CHAPTER 2

DEVELOPMENT OF LARGE SOLID ROCKET MOTORS

Solid Rocket Motors serve as the propulsion back-bone for strategic and tactical missiles as well as satellite launch vehicles. They impart required velocity to the vehicle at burn out of stage. The specification of rocket motor with respect to thrust versus time will be decided after detailed system study considering maximum allowable acceleration of the vehicle and burn out altitude from the point of view of dynamic pressure. Since most missions do not require sophistications of multiple restart and throttling operations, solid propulsion becomes overwhelming choice because of its inherent safety, high reliability, handling ease, simplicity, high density impulse minimum maintenance, packaging efficiency, effective system integration and low cost. The solid rocket motors inherently have high reliability and lower costs because of the following reasons:

- Minimum number of components.
- No moving parts required to provide propulsive force.
- No complex electronic control systems for operation or diagnostics.
- No need for pressurized fluids which may leak or require venting hazardous gases.
- No maintenance of the rocket motor.

Many solid rocket motors use movable nozzles for steering or TVC [87-89]. These TVC systems can be operated with hydraulic, pneumatic or electromechanical systems. The solid rocket motors used in long range missiles and launch vehicles are fairly large in size compared to those used in tactical missiles and sounding rockets. The design principles remain the same irrespective of the size of the solid rocket motor. However, there is a vast difference in the aspects of design choices, performance prediction methods, analysis, choice of materials, manufacturing facilities, casting facilities, inspection, testing and qualification, handling, transportation and storage in case of development of large solid rocket motors compared to the smaller ones. The issues related to the design and development of large solid rocket motors are discussed in this chapter. The solid rocket motors (Figure 1-1) having diameters more than 500 mm and propellant loading of a few tons to several tons may be classified as large motors.

2.1 DESIGN INPUTS

The basic inputs for the design of solid rocket motor are as follows

- Average thrust
- Burn duration
- Take off thrust
- Altitude bracket of operation
- Deployment temperature range
- Tolerance on performance
- Flight loads
- Vibration, shock, acceleration environment

- Handling and transportation loads
- Envelope of the motor (i.e., diameter and length)
- Weight of the motor
- Thrust vectoring requirements

2.2 ROCKET MOTOR CONFIGURATION

Configuration of the rocket motor has to be designed to meet the above mentioned requirements or operational conditions. The grain architecture in case of large motors is essentially case bonded where as it can be free standing / cartridge loaded in smaller motors. In almost all the metallic cases, the motor configuration is segmented. However, composite motors will be of monolithic configuration. The number of segments and the length of each segment depend on the following considerations.

- Take-off thrust and thrust versus time requirements dictate the grain configuration in each segment and the length of the segment in addition to the availability of heat treatment facilities and propellant casting facilities.
- If the number of joints is more, the weight of the hardware will be higher. Keeping the above considerations into account, it is always better to minimize the number of joints and hence the number of segments. The lesser the number of joints the higher is the reliability.

- Mass ratio is defined as the ratio of propellant weight to total weight of rocket motor. This is one of the important parameters, which is used to compare different solid rocket motors. This parameter will serve as a guideline for the design and influences the choice of materials and design aspects. The mass ratio of motors with metallic case is the order of 0.86, whereas in the case of composite casing, it is 0.9 - 0.92.

2.3 GRAIN CONFIGURATION

The grain configuration is to be so designed as to obtain near neutral or M-type thrust time profile and also meeting initial take-off thrust and maximum expected operating pressure (MEOP). This is possible by choosing deep STAR configuration in the head end segment and cylindrical in other segments. STAR parameters can be varied to obtain desired thrust profile. Finocyl configuration is also used in case of monolithic configurations with composite motor cases. Near neutral thrust versus time curve can be obtained with finocyl configuration. Table 2-1 gives the details of the rocket motors with respect to motor configuration and grain configuration. Issues in performance prediction are discussed below.

Table 2-1: Configuration Details of Large Solid Rocket Motors

Parameter	Titan	Shuttle SRM	Ariane -5 Booster
Diameter (m)	3	3.7	3
Length (m)	16.4	3.8	26.8
Weight of propellant (T)	250	500	236.5
No. of segments	5	4	3
Grain configuration	-	HE seg. STAR other seg. Cylindrical	HE seg. STAR other seg. Cylindrical
Case material	D6AC	D6AC	48CDN 4-10
Mass ratio	0.855	0.883	0.89

2.3.1 Incremental Analysis

The propellant specifications viz. burn rate, pressure index, temperature sensitivity, specific impulse are finalized to meet the required thrust versus time envelope after detailed system study of motor. Global analysis method, where the overall mass generation at any instant of burning is determined by applying a uniform burn rate over the complete burning surface area and is then equated to mass discharge rate through the nozzle to solve for pressure, serves the purpose for small motors. But for large motors incremental analysis has to be applied for performance prediction. In this method, the grain is divided into a number of elements. The mass generated from each element of burning surface area is calculated separately based on the local conditions accounting the variation of burning rate. The gas dynamic equations are solved over the length of the grain.

2.3.2 Propellant Port Deformation

In ballistic predictions, the burning surface area is calculated starting from the initial un-pressurized grain. For accurate prediction, internal motor flow field simulations should be coupled with the grain structural analysis. The propellant burn surface area at each instant of time should be evaluated considering the deformed grain geometry under internal pressure.

2.3.3 Nozzle Throat Erosion

Large solid rocket motors have longer burn durations (of tens of seconds) and hence throat diameter of the nozzle will enlarge considerably due to erosion. Initial predictions are based on the erosion data from the static firing of similar class of rocket motors, which will be verified/modified subsequently from the test data of the same motor firings.

2.3.4 Mid- Web Anomaly

The actual pressure in many of solid motor firings when compared to predictions, is found to be high in the middle of the motor operation and low at the end. The difference expressed in terms of burn rate for surface area is up to 2 to 3%. It is termed as "hump factor" or "Mid-web anomaly".

2.3.5 Tail-Off Transient

Tail -off transient has a bearing on the mission and hence needs to be predicted accurately. The tail-off transient will come not only due to the taper provided in the propellant grain port and erosive burning but also due to the pyrolysis gases of the insulation after the propellant burn out which will be more predominant in upper stage motors. Large rocket motors in the terminal stages of a mission and generally operating at high altitudes, generate thrust even after complete propellant burn out. This thrust results from out-gassing from the thermal insulation and is termed as residual thrust. Residual thrust evaluation is essential for estimation of total impulse and precise computation of retro impulse, if a stage separation is desired for the mission. The out-gassing is predominantly due to pyrolysis gases being evolved as a result of long heat soak periods of the thermal insulation during motor equilibrium operation. The chemical kinetics model is used to study the decomposition reactions in the thermal insulation, which results in determination of gases evolved during charring of the insulation.

2.4 PROPELLANT SYSTEM

Aluminized Hydroxyl-Terminated Poly-butadiene (HTPB) [90] based composite propellant with 86 to 88% solid loading is the workhorse propellant in all operational solid rocket motors. The standard sea level specific impulse with this propellant is 245 sec which has reached plateau. Propellants with Ammonium di-nitramide (ADN) as oxidizer in place of Ammonium perchlorate (AP) gives 8 -10% improvements in specific impulse and 5 seconds improvement can be obtained by adding Cyclo tetra methylene tetra nitramine (HMX).

Russians are using the ADN propellants. Its development in INDIA is yet to be realised.

2.5 METALLIC MOTOR CASING

Rocket motor casing can be made of metallic or composite materials. The choice of casing materials is governed by the availability of fabrication technology [91], availability of raw material in the required sizes and forms. The material influences the mass ratio of the rocket motor.

2.5.1 Design Input

The first step in the design of rocket motor casing is the identification of structural loads as given in Table 2-2.

2.5.2 Material Selection

The motor case material selection is based on the following considerations

- High material yield and ultimate strength.
- High weld efficiency (90% min.)
- High fracture toughness to tolerate large flaw sizes.
- Ease of machining, welding and forming.
- Availability of fabrication expertise and infrastructure.
- Simple heat treatment cycle.

The Table 2-3 gives mechanical properties of materials used for large solid rocket motors.

Table 2-2: Structural Loads

S. No.	LOAD	REMARKS
1	Internal pressure	• Mainly dictates the basis thickness sizing of motor case hardware • Critical design driver wherein the buckling of end closures under internal pressure play a role
2	Linear acceleration	• Critical in staged propulsion systems • Critical in slender configuration (high L/D) which may be susceptible to buckling
3	Structurally transmitted vibration	• During transportation and flight
4	Acoustic loads	• Due to propulsion
5	Flight shear force and bending loads	• Depending on trajectory design
6	Shock loads	• Depends on transportation and stage separation conditions
7	Thermal loads	• Storage, external aerodynamic heating and propulsion
8	Slump loads	• During storage
9	Handling loads	• During fabrication, casting of motors and articulation

Table 2-3: Mechanical properties of materials used In Large Solid Rocket Motors

	Titan	Space shuttle	Ariane
Material	D6AC	D6AC	48CDN 4-10
UTS (Kgf/mm^2)	150	150	150
Yield strength (Kgf/mm^2)	130	130	130
Fracture toughness MPa $\sqrt{m}$	100	100	85
Heat treatment	Harden and temper	Harden and temper	Harden and temper

2.5.3 Safety Factors

The choice of appropriate safety factors depend on the confidence levels in material properties, propellant formulation and fabrication uncertainties. There are various standards like the military standards, the aviation publication (AVP-32) etc., which set guide lines for a proper choice of factor of safety. The design factors are applied to maximum expected operating pressure (MEOP).

Table 2-4 gives the safety factors proposed by AVP-32 and MIL-STD and those used in some of the large solid rocket motors.

Table 2-4: Safety Factors - Guide Lines

MIL-STD	• 1.15 X MEOP for pressure vessel • 1.2 X Structural load for other structural members	
AV.P-32	• 1.25 on yield • 1.33 on UTS	When the weapon system in the vicinity of the launcher
	• 1.5 on UTS • 1.125 on yield	When the weapon system is in the vicinity of launcher and the MEOP can be predicted with adequate confidence
ROCKET MOTORS	• 1.25 on UTS • 1.125 on yield strength • 1.1 for proof pressure	

2.5.4 End Dome Selection

Any typical rocket motor hardware comprises of a cylindrical shell, end domes and various joints and interfaces. The end domes are generally of three types, viz., Ellipsoidal dome, Torispherical dome and Spherical dome. The characteristics of these domes are as follows:

Ellipsoidal Dome:

- Varying meridional radius and hence difficult to fabricate especially for large dimensions.

Torispherical Dome:

- Ease of manufacturing
- High compressive stress in the knuckle portion.

Spherical Dome:

- Minimum stress due to discontinuity
- Deep domes

2.5.5 Joints and Sealing

In large rocket motors, performance reliability will be decided by the efficiency of sealing of joints. Challenger failure is due to segment joint failure because of its 'O' ring performance at low temperature. Various joints in large solid rocket motors identified are:

- Igniter-to-motor interface
- Nozzle-to-motor interface
- Motor skirt-to-inter stage joint
- Segment joint (tongue and groove joint)
- Key joint

Figure 2-1 shows typical joints in large rocket motors.

All the joints require a reliable sealing scheme. Usually 'O' rings made of silicon rubber or viton, having a shore hardness of 65 - 75, are used. The major criterion for 'O' ring material possesses good quality of low and high temperature properties, maximum shelf life (of the order of 10 years) and low glass transition temperature. The joints must be designed with such features so as to ensure minimum risk of damage to 'O' rings while assembly and dis-assembly. From operational point of view, the 'O' rings are designed for a compression of 15 - 25 % to provide a leak tight joint. Key joint can be used in place of bolted flange joint as well as segment joint.

2.5.6 Segment Joint

The configuration of segment joint is finalized based on bearing load of the shear pins. Design considerations in the segment joint are:

- Leak tightness under operational conditions.
- Provision of redundancy
- Inter changeability of segment rings
- Easy assembly and dis - assembly

2.5.7 Composite Motor Casing

The major advantage offered by composite casing is the low weight compared to the metallic one. The normally used composite materials for large motor casings are fibre glass, Kevlar and graphite (carbon) with epoxy matrix materials, Table 2-5 gives properties of composite materials used for the construction of composite rocket motor casings.

Table 2-5: Properties of Composite Materials Used for Rocket Motor casing

	KEVLAR / EPOXY	CARBON / EPOXY
Ultimate strength	106 Kgf/mm^2 (1040 MPa)	146 Kgf/mm^2 (1432 MPa)
E_L (fibre direction)	5530 Kgf/mm^2 (54.23 GPa)	13020 Kgf/mm^2 (127.68 GPa)
E_T (Transverse to L)	300 Kgf/mm^2 (2.94 GPa)	601 Kgf/mm^2 (5.89 GPa)
G_{LT}	94.8 Kgf/mm^2 (930 MPa)	261 Kgf/mm^2 (2560 MPa)
Failure strain	20000 μ ε	12000 μ ε

2.5.8 Failure Modes

The generally identified modes of structural failure are: brittle fracture, yielding due to overload of the cross-section, leakage of containment vessels, corrosion, erosion, corrosion fatigue and stress corrosion, instability (buckling) and creep or creep-fatigue interaction. Two types of failure criteria recognized by rocket industry are yielding and fracture. Failure due to yielding is applied to a criterion in which some functional of the stress or strain is exceeded and fracture is applied to a criterion in which an already existing crack extends according to energy balance hypothesis. Experimentation with a variety of materials would show that the theory works well for certain materials but not very well for others. Designer has to establish a suitable failure theory for the intended materials. For any given aero-spaced pressure vessel material, exposure to any known corrosive, stress corrosive or embrittling environment must be avoided. Fracture mechanics methods should not be used to design a pressure vessel to contain such environment.

2.5.9 Stress Corrosion Cracking and Storage

The phenomenon of stress corrosion cracking (SCC) is environmentally assisted When certain materials are exposed to corrosive environment while at the same time are subjected to an appreciable continuously maintained tensile stress (residual stresses), rapid structural failure can occur. This is known as stress corrosion cracking. Systems meant for defence applications require long storage time (10 years or more). Hence it is essential that proper protective coatings are applied that separate the environment from the stressed component.

2.5.10 Thermal Protection System

Technologies in design and development of insulation for rocket motor casings and nozzles have considerably improved to meet the ever-increasing demands of mission requirements of pay loads and range or the stage incremental velocity.

2.5.11 Ablation and Thermal Analysis

Ablation and thermal analysis is essential to understand the thermal behavior of insulation in the entire rocket motor from the temperature distribution along with virgin, char and erosion profiles. This information will be useful for the effective protection of back-up materials and confirms the presence of sufficient virgin material at the end of motor operation.

The thermal analysis procedure follows a number of steps. The process begins with computation of free stream transport properties, using propellant formulation and motor chamber conditions. As suitable insulation is selected from the previous experience on rocket motors of similar class and size. A quasi-one dimensional analysis of fluid flow in the rocket motor is carried out to generate velocity, pressure and temperature profiles.

A one-dimensional thermal analysis code is used to analyse the insulation in the rocket motor chamber, where axial thermal gradients are not predominant. The heat flux input to the insulation is computed using standard empirical relations. Rapid acceleration of flow in the rocket motor nozzle results in axial thermal gradients for which a two-dimensional procedure for in depth thermal analysis is used. The convective heat flux is calculated by an empirical relation as proposed by Bartz. The final thicknesses of insulation are obtained by applying a factor of safety over the char and erosion depths in order to account for uncertainties in heat transfer coefficients, material properties, etc. With the advent of more efficient algorithms and faster processors, analysis techniques are moving towards three-dimensional models for accurate thermal predictions.

The motor case of large rocket motors currently in service, use Rocasin rubber for thermal protection, due to its high percentage of elongation. Carbon-phenolic (CP) is used in convergent-divergent nozzles due its erosion resistance in hot gas flow, while Silica-phenolic which has low values of thermal diffusivity is used as back-up material.

Newer insulation schemes for motor casings include interposition of carbon cloth layers with rocasin, use of high melting point low-density fillers and, Kevlar filled Ethylene propylene diene monomer (EPDM) insulation. Use of sprayable insulators as an alternative insulation scheme can result in reduced labour costs and better quality control. Large rocket motors currently use graphite or carbon-phenolic throat inserts. Carbon - carbon as throat material is a possible future candidate due to its reliability, better performance and lesser erosion rates.

2.6 THRUST VECTOR CONTROL SYSTEMS

Control and guidance [92, 93] of the missile is required basically to: compensate for flight disturbance and vehicle imperfection (misalignment, C.G shifts and wind) which affect the missile attitude and stability and to achieve the required flight trajectory. TVC systems used in large solid rocket motors are

1. SITVC
2. FTC
3. Flex nozzle
4. Fluid bearing
5. Ball and socket swivel nozzle.

Movable nozzles are generally linear response systems (i.e., turning moment is proportional to vector angle although power requirement may not be directly proportional). Choice of system [94] depends on vehicle performance requirement, system weight, cost, reliability, development risk and envelope constraints. The flex nozzle system is most generally used in most of the large solid rocket motors [95-104] because of its simplicity and reliability.

2.7 FLEX NOZZLE SYSTEM

Most of the large solid rocket motors use flex seal based control system having configurations using Aft pivot point or Forward pivot point, Conical or Cylindrical bodies, Spherical or Conical shims.

Basically the flexing element is the seal with alternate layers of metal/composite and elastomer pads axisymmetrically distributed over the throat area, connected at one end to the motor casing through the intermediate dome and aft end connected to movable part of nozzle throat housing. Hydraulic or electromechanical actuators are used to deflect the nozzle through the pivot point with respect to motor axis. The degree of turning and other related specifications used in the current large nozzles and launch vehicles are given in Table 2-6.

Table 2-6: Flex Seal Configuration of Different Motors

SL. No.	Mission	Flex seal configuration	Vectoring angle, Deg	Seal OD (mm)
1	Shuttle SRM	Conical body, spherical shims	±5°	2275
2	Ariane-5/P230	Cylindrical body, spherical shims	±5°	1600
3	P80	Cylindrical body, spherical shims	±6.5°	Not available
4	S200	Cylindrical body, spherical shims	±5.5°	1650

2.7.1 Design and Development of Flex Nozzles

Critical issues to be addressed during development are

- Establishing the envelope for movable nozzle.
- Estimation of the actuator power requirement and sizing the seal in available space.
- Specification of allowable properties of elastomer and reinforcement.
- Strength analysis of seal to calculate axial deflection, offset and integrity.
- Adhesive bonding of elastomers to reinforcement and related moulding operation.
- Development of thermal boot to protect the seal.
- Establishing the ageing properties of elastomer.
- Test methods that adequately simulate the motor operating condition.
- Tooling & fabrication.
- Quality Control of moulded joint.
- Leak proofness of the joint.

After preliminary flex-nozzle-configuration design is carried out based on above considerations, the number of shims and elastomers are arrived at using empirical methods and manufacturing considerations. The flex nozzle torque comprising of Spring torque, Boot torque, Offset torque, Gravitational torque, Inertia torque, Aerodynamic torque and Frictional torque are evaluated by empirical relations and experience to estimate the actuation requirements.

The preliminary design of flex seal is subjected to a thorough analysis using standard Finite element analysis (FEA) tools for the ejection load (effective load on the seal due to rocket motor chamber pressure integrated on the convergent-divergent nozzle contour) and actuation loads. Shim stresses and strains, axial compression, angular deflection for the design loads and seal stiffness will be evaluated prior to various tests for acceptance and qualification.

2.7.2 Materials and Properties Governing the Design of Flex Seal

Reinforcement shims are made of steel or composites. The important properties required are compressive and tensile yield strength, ultimate strength, Modulus of elasticity, peel and shear strength of adhesive bonding. Failure criterion is either compressive yield failure of shims or local wrinkling with debonding. 4130 steel, 304A stainless steel, 17- 7PH annealed stainless steel and l5CDV6 steels are proven in usage.

Composite shims have been formed with S-glass filaments / epoxy resins and S-glass filament-Phenolic resin. The failure mode when composite shims are used is rupture through thickness, interlaminar shear failure between laminae or compressive failure. Elastomer pads may be made of materials like natural rubber, Neoprene/polybutadiene, polyisoprene and silicon. The exact choice is based on shear modulus, shear strength and adhesive bonding of elastomer with shim apart from environmental conditions. Low shear modulus elastomers give low joint spring torque which in turn amount low actuation requirements.

2.8 TESTING AND VALIDATION

Acceptance, Qualification and Integrated testing are usually involved in development of flex seals. The objectives of acceptance testing of flex seals are to:

- Evaluate bonding between shims and elastomers.
- Pressure sealing capability of seal.
- Vectoring capability under pressure load
- Axial deflection and strains due to pressure & vectoring.
- Spring torque.
- Structural integrity of seal.
- Hysterisis characteristics.

The above objectives are to be met by designing suitable test fixtures to carry out: a pull test for clearing bonding between shims and elastomers, proof pressure tests simulating proof pressure usually 1.05 to 1.1 times MEOP of motor and actuation tests simulating individual and simultaneous actuation in pitch and yaw. Extensive instrumentation may be required in terms of strain gauging on shims, axial and angular deflection, actuator load and stroke measurement during developmental phases. Limited qualification tests with incorporation of extreme duty cycles are to be carried out before the flex seal is used in a flying mission. Control system design has to be validated in integrated nozzle control tests carried out on ground to characterize the flex nozzle control system.

2.9 THERMO STRUCTURAL ANALYSIS OF THROAT INSERT

The materials generally used for nozzle throat inserts are high density graphite, carbon phenolic and carbon-carbon. The throat insert is subjected to high thermal and pressure loads during motor operation. Thermo-structural finite element analysis of throat insert has to be carried out considering the temperature distribution in the throat insert (obtained from thermal analysis) and pressure distribution along throat. The induced stresses under MEOP and maximum burn duration should not exceed structural capability of insert material.

2.10 DESIGN OF PYROGEN IGNITER AND IGNITION TRANSIENT PREDICTIONS

A Pyrogen igniter is basically a small rocket motor that is used to ignite large rocket motors. Conventional pyro-technic igniters are generally not used to ignite large rocket motors due to short operating durations and generation of considerable amount of condensed phase particles, which may not suffice to pressurize the free volume in large rocket motors. The free volume of the large rocket motor has to be pressurized to a level so as to ensure stable propellant combustion. Another advantage of a pyrogen igniter is that the charge can be so tailored as to generate the required mass flow rate pattern by suitable grain design.

The modeling and understanding of ignition dynamics has become important with increasing sophistication of rocket motors and mission requirements. The possibility of pressure over- shoot due to erosive burning phenomenon, the visco-elastic nature of propellant, particularly at low temperatures, sensitive pay loads/instruments and structural responses to dynamic loading, all require a detailed knowledge of the ignition transient. Incidentally, the development of large rocket motors at high unit costs also do not allow for an empirical solution or trial and error techniques.

The ignition transient predictions will be made considering the heat transfer and fluid flow phenomena. The heat transfer coefficient is based on empirical co-relations both for impingement and convection based heat transfer. Two-dimensional heat conduction equation is solved for the propellant geometry. The criterion for ignition of propellant is attainment of auto-ignition temperature. Quasi one-dimensional flow model is solved in the port of the rocket motor and empirical co- relations are used for estimation of erosive burning rates. Ignition transient predictions for high performance large rocket motors have to be made considering two-dimensional fluid flow phenomena (particularly for segmented rocket motors and three-dimensional propellant geometries), burning rate variations under rapid pressurization and visco - elastic interactions under dynamic loading conditions.

2.11 STRUCTURAL INTEGRITY OF PROPELLANT GRAINS

Even though the primary design of propellant grains is based on ballistic considerations, structural integrity of propellant grain is to be ensured to achieve the predicted performance. Large solid rocket motors essentially use case - bonded propellants cast insitu in the motor casings or segment of motor casings. Typically HTPB binder based composite propellants are in vogue and the behavior of propellant is visco-elastic in nature (i.e. materials display relaxation under constant strain and creep under constant stress at room temperature).

The propellant materials are nearly incompressible in nature and the Poisson's ratio is nearly equal to 0.5. The dynamic properties (Storage modulus and Loss Tangent) are determined at different frequencies over a wide range of temperature using visco - elastometers to generate the master relaxation modulus curve. The propellant usually characterized for its mechanical properties (Tensile strength, Percentage elongation, Modulus) at different temperatures and strain rates. Failure envelopes are generated based on these characteristics. The stress - strain values inside the failure boundary are safe.

The loads to be considered while analysing the behavior of motors are due to cure shrinkage, cooling, temperature cycling, vibration, shock, transportation/handling, storage, acceleration due to gravity, ignition pressurisation etc. Of these loads, the critical loads governing the structural integrity of propellant grain are the cure shrinkage (thermal), ignition pressure and acceleration loads.

Solid propellant grains cast in motors are usually thick cylinders with propellant, insulation and casing materials as three cylinders. Large rocket motors generally requiring high initial velocities have grain configurations such as star, wagon wheel, finocyl etc. and in simplest form a circular port. Complex geometries of propellants meeting the ballistic requirements are not generally amenable to closed-form / analytical solutions for margin estimations under thermal, ignition pressure and acceleration loads. Finite elements (viz., axisymmetric element, 2-D plane strain element and 3-D brick element) based on Hermann`s formulation will be more appropriate to carryout viscoelastic stress analysis for solid propellant grains in rocket motors.

Modulus of propellant, casing and liner at upper and lower bound operating temperatures are considered for analysis. The induced strains due to thermal loads are compared with the dewetting strain capability of the propellant. The strains induced due to pressure loading are superimposed on strains induced due to thermal loading and compared with the strain capability of propellant. For Acceleration loads, the shear stresses at the interface are obtained and compared with the shear bond strength of interface. The maximum slump displacement under the acceleration load is checked against the envelope of nozzle and other parts for interference. In case, the margins are below minimum required values as is the case with high web grains during thermal cooling, loose flaps are designed and introduced between the propellant insulation and casing to allow free shrinkage of propellant without inducing high shear stresses.

Effect of non linearities like moving boundary of geometry due to burning and deformation, Bulk Modulus variation with pressure and stress concentration effects have to be considered to accurately predict the propellant behavior. Adequate margins against Port Cracking, Interface debonding, and excessive Grain Deformation have to be ensured before usage to ensure success of mission. Typical margins of safety are in the range of 1.15 to 1.25 during preliminary analysis for acceptable design and considering ageing degradation, the margins of safety will be reduced to 0.25 to 0.5.

The shelf life of solid rocket motors used in missiles must be very long of the order of 10 - 15 years unlike for those used in launch vehicles. The shelf life of rocket motor depends on the life of propellant, bond between propellant and insulation and seals. The ageing and the surveillance studies are required to be conducted to ascertain life of various subsystems and hence the overall rocket motor. Aging studies will give an idea of life of propellant and seals but surveillance studies are essential to estimate the life of bond between propellant and insulation. The method of storage either vertical or horizontal will also decide the shelf life. In case of horizontal storage, it is generally required to rotate the motor periodically.

2.12 CONCLUDING REMARKS

The capability of any country to develop intercontinental Ballistic Missiles depends on the capability to design and facilities available in the country. The reliable and successful operation of a strategic weapon delivery system is dependent on efficient design and analysis of solid rocket motors. There are many critical issues, which need to be tackled in design and development of large rocket motors. The design of a flex nozzle system and the detailed design of the flex seal will be covered in the next chapter.

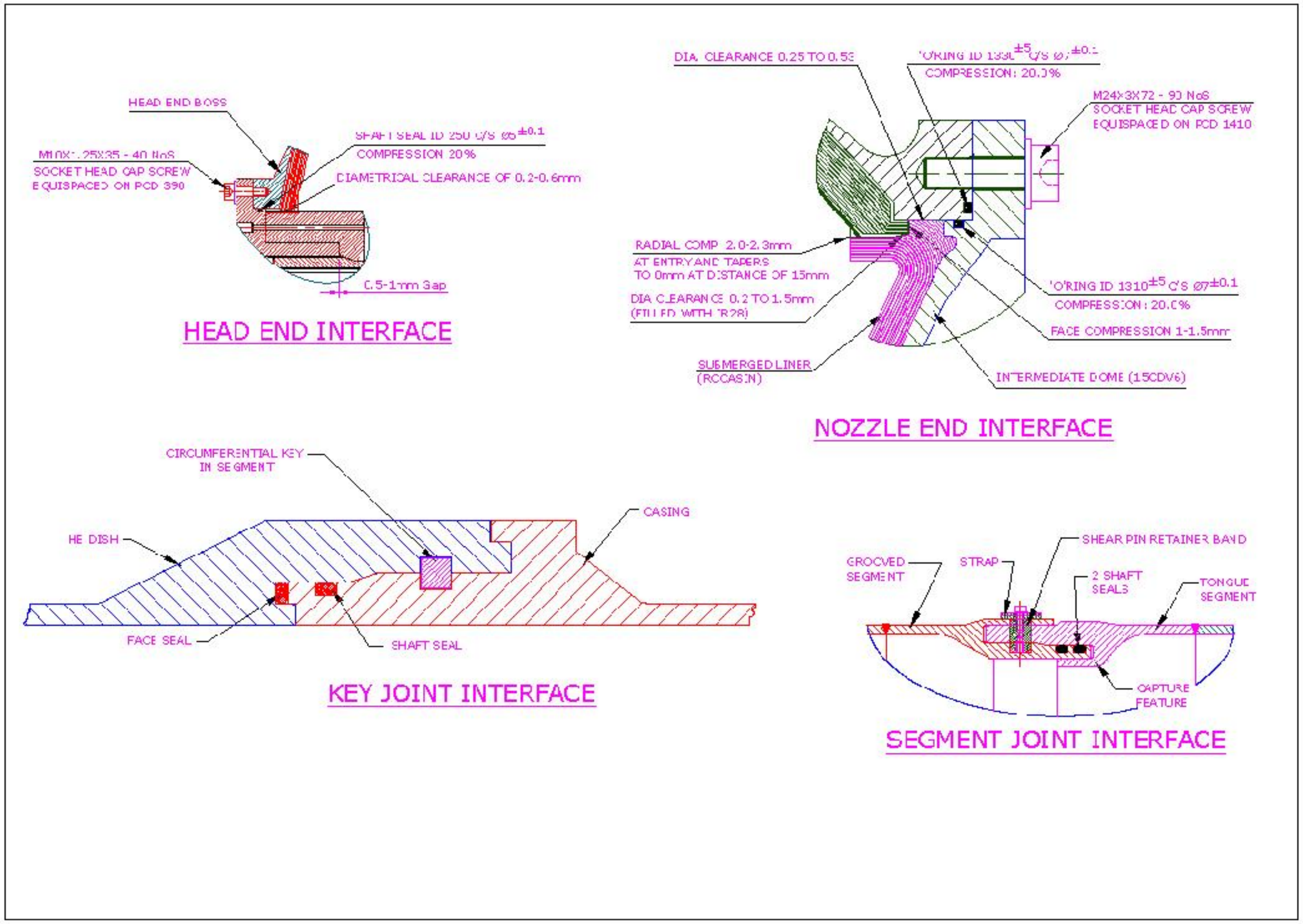

Figure 2-1: Typical Joints in Large Rocket Motors