considered are surface finishes and thermal expansion characteristics and these are detailed in Def Stan 08-5 section 7 (ref 6).

Physical compatibility requirements of all non-energetic materials are with-in the remit of the Materials Department, and all matters are to be discussed with the relevant Technical Authority - see OM90/4: Materials Department Operating Manual (ref 4).

Similarly, matters concerning the physical aspects of explosive material (propellant, powder, casting liquid, etc) should be discussed with Propellant Technology (see OM92/14 [ref 5]), the Laboratory Services Manager and or the relevant Technical Authority.

5.2.5 Final Report

A final report will be issued by Laboratory Services giving the test results and any recommendations or restrictions on the use of the material if these are necessary.

5.3 References

1. TN92/12 - Assessment Scheme for the Chemical Compatibility of Materials with Composite Propellants

2. TN90/95 - Assessment Scheme for the Chemical Compatibility of Materials with Double Base Propellants

3. IMI/SRS/103 - Test Procedures for Determining the Compatibility of Materials

4. OM90/4 - Materials Department Operating Manual

5. OM92/14 - Propellant Technology Operating Manual

6. Def Stan 08-5 - Design requirements for Weapon Systems

5.4 Rigid Insulants

Rigid insulants utilising Novaloc resins have in general, shown themselves to be chemically incompatible with double base propellants containing pNMA stabiliser. The following projects experienced such problems.

Project	Insulation	Problem	Solution
E552 Pointer	RA51	Ignition delays after 12 years	Skin face of charge to relife
E587 Matapan	RA51	Igniter not performing to spec (i.e. action time and pressure) after 12 years	Under consideration
E599 Riga III	RA51	Gas evolution created beaker unbond on accelerated ageing	Change to macerated RA1

PART 6 - SAFETY

6. Safety

Part 6 of TN79/49 describes the systems and procedures, work practices, and safety/handling practices for rocket motors and associated items, both within RMD work areas and in service.

6.1 Safety - Work Areas

The systems and procedures operated in Propellant Manufacturing, Storage and Disposal Areas are documented and consolidated in OM89/4 - Propellant General Systems and Procedures Manual (ref 1). This manual is concerned principally with the Propellant Technology Department and Propellant Section of Production Department, but also included are certain sections of Engineering Services and Quality Assurance Departments which are located within the Propellant Manufacturing Area.

The objective of Manual OM89/4 is not to be a specification in the normally accepted sense, but an internal document only concerned with desseminated relevant information to all levels of staff, and ensuring conformity with approved practices. Nevertheless, the systems/procedures currently in force are mandatory.

OM89/4 is divided into eight (8) sections as follows:

Section 1 - General Regulations
Section 2 - General Building Practices
Section 3 - Permit Systems
Section 4 - Casting Liquid & Casting Powder
Section 5 - Propellant Manufacture
Section 6 - Disposal of Wast Material
Section 7 - General Systems
Section 8 - Training of New Employees.

(Contents may be subject to amendments, and a current copy of the manual should be referred to for further details).

Other references for Safety within RMD are listed in Section 5.3, but this list is by no means exhaustive. Def Stan 08-5 tables information concerned with project safety matters, long term reliability of a store, etc.

6.2 Safety - In Service

6.2.1 Introduction

All live rocket motors and assemblies despatched from RMD are explosive stores, and customers are made aware of safety, handling and firing instructions via relevant mandatory documentation issued by RMD. These "Safety Plans" (i.e., ref 2) outline how RMD meets (or plans to meet) the safety aspects of the customers' technical requirements.

Def Stan 08-5/1 (ref 1) details in-service safety considerations, e.g:

Power Systems

Rocket motors to be designed to Def Stan 08-5 ...any single failure should not allow a hazardous situation to develop - fail safe techniques are to be adopted. The rocket motor should be designed to meet the safety requirements of the launch site or platforms.

Guidance/Control Systems

The system is to provide maximum control of safety if a missile fails through a rogue trajectory by considering fail safe techniques, e.g. loss of guidance signal should result in the missile either self-destructing or manoeuvering to a safe trajectory.

6.2.2 Scope of RMD Safety Instructions

Areas with safety significance in the design mode of operation of the rocket motor are identified, and the trials planned to meet and demonstrate compliance with requirements in these areas are described.

The safety, handling and firing instructions (as applicable) are listed. Markings, painting, packaging, storage, servicing and limitations of use are addressed in order to meet with all specified safety requirements.

6.3 References

1. Def Stan 08-5/1 Part 6 Section 7

2. Safety/Handling/Firing Instructions and related documents issued for each rocket motor.

PART 7 - TESTING

7. Testing

During the development phase, all components of the rocket motor (structural, non-structural, charges and igniters) are tested/inspected in accordance with the customers' technical specifications, in-house procedures, Def Stan 08-5 and other documents listed in section 7.4.

Essentially, testing falls into three basic categories, viz:

i) Hardware testing (pressure, mechanical, and leak testing)
ii) Non-destructive testing (of charges)
iii) Performance tests

Testing adheres to a systematic and methodical procedure, and the precise methods of carrying out the three basic categories of testing (including sampling) are detailed in the appropriate departments' operating manuals, technical notes, manufacturing methods (MM) and examination methods. An outline of tests carried out is illustrated in paragraphs 7.1, 7.2 and 7.3.

7.1 Hardware Testing

Typical (but by no means an exhaustive) list of tests are listed below, and the departments concerned liaise with the Project Manager during testing and analysis of results.

Test	Department/Technical Authority
Structural Hardware	
Pressure testing*	Production Department
Mechanical testing	Materials Department
Pressure & Mechanical testing	Production Department
Leak testing	Production Department
Non-structural Hardware	
Rigid insulant testing	Materials Department
Flexible insulant testing	Materials Department
Rubber testing	Materials Department

* Typical tube pressure test equipment is illustrated in Figure 31.

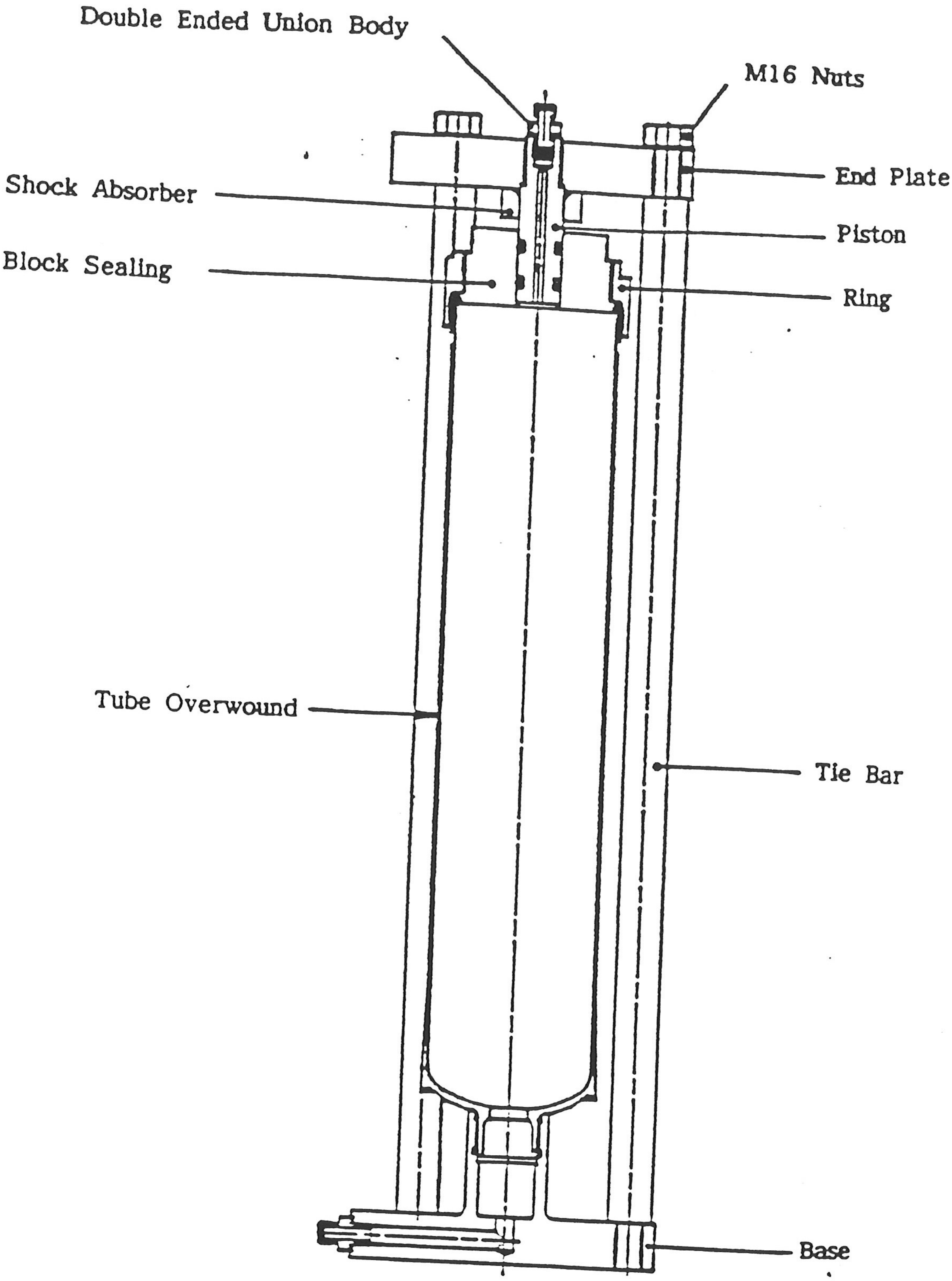


Figure 31. Tube Pressure Test Equipment

7.2 Non-destructive Testing (NDT)

Methods employed within RMD for the non-destructive testing of solid propellants are detailed/laid down by the Engineering Department (Trials and Instrumentation section). The methods developed for NDT have been largely based on ultrasonic tests, but a list of the types of charge inspection currently used are described below.

7.2.1 Visual Inspection

This is the simplist and quickest of the inspection techniques and the one most readily appreciated. Voids, porosity or cracks which extend to the propellant surface can be inspected.

7.2.2 Ultrasonic Tests

Ultrasonic testing detects voids, porosity, cracks, separations (between motor case and insulation, or case insulation and propellant), unbonds and any other change in elastic properties. The three most commonly used methods are:

i) Ultrasonic transmission tests
ii) Ultrasonic resonance techniques
iii) Ultrasonic pulse reflection tests

These techniques are detailed in the relevant MMs, and sentencing in the relevant specifications for different motors.

7.2.3 Magnetic Particle Flow Detection

Magnetic particle flow detection detects cracks, non-metallic inclusions and other discontinuities in or near the surface of ferro-magnetic materials. Not suitable for small or fragile components, and details available in IMI/SRS/232.

7.2.4 Radiography

General procedures for radiographic operations are given in IMI/SRS/150, IMI/SRS/208(F), and other specifications concerned with RMD historical experience.

Radiography detects voids, perosity, cracks, separations, inclusions and other changes in material density.

7.2.5 X-ray Tomography

This method can detect voids, porosity, cracks, inclusions, separations and small changes in density. However, this is an off-site facility and therefore of limited use.

7.2.6 Eddy Current

This is a limited eddy current capability which is useful for detecting surface breaking cracks in small metallic components, and detecting differences in metallic properties.

7.3 Performance Testing

The Project Manager works in conjunction with the relevant departments (eg BMD, Engineering Department, Materials Department and Propellant Technology) during performance tests.

During propellant characterisation, casting powders and propellants undergo "standard test", and the subsequent propellant manufactured is characterised via a series of "characterisation tests", i.e. propellant rheology, ballistic and hazard testing. Static firings may be carried out, and environmental, pre-qualification and qualification trials complete the tests to produce a fully developed rocket motor.

The performance tests carried out include, but are not limited to:

7.3.1 Standard Casting Powder Tests

Heat tests Moisture Total volatile matter Residual solvent Absolute density Bulk density Shadowgraph Vacuum stability	Propellant Technology/ Divisional Laboratory

7.3.2 Standard Propellant Tests

(Detailed in IMI/SRS/103 and ROS/343)

50mm cube crack test Abel heat test Stabiliser tests Tensile tests	Propellant Technology/ Divisional Laboratory

7.3.3 Propellant Chemical Stability

Storage Temperature effects X-ray Vacuum stability test	Divisional Laboratory

7.3.4 Propellant Characterisation

7.3.4.1 Rhelogical Testing

Tensile Dynamic Mechanical Thermal Analysis Other associated testing	BMD/Materials Department

7.3.4.2	**Ballistic Testing**	
	Slabs-fired (burning rates, pressures etc are determined)	BMD/Engineering Department
7.3.4.3	**Hazard Testing**	
	Rotter impact test Mallet friction test Rotary function test Temperature of Ignition Bickford Fuze test Train test Electric spark test Gap test	Propellant Technology/ Divisional Laboratory
7.3.5	**Insensitive Munitions Testing**	
	The study of rocket motors under attack or in fire either directly initiated or on behalf of external establishments	Range (Eng. Department)
7.3.6	**Packaging Testing**	
	The package testing for transport of explosives and dangerous goods	Range (Eng. Department)
7.3.7	**Safety Trials**	
	See Part 6 of TN79/49	
7.3.8	**Environmental Trials**	
	Bump Shock Vibration Accelerated Ageing	Engineering Department

7.3.9 Qualification and Pre-qualification Trials

Bump/shock
Thermal shock
Temperature cycling
Vibration — Engineering Department
Accleration
Accelerated ageing
Humidity
OB Tests/Trials

7.3.10 Flight Testing

7.3.11 Smoke Tunnel Testing

The analysis of smoke from plumes during rocket motor firings, and the subsequent predicted effects in-service due to varying transmission levels

7.4 References

Documents used by RMD during the testing of rocket motors and associated components.

Details To Be Included

PART 8 - RELIABILITY AND MAINTAINABILITY

8.1 Introduction

Part 8 describes those procedures and practices which will be employed by RMD in order to fulfil the Reliability and Maintainability (R & M) requirements with-in the division. R & M work is carried out in the Ballistics and Mathematics Department (BMD) of the Projects/Technical Directorate, but R & M activity which forms part of any contract will be carried out for the Project Manager as a part of the overall project programme. RMD are committed to providing a quality product, which meets the customer's requirements and continues to meet those requirements throughout its life.

The policy within RMD is to carry out all R & M generally in accordance with OM92/20 - BMD Procedures for R & M (ref 1), and Def Stans 00-40 and 00-41 (refs 2 & 3), tailored where necessary for the specific requirement of rocket motors.

8.2 Scope

These procedures cover the design and development of all products within RMD; the production phase is covered by the Quality Assurance Department. The procedures apply specifically to rocket motors and associated equipment, which comprise the product range of the division.

8.3 Applicability

These procedures shall apply to all projects unless the contract for that product contains other specific requirements. If any inconsistency exists between the contract requirements and the procedures laid out in OM92/20, the contract requirements shall prevail.

8.4 Definitions

8.4.1 Definition of Terms

The following definitions are taken from OM92/20 (ref 1):

Reliability The ability of an item to perform a required function under stated conditions for a stated period of time.

NOTE: The term reliability is also used as a reliability characteristic denoting a probability of success, or a success ratio.

Maintainability The ability of an item under stated condition of use, to be returned or restored to a specific condition when maintenance is performed by personnel having specified skill levels under stated conditions and using prescribed procedures and resources.

Failure The event in which any item or part of an item does not perform as previously specified.

Defect Any non-conformance of an item with specified requirements.

8.4 Reliability and Maintainability Planning

All R & M tasks will be included in the overall project plan, tying into appropriate milestones and review meetings.

Where required, a R & M programme plan will be prepared, following the requirements of OM92/20 and Def Stan 00-40 (refs 1 & 2). Such a plan will define the appropriate R & M management structure to the particular project, and define tasks (and appropriate methods to carry out each task) which will together form the R & M programme.

All R & M programme plans will be issued as Technical Notes by the BMD.

8.6 Reliability Models and Reliability Apportionment

RMD (BMD) will create a reliability model of the system using the techniques described in OM92/20 (ref 1) and Def Stan 00-41 (ref 2).

8.7 Reliability Prediction

Throughout the design and development phases, reliability predictions will be prepared and updated by BMD as described in OM92/20 (ref 1).

8.8 Failure Mode and Fault Tree Analysis

In the event of system failure, two methods of assessment may be carried out (as described in OM92/20); essentially, these are:

a) Failure Modes, Effects and Criticality Analysis (FMECA)

FMECA assesses the failure modes of each lowest level item and their effects on the system - a "bottom up" analysis

b) Fault Tree Analysis (FTA)

FTA is a 'top down' assessment of system failure.

8.9 Control of Sub-Contractors

Reliability requirements will be included in the statement of work which is placed on sub-contractors used by RMD. Requirements are as described in OM92/20 (ref 1).

8.10 References

1. OM92/20 Issue 1 - BMD Procedures for Reliability and Maintainability.

2. Defence Standard 00-40 - Reliability and Maintainability.

3. Defence Standard 00-41 - Reliability and Maintainability, MOD Practices and Procedures.

PART 9 - RISK MANAGEMENT

9.1 Introduction

Part 9 describes those procedures and practices which will be employed by RMD in order to fulfil the Risk Management (RM) requirements with-in the division. RM is gaining in importance as there is a growing contractual requirement for risk analysis and management on Royal Ordnance projects.

The Policy within RMD is to carry out all RM generally in accordance with the Manual for Formal Risk Management of Royal Ordnance Activities (ref 1), tailored where necessary for the specific requirements of rocket motors.

Note! RM is not concerned with "risk" in the sense of insurance, marketing or health and safety.

9.2 Objectives

The objectives of RMD's policy of implementing formal risk management are detailed in ref 1, but the main objectives are:-

9.2.1 To minimise the risk of failing to achieve the timescale, cost and performance goals of RMD's activities. Note that in this context:

(a) "RMD's activities" includes:

- private venture programmes
- research and development investigations
- contracted development projects
- manufacturing contracts
- any other substantial, complex business activity

(b) Each activities "goals" should be defined so as to reflect RMD's expectations of the activity concerned. The "goal" needs to be recognised both by the divisional (and corporate) authorities and by the activity managers as defining RMD's interests in the outcome of the activity; achievement of the goal needs to be synonymous with the fulfillment of RMD's interests.

In summary, the main objective of RM is to assert more effective control over the timescales, costs and product quality of the work undertaken.

9.2.2 To provide the (Project) Manager responsible for each activity with sufficient information about the status of the irreducible risk to his activity in order to provide a sound basis for decision making.

9.2.3 To achieve consistent application of the principle of formal RM across RMD's operations, while focusing the company's risk reduction resources where they might most cost effectively be deployed.

9.2.4 To increase the confidence of RMD's customers in the effectiveness of Royal Ordnance's project management practices, of which formal RM forms a part.

9.3 Risk Management Principles

The account set out below is a summary of the more substantial description of the principles of RM set out in ref 1 (Manual for Formal Risk Management).

9.3.1 The Nature Of Risk

A risk is a potential problem that may affect an activity's ability to perform satisfactorily against its goals.

A risk is characterised by:

- uncertainty as to whether it will occur
- potential for a detrimental effect on the activity's interests if it does.

Risk analysis and management are scoped to consider all of:

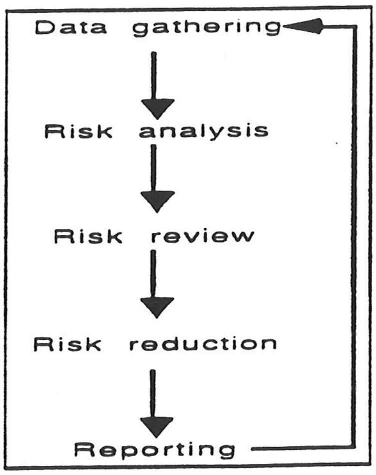
- risks to timescale, performance & cost
- risks from activity, corporate or user sources
- risks applying at every stage of the activity lifecycle.

9.3.2 Mission Of Risk Management is:

- to increase awareness of the risk threatening delivery to time, budget and specification
- to identify and eliminate the weaknesses in current risk reduction action
- to ensure that managers have the information they need about risk in order to make high quality decisions
- to enable a contractor and his customer to share realistic expectations about their activity's outcome, and to co-operate in addressing the risk faced.

9.3.3 Practical Approach

A practical approach is implemented through a cycle of regular risk management activity: -



Information is gathered through contact with personnel acquainted with the factors affecting the success of the activity, either through structured interview (a "top down" approach) or through written requests to a wider audience (ie from the "bottom up").

Risk analysis takes two basic forms:

- qualitative analysis to identify structure within the risk information and to put each risk into the context of its effect on the outcome of the activity as a whole

- quantitative analysis to measure the overall impact of the risk and the potential benefit from the risk reduction action available.

Risk review is a process whereby the risk information and the context established by the risk analysis is considered by personnel who offer a perspective across all the facts and circumstances pertinent to the activity. The risk issues postulated are validated, being either accepted or rejected, and the perception of their significance amended in the light of this knowledge; the analysis is re-visited as necessary.

Risk reduction is achieved by using the risk analysis to identify the most damaging risk issues, by reviewing the adequacy of the action already in place in respect of the key risks and by commissioning further action as appropriate. Responsibility for action is assigned to a nominated "risk owner".

Reports are produced based on information gained from the analysis. Every activity shall consider the need for reporting the status of risk and risk reduction to any or all of:

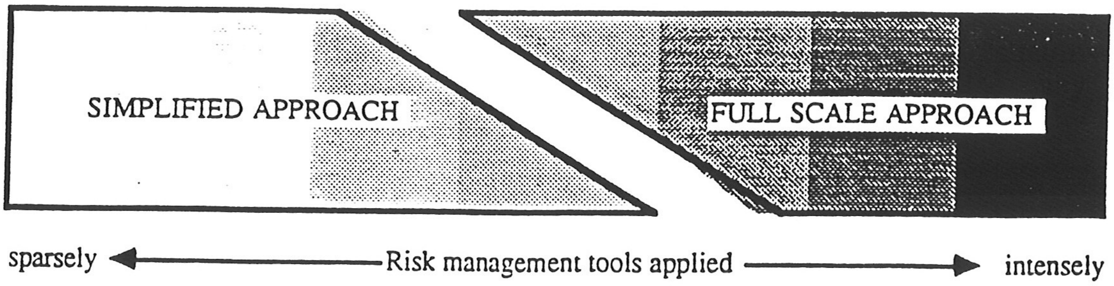
- the customer
- divisional authorities
- managers with-in the activity concerned

9.3.4 Intensity Of Risk Management

The tools and techniques available for the conduct of risk analysis and RM may be deployed very intensively, very sparsely or at an infinite gradation of "shades of grey" in between. RM measures implemented should be closely tailored to the case-specific requirements and resource availability of each activity concerned. A suitable intensity of RM should be selected, based on one of two basic alternative approaches:

- for a high intensity "darker shades of grey" requirement a "full share" approach based on software tools and the input of qualified risk management expertise may be appropriate

- for a lower intensity "lighter shades of grey" requirement a "simplified" approach based on paper-based, template driven, low expertise may be appropriate.



The full scale approach entails the definition of a "toolset" appropriate for the activity concerned, drawn from the "tool box" set out in Annex C of the Manual for Formal Risk Management (ref 1).

The simplified approach will entail the implementation of a simplified Project Risk Management Pack (SPRiMP) as documented and described in Annex F of the Manual for Formal Risk Management (ref 1). Implementation requires selection of a suitable set of tools, just as for the full scale approach, albeit from a more limited "tool box".

9.4 References and Standards

The procedures and practices associated with the risk analysis of RMD activities are detailed in

1. Manual for Formal Risk Management of Royal Ordnance Activities.

The Risk Management Manual conforms to the following formal standards:

2. Risk Management in Defence Procurement, issued by MOD(PE), D/DPP/(PM)/2/1/12, 15 January 1992

3. Risk Questionnaires, issued by MOD(PE) June 1991

4. Engineering Management, MIL-STD-499A (USAF), 1 May 1974, 10.1.2 (Program Risk Analysis)

5. Royal Ordnance company standards

6. Recognised good risk management practice, on the basis of BAe-Sema (CORDA) dealings with customers and contractors in defence procurement.

9.5 Projects With Risk Management Requirements

Project	Type Of Analysis
E615 Antony and GVMLI Launcher	"Simplified" approach, proformae driven analysis, interface with RO (Chorley)
E613 HTPB ASRAAM E614 EMCDB ASRAAM	"Simplified" approach, proformae driven analysis. Interface with BAe Defence/Logica

PART 10 - PACKAGING

10.1 Introduction

Part 10 of Tech Note 79/49 states the design requirements for packaging of rocket motors within RMD. All packaging shall be designed to assure, in the most cost effective manner, the safety and serviceability of equipment during transport, handling and storage under all conditions specified in the technical specification appropriate to the particular rocket motor or items (e.g. igniter, blast tubes, etc.).

Documents used in the design and control procedures for packaging of rocket motors and associated items are listed in Section 10.5. OM92/23-RMD Code of Practice for the Packaging of Dangerous Goods (ref 1) defines the UK legal requirements which must be applied to the packaging of explosives, and the related international standards. All packaging shall be designed in accordance with Def Stan 81-41 and Def Stan 08-8 (refs 3 and 4).

10.2 Legal Requirements

OM 92/23 (ref 1) defines the regulations that packaging of explosives are currently subject to within the UK. The requirements of the United Nations publication commonly known as the "Orange Book" (ref 6) have been adopted in international agreements as the standard for methods of packaging of all classes of dangerous goods, and the international regulations currently in force are addressed accordingly for transport by air, sea, rail and road.

8980 Paint

1. Scope

This specification refers to a rubber paint produced by dispersing the rubber stock in a solvent to give a paint which is suitable for use in contact with cast double base propellant.

2. Description

The rubber stock is Hypalon CL 8980 formulation and is dispersed in toluene to give a free flowing paint which contains no undispersed rubber or obvious contamination.

3. Related Documents

a) Specification IMI/SRS/41 - Hypalon CL 8980 rubber sheet and slab.

b) Specification IMI/SRS/50 UTR 19

4. Composition

a) The rubber paint shall consist of the ingredients given below in the proportions by weight indicated:

Constituent	Parts by weight	Supplier	Specification
Hypalon CL 8980 rubber	42 $\pm$ 2	Northern Rubber Co.	IMI/SRS/41
Toluene	58 $\pm$ 2		

b) The Hypalon CL 8980 rubber will be taken from a freshly milled mix in the form of 9 mm slab. The age of the slab will not exceed 8 weeks after milling unless otherwise authorised by the Design Authority. Calendered sheet, offcuts, or other sources of CL 8980 rubber will not be used.

5. Processing

a) The two components will be mixed together by an approved procedure.

b) Each batch produced will be given a batch number.

6. Testing

a) The following test requirements apply:

Test	Test Parameters	Test Specification
Total solids content	38 - 44% by weight	IMI/SRS/50 UTR/19
Viscosity	20-250 poise	IMI/SRS/50 UTR/19

b) If the total solids content exceeds the upper limit of 44%, further toluene can be added, the paint remixed and retested for total solids content.

c) If the total solids content is below the lower limit of 38%, further CL 8980 stock can be dispersed in the mix and the batch retested.

7. <u>Frequency of testing</u>

a) One sample from each batch of material produced will be tested and meet the requirements of para. 6 (a).

b) On satisfactorily meeting the requirements of para. 6 a) the batch of CL 8980 paint shall be cleared for process use and allotted an initial life of 2 months.

c) Each container shall be clearly labelled with its user test date and final expiry date.

d) Any batch or part of any batch unused after the User Test Date shall be retested to the requirements of IMI/SRS/50 UTR 19.

8. <u>Delivery requirements</u>

a) Each batch of paint must comply with requirements stated in the contract.

b) The batch number, total solids content and date of mixing will be clearly marked on the cans and despatch notes for each delivery.

c) The rubber paint is to be delivered in tightly sealed cans.

d) Each batch must be delivered within 2 weeks of mixing.

3. SENTENCING

3.1 The batch of material is acceptable if all the test results fall within the control limits.

4. RETESTS

4.1 If a test result does not fall within the control limits of paragraph 2 a retest is permitted.

4.2 If the repeat result meets the control limits the Material Controller/TA shall be consulted to determine whether the material is acceptable or whether a confirmatory test shall be conducted.

4.3 If the repeat result does not meet the control limits then the Material Controller/TA shall be consulted immediately to determine further action.

SECTION 4 - COMPOSITION

The rubber mix shall consist only of the ingredients given, in the parts by weight indicated:-

CONSTITUENT	PARTS BY WEIGHT	SUPPLIER	GRADE
Ethylene propylene terpolymer	97 ± 2	Uniroyal	Royalene 501
Chloro-sulphonated polyethylene	3.00 ± 0.75	Du Pont (UK) Ltd	Hypalon 40
Silica	40 ± 2	ID Chemicals	Ultrasil VN-3/ VN-2
		Degussa	Aerosil 150
Zinc oxide	5.0 ± 0.5	Durham Raw materials	Zinc oxide R108
Polyethylene glycol	3.0 ± 0.25	Union Carbide Ltd	Carbowax 6000
Peroxide see 5.6	7.5 ± 0.25	Novadel	Triganox 29/40
or	4.0 ± 0.25	Hercules	Dicup 40C
Teijin Conex Fibre	10.0 ± 0.5	A Waxman (Fibres) Ltd	2 denix 3 mm cut fibre
Polybutadiene	10.0 ± 0.5	Nippon Soda Co Tokio	Nisso PB3000

SECTION 5 - ACCEPTANCE CRITERIA (RAW MATERIALS)

5.1 The ethylene terpolymer shall have a relative density of 0.86 ± 0.005 at 20/20°C.

5.2 The precipitated silica will meet the following requirements:-

Particle size (surface area)	110 - 190 m^2/g
Silica content	89.5 to 93.5%
Moisture Content	4.0 to 7.0%
Loss on ignition of dried sample at 900°C	4.5 - 7.0
pH of aqueous extract	5.5 to 7.5

5.3 The Conex fibre shall be commercial grade cut to 3 mm supplied by the manufacturer or his agent.

1 Scope and Related Documents

1.1 This specification relates to the evaluation of the cure by Rheometer of natural and synthetic compounded rubbers (used within the Royal Ordnance Organisation) listed in Appendix A together with their material specifications.

1.2 Related documents:

UTR 55: Compounded rubbers - Material selection via Rheometer cure curve determination.

2 Performance of Rheometer Cure Curve Determination

2.1 An approved instrument is the "Monsanto Rheometer - Model 100 S" equipped with Micro Production Control (MPC) dies and micro rotor.
Monsanto Designation
Lower Die: AP108
Upper Die: AP109
Micro rotor: AR177

The dies and rotor shall not be coated with any release agent. The MPC die system uses a Teflon seal around the rotor shaft.

2.2 A sample of the unvulcanised rubber under test, stored at workshop conditions for at least 24 hours shall be cut into approximately 35mm squares and be of sufficient thickness so as to give a sample weight of 12 ± 2g.

2.3 The amplitude of the rotor oscillation shall be $\pm 1°$ about the centre position. The required Rheometer settings for each rubber are given in Appendix A.

Note: The test shall be in general accordance with BS1673 part 10 1977.

3. Basic operation of Monsanto Rheometer 100S

3.1 Check MCP dies and rotor are fitted.

3.2 Ensure that the Rheometer 100S and its recorder have been switched on for one hour before commencing testing.

3.3 Check that the temperature has stabilised at the desired values.

3.4 Check zero and full scale calibration.

3.5 Select the desired "full scale time" on the recorder.

3.6 Select the torque range required.

3.7 Select 'record torque' on recorder rear module.

3.8 Place 'rheograph' onto recorder.

3.9 Check rotor is clamped and motor is switched on

3.10 Open platens (recorder pen will lift and return to zero)

3.11 Select 'remote' on recorder pen control switch.

3.12 Load sample and close platens (pen will drop and recorder will start).

3.13 At end of test open platens (pen will lift and reset to start position). Unload sample change rheograph (if required) load new sample and close platens.

3.14 Note that if recorder is left running beyond selected full scale time, it will automatically reset and continue trace. Allow 9 seconds for pen return).

4 <u>Sample Loading and Unloading</u>

4.1 Quick and efficient sample removal and reloading are essential factors in obtaining repeatable results.

4.2 Gloves, as supplied, should be worn at all times during this process to avoid the possibility of burns from the heated platens.

4.3 To remove the sample, first open the platens and insert the brass pry bar under the tab on the front edge of the sample. Lift the tab sufficiently to enable the pry bar to be pushed across the top of the rotor. This action will peel the sample from the rotor. Assistance can be given with the gloved hand. Check the underside of the removed sample to see if any material may still be trapped underneath the rotor. If this is the case unclamp the rotor and lift it to remove any residual material. Reclamp the rotor, by pressing down the rotor onto its end stop while operating the clamping mechanism.

4.4 Load a new sample and close the platens.

4.5 With some very high modulus stock it may be found to be impossible to remove the sample as described above. In these cases the rotor should be unclamped and removed with the sample. Away from the machine the sample may be prised off or cut off with scissors.

5 Data Interpretation

5.1 The following parameters are to be obtained from the following Monsanto Rheometer cure curves;

Figure 1 Cure to equilibrium torque

Figure 2 Cure to maximum torque with reversion

Figure 3 Cure to no equilibrium or maximum torque

(a) M_L, Minimum torque (in dN-m)

(b) t_{s2} Scorch time (in mins) at M_L + 2 torque units (in dN-m)

(c) M_{HF} plateau torque, (in dN-m) (Figure 1)

or M_{HR}, Maximum torque (in dN-m) (Figure 2)

or M_H, highest torque value after a specified time (t) where no plateau or maximum is obtained (in dN-m) (Figure 3).

(d) $t_c(90)$, Cure time to 90% of full cure given by the expression for time $t_c(90)$, as

$$t_c(90) = [(M_{HF} - M_L)(90/100) + M_L)] \text{ mins.}$$

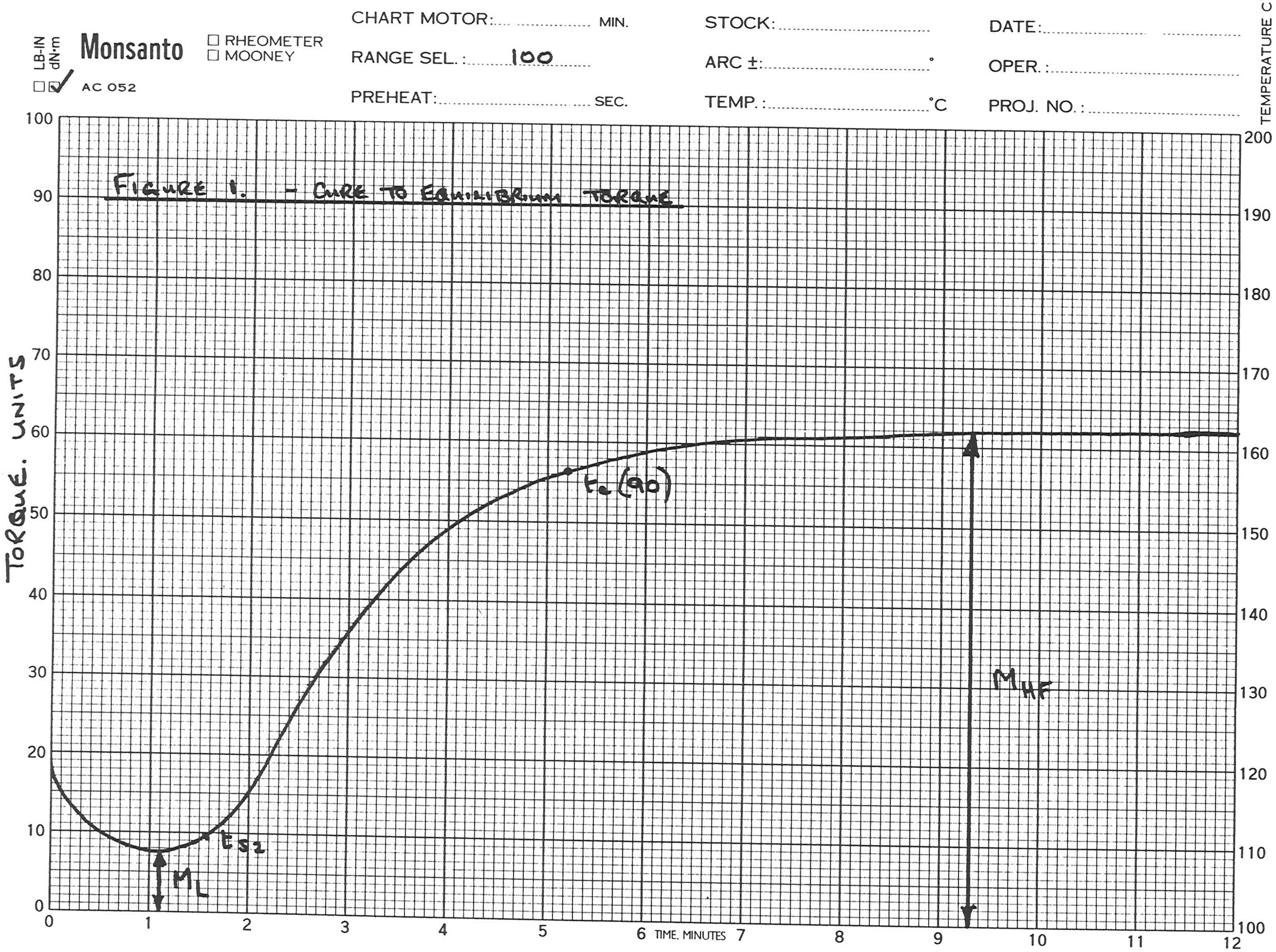
Note Figure 4 gives an actual example of a cure determination using the Monsanto Rheometer. It is important to note that when t_{s2} is calculated the torque units shall equate to the torque range scale selected.

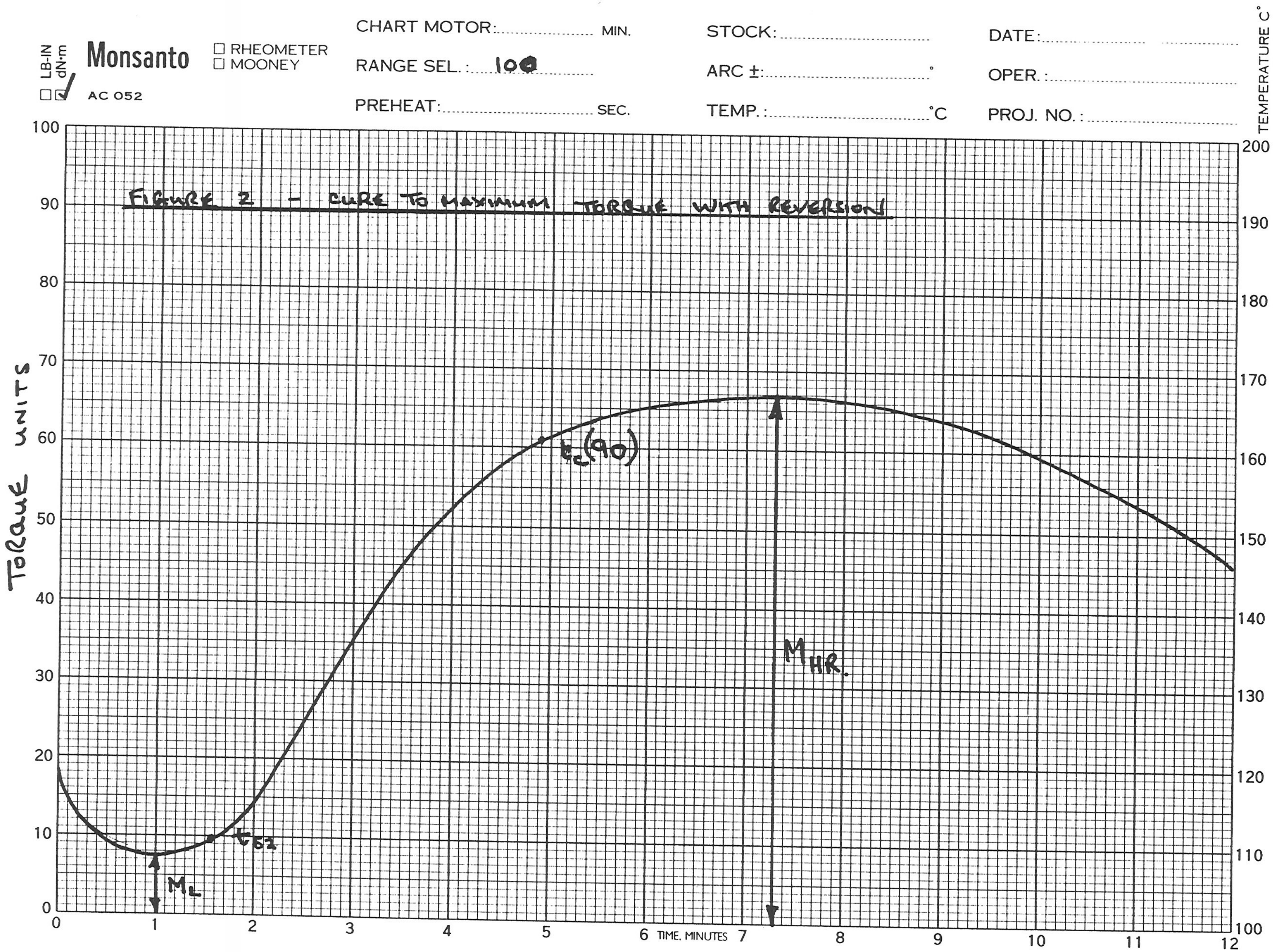
6 Reporting

6.1 The resulting parameters of the Rheometer cure curve shall be recorded on the Rubber Selection Sheet A48 D11 1036

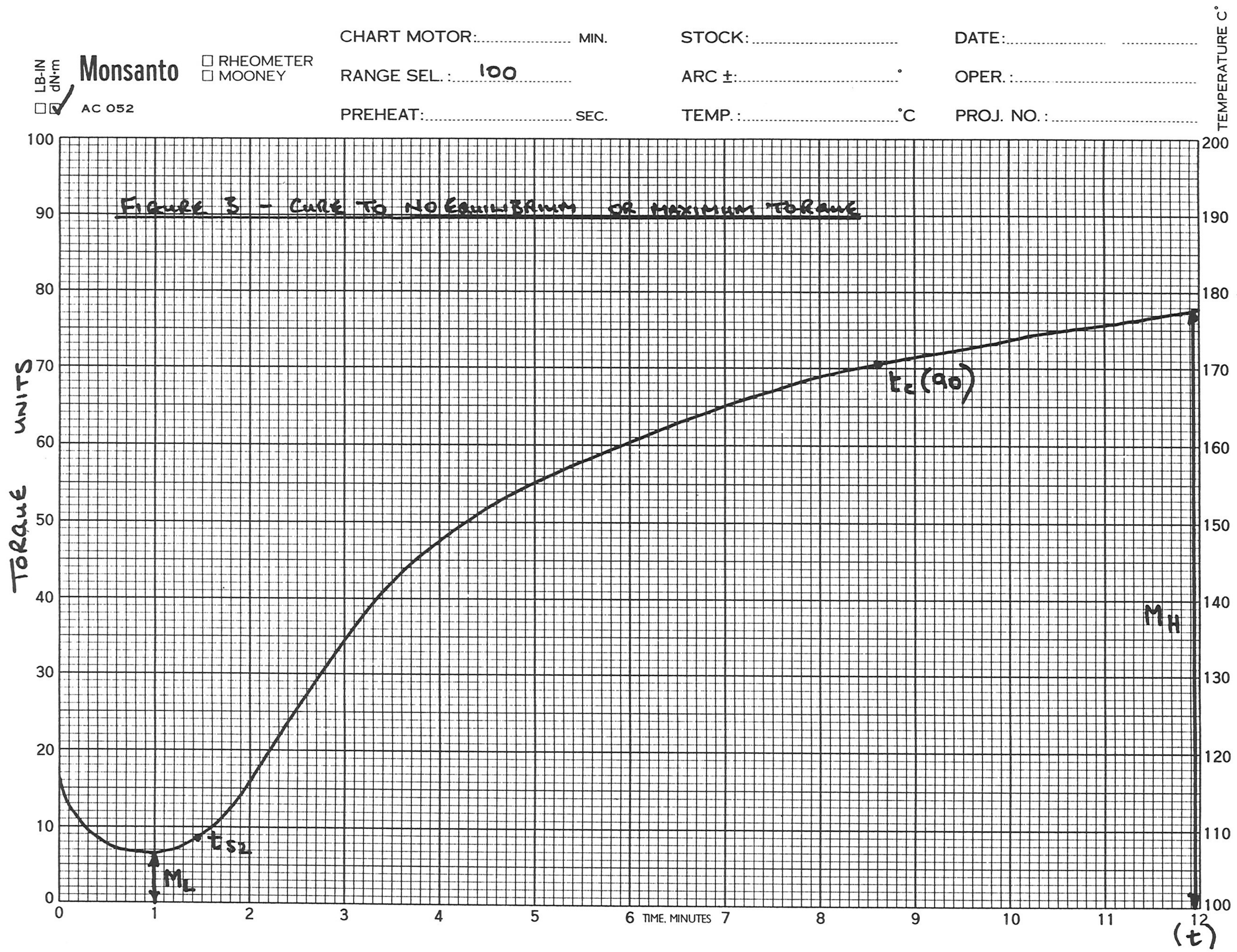
Appendix A: Rheometer Settings

Material Designation	Specification Number		Chart Motor (mins)	Torque Range Selected (dN-m)	Temp (°C)
Butyl QX50	Def Stan 93-4	Butyl Rubber Type QX	60	50	160
EPQX60	RO Spec 10530-01	Ethylene-Propylene Rubber Type QX	60	100	160
EPQX80	" " "	" " " " "	60	100	160
EPDM1005	RO Spec 50038-01	Ethylene-Propylene-diene rubber 1005 (low compression set)	30	50	160
EPDM65	AFS1471	Ethylene-propylene-diene terpolymer rubber 65 IRHD, Type QX	60	100	160
Rowanite 8205	RO Spec 50079-01	Bromobutyl	60	50	150
Rowanite 8206	RO Spec 10597-01	Ethylene propylene rubber for contact with hydrazine (Rowanite 8206)	60	100	160


LB-IN
dN·m
Monsanto
RHEOMETER
MOONEY
AC 052
CHART MOTOR: MIN.
RANGE SEL.: 100
PREHEAT: SEC.
STOCK:
ARC ±: °
TEMP.: °C
DATE:
OPER.:
PROJ. NO.:
TEMPERATURE C°
FIGURE 1. - CURE TO EQUILIBRIUM TORQUE
TORQUE. UNITS
TIME, MINUTES
$t_c(90)$
t_{s2}
M_L
M_{HF}



Monsanto
AC 052
LB-IN dN-m
RHEOMETER
MOONEY
CHART MOTOR: MIN.
RANGE SEL.: 100
PREHEAT: SEC.
STOCK:
ARC ±: °
TEMP.: °C
DATE:
OPER.:
PROJ. NO.:
FIGURE 2 - CURE TO MAXIMUM TORQUE WITH REVERSION
TORQUE UNITS
TEMPERATURE C°
TIME. MINUTES
$t_c(90)$
t_{s2}
M_L
M_{HR}
0 10 20 30 40 50 60 70 80 90 100
100 110 120 130 140 150 160 170 180 190 200
0 1 2 3 4 5 6 7 8 9 10 11 12


Monsanto
LB-IN
dN·m
AC 052
RHEOMETER
MOONEY
CHART MOTOR: MIN.
RANGE SEL.: 100
PREHEAT: SEC.
STOCK:
ARC ±: °
TEMP.: °C
DATE:
OPER.:
PROJ. NO.:
TEMPERATURE C°
FIGURE 3 - CURE TO NO EQUILIBRIUM OR MAXIMUM TORQUE
TORQUE UNITS
TIME, MINUTES
(t)
M_L
t_{s2}
$t_c(90)$
M_H
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
7
8
9
10
11
12
110
120
130
140
150
160
170
180
190
200

STATUTORY INSTRUMENTS

1989 No. 1790

HEALTH AND SAFETY

The Noise at Work Regulations 1989

Made - - - -	*2nd October 1989*
Laid before Parliament	*5th October 1989*
Coming into force -	*1st January 1990*

The Secretary of State, in exercise of the powers conferred on him by section 15(1), (2), (3)(a) and (b) and (5)(b) of, and paragraphs 1(1)(a) and (2), 6, 7, 8(1), 9, 11, 13(2) and (3), 15(1) and 16 of Schedule 3 to, the Health and Safety at Work etc. Act 1974(a) ("the 1974 Act") and of all other powers enabling him in that behalf and for the purpose of giving effect without modifications to proposals submitted to him by the Health and Safety Commission under section 11(2)(d) of the 1974 Act after the carrying out by the said Commission of consultations in accordance with section 50(3) of that Act, hereby makes the following Regulations:–

ARRANGEMENT OF REGULATIONS

(a) 1974 c.37; sections 15 and 50 were amended by the Employment Protection Act 1975 (c.71), Schedule 15, paragraphs 6 and 16 respectively.

Citation and commencement

1. These Regulations may be cited as the Noise at Work Regulations 1989 and shall come into force on 1st January 1990.

Interpretation

2.—(1) In these Regulations, unless the context otherwise requires–

"daily personal noise exposure" means the level of daily personal noise exposure of an employee ascertained in accordance with Part I of the Schedule to these Regulations, but taking no account of the effect of any personal ear protector used;

"exposed" means exposed whilst at work, and "exposure" shall be construed accordingly;

"the first action level" means a daily personal noise exposure of 85 dB(A);

"the peak action level" means a level of peak sound pressure of 200 pascals;

"the second action level" means a daily personal noise exposure of 90 dB(A).

(2) In these Regulations, unless the context otherwise requires, any reference to–

(a) an employer includes a reference to a self-employed person and any duty imposed by these Regulations on an employer in respect of his employees shall extend to a self-employed person in respect of himself;

(b) an employee includes a reference to a self-employed person;

and where any duty is placed by these Regulations on an employer in respect of his employees, that employer shall, so far as is reasonably practicable, be under a like duty in respect of any other person at work who may be affected by the work carried on by him.

(3) Duties under these Regulations imposed upon an employer shall also be imposed upon the manager of a mine or a quarry (within in either case the meaning of section 180 of the Mines and Quarries Act 1954(**a**)) in so far as those duties relate to the mine or quarry or part of the quarry of which he is the manager and to matters under his control.

(4) Unless the context otherwise requires, any reference in these Regulations to–

(a) a numbered regulation is a reference to the regulation in these Regulations so numbered; and

(b) a numbered paragraph is a reference to the paragraph so numbered in the regulation in which the reference appears.

Disapplication of duties

3. The duties imposed by these Regulations shall not extend to–

(a) the master or crew of a sea-going ship or to the employer of such persons, in relation to the normal ship-board activities of a ship's crew under the direction of the master; or

(b) the crew of any aircraft or hovercraft which is moving under its own power or any other person on board any such aircraft or hovercraft who is at work in connection with its operation.

Assessment of exposure

4.—(1) Every employer shall, when any of his employees is likely to be exposed to the

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(**a**) 1954 c.70; section 180 was modified by S.I. 1974/2013, Schedule 2, Part I, paragraph 3.

first action level or above or to the peak action level or above, ensure that a competent person makes a noise assessment which is adequate for the purposes–

(a) of identifying which of his employees are so exposed; and

(b) of providing him with such information with regard to the noise to which those employees may be exposed as will facilitate compliance with his duties under regulations 7, 8, 9 and 11.

(2) The noise assessment required by paragraph (1) shall be reviewed when–

(a) there is reason to suspect that the assessment is no longer valid; or

(b) there has been a significant change in the work to which the assessment relates;

and, where as a result of the review changes in the assessment are required, those changes shall be made.

Assessment records

5. Following any noise assessment made pursuant to regulation 4(1), the employer shall ensure that an adequate record of that assessment, and of any review thereof carried out pursuant to regulation 4(2), is kept until a further noise assessment is made pursuant to regulation 4(1).

Reduction of risk of hearing damage

6. Every employer shall reduce the risk of damage to the hearing of his employees from exposure to noise to the lowest level reasonably practicable.

Reduction of noise exposure

7. Every employer shall, when any of his employees is likely to be exposed to the second action level or above or to the peak action level or above, reduce, so far as is reasonably practicable (other than by the provision of personal ear protectors), the exposure to noise of that employee.

Ear protection

8.—(1) Every employer shall ensure, so far as is practicable, that when any of his employees is likely to be exposed to the first action level or above in circumstances where the daily personal noise exposure of that employee is likely to be less than 90 dB(A), that employee is provided, at his request, with suitable and efficient personal ear protectors.

(2) Every employer shall ensure, so far as is practicable, that when any of his employees is likely to be exposed to the second action level or above or to the peak action level or above, that employee is provided with suitable personal ear protectors which, when properly worn, can reasonably be expected to keep the risk of damage to that employee's hearing to below that arising from exposure to the second action level or, as the case may be, to the peak action level.

Ear protection zones

9.—(1) Every employer shall, in respect of any premises under his control, ensure, so far as is reasonably practicable, that–

(a) each ear protection zone is demarcated and identified by means of the sign specified in paragraph A.3.3 of Appendix A to Part 1 of BS 5378, which sign shall include such text as indicates–

(i) that it is an ear protection zone, and

(ii) the need for his employees to wear personal ear protectors whilst in any such zone; and

(b) none of his employees enters any such zone unless that employee is wearing personal ear protectors.

(2) In this regulation, "ear protection zone" means any part of the premises referred to in paragraph (1) where any employee is likely to be exposed to the second action level or

above or to the peak action level or above, and "Part 1 of BS 5378" has the same meaning as in regulation 2(1) of the Safety Signs Regulations 1980(**a**).

Maintenance and use of equipment

10.—(1) Every employer shall–

(a) ensure, so far as is practicable, that anything provided by him to or for the benefit of an employee in compliance with his duties under these Regulations (other than personal ear protectors provided pursuant to regulation 8(1)) is fully and properly used; and

(b) ensure, so far as is practicable, that anything provided by him in compliance with his duties under these Regulations is maintained in an efficient state, in efficient working order and in good repair.

(2) Every employee shall, so far as is practicable, fully and properly use personal ear protectors when they are provided by his employer pursuant to regulation 8(2) and any other protective measures provided by his employer in compliance with his duties under these Regulations; and, if the employee discovers any defect therein, he shall report it forthwith to his employer.

Provision of information to employees

11. Every employer shall, in respect of any premises under his control, provide each of his employees who is likely to be exposed to the first action level or above or to the peak action level or above with adequate information, instruction and training on–

(a) the risk of damage to that employee's hearing that such exposure may cause;

(b) what steps that employee can take to minimise that risk;

(c) the steps that that employee must take in order to obtain the personal ear protectors referred to in regulation 8(1); and

(d) that employee's obligations under these Regulations.

Modification of duties of manufacturers etc. of articles for use at work and articles of fairground equipment

12. In the case of articles for use at work or articles of fairground equipment, section 6 of the Health and Safety at Work etc. Act 1974(**b**) (which imposes general duties on manufacturers etc. as regards articles for use at work, substances and articles of fairground equipment) shall be modified so that any duty imposed on any person by subsection (1) of that section shall include a duty to ensure that, where any such article as is referred to therein is likely to cause any employee to be exposed to the first action level or above or to the peak action level or above, adequate information is provided concerning the noise likely to be generated by that article.

Exemptions

13.—(1) Subject to paragraph (2), the Health and Safety Executive may, by a certificate in writing, exempt any employer from–

(a) the requirement in regulation 7, where the daily personal noise exposure of the relevant employee, averaged over a week and ascertained in accordance with Part II of the Schedule to these Regulations, is below 90 dB(A) and there are adequate arrangements for ensuring that that average will not be exceeded; or

(b) the requirement in regulation 8(2), where–

(i) the daily personal noise exposure of the relevant employee, averaged over a week and ascertained in accordance with Part II of the Schedule to these Regulations, is below 90 dB(A) and there are adequate arrangements for ensuring that that average will not be exceeded,

(ii) the full and proper use of the personal ear protectors referred to in that

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(**a**) S.I. 1980/1471.
(**b**) 1974 c.37; section 6 was amended by the Consumer Protection Act 1987 (c.43), Schedule 3, paragraph 1.

paragraph would be likely to cause risks to the health or safety of the user, or

(iii) (subject to the use of personal ear protectors affording the highest degree of personal protection which it is reasonably practicable to achieve in the circumstances) compliance with that requirement is not reasonably practicable;

and any such exemption may be granted subject to conditions and to a limit of time and may be revoked at any time by a certificate in writing.

(2) The Executive shall not grant any such exemption unless, having regard to the circumstances of the case and in particular to–

(a) the conditions, if any, which it proposes to attach to the exemption; and

(b) any other requirements imposed by or under any enactments which apply to the case,

it is satisfied that the health and safety of persons who are likely to be affected by the exemption will not be prejudiced in consequence of it.

Modifications relating to the Ministry of Defence etc.

14.—(1) In this regulation, any reference to–

(a) "visiting forces" is a reference to visiting forces within the meaning of any provision of Part I of the Visiting Forces Act 1952(**a**); and

(b) "headquarters or organisation" is a reference to a headquarters or organisation designated for the purposes of the International Headquarters and Defence Organisations Act 1964(**b**).

(2) The Secretary of State for Defence may, in the interests of national security, by a certificate in writing exempt–

(a) Her Majesty's Forces;

(b) visiting forces; or

(c) any member of a visiting force working in or attached to any headquarters or organisation,

from any requirement imposed by these Regulations and any such exemption may be granted subject to conditions and to a limit of time and may be revoked at any time by a certificate in writing, except that, before any such exemption is granted, the Secretary of State for Defence must be satisfied that suitable arrangements have been made for the assessment of the health risks created by the work involving exposure to noise and for adequately controlling the exposure to noise of persons to whom the exemption relates.

Revocation

15. Regulation 44 of the Woodworking Machines Regulations 1974(**c**) is hereby revoked.

Signed by order of the Secretary of State.

Patrick Nicholls
Parliamentary Under Secretary of State,
Department of Employment

2nd October 1989

(**a**) 1952 c.67.
(**b**) 1964 c.5.
(**c**) S.I. 1974/903, to which there are amendments not relevant to these Regulations.

Regulations 2(1) and 13(1)

THE SCHEDULE

PART I

DAILY PERSONAL NOISE EXPOSURE OF EMPLOYEES

The daily personal noise exposure of an employee ($L_{EP,d}$) is expressed in dB(A) and is ascertained using the formula:

$$L_{EP,d} = 10 \log_{10} \left\{ \frac{1}{T_0} \int_0^{T_e} \left[\frac{p_A(t)}{p_0} \right]^2 dt \right\}$$

where–

T_e = the duration of the person's personal exposure to sound;

T_0 = 8 hours = 28,800 seconds;

p_0 = 20 μPa; and

$P_A(t)$ = the time-varying value of A—weighted instantaneous sound pressure in pascals in the undisturbed field in air at atmospheric pressure to which the person is exposed (in the locations occupied during the day), or the pressure of the disturbed field adjacent to the person's head adjusted to provide a notional equivalent undisturbed field pressure.

PART II

WEEKLY AVERAGE OF DAILY PERSONAL NOISE EXPOSURE OF EMPLOYEES

The weekly average of an employee's daily personal noise exposure ($L_{EP,w}$) is expressed in dB(A) and is ascerrtained using the formula:

$$L_{EP,w} = 10 \log_{10} \left[\frac{1}{5} \sum_{k=1}^{k=m} 10^{0.1(L_{EP,d})_k} \right]$$

where–

$(L_{EP,d})_k$ = the values of $L_{EP,d}$ for each of the m working days in the week being considered.

EXPLANATORY NOTE

(This note is not part of the Regulations)

These Regulations give effect as respects Great Britain to provisions of Council Directive 86/188/EEC (OJ No. L137, 24.5.86, p.28) on the protection of workers from the risks related to exposure to noise at work.

The Regulations–

(a) impose requirements on employers with respect to the making and review of noise assessments (*regulation 4*);

(b) impose requirements on employers with respect to the keeping of records of noise assessments and reviews thereof (*regulation 5*);

(c) impose requirements on employers with respect to the reduction of risk of damage to the hearing of their employees from exposure to noise (*regulation 6*);

(d) impose requirements on employers with respect to the reduction of exposure to noise of their employees (*regulation 7*);

(e) impose requirements on employers with respect to the provision to their employees of personal ear protectors (*regulation 8*);

(f) impose requirements on employers with respect to the marking of, and entry of their employees into, ear protection zones (*regulation 9*);

(g) impose requirements on employers and employees with respect to the use and maintenance of equipment provided by employers pursuant to the provisions of the Regulations (*regulation 10*);

(h) impose requirements on employers with respect to the provision of information, instruction and training to such of their employees as are likely to be exposed to specified noise levels (*regulation 11*);

(i) modify section 6(1) of the Health and Safety at Work etc. Act 1974 (c.37) (general duties of designers, etc., of articles for use at work and articles of fairground equipment) so that any duty imposed by that subsection includes in specified circumstances a duty to provide certain information relating to noise generation (*regulation 12*);

(j) provide for the issue of certificates of exemption by the Health and Safety Executive and the Secretary of State for Defence (*regulations 13 and 14 respectively*); and

(k) revoke regulation 44 of the Woodworking Machines Regulations 1974 (S.I. 1974/903) (*regulation 15*).

The duties imposed by the Regulations do not (in the circumstances specified in regulation 3(a)) extend to the masters and crews of sea-going ships or to their employers; nor do they (in the circumstances specified in regulation 3(b)) extend to the crews of aircraft and hovercraft or to other persons on board such craft.

FOR S.R.S. EYES ONLY.

THIS SPECIFICATION NUMBER COVERS
CODE __RUBBER EV.
WHICH IS ALSO KNOWN AS :-

THIS SPECIFICATION IS CALLED UP IN SPECIFICATIONS AND MANUFACTURING METHODS USED FOR FOREIGN CONTRACTS AND IT MUST THEREFORE NOT BE DIVULGED TO ANY DEPARTMENT/ PERSON OTHER THAN S.R.S. EMPLOYEES WITHOUT MANAGEMENT APPROVAL.

IF APPROVAL IS GIVEN FOR ISSUE TO AN EXTERNAL ORGANISATION THIS COVER SHEET IS TO BE DELETED.

PRINT ROOM
-6 FEB 1992
R.O. SUMMERFIELD

ISSUE ~~A~~ B

CONTRACTOR:- IMPERIAL METAL INDUSTRIES LTD. KIDDERMINSTER, WORCESTERSHIRE.	SERVICE LETTER

TITLE:- EPDM RUBBER SHEET AND SLAB GRADE CL7225.	COVER SHEET	SPECIFICATION No:- IMI/SRS/231.

PROJECT :- General

SUBJECT :- EPDM Rubber Sheet and Slab Grade CL 7225

APPROVED BY :- [signature] DATE :- 24.8.81

(ON BEHALF OF DESIGN AUTHORITY)

SHT.	ISSUE	SHT.	ISSUE	SHT.	ISSUE
7	E				
6	E				
5	~~B C D~~ E				
4	~~A B C D~~ E				
3	~~A~~ B ~~C D~~ E				
2	~~A B C D E~~ F				
1	SEE BELOW.				

... BY HEAD OF MATERIALS
... DEPARTMENT
... AIRCRAFT ESTABLISHMENT
...
Reference No: RAE(F)MS1/IMI/NMI
Date: 21 NOV 84
Signed: [signature]

THIS SPECIFICATION COMPRISES ..7...... SHEETS. ITS ISSUE IS KNOWN BY THE ISSUE OF SHEET 1 (BELOW) BUT THE ISSUE OF ALL OTHER SHEETS IS STATED ABOVE.

MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE
									SA 1762	C	6.3.85
						SA 2561	F	17.7.89	SA 1592	B	20.4.84
						SA 1979	E	14.7.86	FROZEN BY IMI		
						SA 1787	D	15.8.85	1st Issue	A	21.7.81

CONTRACTOR:- IMI SUMMERFIELD.
KIDDERMINSTER, WORCESTERSHIRE.

SERVICE LETTER

COMPILED BY	TITLE :-	SHEET	SPECIFICATION No :-
KJS	EPDM Rubber Sheet and Slab Grade CL 7225	1 OF 7 SHTS	IMI/SRS/231

1. Scope

1.1 This specification refers to a filled rubber based on ethylene propylene diene monomer (EPDM) suitable for use as a rocket motor body lining material.

2. Description

2.1 The rubber is a dark grey material supplied in sheet or slab form. Its surface shall not be treated with any release agents.

3. Related Document

3.1 BS 903 Methods of testing vulcanised rubber.

4. Composition

4.1 The rubber mix shall consist only of the ingredients given in the parts by weight indicated below. Proposed changes of ingredient supplier or ingredient quality shall be submitted to the Design Authority for consideration before manufacture.

4.2 Constituent	Parts by Weight	Supplier	Grade
EPDM	97 $\pm$ 2	Uniroyal via Croxton & Garry Ltd.	Royalene 501
Chloro-sulphonated polyethylene	3.00 $\pm$ 0.75	Du Pont (UK) Ltd	Hypalon 40
Silica	40 $\pm$ 2	ID Chemicals Ltd	Ultrasil VN-2
Zinc oxide	5.0 $\pm$ 0.5	Durham Raw Materials	Zinc Oxide R108
Polyethylene glycol	3.0 $\pm$ 0.25	Union Carbide Ltd	Carbowax 6000
Dipentamethylene thiuram tetra-sulphide	2.5 $\pm$ 0.25	Robinson Bros Ltd	Robac P-25
Coumarone resin	10.0 $\pm$ 0.5	Anchor Chemical Co. Ltd.	Pale liquid Coumarone Resin
Stearic acid	1.00 $\pm$ 0.25	Mead, King Robinson	Hydrodest or P/1655
Zinc diethyl-dithiocarbamate	0.50 $\pm$ 0.10	VULNAX Limited	Vulcafor ZDC
Chopped Conex Fibre	10.0 $\pm$ 0.5	See Section 4.5	-
Blythe Black	2.0 $\pm$ 0.25	Blythe Pigments	-

4.3 The EPDM shall have a relative density of 0.860 $\pm$ 0.005 at 20°C.

4.4 The silica shall meet the following requirements:-

Surface area (m^2/g)	110-150
Silica content (%)	90 min
Moisture content (%)	4.0 - 7.0
Loss on ignition of dried sample at 900°C (%)	4.5 - 7.0
pH of aqueous extract	5.5 - 7.5

4.5 The chopped Conex fibre shall be obtained from carded Conex fibre as follows:-

4.5.1 Carded Conex Fibre

a) Supplier:- A. Waxman (Fibres) Limited., Grove Mills, Elland, Yorks HX5 9DX.

b) Material:- Teijin Conex fibre 2 Den x 51 or 76 mm; carded in a continuous band suitable for feeding into cutting machinery.

c) Packing:- Cardboard cartons containing approximately 17 kg of fibre each.

NB On receipt the fibre in the containers is not to be disturbed as this would complicate the next operation.

4.5.2 Chopped Conex Fibre

a) Carded Conex fibre together with one 700 x 900 mm (approx) polythene bag per 2 kg of fibre to be sent, free issue, by IMI(S) to J.J. & M.D. Knight, Park Works, Kirby Gate, Melton Mowbray, Leics., LE14 2DU.

b) Associated order to state:-

(i) Chop Conex fibre supplied to 5 mm length.

(ii) Chopping machine to be set to 5 mm nominal gap.

(iii) Care shall be taken to ensure reasonable freedom from contamination.

(iv) Chopping machine shall be hand fed to ensure good dispersion.

(v) After chopping material shall be loosely packed in the bags provided.

(vi) When completion advised, IMI(S) will provide transport for collection.

N.B. IMI(S) road transport is recommended due to the large volume of fibre per kg, particularly when chopped.

4.6 The zinc oxide shall meet the following requirements:-

Retained on B.S. No. 120 sieve	0.004% maximum
Retained on B.S. No. 240 sieve	0.03% maximum
Zinc oxide content	99.5% minimum
Water content	0.5% maximum

4.7 The stearic acid shall have an iodine value of 10 maximum.

4.8 The Coumarone resin shall meet the following requirements:-

Acidity (expressed as H_2SO_4)	0.1% maximum
Ash content	0.1% maximum

5. Batch size

5.1 The rubber shall be compounded in lots of approximately 30 kg which will be referred to in this specification as the compounded mix.

5.2 Up to 6 compounded mixes, depending on requirements, may be blended to make a batch and will be referred to in this specification as the blended batch.

6. Test Requirements

6.1 Test samples

6.1.1 From each compounded mix a small rubber sheet, or button, nominally 6.5 mm thick, shall be prepared for testing by press moulding using a cure cycle of 60 $\pm$ 5 min at 150$\pm$5°C.

6.1.2 From each blended batch, a sheet, nominally 2 mm thick, shall be prepared for testing by press moulding using a cure cycle of 60$\pm$5 min at 150$\pm$5°C. If more than one layer of material is used then each layer shall be placed in the mould with calendering grains parallel. The direction of calendering grain shall be marked on the moulding.

6.2 Testing - Unvulcanised Rubber

6.2.1 From each blended batch unvulcanised rubber shall be checked for viscosity. Using the Monsanto Rheometer Model 100 the limits given in paragraph 6.2.2. apply.

6.2.2 Testing at 150°C using microdies and with an oscillation angle of $\pm$ 3° shall give a minimum torque figure of less than 25 scale units.

6.3 Testing - Vulcanised Rubber

6.3.1 Each compounded mix shall be checked for Test Nos. 3 & 4 below on test pieces prepared in paragraph 6.1.1.

6.3.2 Each blended batch shall be checked for Test Nos. 1, 2, 3, 4 & 5 below on test pieces prepared in paragraph 6.1.2.

Test No.	Test	Test Parameters	Test Method
1	Tensile strength (MN/m^2) in direction of calendering grain		BS 903 Part A2
	a) at maximum	6.8 min	
	b) at break	4.5 min	
2	Elongation at break (%) in direction of calendering grain	120 min	BS 903 Part A2
3	Specific gravity	1.10$\pm$0.10	BS 903 Part A1
4	Hardness (IRHD degrees)	85$\pm$5	BS 903 Part A26
5	pH of water extract: Standard method	8.0$\pm$2.0	BS 903 Part B19
	Alternative method	6.5$\pm$1.5	Annex A

7. Processing and Delivery Requirements

7.1 The manufacturer is at liberty to choose the manufacturing method and to agree with the Design Authority the acceptability of the material produced by that method. Once agreement has been reached no changes are to be made to that method without the approval of the Design Authority.

7.2 In order to avoid visible fibrous strings in the finished product (resulting from inadequate dispersion of the Conex fibre) it is necessary to process the material in several stages.

Stage 1 involves mixing with the omission of curing agents and accelerators followed by a maturing time of about 1 day.

Stage 2 involves softening on a cracker mill followed by cross-blending in an internal mixer.

Stage 3 involves one of three alternatives.

either a) rough calendering to a thickness of less than 1 mm and then removing by hand any fibrous strings visible from both sides of the sheet,

or b) passing repeatedly through a mill set with a gap of approximately 0.5 mm until the fibrous strings have dispersed,

or c) passing through a calender set at approximately 0.3 mm, allowing a maturing period of approximately one day, softening on a cracker mill and repassing through the calender.

Stage 4 involves mixing with the curing agents and accelerators followed by sheeting out for moulding slab or calendering for sheet as required.

7.3 a) Moulding slab shall be homogeneous in composition and free from visible foreign and fibrous strings.

b) Calendered sheet shall

i) be free from obvious foreign matter and blisters,

ii) have limited pitting, seams and laminations in accordance with the following qualifications: Individual defects of the above nature, not exceeding 15 sq. mm in area, which do not reduce the thickness to less than 75% of the minimum thickness specified on the drawing or contract, are permissible, provided that such defects are at least 75 mm apart. There shall not be more than five such defects in a one metre length of 660 mm wide sheet,

iii) be substantially free from fibrous strings and/or their associated splits.

iv) be substanially free from pin-holes in excess of 1.0 mm diameter,

v) have limited pin-holes up to 1.0 mm diameter: provided that they are at least 20 mm apart up to 10 such defects are permissible in a one metre length of 660 mm wide sheet.

c) On receipt inspection of calendered sheet shall be carried out by the user passing it over an illuminated table in a dark room. The positions of

i) foreign matter and blisters

ii) pitting seams and laminations in excess of the permissible limit in 7.3 (b) (ii),

iii) fibrous strings and/or their associated splits.

iv) pin-holes in excess of 1.0 mm diameter,

v) pin-holes up to 1.0 mm diameter in excess of the permissible limit in 7.3 (b) (v).

shall be clearly marked and recorded on a report sheet.

7.4 Each blended batch of material delivered must comply to any dimensions required in the contract. Interleaving materials, such as polythene, may be used to prevent stiction.

7.5 Each blended batch is to be clearly identified with its batch number and thickness.

7.6 The manufacturer shall supply a release note with each blended batch of material supplied.

Annex A

Room Temperature Extraction Method for the Determination of the pH of Vulcanised Rubber

1. Apparatus

a) The extraction apparatus shall consist of a borosilicate flat bottom glass flask, 250 or 500 ml, to the top of which shall be fitted a guard tube with a suitable reagent for the exclusion of carbon dioxide and atmospheric impurities.

b) Magnetic stirrer

2. Procedure

Clean the surface of the sample with a cotton wool pad, moistened with distilled water, to remove contamination, and then dry between filter papers. Cut the sample into cubes with sides of about 3 mm or (when thhe tickness is less than 3 mm) into 3 mm squares.

To prepare the water extract, weigh 5-15 g of the prepared sample into the flask and add to the test portion 10 times its weight of freshly distilled deionised water. Fit the guard tube and stir for 1.5 $\pm$ 0.1 hours at 25 $\pm$ 10°C.

The pH of the liquor shall be determined within thrity minutes of the completion of the extraction.

FOR S.R.S. EYES ONLY.

THIS SPECIFICATION NUMBER COVERS

CODE RUBBER HC.

WHICH IS ALSO KNOWN AS :-

HYPALON CL 8980 SHEET.

THIS SPECIFICATION IS CALLED UP IN SPECIFICATIONS AND MANUFACTURING METHODS USED FOR FORIEGN CONTRACTS AND IT MUST THEREFORE NOT BE DIVULGED TO ANY DEPARTMENT/ PERSON OTHER THAN S.R.S. EMPLOYEES WITHOUT MANAGEMENT APPROVAL.

IF APPROVAL IS GIVEN FOR ISSUE TO AN EXTERNAL ORGANISATION THIS COVER SHEET IS TO BE DELETED.

R.O. SUMMERFIELD
SPECIAL COPY
2 FEB 1995
WILL NOT BE UPDATED

THIS MATERIAL IS "AS APPROVED UNDER MQAD/ AFS 1385".

ISSUE Ø~~E~~F.

CONTRACTOR:- IMPERIAL METAL INDUSTRIES LTD. KIDDERMINSTER, WORCESTERSHIRE.		SERVICE LETTER
TITLE:- HYPALON CL 8980 RUBBER SHEET & SLAB.	COVER SHEET	SPECIFICATION No:- IMI/SRS/41

USED ON

PROJECT :- General

SUBJECT :- Hypalon CL 8980 Sheet and Slab

APPROVED BY :- [signature] DATE :- 11.6.86
(ON BEHALF OF DESIGN AUTHORITY)

APPROVED BY :- [signature] DATE :- 12.6.86
(ON BEHALF OF QUALITY ASSURANCE)

SHT.	ISSUE	SHT.	ISSUE	SHT.	ISSUE
6	G				
5	G				
4	G				
3	G				
2	G				
1	SEE BELOW.				

THIS SPECIFICATION COMPRISES ....6...... SHEETS. ITS ISSUE IS KNOWN BY THE ISSUE OF SHEET 1 (BELOW) BUT THE ISSUE OF ALL OTHER SHEETS IS STATED ABOVE.

MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE
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CONTRACTOR :- IMI SUMMERFIELD.
KIDDERMINSTER, WORCESTERSHIRE.

SERVICE LETT[illegible]

COMPILED BY [signature]

TITLE :- Hypalon CL 8980 Sheet and Slab

SHEET 1 OF 6 SHTS

SPECIFICATION No :- IMI/SRS/41

+ COVER.

1. Scope

This specification refers to a filled chlorosulphonated polyethylene rubber suitable for the fabrication of moulded components. The rubber may be supplied in either slab form or calendered sheet. The material as cured in accordance with an approved method is suitable for use in contact with cast double base propellant.

2. Description

The uncured rubber is a dark brown material free from obvious foreign matter. The surface of calendered sheets or slabs is not to be treated with any release agents. Polythene sheet may be used during packing and transportation to prevent stiction between sheets and/or slab.

3. Related Documents

a) Reference is made herein to:-

i) British Standard 903, Part A1 , Part A2 , Part B19 , Part B13. Methods for testing vulcanised rubber.

ii) Specification TS10102 Iron oxide

iii) Specification TS10103 Magnesium oxide

iv) Du Pont Sales Specification A 52670 Issue 7 for Hypalon 40

v) Robinson Brothers Ltd. Technical Bulletin 171161 for Robac Thiuram P25

4. Composition

a) The rubber mix shall consist only of the ingredients given on the next page, in the proportions by weight indicated:-

Constituent	Parts by weight	Supplier	Grade	Specification
Unvulcanised chloro-sulphonated polyethylene rubber	100 ± 2	Du Pont (UK) Ltd.	Hypalon 40	Du Pont Sales specification A 52670 issue 7 1970
Magnesium oxide	10 ± 0.5	Summerfield Research Station	Maglite 'D' (Croxton & Garry)	TS10103
Dipenta-methylene thiuram tetrasulphide	2 ± 0.025	Robinson Bros. Ltd.	Thiuram P25	Robac Thiuram P25 Technical Bulletin 171161
Ferric Oxide	320 ± 3	Summerfield Research Station	Bayer Chemical Co. Grade GR720 (Hawleys Ltd)	TS10102

b) The unvulcanised chlorosulphonated polyethylene rubber (Hypalon 40) will comply with the requirements of the agreed purchasing specification. Du Pont Sales Specification A52670 issue 7 1970.

c) The dipentamethylene thiuram tetrasulphide (Thiuram P25) will comply with the requirements of the agreed purchasing specification. Robac Thiuram P25 Technical Bulletin 171161.

d) The ferric oxide shall comply with the requirements of specification TS10102.

e) The magnesium oxide shall comply with the requirements of specification TS10103.

f) The supplier of each constituent will issue a release note with each delivery stating that the material complies with the standard laid down in the agreed purchasing specification. The rubber manufacturer will report any deviation contained in the release note from the purchasing specification to the Design Authority before proceeding with his process. He will not change the above approved suppliers for the constituents without the consent of the Design Authority.

5. Batch Size

a) The compounded rubber will be compounded and mixed in 35 kg (75 lb) batches and will be referred to hereafter as the compounded mix.

b) A maximum of six compounded mixes will be blended together to make a batch and will be referred to in this specification as a blended batch. One or more batches may be delivered as a consignment.

c) Where a single compound mix is required for an order, this will be treated as a blended batch for testing purposes.

d) A consignment can consist of either unvulcanised slab or unvulcanised calendered sheet of varying thickness.

6. Test Requirements

a) Test samples

i) From each compounded mix a small piece, nominally 4.75mm (0.1875 in) thick will be prepared by press moulding. The piece will be vulcanised for 30 ± 1 min at 153 ± 4°C

ii) From each blended batch a sheet nominally 2mm (0.08 in) thick will be prepared for testing by press moulding. The sheet will be vulcanised for 30 ± 1 min at 153 ± 4°C.

b) Testing - unvulcanised rubber

i) If the delivered consignment is to consist of blended batches of slab, then each blended batch will be checked for Wallace plasticity. If a consignment of calendered sheet is required, then the Wallace plasticity tests can be omitted.

ii) The Wallace plasticity is to be determined as described in Appendix 1. This plasticity figure must lie on or below the figure calculated from the following equations:-

Calculated plasticity = 550 T - 7.0 (where T is the plied or slab sample thickness in inches)

or = 21.6 T - 7.0 (where T is the plied or slab sample thickness in millimetres)

c) Testing - vulcanised rubber

i) Test pieces for tensile testing, ash content, relative density and pH of aqueous extract shall be cut from the vulcanised sheet prepared in sub-paragraph 6 a) ii).

ii) The following table gives test requirements:-

Test	Test Parameters	Test Method
Tensile strength psi MN/m^2	1,450 min 10 min	BS 903 Part A2
Elongation %	50 min	BS 903 Part A2
Relative Density	2.79-2.92 Mg/m^3	BS 903 Part A1 Method A
Ash Content % (at 600 ± 25°C)	75.0-78.5	BS903 Part B13 Section 2
pH of water extract	5.0-8.0	BS 903 Part B19

d) <u>Frequency of testing</u>

i) Each compounded mix will be tested for relative density on test pieces taken from the vulcanised rubber prepared in sub-paragraph 6 a) i).

ii) Each blended batch will be tested for Wallace plasticity on the unvulcanised rubber as defined in paragraph 6 b) i) and to the requirements of sub-paragraph 6 c) ii).

7. <u>Processing and Delivery Requirements</u>

a) The material shall be in the form of sheet or slab as specified in the contract or order. The material shall be homogeneous in composition and free from foreign matter, blisters, lumps, holes and cracks.

Additionally for sheet material the incidence of delamination, pitting, seams, or other defects shall not exceed a total of 5 such defects per m^2, and not more than one such defect shall be present per 50 cm^2 of the area of any sheet. The lateral dimensions of such defects shall not exceed 7.0 x 2.0mm and no defect shall have a depth such that the thickness of the sheet is reduced to less than 75% of the minimum thickness specified in the relevant drawing or in the contract or order.

b) Each consignment of material delivered must comply to any dimensions required in the contract.

c) Each delivery of sheet or slab is to be clearly identified with the consignment number and thicknesses. The direction of calendering will be marked on each slab.

d) The manufacturer will supply a certificate of test results with each consignment of material supplied.

APPENDIX 1

Wallace Plasticity Test

This is carried out in accordance with the 'Wallace Rapid Plastimeter Operating Instructions, Ref. P1, issued January, 1961'.

The upper platen used is 5.00mm (0.20 in) diameter giving an area of 19.6 sq mm (0.031 sq in).

The slab sample is sliced to a thickness of 3.15 - 3.30mm (0.122 - 0.130 in).

The sheet sample is plied up, where necessary to give a thickness which must lie between 1.75mm (0.070 in) and 3.30mm (0.130 in).

The slab slices or sheet samples are cut into discs 12.7mm (0.50 in) diameter using the standard cutter supplied with the plastimeter.

The final sample thickness is to be accurately measured (this measurement is T in the equations in the calculation is sub-paragraph 6 b) iii). This thickness and the number of plies where applicable must be recorded.

Six determinations are made for a particular slab or sheet sample. Marked eccentricity of the upper platen plunger in relation to the test piece gives a poor result. These poor results are rejected and another determination is made to replace the reject figure.

The arithmetic mean of the values is the Wallace Plasticity of the sample.

FOR S.R.S. EYES ONLY.

THIS SPECIFICATION NUMBER COVERS

CODE RUBBER HA

WHICH IS ALSO KNOWN AS :-

HYPALON CL 2759 SHEET AND SLAB

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AFS 1384

ISSUE	CONTRACTOR:- IMPERIAL METAL INDUSTRIES LTD. KIDDERMINSTER, WORCESTERSHIRE.	SERVICE LETTE
TITLE:- CHLOROSULPHONATED POLYETHYLENE RUBBER HYPALON CL 2759 CALENDERED SHEET AND SLAB	COVER SHEET	SPECIFICATION No:- IMI/SRS/ 104

USED ON

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PROJECT :- General

SUBJECT :- Hypalon CL 2759 Sheet and Slab

APPROVED BY :- H. Buckler DATE :- 11.6.86
(ON BEHALF OF DESIGN AUTHORITY)

APPROVED BY :- A. Noakes DATE :- 12-6-86
(ON BEHALF OF QUALITY ASSURANCE)

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SHT:	ISSUE	SHT:	ISSUE	SHT:	ISSUE

THIS SPECIFICATION COMPRISES ....9.../...SHEETS. ITS ISSUE IS KNOWN BY THE ISSUE OF SHEET .1 (BELOW) BUT THE ISSUE OF ALL OTHER SHEETS IS STATED ABOVE.

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									SA 2684	C	24.4.9
									SA 1948	B	12.6.8
MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DATE	MOD. No.	ISSUE	DAT

CONTRACTOR:- IMI SUMMERFIELD.
KIDDERMINSTER, WORCESTERSHIRE.

SERVICE LETT

COMPILED BY
DF

TITLE :-
Chlorosulphonated polyethylene rubber
Hypalon CL 2759 Calendered sheet and Slab

SHEET 1 OF 9 SHTS + COVER.

SPECIFICATION No :- IMI/SRS/104

4. Composition

4.1 The rubber mix shall consist only of the ingredients given in the proportions by weight indicated.

Table 1

Constituent	Proportion by weight	Supplier	Grade or Specification
Unvulcanised chlorosulphonated polyethylene rubber	100 ± 2	Du Pont (UK) Ltd	Hypalon 20
Natural rubber	7.0 ± 0.5	-	SMR L
Lead Monoxide	40 ± 2	Heubach & Lindgen W Germany or Associated Lead	TS560A
Antimony trioxide	25 ± 1	Cookson Ceramics Ltd Antimony Ltd	BS338
Precipitated silica	60 ± 2	ID Chemicals Ltd	Ultrasil VN2
Iron Oxide, red	6.0 ± 1.0	RO Summerfield	TS10102 (Hawleys Ltd)
Chrome yellow	4.0 ± 0.5	TL Gould Ltd	Chrome yellow 8048
Stabelite resin	2.50 ± 0.25	Hercules Ltd, USA	
Di-benzthiozyl disulphate	0.50 ± 0.05	Vulnax	
Dipentamethylene thiuram tetrasulphide	0.75 ± 0.07	Robinson Bros Ltd	Robac P25

4.2 The unvulcanised chlorosulphonated polyethylene rubber (Hypalon 20) will comply with the requirements of the agreed purchasing specification, Du Pont Sales Specification, latest issue.

4.3 The dipentamethylene thiuram tetrasulphide (Robac P25) will comply with the requirements of the agreed purchasing specification, Robac Thiuram P25 Technical Bulletin 171161.

4.4 Ferric oxide shall comply with the requirements of specification TS10102.

4.5 The lead monoxide shall comply with the requirements of specification TS560A.

4.6 The antimony trioxide shall comply with the requirements of BS338.

4.7 The precipitated silica shall comply with the requirements of:-

	(VN2)	(VN3)
Surface Area	110-150 m^2/g	160-190m^2/g
Silica content as SiO_2 (on dry sample)	90% min	90%
Moisture content (loss at 105°C)	4.0-7.0%	4.0-7.0%
Loss on ignition at 900°C (on dry sample)	4.5-7.0%	4.5%-7.0%
pH of aqueous extract	5.5-7.5	5.5-7.5

VN2 may be used of a direct replacement for VN3 where easier processing of the compound is required.

4.8 The lead monoxide is incorporated into the rubber as a litharge master batch, designated R (NR-1) M85. The composition is as follows:-

Natural Rubber SMR L	15 parts by weight
Lead monoxide	85 parts by weight
Ferric oxide	4.28 parts by weight
Stabelite resin	0.75 parts by weight

4.9 The manufacturer of the compounded mix shall report any proposed changes in the quality, specifications or approved supplier of any of the above constituents. Prior agreement for any change must be obtained from the Design Authority.

5. Batch Sizes

5.1 The compounded rubber will be mill mixed in approximately 27kg lots and will be referred to in this specification as the compounded mix.

5.2 A maximum of six compounded mixes may be blended together to make a batch and will be referred to in this specification as a blended batch.

5.3 The procedure for blending compounded mixes to give the blended batch is described in Appendix 1.

5.4 Where a single compounded mix is required for an order, this will be treated as a blended batch for testing purposes.

1. Scope

1.1 This specification refers to an unvulcanised chlorosulphonated polyethylene rubber compound suitable for the lining of rocket motors and the moulding of rubber components. The rubber will be supplied as callendered sheet or slab and is suitable for use in contact with cast double base and composite propellant when cured in accordance with an approved method.

2. Description

2.1 The rubber is a medium red brown colour, free from obvious foreign matter. The surface of the slab is not to be treated with any release agent. Polythene sheet or release film may be used during packing and transportation to prevent stiction.

3. Related Documents

3.1 Reference is made to:-

a) British Standard 903, part A1, part A2, part A26 part B19 - methods of testing unvulcanised rubber.

b) British Standard 338 - Antimony Trioxide

c) Specification TS560A - Lead monoxide

d) Specification TS10102 - Iron oxide

e) American Society for Testing Materials ASTM D2084-75

f) Rubber Research Institute of Malaya - Natural rubber, grade SMR L

g) Du Pont Sales Specification for Hypalon 20

h) Robinson Brothers Ltd. Technical Bulletin 171161 for Robac Thiuram P25.

6. Test Requirements

Table 2

Part	Material Description	Test Sample Preparation	Testing Schedule	Test Method	Test Parameters
A	Compounded Mix	Unvulcanised sample	Rheometer test	Appendix 2	See App 2 graph
		6.0 mm (nominal) thick test piece vulcanised for 30 ± 1 minute at 153 ± 4°	Relative density	BS903 Part A1	1.73-1.81 Mg/m^3
			Apparent hardness	BS903 Part A26	85 ± 5
B	Blended Batch	Unvulcanised sample	Rheometer test	Appendix 2	See App 2 graph
		6.0 mm (nominal) thick piece vulcanised for 30 ± 1 minute at 153 ± 4°C	Relative density	BS903 Part A1	1.73-1.81 Mg/m^3
			Apparent hardness	BS903 Part A26	85 ± 5
		2mm (nominal) thick sheet vulcanised for 30 ± 1 min at 153 ± 4°C.	Tensile strength	BS903 Part A2	8.0 MN/m^2 min
			Elongation at break	BS903 Part A2	120% minimum
			pH of water extract	BS903 Part B19	5.0-8.0

7. Frequency of Testing

7.1 Each compounded mix will be tested to the requirements of paragraph 6, table 2, part A.

7.2 Each blended batch will be tested to the requirements of paragraph 6, table 2, part B.

8. Visual and Delivery Requirements

8.1 Each blended batch of sheet or slab delivered shall be uniform in colour and free from obvious foreign matter and contamination and shall be homogenous in composition.

8.2 Each batch of sheet shall be further inspected as follows:-

The incidence of delamination, pitting, seams, or other defects shall not exceed a total of 5 such defects per m^2 and not more than one such defect shall be present per 50 cm^2 of the area of any sheet. The lateral dimensions of such defects shall not exceed 7.0 x 2.0mm and no defect shall have a depth such that the thickness of the sheet is reduced to less than 75% of the minimum thickness specified in the relevant drawing or in the contract or order.

8.3 Each blended batch of sheet or slab delivered must comply to any dimensions required in the contract and must be clearly marked with its blended batch number and unless obvious, the direction of calendering is also to be indicated. The blended batch is to be delivered within 4 weeks of mixing.

8.4 The manufacturer will supply a Certificate of Test Results with each delivery of material. The date of mill mixing must be stated.

NOTE: Storage and Life

Unvulcanised Hypalon materials have a limited shelf life therefore they shall be stored in cool conditions of 4 to 8°C. Relifing shall be carried out in accordance with IMI/SRS/50.

Appendix 1

Determination of Wallace Plasticity

1. This is carrried out in accordance with the "Wallace Rapid Plastimeter Operating Instructions, Ref P1, issued January, 1961".

2. The upper platon used is 5.00mm diameter giving an area of 19.6sq.mm

3. The slab sample is sliced to a thickness of 3.15 to 3.30mm. Reject any slices outside these dimensions.

4. The slab slices are cut into discs 12.7mm diameter using the standard cutter supplied with the plastimeter.

5. Six determinations are made for a particular slab sample. The highest and lowest results are rejected.

6. The arithmetic mean of the remaining 4 values is the Wallace Plasticity of the sample.

Note: Marked concentricity of the upper platon plunger in relation to the test piece gives a low result.

Appendix 2

Determination of Rheometer Torque

1. The instrument used shall be the "Monsanto Rheometer-100" equipped with its standard rotor and micro-dies and a 60 minute motor. The dies and rotor shall not be coated with release agent.

2. A sample of unvulcanised rubber shall be cut to a size which gives a small excess of material when the dies are closed upon it.

3. The dies shall be set at a temperature of 150°C and there shall be no pre-heat time. The amplitude of the disc oscillation shall be ± 3° about the centre position.

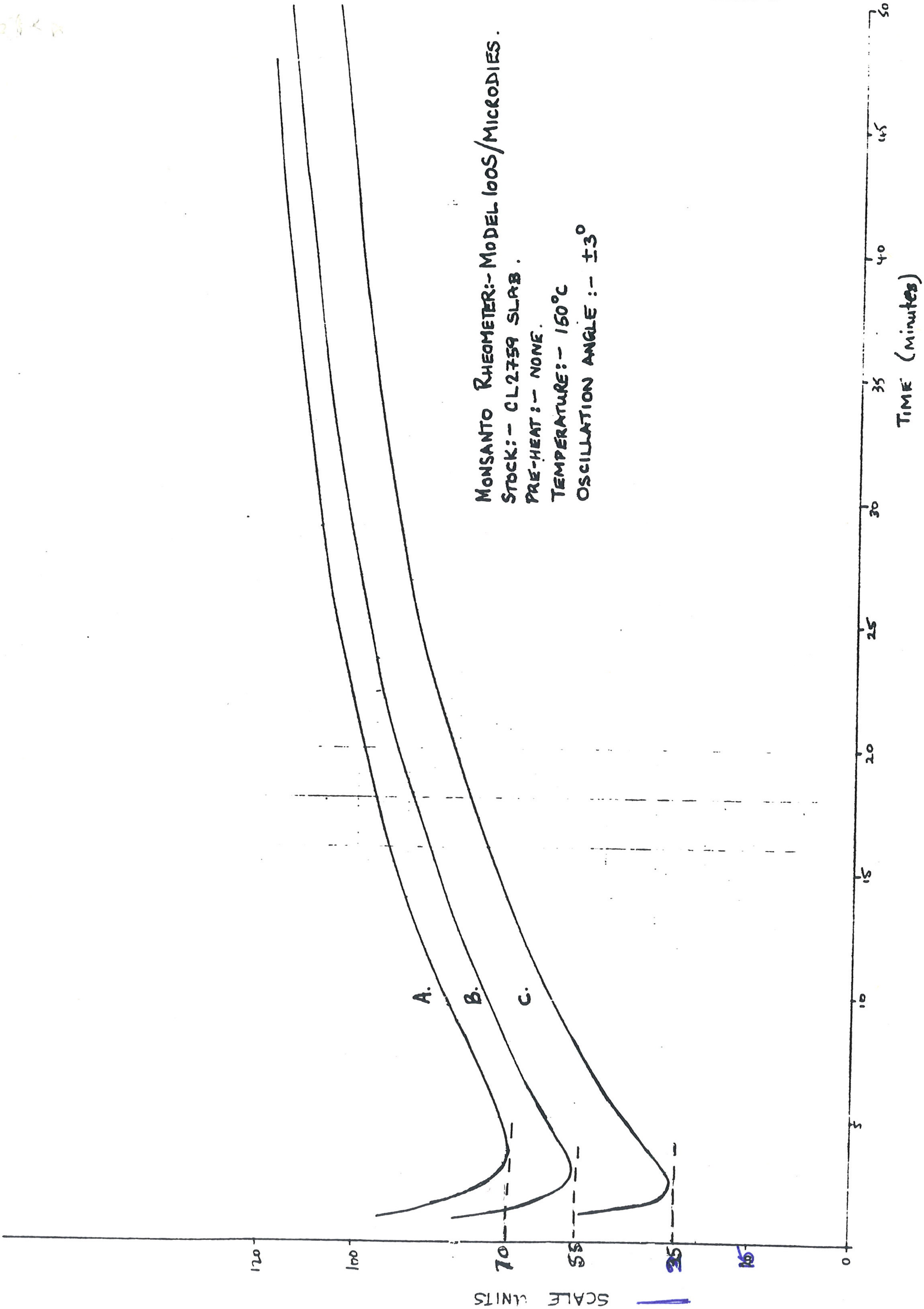
4. In all other respects testing shall be in accordance with ASTM D2084-75.

5. Requirements

5.1 The curve produced by the automatic torque/time print-out recorder shall lie within the limits B and C shown on the attached graph, ie minimum torque between ~~35~~ 25 and 55 scale units. (See Note)

5.2 The Design Authority and customer will be notified immediately if results of the blended batch are above curve B, ie minimum torque above 55 scale units or below curve C ie below ~~35~~ 25 scale units.

NOTE Hypalon raw rubber varies considerably in processibiity. Occasionally a compounded mix will be produced below curve C. This presents no problem in practice since it will be blended off with other compounded mixes to form the batch. If a batch falls below 35 minimum torque units this figure can be raised by stoving.


MONSANTO RHEOMETER:- MODEL 100S/MICRODIES.
STOCK:- CL2759 SLAB.
PRE-HEAT:- NONE.
TEMPERATURE:- 150°C
OSCILLATION ANGLE:- ±3°
A.
B.
C.
TIME (Minutes)
0
5
10
15
20
25
30
35
40
45
50
SCALE UNITS
120
100
70
55
35
15

8980

Constituent	Parts by weight	Supplier	Grade	Specification
Unvulcanised chloro-sulphonated polyethylene rubber	100 ± 2	Du Pont (UK) Ltd.	Hypalon 40	Du Pont Sales specification A 52670 issue 7 1970
Magnesium oxide	10 ± 0.5	Summerfield Research Station	Maglite 'D' (Croxton & Garry)	TS10103
Dipenta-methylene thiuram tetrasulphide	2 ± 0.025	Robinson Bros. Ltd.	Thiuram P25	Robac Thiuram P25 Technical Bulletin 171161
Ferric Oxide	320 ± 3	Summerfield Research Station	Bayer Chemical Co. Grade GR720 (Hawleys Ltd)	TS10102

b) The unvulcanised chlorosulphonated polyethylene rubber (Hypalon 40) will comply with the requirements of the agreed purchasing specification. Du Pont Sales Specification A52670 issue 7 1970.

c) The dipentamethylene thiuram tetrasulphide (Thiuram P25) will comply with the requirements of the agreed purchasing specification. Robac Thiuram P25 Technical Bulletin 171161.

d) The ferric oxide shall comply with the requirements of specification TS10102.

e) The magnesium oxide shall comply with the requirements of specification TS10103.

f) The supplier of each constituent will issue a release note with each delivery stating that the material complies with the standard laid down in the agreed purchasing specification. The rubber manufacturer will report any deviation contained in the release note from the purchasing specification to the Design Authority before proceeding with his process. He will not change the above approved suppliers for the constituents without the consent of the Design Authority.

5. <u>Batch Size</u>

a) The compounded rubber will be compounded and mixed in 35 kg (75 lb) batches and will be referred to hereafter as the compounded mix.

b) A maximum of six compounded mixes will be blended together to make a batch and will be referred to in this specification as a blended batch. One or more batches may be delivered as a consignment.

c) Where a single compound mix is required for an order, this will be treated as a blended batch for testing purposes.

USED ON

PROJECT :- General

APPROVED BY : Harold Butler DATE :- 9.2.87
(ON BEHALF OF DESIGN AUTHORITY)

SHEET	ISSUE	SHEET	ISSUE	SHEET	ISSUE
9	A				
8	~~A~~ B				12 DEC 1989
7	A				
6	A				
5	~~A~~ B				
4	A				
3	~~A~~ C				
2	A				
1	SEE BELOW				

THIS SPECIFICATION COMPRISES 9 SHEETS ITS ISSUE IS KNOWN BY THE ISSUE OF SHEET 1 BELOW BUT THE ISSUE OF ALL OTHER SHEETS IS STATED ABOVE.

MOD: No.	ISSUE	DATE	MOD: No.	ISSUE	DATE	MOD: No.	ISSUE	DATE	MOD: No.	ISSUE	DATE
									SA 2563	C	19.7.89
									SA 2476	B	12.1.89
									FROZEN BY IMI KYNOCH	LIMITED	
									1st Iss	A	9.2.87

CONTRACTOR :— IMI KYNOCH LIMITED.
SUMMERFIELD, KIDDERMINSTER,
WORCESTERSHIRE.

COMPILED BY	TITLE	Sheet 1 Of 9 Sheets	SPECIFICATION
MJC	EPDM Rubber Sheet and Slab CL 7806		IMI/SRS/317

1. Scope

This specification refers to a filled rubber based on ethylene propylene diene monomer (EPDM) suitable for use as a rocket motor body lining material. The use of a fibrous filler imparts anisotropic mechanical properties, particularly to calendered sheet.

2. Description

The rubber is an off-white material supplied in sheet or slab form. Its surface shall not be treated with any release agents.

3. Related Documents

a)	BS 903	: Methods of Testing Rubber
b)	Section 6 of Specification IMI/SRS/123	: Storage Conditions for EPDM CL 7806
c)	UTR 50 of Specification IMI/SRS/50	: User Test Requirement for EPDM CL 7806

4. Composition

The rubber mix shall consist only of the ingredients given below in the parts by weight indicated. Proposed changes of ingredient supplier or ingredient quality shall be submitted to the Design Authority for consideration before manufacture. Ingredient batches shall be identified and traceability maintained through to rubber batches.

Constituent	Parts by Weight	Supplier	Grade	Spec
EPDM	97 ± 2	Uniroyal via Croxton & Garry Ltd, Newport	Royalene 501	App.1, para.1
Chloro-sulphonated polyethylene	3.00 ± 0.75	Du Pont (UK) Ltd., Hemel Hempstead	Hypalon 40	App.1, para.2
Silica	40 ± 2	ID Chemicals Ltd., Runcorn	Ultrasil VN-2	App.1, para.3
Zinc oxide	5.0 ± 0.5	Durham Raw Materials	Zinc Oxide R100	App.1, para.4
Conex	10.0 ± 0.5	Teijin Ltd.,Japan,via A.Waxman(Fibres)Ltd., Elland, Yorks	3 mm x 2DE dry,cut fibre	App.1, para.5
Peroxide	7.6 ± 0.1	Akzo Chemie(UK)Ltd., Hersham	Triganox 29-40B	App.1, para.6
Polybutene	10.0 ± 0.5	Nippon Soda Co.Ltd., Japan,via British Traders & Shippers Ltd., Dagenham	Nisso PB-B.3000	App.1, para.7
Polyethylene Glycol	3.00 ± 0.25	Union Carbide Ltd.	Carbowax 6000	-

5. Batch Size

The rubber shall be compounded in lots of approximately 30 kg which will be referred to in this specification as the compounded mix.

Up to 6 compounded mixes, depending on requirements, may be blended to make a batch and will be referred to in this specification as the blended batch.

6. Processing

a) The manufacturer is at liberty to choose the manufacturing method and to agree with the Design Authority the acceptability of the material produced by that method. Once agreement has been reached no changes are to be made to that method without the approval of the Design Authority.

b) To avoid visible fibrous strings in the finished product, resulting from inadequate dispersion of the fibre, it is necessary to process the material in several stages.

Stage 1 involves compounding premixes with the omission of curing agents followed by a maturing time of at least 1 day.

Stage 2 involves softening on a cracker mill followed by cross-blending on a two-roll mill followed immediately by Stage 3.

Stage 3 involves three passes through a calender set at approximately 0.3mm.

Stage 4 involves mixing with the curing agents.

Stage 5 involves cross-blending and sheeting out by calendering to give the thickness required.

c) Interleaving materials, such as cotton fabric or polythene, must be used as necessary to prevent stiction.

7. Quality Assurance Tests Carried Out by the Supplier

The material shall be tested and inspected as follows:-

Material	State of cure	Test			
		Description	Units	Control Limits	Method
One sample from each compounded mix	Unvulcanised	Minimum Viscosity	Scale units*	30 ± 10	App.2, para.1
	Vulcanised by press moulding for 60±5 min at 150±5°C	Specific gravity	-	1.10 ± 0.10	BS.903, Part A1
		Hardness	°BS	85 + 5 - 10	BS.903, Part A26
One sample from each blended batch	Unvulcanised	Minimum Viscosity	Scale Units*	30 ± 10	App.2, para.1
	Vulcanised by press moulding for 60±5 min at 150±5°C	Specific gravity	-	1.10 ± 0.10	BS.903, Part A1
		Hardness	°BS	85 ± 5	BS.903, Part A26
		Maximum tensile strength in grain direction	MN/m^2	7.0 min	App.2, para.2
		Elongation associated with maximum tensile strength in grain direction	%	30 min	App.2, para.2
		pH (hot method)	-	7.5 ± 1.5	BS.903, Part B19
Each piece of moulding slab	Unvulcanised	Visual inspection	-	App. 2,para.3	
Each calendered roll	Unvulcanised	Visual inspection	-	App. 2,para.4	

* A scale unit is 0.1 Nm

8. Delivery

Each blended batch shall:

a) comply with the dimensions stated on the order,
b) be identified with its grade number, blended batch number and nominal thickness,
c) be supplied with a release note, and,
d) be supplied to the user within 30 days of initial mixing.

9. Storage by the customer

General storage by the customer prior to issue to the user department shall be in accordance with section 6 of Specification IMI/SRS/123.

10. Quality Assurance Tests Carried Out by the Customer

The material shall be tested, inspected and a sample retained in accordance with UTR 50 of Specification IMI/SRS/50.

Appendix 1

Ingredient Specifications

1. EPDM

The Royalene 501 shall have a relative density of 0.860 ± 0.005 at 20°C.

2. Chloro-sulphonated Polyethylene

The Hypalon 40 shall comply with the requirements of the Du Pont Sales Specification.

3. Silica

The VN-2 shall meet the following requirements:-

Surface area (m^2/g)	110-150
Silica content (%)	90 min
Moisture content (%)	4.0-7.0
Loss on ignition of dried sample at 900°C (%)	4.5 - 7.0
pH of aqueous extract	5.5 - 7.5

4. Zinc Oxide

The R108 shall meet the following requirements:-

Retained on BS No. 120 sieve	0.004% maximum
Retained on BS No. 240 sieve	0.03% maximum
Zinc oxide content	99.5% minimum
Water content	0.5% maximum

5. Conex

One sample shall be taken from every 20 kg of 3 mm x 2 DE dry, cut fibre and shall meet the following requirements:-

a) Length

The sample is to be pulled apart by hand. It must be obvious that the fibres are nominally 3 mm in length.

b) Diameter

Some of the sample is to be viewed on a miscroscope at x250 magnification when contained between glass plates. Dark field illumination is to be used. The fibre diameter is to be measured in 5 random positions and shall be 0.016 ± 0.002 mm.

c) Decomposition at 300°C

Some of the sample shall be weighed in a crucible fitted with a lid and placed in a furnace set at 300 ± 25°C for 45 ± 15 minutes. After removing from the furnace there shall be:-

i) no signs of shrinking

ii) charring limited to a ginger colouration

iii) a weight loss of 7 ± 3%

d) Decomposition at 425°C

The same sample in the same crucible again fitted with a lid shall be placed in a furnace set at 425 ± 25°C for 45 ± 5 mins. After removing from the furnace these shall be:-

i) no signs of melting

ii) positive signs of shrinking

iii) positive signs of charring

iv) a weight loss, including that from 5(c)(iii), of 30% max.

6. Peroxide

The Triganox 29-40 B shall meet the following requirements:-

a) Physical properties	:	Off-white powder with 0.59 Mg/m^3 bulk density
b) Active ingredient	:	40 ± 1% of 1.1 di-tertiary butyl peroxide 3.3.5 tri-methyl cyclohexane with molecular weight of 302 and a maximum tertiary butyl hydro peroxide content of 0.5%.
c) Carrier	:	Calcium carbonate and silica mixture. (The ratio of these two ingredients may vary slightly to facilitate satisfactory formulation).

7. Polybutene

The Nisso PB-B.3000 shall meet the following requirements:

a) Physical properties	:	Liquid with viscosity of 200-350 poise at 45°C and SG of 0.87
b) Chemical constitution	:	1.2 polybutadiene with vinyl content 90% minimum, functionality nil and molecular weight 3000 ± 300.

Appendix 2

Quality Assurance Tests Carried Out by the Supplier

1. Minimum Viscosity

150 for
7225

The test shall be carried out using a Monsanto Rheometer Model 100.S set at a temperature of 180°C using micro dies and an oscillation angle of ±3°. The lowest point on the resulting cure curve is the minimum viscosity.

2. Tensile Strength and Elongation

If more than one layer of material is used then each layer shall be placed in the mould with calendering grains parallel. The direction of calendering grain shall be marked on the moulding.

The test shall then be carried out at room temperature in accordance with BS 903 part A2 except that only the maximum tensile strength, and the elongation associated with that strength, shall be recorded.

3. Visual Inspection of Slab

Moulding slab shall be homogeneous in composition and free from visible foreign matter and fibrous strings.

4. Visual Inspection of Sheet

Calendered sheet shall

a) be free from obvious foreign matter, blisters, pitting, seams, laminations, fibrous strings and holes in excess of 2.0 mm diameter,

b) be substantially free from holes of 1.00-2.00 mm diameter, and,

c) have limited pin-holes up to 1.0 mm diameter: provided that they are at least 20 mm apart up to 10 such defects are permissible in a one metre length of 660 mm wide sheet.

Any of these faults found on inspection shall be clearly marked and a weight allowance made to compensate for unusable sheet.