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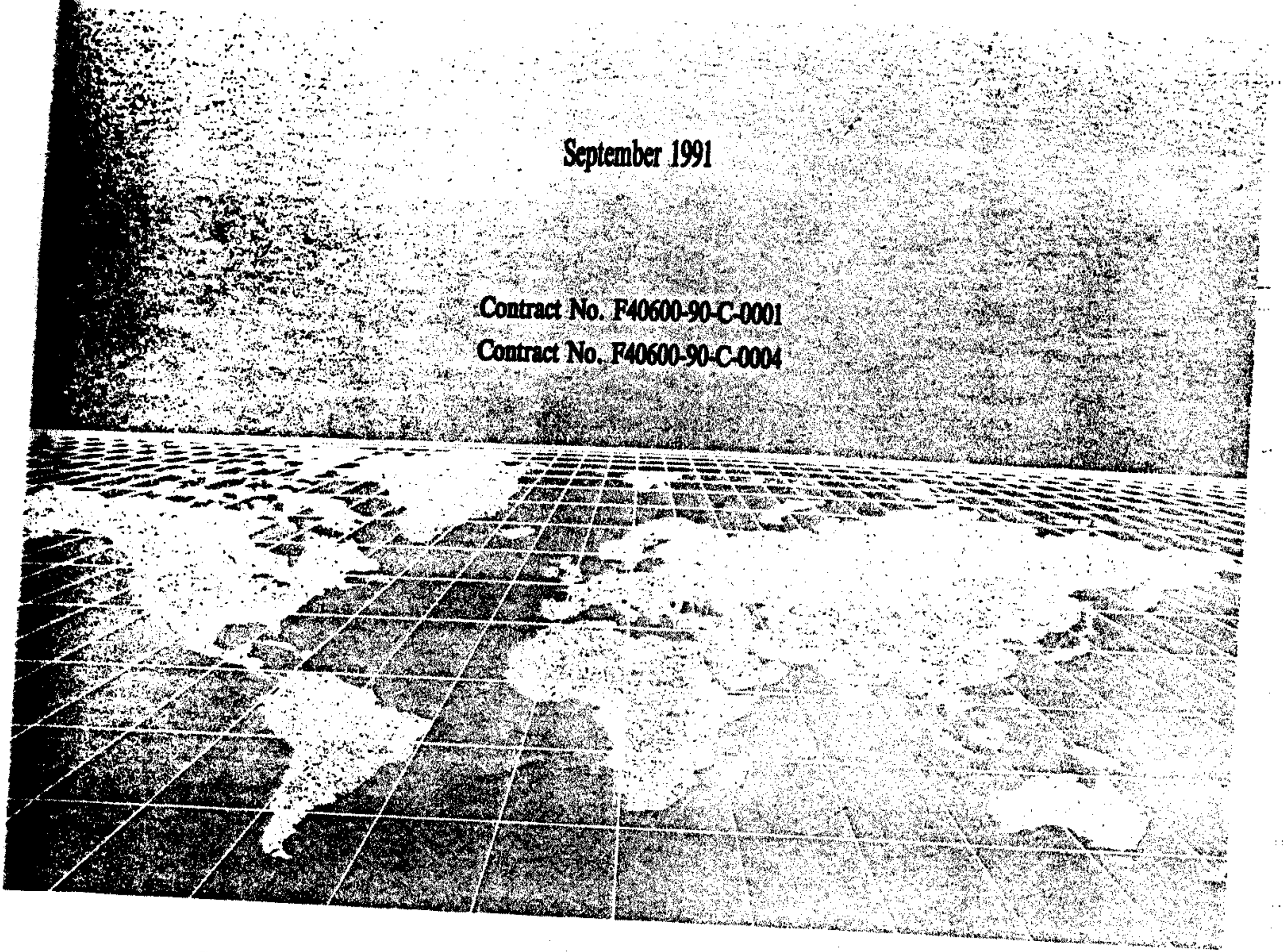
NAUTILUS--

Short-Range Ballistic Missile (SRBM) Infrastructure Requirements for Third World Countries



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PREFACE

This study was conducted at the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), at the request of the Central Intelligence Agency, Langley, Virginia. The analysis was performed by the AEDC Intelligence Office using the GOCO (Government-Owned, Contractor-Operated) status of Sverdrup Technology, Inc., AEDC Group, and SSI Services, Inc., operating contractors for the AEDC, AFSC, Arnold Air Force Base, Tennessee.

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SECTION I

EXECUTIVE SUMMARY

1.1 INTRODUCTION

This report discusses the industrial complex, materials, technology, and work force that are required for a Third World country to develop an indigenous tactical ballistic missile system. Collectively, these capabilities form the indigenous infrastructure necessary to accomplish ballistic missile design, development, production, test, and deployment. A country that possesses these attributes is said to have an indigenous ballistic missile capability. The term *indigenous* requires clarification. In a strict sense, this term means, "having originated in and being produced in a particular country." However, in this report, common materials and equipment that are not usually covered by export controls of other nations are permitted to be included while maintaining the applicability of the word *indigenous*. The steel required for a rocket motor case is an example of such a material.

The ballistic missile discussed herein is called a short-range ballistic missile (SRBM), where SRBM means a one- or two-stage weapon with a tactical range between 300 and 1,000 km (190 to 620 miles). The SRBM is guided only during the powered portion of flight; that is, it is powered by rocket propulsion and flies a ballistic trajectory (after termination of rocket thrust) subject only to gravitational and aerodynamic forces. Target ranges discussed herein are calculated for a nonrotating spherical Earth.

1.2 OBJECTIVES

The primary objective of this report is to define the infrastructure required for an indigenous Third World country's short-range ballistic missile capability. These requirements are described in terms of the technology and hardware that comprise the design, manufacturing processes, assembly, testing, and deployment of a tactical SRBM. A secondary objective is to provide a training aid for ballistic missile fundamentals.

1.3 SCOPE

The work discussed in this report is as comprehensive as practical and is sufficiently general to be applicable to essentially any SRBM system of Third World countries. In cases where specific computations are required, such computations assume a system designed to deliver a 1-metric-ton (2,205 lb) payload up to 1,000 km (621 miles). Both solid- and liquid-propellant rocket propulsion capabilities are considered. The report contains no discussion of nuclear payloads nor treatment of postboost trajectory control.

Third World countries typically do not possess, nor have the capabilities to implement, current superpower technologies. In addition, export laws may preclude or at least hinder the use of ideal or even desirable materials, components, and manufacturing and assembly processes. Therefore, this report emphasizes older technologies and various techniques or work-arounds necessary to utilize available limited resources and to bypass foreign imposed sanctions. Figure 1 is a photograph of two Iraqi-modified Soviet Scud B SRBMs. Although these missiles are not indigenous to Iraq, the associated older technologies make them typical of Third World SRBMs.

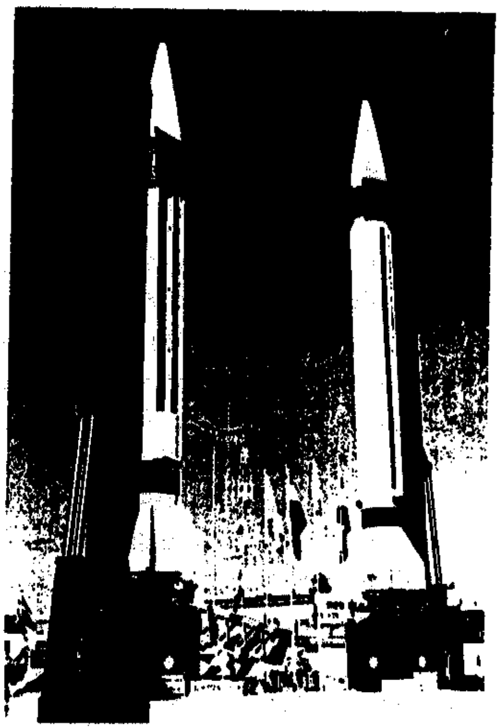


Figure 1. Typical Third World short-range ballistic missiles.

1.4 BALLISTIC MISSILE INFRASTRUCTURE

The development of the infrastructure necessary for a short-range ballistic missile capability is within reason for many Third World countries. Several Third World countries already have ballistic missile capabilities. Starting from scratch is a formidable but manageable missiles endeavor. SRBMs need not have 1990s technology. An SRBM capable of delivering a 1-metric-ton payload 1,000 km, which weighs less than 7 metric tons and is therefore a mobile weapon, can be built with 1960 technology. That technology (1960s) is not bad — the U. S. uses 1960s technology for much of their space-launch capability. Considering the vast amount of unclassified literature available, any country with a modest industrial base and a procurement network for equipment and materials should be able to indigenously construct an SRBM within 10 yr from an initial start.

The most sophisticated component of an SRBM is the inertial guidance. The most demanding requirement of the guidance system is the need for friction-free bearings for the onboard gyroscopes. The propulsion system must be reliable and must have repeatable thrust-termination capability. A crude but reliable two-stage solid-propellant rocket propulsion system can be built that weighs under 6 metric tons. The propellant mass fraction (ratio of propellant to total propulsion weight) needs to be no higher than 0.82, which can be constructed with alloy steel motor cases. The propulsion system is about 85 percent of the SRBM launch weight.

To develop the infrastructure, a Third World country needs to educate and train a work force, expand existing industrial capability, develop new industrial capability, acquire raw material procurement channels, hire a few good mercenaries, and select outstanding leadership.

The existing industrial base can be expanded, as shown in Fig. 2, to form the backbone of the SRBM infrastructure. The existing chemical, tire, fertilizer, and food-processing industries would provide the foundation for the propellant chemistry, mixing, casting, and curing manufacturing base. Existing automotive industries would form the core of the structural design, fabrication, and assembly needs, and provide the transporter-erector-launcher (TEL). Any existing aircraft industry would provide the core of the lightweight structure fabrication business, and the existing electronics industry would provide the evolution into guidance and control. Agricultural tractor businesses could provide the "know how" on hydraulic actuators and feedback servo-systems.

Developing the infrastructure would not be easy, but it can be done. Institutions of higher learning would be responsible for training in a multitude of disciplines. Astronomers with centuries-old understanding of orbital mechanics would team with Army artillery experts to decipher the solid-body mechanics required for guidance and thrust-termination algorithms. The artillery experts would form the core of the warhead, fusing, safe-and-arm, igniter, and separation pyrotechnics design team.

A guidance laboratory would be established for the development of lightweight accelerometers, gyroscopes, computers, and inertial platforms. Trial-and-error experimentation would be time consuming, but the effort would result in an indigenous inertial guidance capability. The laboratory would develop the transformation techniques required for converting inertial measurements to targeting information.

Only modest aeronautical engineering education and experience are required for the prediction of missile and reentry vehicle drag and aerodynamic heating magnitudes. Model testing in both subsonic and supersonic wind tunnels would probably be required to determine body stability derivatives that are required for sizing the control system and determining control system gains. Subscale wind tunnel testing could be provided by the higher education institutions.

Few engineering endevors are more challenging or learning processes more exciting than the development of a flight weapons system from conception through flight test. Third World countries aiming for a successful SRBM infrastructure will use this challenging program to draw capable leaders and an ambitious staff. The leadership must be focused on product development but remain tolerant of the flexibility and innovation required in the laboratory environment.

There is no shortage of experienced personnel worldwide that can be hired to help a Third World country in the areas of critical expertise such as guidance, guidance computers, dynamic stability, polymer chemistry, thrust vector control, lightweight pressure vessel fabrication,

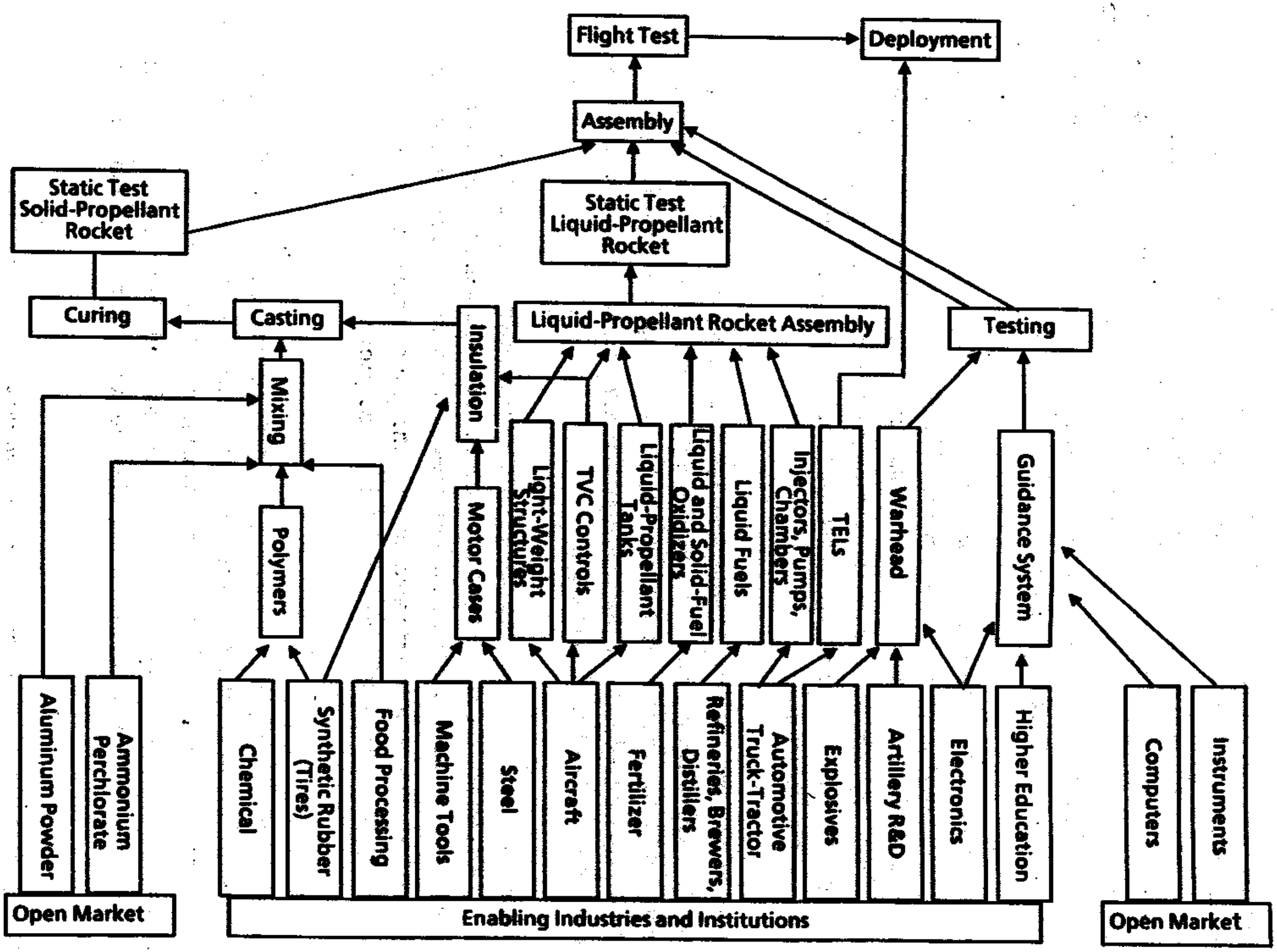


Figure 2. Indigenous ballistic missile infrastructure.

propellant rheology, and high-temperature material technology. These areas of expertise can, moreover, be homegrown with perhaps some foreign education. The U. S. went from airplanes to intercontinental ballistic missiles in the time period from 1945 to 1958, building on the airplane, inertial navigation, sounding rocket, SRBM, and IRBM infrastructure. Since most, if not all, of that technology has been published in the open literature, a Third World country could now develop an SRBM indigenous capability in 10 yr and, with hired help, do the job in 6 yr.

1.5 OVERVIEW OF REPORT CONTENTS

For descriptive purposes, an SRBM can be broken down into four systems: guidance, propulsion, structures, and payload, as illustrated in Fig. 3. This report includes guidance (Section II), solid-propellant rocket propulsion (Section III), liquid-propellant rocket propulsion (Section IV), structures and materials (Section V), testing and deployment (Section VI), and infrastructure (Section VII). Each section describes both SRBM fundamentals and indigenous production requirements. The requirements provided in each section describe the minimum effort that a Third World country needs for an indigenous SRBM capability. The final section discusses a typical philosophy that might be employed in the development of the infrastructure.

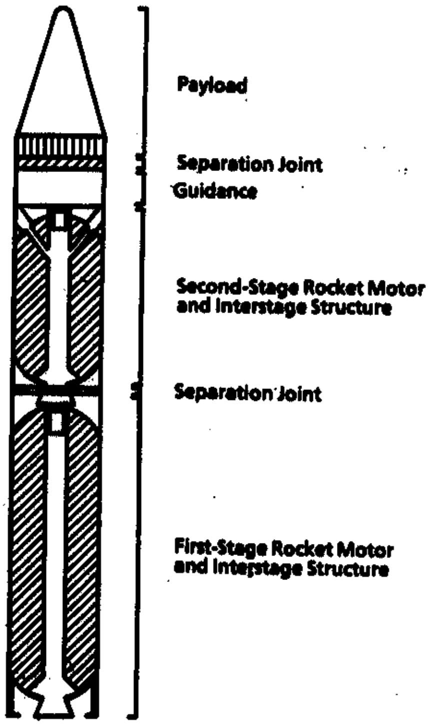


Figure 3. SRBM major systems for two-stage solid-propellant rocket propulsion.

SECTION II

GUIDANCE

An active on-board guidance system is employed during the rocket-powered portion of the SRBM flight. The guidance system maintains azimuth, flight-path angle, continuously computes the velocity to be gained in order to impact the target, and provides a thrust-termination signal at the proper time. An inertial guidance system (IGS) is the preferred method of guiding ballistic missiles. Inertial guidance systems are uniquely valuable because they can provide good navigation accuracy in a self-contained system virtually immune to countermeasures. Inertial guidance is also viewed as the most challenging missile-related technology for any Third World country to develop. The basic IGS theory is well documented and generally understood, but manufacturing inertial grade components and systems requires advanced skills that blend art and technology.

To understand the IGS, it is first necessary to understand the mechanics of ballistic missile flight. The fundamentals of flight mechanics, inertial guidance, guidance accuracy, and inertial grade component manufacturing are discussed in the following paragraphs. In all of these discussions, it is assumed that postboost control and reentry vehicle control are beyond the near-term (up to 10-yr) capability of Third World countries.

2.1 FLIGHT MECHANICS

Ballistic missiles are launched vertically, rolled to the proper azimuth if necessary, and tilted to establish a near-gravity-turn trajectory. A gravity-turn trajectory is one in which the only vehicle turning moment is that moment caused by the missile weight component normal to the vehicle flight path. Flight-path angle and azimuth are affected by the propulsion thrust vector control (TVC) system, and roll position by the roll control system. Flight-path angle is the angle between the missile flight path and the local horizontal. Azimuth is the flight-path heading measured clockwise from geometric north in the horizontal plane. The job to be accomplished by the guidance system is to control the powered phase of flight to the desired flight-path angle and determine thrust-termination time.

Ballistic missile flight is characterized by three phases of flight as shown in Fig. 4. These flight phases are (1) powered flight, (2) coasting or free flight, and (3) reentry flight. During the powered flight, the rocket propulsion system boosts the vehicle to a cut-off point with velocity V_{co}, altitude h_{co}, and flight angle between the velocity vector and the local horizontal, θ_{co}. Rocket propulsion is terminated at the cut-off point. Coasting flight occurs primarily in a vacuum where the reentry body with payload is subjected only to the central force field (gravity). About 90 percent of the range (for the maximum 1,000-km-range trajectory) occurs

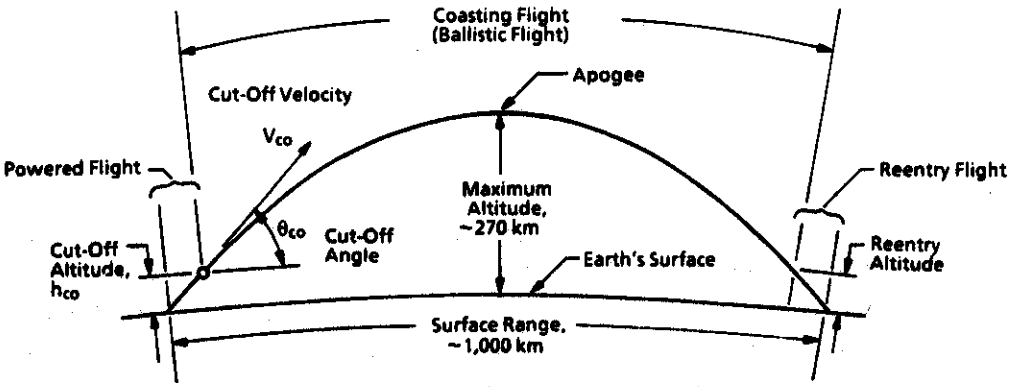
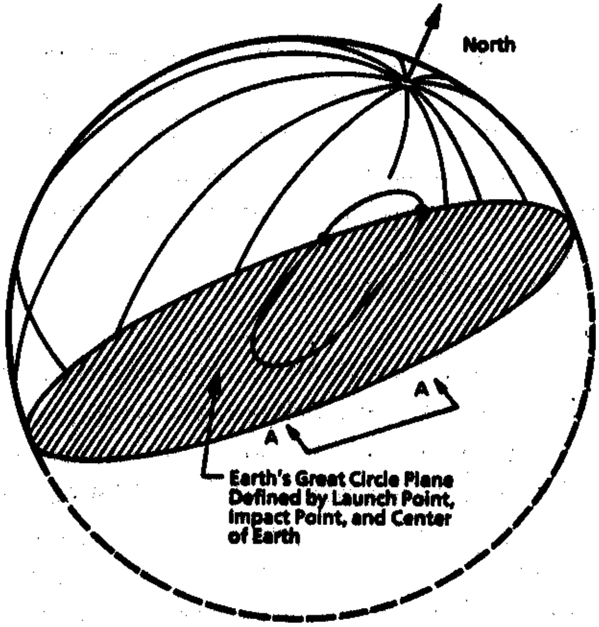


Figure 4. Powered, coasting, and reentry flight.

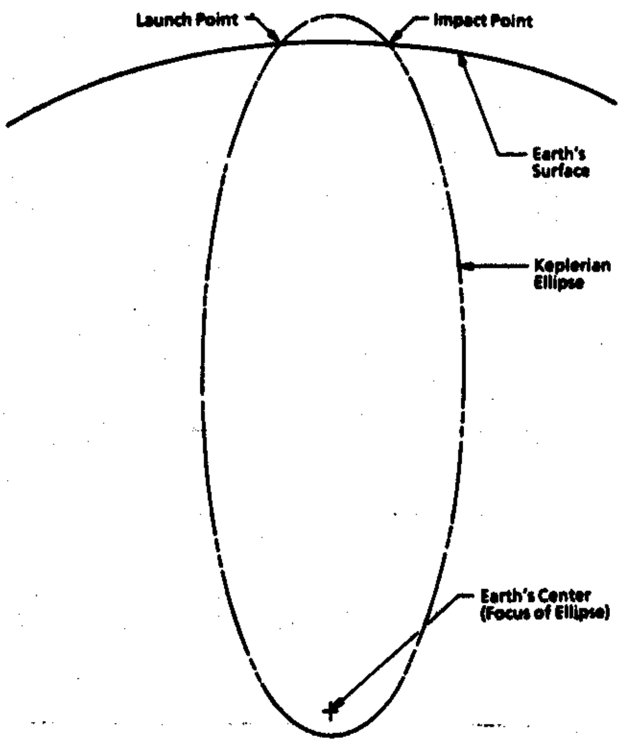
during coasting flight. Coasting flight lasts until reentry, which occurs as the reentry vehicle encounters the atmosphere.

The motion of the vehicle during the coasting phase of flight is subjected to the same physics as all bodies in a central force field (Ref. 1). The motion obeys the Keplerian laws that were derived empirically in the 17th century and were later proven to be mathematically correct by Newton. The planets travel about the sun in Keplerian ellipses, and satellites travel about Earth in Keplerian ellipses with the center of the Earth as a focus. Ballistic missiles travel in Keplerian ellipses with the unique attribute that the ellipse intersects the Earth's surface at two points (roughly the launch point and the target). The ballistic trajectory occurs in a great circle plane of the Earth as shown in Fig. 5. The elliptical trajectory, also shown in Fig. 5, is completely defined by the three cut-off parameters V_{co}, h_{co}, and θ_{co} (Ref. 2). These three parameters define the ellipse eccentricity and therefore the flight-path surface range and time of flight. The surface range, as a function of V_{co} and θ_{co}, is shown in Fig. 6 for a fixed h_{co}. Desired ranges are achieved by terminating thrust at the time the guidance computer determines that the impact point is the desired target. Missile range as a function of burn time for a typical two-stage solid-propellant rocket-powered SRBM is shown in Fig. 7.

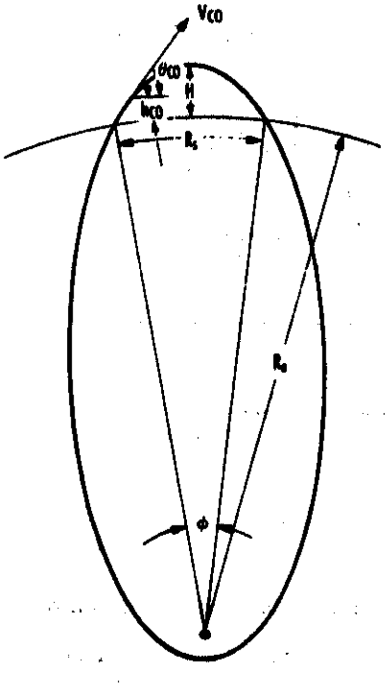


a. Great circle plane of the Earth

Figure 5. Ballistic missile trajectory.



b. View A-A (from Fig. 5a) showing Keplerian ellipse



μ = Earth Gravitational Constant = 1.4087×10^{16} ft³/sec²

h_{CO} = Cut-Off Altitude, ft

V_{CO} = Cut-Off Velocity, ft/sec

θ_{CO} = Cut-Off Angle, rad

ϵ = Ellipse Eccentricity

ϕ = Angular Range, rad

R_e = Earth Radius = 20.925×10^6 ft

H = Maximum Altitude, ft

t_f = Flight Time (Cut-Off to Reentry), sec

R_s = Surface Range, km

R_{CO} = $R_e + h_{CO}$

$$\epsilon = \sqrt{\left(\frac{R_{CO}\,V_{CO}^2}{\mu} - 1\right)^2 \cos^2\theta_{CO} + \sin^2\theta_{CO}}$$

$$\phi = 2\tan^{-1}\left[\frac{\sin(2\,\theta_{CO})}{\frac{2\mu}{R_{CO}\,V_{CO}^2} - 2\cos^2\theta_{CO}}\right]$$

$$R_s = 0.0003048\,R_e\phi$$

$$H = h_{CO} + R_{CO}\left\{\left(\frac{\epsilon}{1-\epsilon}\right)\left[1 - \cos\left(\frac{\phi}{2}\right)\right]\right\}$$

$$t_f = \frac{2}{\sqrt{\mu}}\left(\frac{R_e + H}{1+\epsilon}\right)^{3/2}\left\{\pi - \left[2\tan^{-1}\left(\sqrt{\frac{1-\epsilon}{1+\epsilon}}\tan\frac{\phi}{2}\left(\pi - \frac{\phi}{2}\right)\right) - \frac{\epsilon\sqrt{1-\epsilon^2}\sin\left(\pi - \frac{\phi}{2}\right)}{1 + \epsilon\cos\left(\pi - \frac{\phi}{2}\right)}\right]\right\}$$

$$\theta_{CO_{opt}} = \frac{1}{2}\cos^{-1}\left[\frac{1}{\frac{2\mu}{R_{CO}\,V_{CO}^2} - 1}\right]$$

c. Trajectory relationships

Figure 5. Concluded.

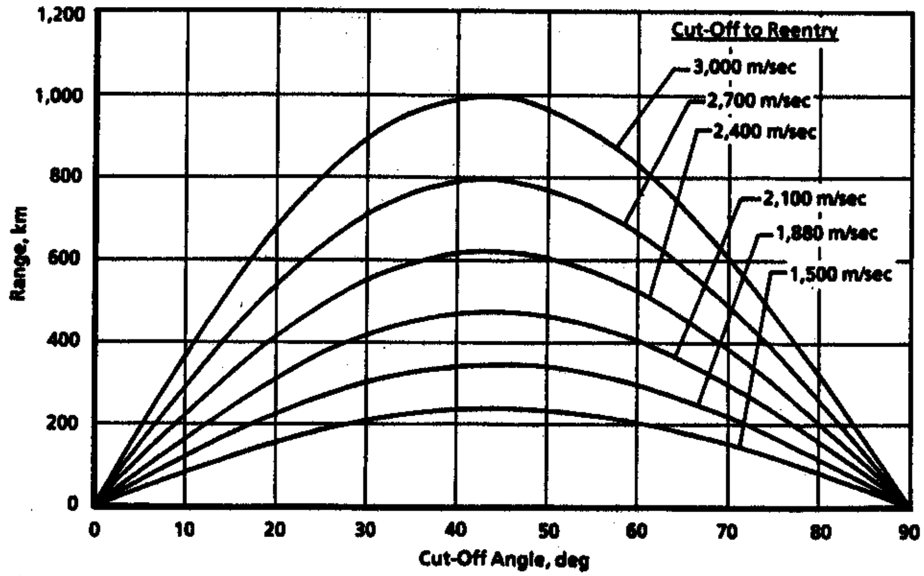


Figure 6. Range as a function of cut-off angle for various cut-off velocities.

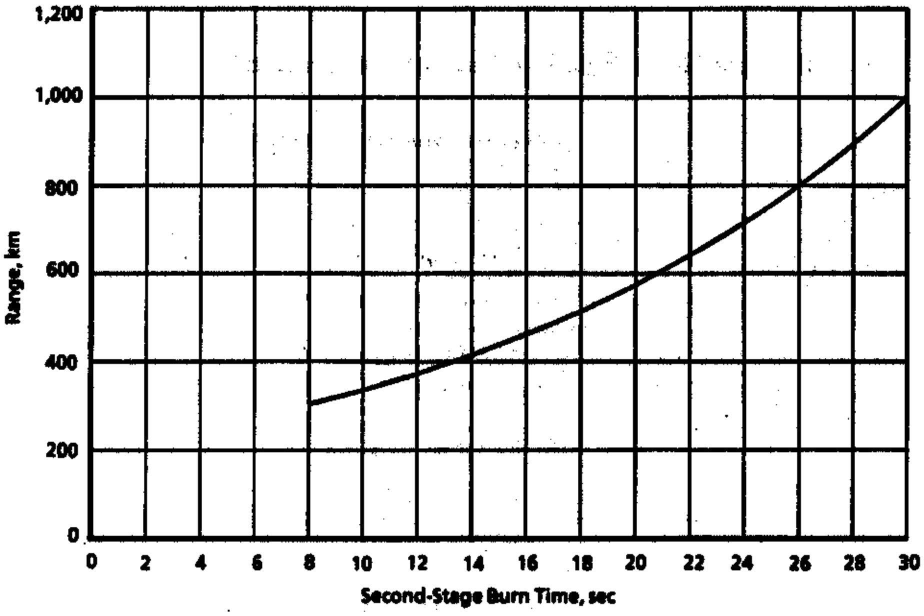
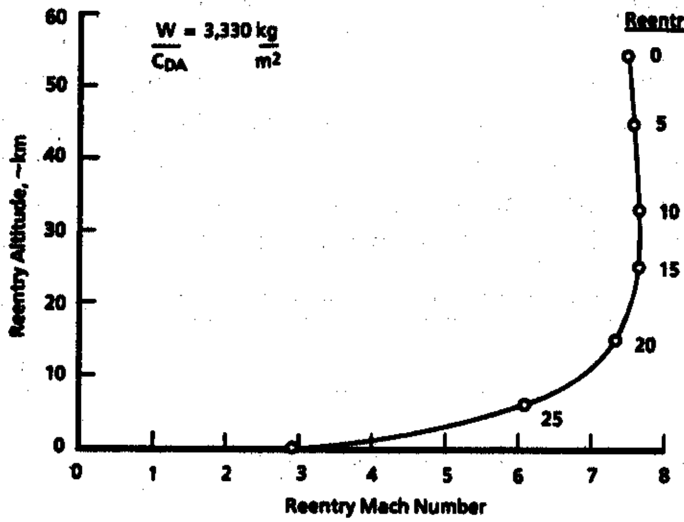
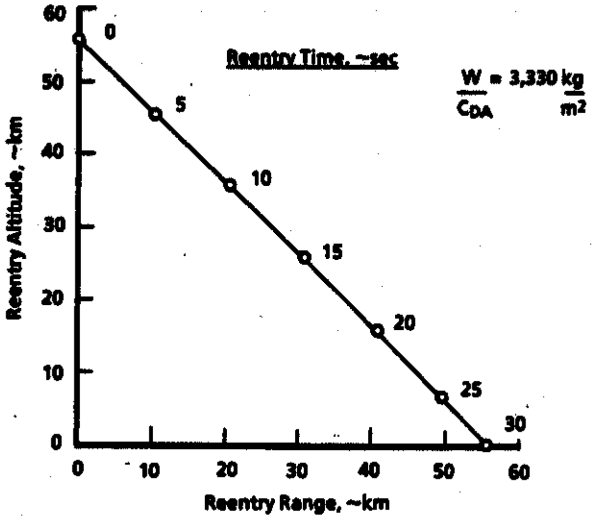


Figure 7. Range as a function of second-stage burn time.

The warhead and fuse are housed in a supporting structure and collectively form the reentry vehicle. The reentry vehicle should be separated from the boost vehicle shortly after thrust termination. In addition to affording a more aerodynamically reproducible and stable flight vehicle, the separated reentry body presents a much lower radar cross section than the spent propulsion stage. A fairing may be used to adjust the ballistic coefficient (W/C_DA) of the reentry body to a desired value. Low-drag, high-weight (high ballistic coefficient) bodies reenter at high velocity and decelerate at low altitudes. They, therefore, have less dispersion from aerodynamic influences and are harder to intercept by antiballistic missiles. Although the reentry body heating rate is proportional to the reentry velocity cubed, SRBM velocities are low enough that nose-tip heating can be easily handled. With a typical 30-deg included angle conic configuration, the impact Mach number will be 2.90. The reentry Mach number (at 55-km altitude) is 8.75. The payload Mach number is above 5.0 for all altitudes above 3 km as shown in Fig. 8. The maximum heating rate for this reentry warhead is 14 percent of the



a. Mach number



b. Reentry range

Figure 8. Reentry Mach number and reentry range as a function of altitude for 1,000-km range SRBMs.

rate for an ICBM, and the total heat input to the SRBM reentry body is 17 percent of that for an ICBM reentry with the same ballistic coefficient.

It is extremely difficult to combine all of the ingredients of a ballistic missile into an effective military weapon using a high-explosive (HE) warhead because of the relatively small area of destructive blast-overpressure for conventional high explosives. The warhead weight is, therefore, made as large as possible to be compatible with a transportable mobile missile. The objective of missile designs discussed herein is to approach 1-metric-ton warhead size in a missile with a launch weight less than 11 metric tons. For the purpose of discussion in this report, the payload weight of 1 metric ton (2,205 lbm) was selected.

Payload weight is a significant design parameter in the ballistic missile. It has a sensitive relationship to the cut-off velocity and range as shown in Fig. 9. For the 1,000-km-range SRBM, doubling the payload weight (constant propulsion package) decreases the range by 52 percent, whereas halving the payload weight increases the range by 76 percent. Target destruction capacity is intractably linked with payload weight and targeting accuracy.

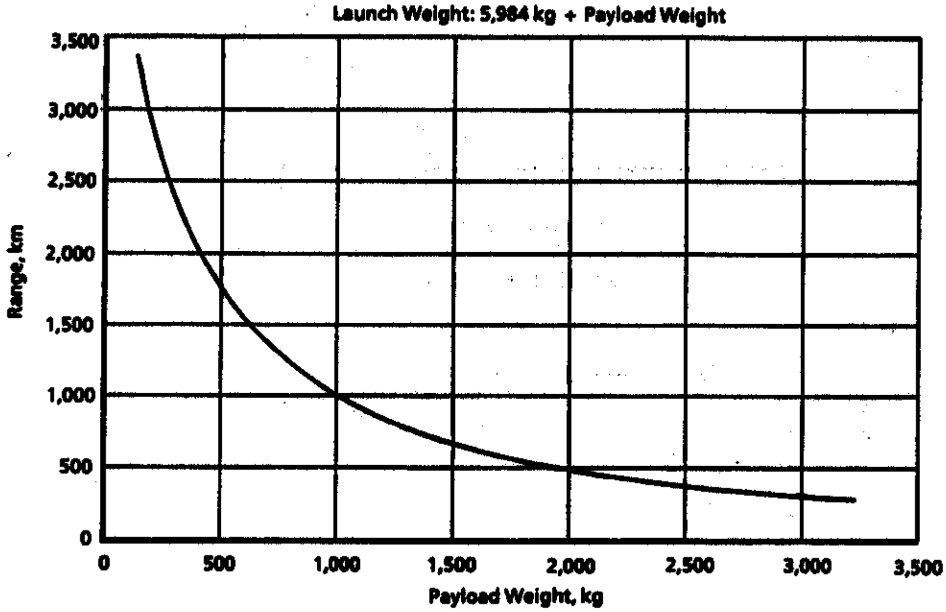


Figure 9. Payload weight effect on range.

2.2 INERTIAL GUIDANCE SYSTEM (IGS)

Inertia is the property of matter that opposes change of motion. Inertial guidance uses this property to detect and measure linear accelerations and rotations and thus arrive at velocity change and position displacement from some known initial state.

The type of inertial instruments normally employed in ballistic missiles to measure accelerations and rotations are accelerometers and gyroscopes (henceforth, gyros). Since the range and the accuracy requirements of various missiles differ considerably, so too will the number, refinement, and complexity of the inertial components needed. An SRBM will usually carry fewer and coarser instruments than a long-range ballistic missile.

Guidance is usually understood to include navigation, stability, and control. Navigation is only a part of the guidance process. A guidance system integrates the process of measurement and computation to produce steering and engine control signals. By the use of the same (or an additional set of) gyros used for angular measurement, vehicle stability may be provided through a servo feedback system to the thrust vector control system. With such a system, the vehicle need not be aerodynamically stable, and external air vanes may be eliminated. Both static and dynamic stability are provided by the guidance-thrust vector-servo feedback control system. This control system reduces the sensitivity of the missile to distrubing influences such as wind gusts, thrust misalignment, and signal noise. With the control system linked to the digital computer, it is possible to give the TVC actuator inputs not only proportional to missile deviation from the desired attitude, but also proportional to velocity and acceleration of this deviation. This so-called proportional feedback causes the TVC to react aggressively to rapid deviations.

Navigation consists of computing the present state of the vehicle from measured values of selected physical quantities. Given a prior knowledge of time, the gravitational field, and the launch position, an inertial navigation system (INS) is capable of indicating its present position without the aid of external information. The system uses accelerometers and gyros to measure acceleration and angular velocity with respect to inertial space. Velocity is given by the first integration of acceleration with respect to time. Distance (position) is given by the second integration of acceleration with respect to time.

The simple principle that position is given by the double integration of acceleration places four basic requirements on any inertial navigation system. First, the system must store the reference frame in which the acceleration measurements are to be taken. Second, the system must measure acceleration components in the stored frame. Third, because the measured acceleration is the vector difference between gravitation and inertial acceleration, the system must have prior knowledge of the gravitational field to compute inertial acceleration from the measurements. Fourth, the system must perform the double integration. The first requirement is made possible by the use of gyros. After initial alignment of the stored reference frame, the gyros will measure any future angular velocity of the frame with respect to inertial space. The second requirement is performed by the accelerometers. The third requirement for knowledge of the gravitational field can be provided analytically by a computer. The fourth and final requirement for double integration can be provided by a computer or by geometeric computation.

Position is deduced from physical measurements through either analytic or geometric computations or a combination of both. The techniques used to track the coordinate systems (or reference frames) define a classification for inertial navigation systems. The two basic reference frames are the inertial frame and the navigation frame. If the two basic frames are physically instrumented in a gimballed system, the INS is classified as a geometric or gimballed system. If the basic reference frames are calculated analytically, the INS is classified as an analytic or strapdown system. If a combination of the gimballed system and a strapdown system is used, the INS is classified as a semianalytical system.

The gimballed system has been used frequently because it has the most highly developed technology. It consists of three single-degree-of-freedom gyros and three accelerometers mounted on a platform in such a way that the input axes of each trio of instruments are mutually perpendicular, sensing motion about or along the X (roll), Y (yaw), and Z (pitch) axes of the inner gimbal as shown in Fig. 10. The gyros and associated servo loops drive the inner, middle, and outer gimbals to maintain instrument stability regardless of vehicle angular motion. Each gimbal has an electromechanical readout device, such as an Autosyn®, to measure gimbal position. These gimbal angles, along with acceleration data, are used as inputs to a computer that generates navigation information, guidance commands, and compensation for inertial-sensing errors. Compensation is necessary because no one has yet made a perfect instrument. Systematic gyro and accelerometer errors can be predicted, however, so it is possible to compensate for them during operation. Gimballed inertial systems are used in a wide range of applications: land vehicles, aircraft, ships and submarines, and missiles. In general, a gimballed system is preferred for high accuracy if cost is not a driving factor.

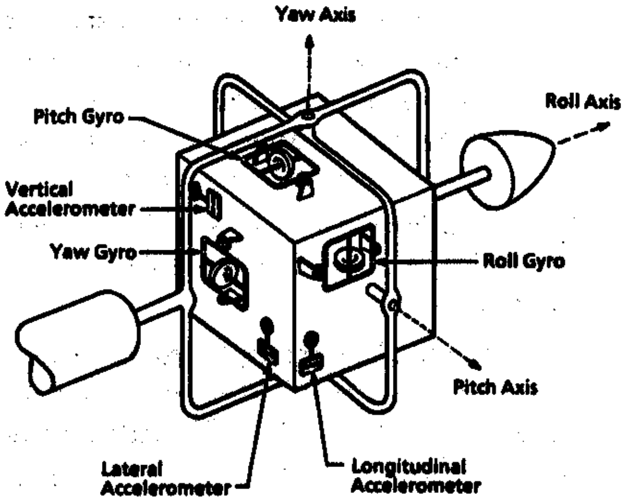


Figure 10. Gimballed inertial navigation system.

As its name implies, a strapdown system mounts all of the sensors directly onto the vehicle structure. The output of each set of sensors (gyros and accelerometers) is body angular rotation about the X, Y, and Z axes, or acceleration along those axes. These data are supplied to a digital computer that, in addition to its normal guidance, navigation, and control functions, converts body-referenced information to a suitable navigation frame. Strapdown systems gain mechanical precision and reduce manufacturing costs at the expense of a more complex digital computer. Given the present capability of microprocessors, the need for a complex digital computer should not be considered a deterrent. A sophisticated computer provides the means of compensation for a wide variety of performance variables such as atmospheric density and winds, and known gyro drift rates. The digital computer can also serve as the gravity resolver, coordinate vehicle stability and control, provide fusing and arming commands, and account for vehicle motion on a rotating Earth (coriolis acceleration).

The basic principles of inertial navigation indicate a requirement for initial alignment of any inertial system. The reference frame must be aligned, and the coordinates of initial position must be known. Given an approximate alignment, the system itself can be made to find these directions while at rest by functioning as a damped vertical indicating system and a gyrocompass, respectively as described in Ref. 3.

The inertial guidance system is generally housed in a module located between the propulsion system and the payload. The guidance system is composed of gyros, accelerometers, a digital computer, a power supply, and necessary associated equipment. The key elements of any inertial guidance system configuration are accelerometers and gyros. Gyros track (and sometimes control) the orientation of the accelerometers. The three-axis reference needed to track orientations in three-dimensional space can be provided by either three single-degree-of-freedom gyros or two, two-degrees-of-freedom gyros, or a combination thereof. Accelerometers and gyros for ballistic missiles are discussed in the next two sections. Much of these discussions were adapted from Ref. 4.

2.2.1 Accelerometers

Acceleration is a vector quantity characterized by both direction and magnitude. An accelerometer is a device that measures acceleration in a specific direction. Gyros are the devices by which the INS determines the direction in which the acceleration is measured. Accelerometers are the primary sensors in a ballistic missile INS. Velocity, altitude, and range are provided instantaneously by single and double integration of the accelerometer's measurements. The limiting factor in ballistic missile accuracy is often the accuracy of the acceleration measurement.

Two prime forces act on the accelerometer. One is the force of gravity; the other is the inertial-reaction force caused by any changes in velocity, primarily from the propulsion system. An important point of inertial guidance is that the accelerometer cannot distinguish between the force of gravity and an actual acceleration. Acceleration caused by the force of gravity must be determined analytically from models of Earth gravity as a function of position.

Accelerometers for missile applications do not differ greatly from those required for aircraft use. Aircraft inertial navigation systems, in some cases, can be used directly in cruise missiles. Before they can be used in ballistic missiles, however, such systems would require major modifications because of the high accelerations occurring during the rocket-powered flight.

If three single-axis accelerometers are mounted so that their input axes are orthogonal, and if the accelerometer assembly is referenced to a coordinate system that can be maintained or defined in a precision manner, any acceleration of this assembly can be resolved to define an acceleration vector. It does not matter how the orthogonal axes are oriented, as long as their orientation is known. Gyros track (and sometimes control) the orientation of the accelerometers. The three-axis reference needed to track orientations in three-dimensional space can be provided by either three single-degree-of-freedom gyros or two, two-degrees-of-freedom gyros, or combinations thereof. The accelerometers are mounted to the gyro reference package, which provides a defined reference direction for the measured acceleration vector. The calculational process for inertial navigation consists of computing net acceleration (as the difference of measured specific force and calculated gravity in three dimensions), obtaining changes in vehicle velocity and position by integrating the acceleration, and updating the velocity and position by adding these changes to the initial-condition values.

The field of accelerometry is not new, and a great number of devices for measuring static and dynamic acceleration are in use. Many different methods can be used to measure this value. The choice of method depends mainly on the frequencies present, whether or not acceleration is changing, and the type of output desired.

Types of Accelerometers: Two principal types of accelerometers are open-loop and servo force-balance. In open-loop accelerators, the inertial reaction force of the mass causes a displacement of the mass in an elastic mounting system. The displacement is then measured by any of several methods. Figure 11 shows a simple accelerometer. If the base of the accelerometer is accelerated in a direction parallel to the springs on which the mass is mounted, the mass will tend to remain at rest, and the wiper attached to the mass will move along the resistor. This movement will cause the resistance and the current through the circuit to change. When the unit is moving at a constant velocity, the mass will be centered and no acceleration signal will be developed. The movement of a mass can be used to operate a variable capacitor or a variable inductance or to change the coupling between two circuits to produce an electric output suitable for a navigation signal.

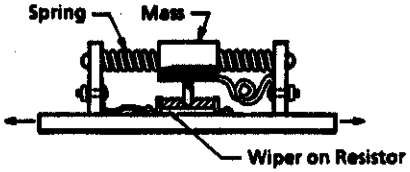


Figure 11. Simple accelerometer.

The second type of accelerometer, the servo force-balance type, operates on a fundamentally different principle. The force that counteracts the inertial reaction force of the mass is supplied by an electric current. In this system, when a small deflection of the mass is detected, a force is instantly applied to the mass to prevent any further motion. Acceleration is indicated by the magnitude of the force that must be applied to the mass (by the electric current or whatever other means is used) to prevent deflection of the mass.

Restrained pendulum/mass, force-balance accelerometers are likely choices for Third World use. These devices are available and inexpensive on the commercial market. The restrained pendulum force-balance accelerometer is a common type used for inertial navigation. It takes the form of a pendulum suspended inside a case by means of a pivot that constrains the pendulum to swing about a single axis, with force coils to hold the pendulum in the null position. This pivot must be frictionless and often takes the form of a thin quartz hinge. A coil fixed to the pendulum is placed in the field of a permanent magnet fixed to the case, and current through the coil produces a force on the pendulum. An electromagnetic pickoff device senses the position of the pendulum (Fig. 12). When the instrument case is accelerated along the direction normal to the pivot axis, the pendulum tends to lag behind. The resulting displacement is sensed by the pickoff, whose output is amplified and applied to the force coil as a current to return the pendulum to the neutral position (null). When at null, the force caused by the coil counteracts the force caused by acceleration; thus, the current gives a direct measure of acceleration.

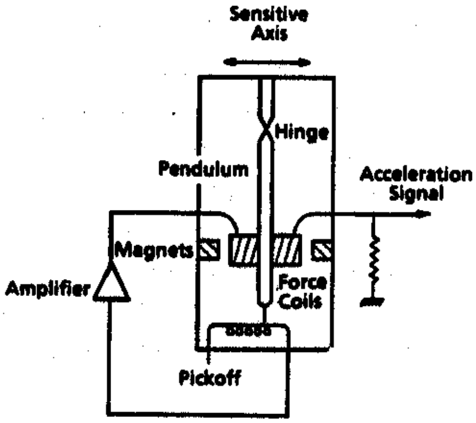


Figure 12. Pendulous force-balance accelerometer.

2.2.2 Gyros

Gyroscopes, or simply gyros, have been employed as navigation aids since the early part of the 20th century. Elmer Sperry produced a gyrocompass in the U. S. in 1911. Gyros have been used in aircraft artificial-horizon indicators for decades. The most common type of gyro is a precisely balanced flywheel rotating with high angular velocity about a spin axis through its center of gravity. Most people are aware of the behavior of a gyro — the rapidly rotating flywheel tends to maintain its spin axis in a fixed direction and displays an unexpected "resistance" when an attempt is made to rotate this axis. Gyros have two important characteristics that make them useful in inertial guidance systems (IGS), gyroscopic inertia and gyroscopic precession.

Gyroscopic Inertia. What makes the gyro useful as a reference or sensor in controlling the flight of a missile is its characteristic of rigidity in space. Rigidity, or gyroscopic inertia, is the property of a gyro that resists any force tending to displace the rotor from its plane of rotation. Three factors determine a gyro's rigidity: (1) the mass of its rotor, (2) the distribution of this mass, and (3) the speed at which the rotor spins. Rigidity can be increased by adding to the mass of the rotor (a gyro with a heavy rotor has more rigidity than one with a light rotor for a given speed of rotation); by distributing the mass of the gyro to the outer rim of the rotor as far from the spin axis as possible without increasing the mass; and, by increasing the speed of rotation (a slowly spinning rotor gives the gyro little or no rigidity).

Gyroscopic Precession. Gyroscopic precession, the other important characteristic of a gyro, is the property of a gyro that causes the rotor to be displaced, not in line with an applied force, but 90 deg away from the force and in the direction of rotor rotation. This behavior demonstrates a basic law governing a body rotating about its center of gravity. When disturbed, the gyro axis turns not in the plane of the applied force but in a plane perpendicular to it. This law of gyroscopic precession is a reversible one. Just as a torque input results in an angular velocity output, an angular velocity input results in a torque output along the corresponding axis. It is the knowledge of how torque, precession rate, and angular momentum are predictably related that allows a gyro to be an inertial reference. This property of reversibility also allows a gyro to be torqued to provide a desired pitch program for flight-path control.

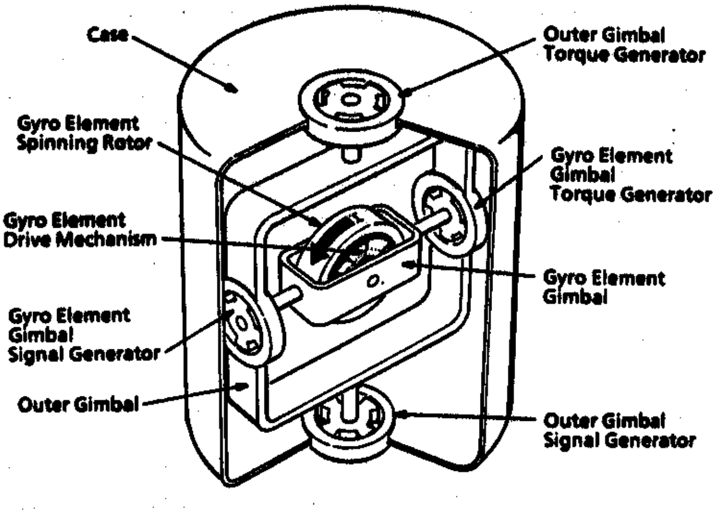


Figure 13. Elements of a two-degree-of-freedom gyro.

Gyro Classification. A common way to classify gyros is by degrees-of-freedom. Another classification method is to specify what the gyro measures. Rate gyros (single-degree-of-freedom) measure angular velocity; displacement gyros (two-degrees-of-freedom) measure angular rotation. The two-degrees-of-freedom gyro, shown in Fig. 13, is characterized by a support that permits the spin axis to have two degrees of rotational freedom. The single-degree-of-freedom gyro has no gimbal other than that of the gyro element. Such a gyro operates by nulling the torques applied about the output axis, rather than by the geometrical freedom of the two-degrees-of-freedom gyro. The single-degree-of-freedom is called a rate gyro if the primary restraining torque is elastic. If the primary restraining torque

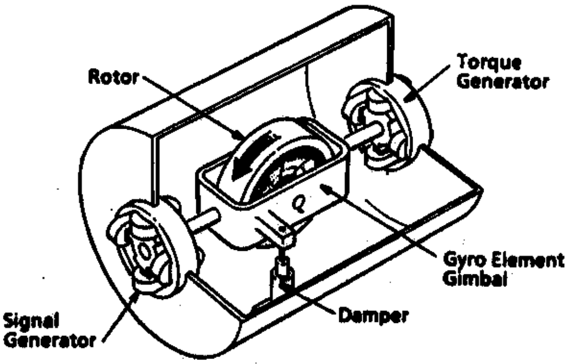


Figure 14. Essential elements of a single-degree-of-freedom integrating gyro.

is a damping reaction, as shown in Fig. 14, it is called an integrating gyro. The term, integrating, refers to the fact that the output (deflection of gyro element relative to the case) is a measure of the integral of angular velocity — that is the angular change. The deflection angle of the rate gyro is a measure of angular velocity and requires additional hardware or a computer for the integration to give angular change. Integration is a mathematical term for summing up. If the bits of angular velocity over a given time span are summed up, the result is the total angle traveled. That is what happens in an integrating gyro. The angular velocity about the input axis is summed up, or integrated, about the output axis. The gimbal axis puts out a signal proportional to the integral of the input axis angular velocity.

A stable platform is an example of a three-degrees-of-freedom system. A three-degrees-of-freedom system can be built with two, two-degrees-of-freedom gyros and a directional gyro, or three single-degree-of-freedom gyros. The angle-measuring devices on a stable platform measure deviation about three mutually perpendicular axes that form a space-stabilized coordinate system. Since the pickoffs on a gyro measure angles, not linear distance, they measure the amount that the support structure has rotated, not translated. These angles are measured about a stabilized reference line and are located with respect to three mutually perpendicular axes. The latter are conventionally called roll, pitch, and yaw; the angles through which the missile rotates about these axes are called roll angle, pitch angle, and yaw angle.

Gyroscopic Drift. Since gyros provide references for navigational, guidance, or stabilization purposes, a reference must be either inherently invariable or predictably variable. Hypothetically, the spin axis of an ideal gyro, when not acted on by external forces, remains immobile in inertial space. "Inertial space" simply means a system of coordinates that is unaccelerated with respect to "fixed stars." However, actual gyros do not maintain absolute immobility but deviate from their initial fixed position. The rate of deviation is a measure of gyro performance — the lower this "drift" rate, the better the gyro. Gyroscopic drift rate is the single most important figure-of-merit describing the performance of a gyro.

Drift errors are undesired motions caused by design limitations or construction deficiencies in a gyro. Precession-axis drift sources are inherent parts of the gyro design, e.g., in the precession axis supports, electrical flex leads, mass unbalance, and electrical reaction torques.

A gyro often becomes dynamically unbalanced when operating at a speed or temperature other than that for which it was designed. Some unbalance exists in any gyro, since manufacturing processes do not ensure perfect symmetry.

Examples of specific design considerations are bearings, anisoelasticity, and gimbal imperfections. Friction in gimbal bearings results in lost energy and incorrect gimbal positions. Friction in spin-axis bearings causes drift only if the friction is not symmetrical. An even amount of friction all around in a bearing results only in a change of the rate of rotation. Anisoelasticity of a structure is defined as nonuniform elastic deformation that varies with the angle at which a load is applied. This anisoelastic effect in a gyro rotor bearing produces a torque that can be sensed by the gyro, causing a drift error.

Although a gyro appears to be mounted rigidly in its metal gimbals, any metal structure is somewhat unrigid. It acts like a very stiff spring, which means that the construction will yield and give under sufficient force. If the spring constant is the same in all directions, the mass shifts along the line of acceleration during the acceleration, and no torque is produced. However, it is virtually impossible to design such a mechanical structure. The term given to the structure with equal spring constants in all directions is isoelastic, but generally a gyro structure is nonisoelastic or anisoelastic. Anisoelasticity causes the gyro rotor to deflect along a line not coincident with the line of acceleration. Consequently, the line of force resulting from the acceleration acting on the rotor mass does not pass between the rotor center of gravity and the gimbal axis, and this offset results in a torque about the gimbal axis. Under vibrations, the torque is rectified, and a constant undesirable error is present because of the anisoelasticity. This effect is particularly serious since it varies not with the first power of acceleration but with the square of acceleration and will therefore be especially troublesome during high acceleration.

The complete elimination of drift in gyros appears to be an impossibility. However, great strides have been made in recent years toward reducing the amount of drift. Gyroscopic drift is usually measured in terms of drift rate, which is expressed as a measure of displacement per unit time. The most widely used unit for gyroscopic drift is degrees per hour (deg/hr).

Hermetically Sealed Integrating Gyros (HIG). Gyros used for ballistic missile guidance are built around a comparatively large, high-speed rotor capable of tremendous angular momentum and supported on microfriction (less force than the weight of a flea) gimbal bearings. The single-degree-of-freedom floated integrating gyro is a popular choice for ballistic missile applications and is often referred to as a hermetically sealed, integrating gyro, or HIG.

Figure 15 shows a cutaway view of an HIG gyro. The gyro rotor is part of a synchronous motor, the stator of which is mounted in a cylindrical, hermetically sealed can filled with an inert gas, with the spin axis across the diameter of the can. The sealed can is mounted inside an outer case by means of pivots at each end of its long axis. Rotational displacement of the can about this axis is sensed by a pickoff system, and a set of coils fixed to the can react with magnets set on the outer case, providing control torque about the can axis.

If the outer case is rotated about an axis perpendicular to the spin axis and the can axis, torque is applied via the can pivots to the rotor. This produces a gyroscopic torque about the can axis, causing the can, with the rotor, to rotate about that axis. The pickoff senses this rotation and produces an output signal. In accordance with Fig. 15, the rotor axis is termed the *spin axis*, the can axis is the *output axis*, and the orthogonal axis about which the gyro is sensitive to rotations is the *input axis*.

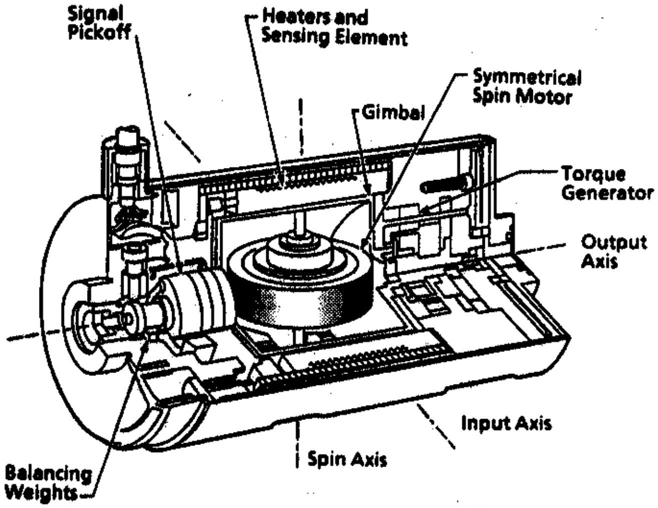


Figure 15. Hermetically sealed integrating gyro (HIG).

The gyro operates by using can rotation as an indication of the sum of the torques acting about the output axis. Thus, these torques must be known, and any indeterminate source of torque must be eliminated to the extent possible. A major source of error torque is friction at the can pivots. A major breakthrough in gyro technology came with the idea of filling the space between the can and the outer case with a fluid whose density was the same as the mean density of the can and the gyro rotor. When this is done, the can is neutrally buoyant and is supported against gravity and other acceleration forces by the fluid. The pivots carry no gravitational load and thus introduce almost no frictional torque. This simple concept, the floated gyro, improved gyro performance by several orders of magnitude.

The flotation fluid in a floated gyro has some viscosity, which has the effect of modifying gyro behavior. When the gyro is subject to a rotation about the input axis, the rotor reacts with a torque about the output axis proportional to the input rate. The can accelerates in response to this torque, but the relative motion between the can and the case produces a viscous drag torque because of the fluid. This torque is proportional to the angular rate of the can. With no other torque being applied, a steady state is reached in which the gyroscopic torque is balanced by the drag, the output angular rate is proportional to the input rate, and the output angle is proportional to the integral of the input rate, hence the term "integrating gyro."

Although the inclusion of the flotation fluid brought about a major improvement in the performance of gyros, it was not without its own penalties. Both the density and viscosity of the fluid are functions of temperature, and to achieve flotation the gyro has to be operated at a constant temperature. Heaters maintain this temperature, which has to be considerably above normal operating ambient temperature, typically 70°C. The power and time required to bring the system up to operating temperature constitute one of the drawbacks of this type of gyro.

When operated in a stabilized platform system, the gyro is used in a servo mode. The gyro is mounted in a gimbal with its input axis parallel to the gimbal axis. A motor can rotate the gimbal about this axis. Any rotation of the gyro case about its input axis produces an equivalent rotation of the can about its output axis. The resulting pickoff signal drives the motor in the opposite direction, canceling the applied rotation. Thus, the gimbal remains space-stabilized despite external disturbances.

If a torque is applied about the output axis of the gyro by means of the torque coils, then initially an input rotation will produce a rotation of the can, but the pickoff signal will drive the motor as before. When the gyroscopic torque balances the applied torque, a steady state is reached in which the gimbal is rotating at a rate proportional to the applied torque coil current. In this way, gimbal orientation can be controlled.

Dynamically Tuned Gyros (DTG). The floated gyro has reigned supreme for many years and has been developed to incredible accuracies. The floated gryo is currently used in many U. S. and foreign ICBM missile systems because of its high accuracy. However, the presence of the flotation fluid makes repair difficult, and many faults, particularly those affecting performance, are not detectable until the whole gyro has been built, thus making repair costly. It was in part the aim of finding an alternative, nonfloated gyro that led to the development of the dynamically tuned gyro (DTG), sometimes called the dry-tuned gyro.

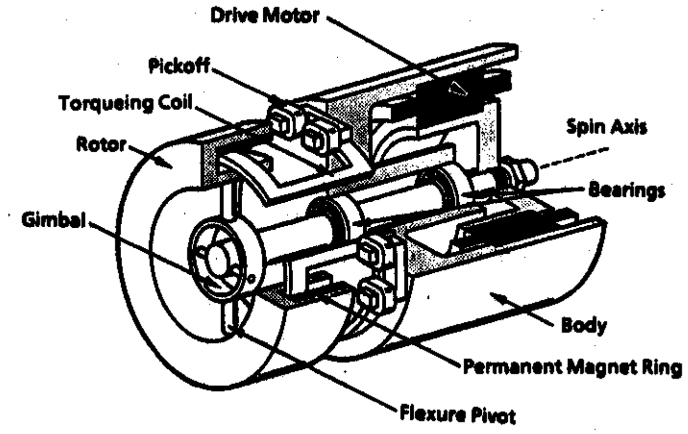


Figure 16. Cutaway of a dynamically tuned gyro (DTG).

Figure 16 shows the general construction of a DTG. The gyro rotor, separate from the motor, is supported on the motor shaft by means of a flexible joint, which allows the rotor to move relative to the shaft about axes normal to the shaft. The flexible joint is torsionally stiff, providing the torque for spinning up the rotor. The flexible joint has two sets of

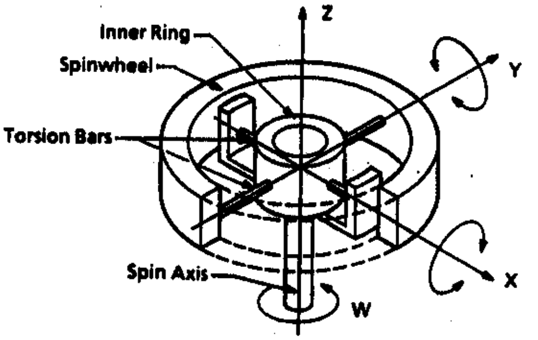


Figure 17. Example of a DTG flexible rotor.

pivots spaced at right angles with an intermediate gimbal between them as shown in Fig. 17. This flexible joint arrangement is called a Hooke's joint after Hooke's Law for stress proportional to strain. The pivots usually take the form of crossed springs, eliminating friction but introducing torques on the rotor when it is displaced from the postion normal to the shaft. This means the rotor will tend to follow any displacement of the shaft, and the directional memory will be lost. However, when the rotor is displaced, the intermediate gimbal is forced to oscillate one cycle for each half-rotation of the shaft. This motion imposes additional torques on the rotor, transmitted via the torsion bars, that act to increase the deflection from the normal attitude; i.e., they appear as negative spring torques. The magnitude of this effect is a function of the wheel speed and the relative moments of inertia of the gimbal. For any given design, there is a particular wheel speed at which the spring torque is balanced by the dynamic torques, and the rotor behaves as if it were freely suspended from the shaft, with the plane of the rotor defining a fixed direction in space. This speed is known as the "tuned" speed, hence the term "dynamically tuned gyro." The displacement of the rotor from the position normal to the shaft is detected by two sets of pickoffs, which sense the angular displacement about two orthogonal axes. The gyro is thus a two-axis sensor, unlike the floated gyro. Two sets of torque coils, also set at right angles, react with magnets set in the rotor to provide control torques, as in the case of the floated gyro.

The DTG approaches the performance of the best single-degree-of-freedom devices. Its construction is simple because of the absence of fluid, which eliminates the need for a sealed float, and it is possible to build and test the rotor and shell as separate entities. This leads to a considerable reduction in manufacturing costs. Since the DTG is a two-axis sensor, only two gyros are required for a system, rather than three single-axis devices. This makes the unit more cost-effective and reduces the size of the cluster and the gimbal system.

Missile Stability. In addition to the angular deflection measurements required for guidance, the ballistic missile needs a rate of angular deflection for smooth, accurate control of vehicle position and for vehicle stability. This rate-of-deviation can be supplied by a rate gyro or by the guidance computer system from integrating gyro measurements. The thrust vector control system is used to effect both missile control and stability. Artificial stability is of prime importance to ballistic missiles without external air vanes.

Initial Alignment. An inertial system's usefulness depends largely on the accuracy to which its stable platform can be aligned initially. A self-contained alignment capability within the system is desirable, particularly for an SRBM, when speed and accuracy are equally essential. Using the same inertial sensors that stabilize the platform makes it possible to devise a gyrocompassing system that is fundamentally an automatic self-contained method for establishing true heading. A gyro-stable platform can be implemented in a number of ways to perform gyrocompassing.

A gyrocompass senses the Earth's rotation and uses that information to process the gyro until its spin axis is coplanar with the Earth's axis. Such an instrument is distinctive in its ability to indicate true geographic north independent of the Earth's magnetic field. Gyrocompassing is not an instantaneous function but requires time to reach a fair degree of accuracy. Alignment time depends on such factors as initial conditions, alignment loop gain, and damping. Portable gyrocompassing instruments have been developed that determine north with a degree of accuracy comparable to that obtained by means of star observations; they are commonly used for establishing base lines and heading data for mobile missile units.

2.2.3 System Configurations

Inertial Gimballed Platform Technology. A simplified diagram of a basic, gimballed platform inertial measurement unit (IMU) is shown in Fig. 18. Three single-axis accelerometers are mounted on the stabilized cluster, whose orientation in space is controlled by three single-degree-of-freedom, rate-integrating gyros. The cluster is supported in a set of three gimbals, each having a drive motor controlled by the gyro signals.

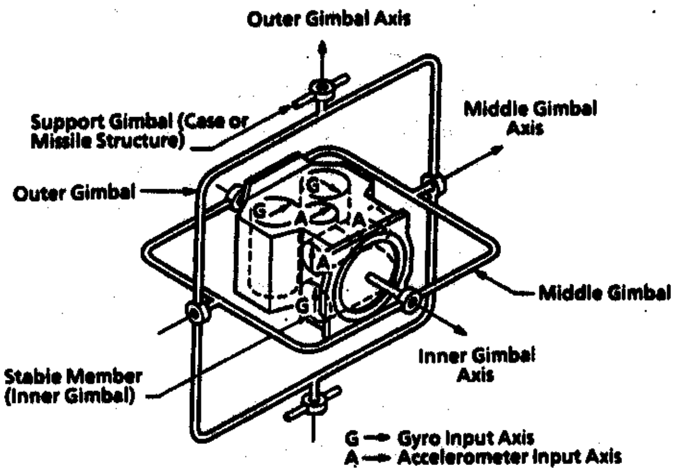


Figure 18. Gimballed platform inertial measurement unit.

The three gyros generate signals proportional to the angular displacement of their cases in space. The displacement signals become attitude-error signals for the servo electronics that drive gimbal-axis torque motors to keep the inner gimbal spatially nonrotating in spite of the rotations of the missile and the stable-platform support structure. The platform will hold an orientation in space established by an initial alignment process accomplished on the ground before launch. The angular rotations are the components of missile angular motion with respect to the reference orientation determined by the prelaunch alignment. These are the roll, pitch, and yaw rotational outputs of the inertial-sensing system. The translational outputs are the acceleration components measured by the accelerometers mounted on the nonrotating platform.

A complete stabilized platform, inertial navigation system consists of (1) a stable platform on which longitudinal and lateral accelerometers are mounted; (2) two or three gyros mounted so that they will signal corrections for pitch, roll, and yaw; (3) integrators to determine, from accelerometer signals, displacement and distance traveled; and (4) a computer that continuously solves the navigation problems. The computer uses the information from the integrators to determine the position of the vehicle and the distance and direction yet to be traveled.

The computer calculates velocity and position information from the accelerometer outputs; computes gravity; calculates Earth rotation; stores the missile's prescribed course; acts as a time reference; and gives steering, engine cutoff, and prearm commands to the missile system. Early inertial navigation systems employed analog techniques to perform navigation calculations, but the accuracy required of guidance computers stretched the state-of-the-analog-computing art. Generally, an overall accuracy of 0.1 percent is required to match the potential accuracy capabilities of the inertial instruments, implying individual accuracies several times better. The development of the miniature high-speed digital computer revolutionized inertial navigation systems. Computing accuracy was no longer limited, and the complexity of the calculations was no longer a major problem. Thus, alternative coordinate systems became more popular since they gave a worldwide operational capability at no extra cost.

The intoduction of digital computers also brought a significant increase in the reliability of inertial guidance systems, which, with complex analog computers, had previously been very low. As digital technology improved, systems could be made smaller, and single-box systems became viable.

Strapdown Systems. Gimballed inertial navigation devices have now reached a high level of sophistication. Many thousands are in military and civil service, and their position error rates are significantly better than one nautical mile per hour (nm/hr). A 1-nm/hr position accuracy requires a gyro of about one-hundredth of a degree per hour (0.01 deg/hr) random drift. However, such systems are still expensive and costly to maintain. One element of the cost is the complex gimbal system, which requires special clean facilities for repair. And although the computer is digital, the gimbal servos generally use analog circuitry, which is less reliable. Any technical innovation that could eliminate the gimbal system is therefore of great interest. Such an innovation is the *strapdown system.*

In a typical strapdown system, the gyros and accelerometers are mounted on a very rigid structure on the host vehicle. Instead of using gyros to keep the accelerometers pointed in a constant direction, a strapdown system allows the accelerometers to rotate with the vehicle and uses the gyros to keep track of where each accelerometer is pointed. Because the accelerometers are no longer oriented along convenient reference axes, the mathematics becomes more complex; but with digital computers, this is no longer an obstacle. A strapdown inertial guidance system from SAGEM that uses miniature gyros and accelerometers and microelectronic circuitry is shown in Fig. 19.

Strapdown inertial navigation systems offer improved reliability, lower costs, and the potential for integration with other flight systems. The keys to strapdown performance are the gyros and the software. Because of these characteristics, the strapdown INS may find wide application as a replacement for attitude and heading reference and attitude or direction indicators in both military and civil land, sea, air, and space systems. Such expanded uses would lead to extensive product markets and rapidly proliferating INS capabilities. In addition, integration of outputs from remote sensors and other instrumentation units through onboard microcomputers may enable new functional applications.

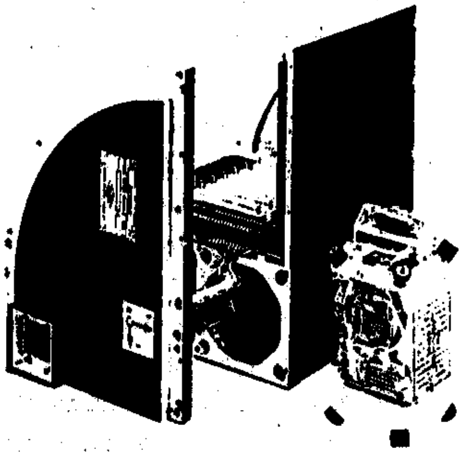


Figure 19. Strapdown inertial guidance system (from SAGEM, France).

2.2.4 New Technology

The traditional gyros discussed in Section 2.2 are being supplemented by a new family of gyros, some of which do not use a rapidly rotating disk. Initially one may consider these new technology devices to be impractical for Third World countries, but the new technology offers some practical advantages in fabrication techniques and, therefore, may offer lower life-cycle costs than traditional hardware.

Ring Laser Gyros (RLG). The earliest ring laser gyros appeared soon after the discovery of the laser itself. Honeywell, with U. S. Navy support, demonstrated the first really workable INS using RLGs in 1975. Since then, development has proceeded apace by many companies in the U. S., U. K., France, Germany, and the Soviet Union. Ring-laser-gyro INSs are now used in civil aircraft, the Boeing 757/767 series, and a number of Airbus Industries A310s.

The RLG, which is an inertial sensor very different from a conventional gyro, is basically simple in its principle of operation but complex in the detail of the physical processes involved.

Its operation is based on the rotation-induced difference in optical path length, which is called the "Sagnac effect." The RLG has an optical cavity, most commonly either triangular or square, with mirrors at each corner. Light, generated by lasing action in the cavity, is propagated in opposite directions. If the RLG is installed in a strapdown INS, missile rotation causes the transit times for the light propagation to differ. The difference in frequency between the two light beams is proportional to the missile rotation rate.

A phenomenon known as "lock-in" results from small amounts of energy from each beam being backscattered into the opposite beam, causing the beam frequencies to pull together. Eventually, when they are sufficiently close in frequency, the two beams synchronize. The main cause of the energy coupling is backscatter from corner mirrors.

The most practical method of circumventing the effects of lock-in was introduced by Honeywell and consists of a technique known as mechanical dither. Dither involves oscillating the lasing ring about its input axis, thereby adding a zero-mean motion to an externally applied rate. The level of the applied oscillation is set at least two orders of magnitude greater than the lock-in rate.

Figure 20 is a simplified sketch of a very basic RLG mounted on its dither mechanism, which is the central cartwheel spring. The closed optical path is formed by drilling narrow bores in a glass ceramic block, chosen for its extremely low thermal coefficient of linear expansion. Four mirrors, which are mounted on the corners of the block, seal the bores. The laser is provided by filling the bores with a low-pressure mixture of helium and neon gases. These are excited by a d-c electrical discharge between the large cathode and a pair of anodes.

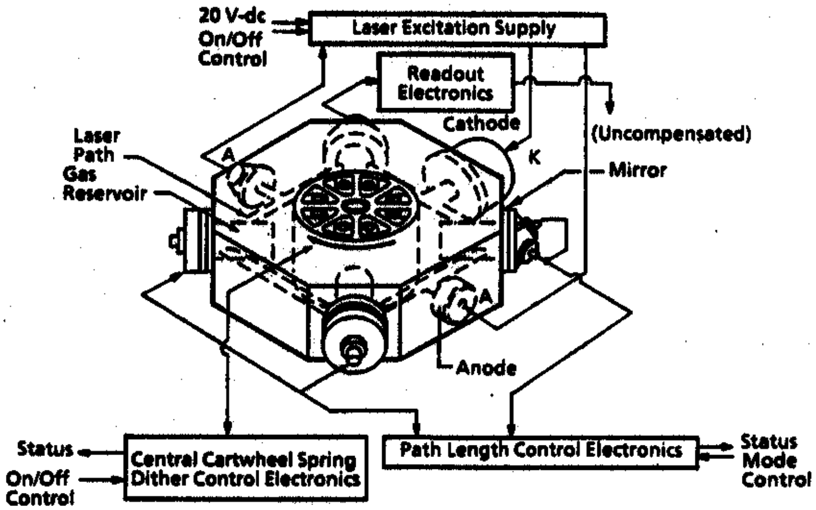


Figure 20. Typical ring laser gyro (RLG).

RLGs are characterized by high reliability with no rotating parts, high acceleration capability, no bearings or fluids, and low operational and maintenance costs. These commendable attributes coupled with the potential for low-cost fabrication using molded cavities and optical surfaces give RLG technology the potential of providing inertial grade gyros at one-third the cost of conventionally produced units. Other low-cost instrumentation technology, innovative assembly techniques, and the development of the molded IMU will further reduce acquisition and life-cycle costs of inertial systems, especially for a short-lifetime SRBM. Transfer of technology in this area could conceivably provide a country with the capability of greatly expanding its use of INS for a given economic investment.

Fiber-Optic Gyros (FOG). The fiber-optic gyro (FOG) is the newest generation of rotation sensors being developed for applications ranging from missile guidance to precision-pointing in space. In principle, it is similar to the ring laser gyro, but it uses optical fiber components rather than gas channels for the light path. The light source is a semiconductor laser diode used in conjunction with a unique wavelength monitor to provide a stable light source. Up to a kilometer of fiber-optic material is coiled in a loop to provide a closed light path. Sensitivity increases with fiber length. Like the ring laser gyro, the FOG operation is based on the "Sagnac effect" where rotation causes a phase shift between counter-rotating light waves, and the optical phase shift results in an interference that changes the detected power.

FOG offers the potential of high reliability with low-cost manufacturing. It is rugged, has few parts, no moving parts, high acceleration capability, and operates at low power and voltage. FOGs are being developed in the U. S., Germany, France, England, Japan, and the Soviet Union.

Electrostatically Suspended Gyros (ESG). The electrostatically suspended gyro (ESG) is a high-precision inertial sensor measuring angular motion in two axes with only a single moving part, the gyro ball. The ESG uses a 1-cm-diam solid or hollow beryllium ball suspended electrostatically in a vacuum. The ball is very precisely machined from beryllium in which three tantalum or indium wires are embedded. These wires are arranged to move the center of mass slightly away from the geometric center of the ball, and the ball therefore wobbles as it spins at about 150,000 rpm by a rotating electric field. This type of instrument is sometimes referred to as a "mass unbalance measurement" or MUM device. Pickoff sensors mounted in the case of the unit detect the motion of the ball and provide analog output signals that vary as the unit itself undergoes any angular motion. A single ESG can detect motion in two axes, and a full three-axis inertial system therefore only needs two of these units.

The unique physical, chemical, and mechanical properties of beryllium make it an ideal metal for gyros, accelerometers, and other components where low-weight, stiffness, and stable dimensions are required. ESGs are available commercially from SAGEM of France. In the U. S., Honeywell is the primary source for ESG instruments.

2.3 ACCURACY

A ballistic missile's target miss distance is expressed by a statistical parameter called circular error probable (CEP). The CEP measure of warhead dispersion is defined as the radius of a circle, at a specific range, in which 50 percent of the warheads will impact. CEP for ballistic missiles is measured in the ground plane.

The guidance system is the major contributor to the missile system error budget. Since the guidance system includes guidance hardware (gyros, accelerometers, guidance system structure, and computers) and guidance software, most of the CEP is budgeted to the guidance system. A large part of the remaining budget is attributed to reentry anomalies. In addition to the accelerometer and gyro errors, the guidance system errors include initial alignment; geodetic and gravimetric; computer round-off, truncation, and numerical integration; and software imperfections and approximations. Geodetic and gravimetric errors consist of launch point position and gravity errors, in-flight gravity errors, and target position errors.

Although position is calculated from accelerometer measurements, the direction of the accelerometers is determined by the gyros. The errors normally associated with gyros are random drift from stray torques caused by manufacturing or environmental sources (temperature, acceleration) and magnetic fields.

It is indeed a formidable task to develop an SRBM with only a few hundred meters CEP. The CEP is fairly insensitive to small errors in cut-off altitude (h_{co}), range (R_{co}), and angle (θ_{co}) but is very sensitive to small errors in cut-off velocity (V_{co}). At maximum range (1,000 km), a cut-off velocity error of one part in a thousand (3.02 m/sec) causes a miss distance of 1,920 m. Obviously, velocity computation and control are very critical. By reducing the velocity error to one part in 10,000, the miss distance is reduced to 192 m. Each accelerometer should be accurate to one order of magnitude better or one part in 100,000. ICBM accelerometers need to be accurate to one part in a million.

The insensitivity to cut-off flight-path angle (θ_{co}) is because, at the optimum angle, the slope of the curve of range versus cut-off angle is zero, as was shown in Fig. 6. For nonoptimum trajectories, CEP is sensitive to cut-off angle errors.

2.4 INERTIAL GUIDANCE COMPONENT MANUFACTURING

Manufacturing quality inertial instruments requires highly skilled personnel paying rigorous attention to detail. The successful development of high-performance guidance and navigation systems can be related to a number of key components as summarized in Table 1.

Table 1. Examples of Key Manufacturing Technologies for Inertial Guidance Systems

Large-Scale Production of Close-Tolerance, Accurate, Miniaturized Components

- Gyros (Dry-Tuned Rotor, Floated, Electrostatic, RLG, FOG)
- Accelerometers (Force-Balance, Pendulous Integrating Gyro)
- Low-Friction Precision Bearings

Precision Production/Calibration Machinery

- Precision Castings
- Bearings
- Slip Rings
- Torquers
- Synchros
- Microelectronics
- Robotics
- Automation
- Plastic Molds
- Fiber Optics
- CNC Machine Tools
- Metrology

Special Tooling for Precise Measurement and Inspection

Controlled Atmosphere ("Clean Room") Manufacturing and Assembly.

2.4.1 Clean Rooms

The necessity of clean rooms is dependent upon the stage of development and sophistication of the current missile technology. In the early years of development, clean room specifications were either nonexistent or minimal compared to the present state-of-the-art. The result in these years was inaccurate or erratic trajectories, malfunctions of components, and a high percentage of failures.

The absolute elimination of dirt or dust, close control of moisture and humidity, and close control of temperature are extremely important in the construction of many SRBM components. A small foreign particle weighing a milligram (one-thousandth) can introduce a drift rate equivalent to one knot in an inertial-grade gyro (Ref. 3). Current technology requires clean room assembly and inspection of gyros, accelerometers, bearings, safe-and-arm, fusing, and TVC systems.

A clean room is an enclosed area employing control over the particulate matter in air with temperature, humidity, and pressure control. Classifications of clean rooms (Table 2) are based upon the particle count with a maximum allowable number of particles per unit volume permissible of 0.5 μm and larger or of 5.0 μm and larger. Typically, a Class 100 clean room is required for inertial grade instruments.

The rooms in which the gyros are built are usually temperature- and humidity-controlled. People who work in these rooms are required to wear special clothing and special hats; nylon smocks are worn to eliminate possibilities of lint or dust. Special gummed mats are used outside of the assembly room doors to pick up flakes of dust and dirt that may be on shoes. Makeup is not permitted since flakes of powder might get into the very delicate mechanisms. No pencils or erasers are permitted in the rooms because of the possibilities of graphite chips or eraser rubbings.

Table 2. Clean Room Classifications

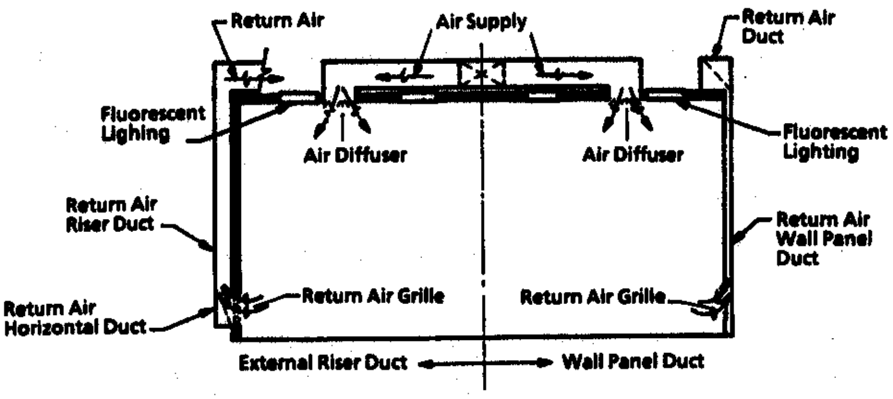
Class, English Units (Metric Units)	Maximum Number of Particles/ft^3, 0.5-μm or Larger, per liter	Maximum Number of Particles/ft^3, 5.0-μm or Larger, per liter
100 (3.5)	100 (3.5)	*
10,000 (350)	10,000 (350)	65 (2.3)
100,000 (3,500)	100,000 (3,500)	700 (25)

*Counts Below 10 (0.35) Particles/ft^3 (Liter) Are Unreliable Except When a Large Number of Samples Are Taken.

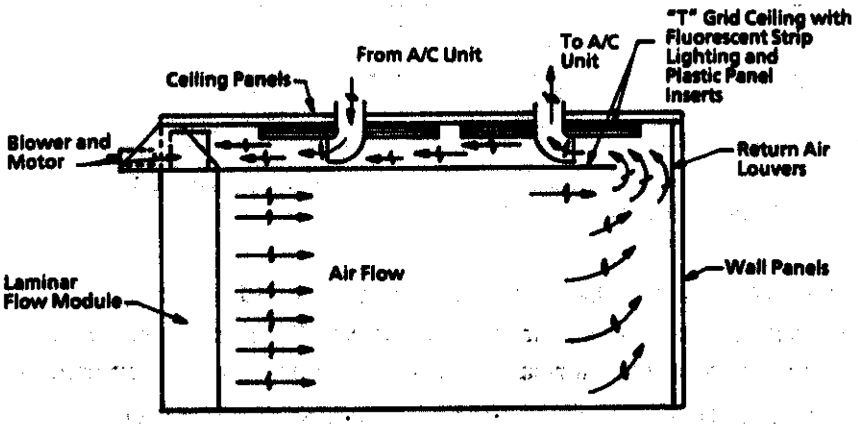
Special attention is given to the construction of a clean room. Since standard construction materials and finishes tend to be a source of airborne particulates from shedding and flaking, walls and ceilings are of a modular sandwich-type construction incorporating an insulated boardfoam core with two facing sheets bonded or laminated to the core. The panel surfaces may be finished with baked acrylic, Epoxy®, melamine, or stainless steel. Floors are of particular concern and are covered with dust-resistant, nonconductive (static electricity), vinyl sheet, minimum thickness of 0.090 in., Armstrong Vinyl Corlon® or equal. The flooring material usually extends up the sidewalls a minimum of 4 in. The enclosure structure must be capable of maintaining a positive air pressure of 0.1 to 0.2 in. (water gage) to prevent exterior air infiltration.

Filtered airflows are described as conventional or nonlaminar, horizontal laminar, or vertical laminar flows. Vertical, laminar airflow provides the most closely controlled clean environment and adds a raised floor to the clean room requirements. This system discharges the air through a bank of high-efficiency particulate air (HEPA) or "absolute" filters covering the entire ceiling area of the clean room and flows vertically downward and exits through a floor grille covering the entire floor area into a return plenum as shown in Fig. 21.

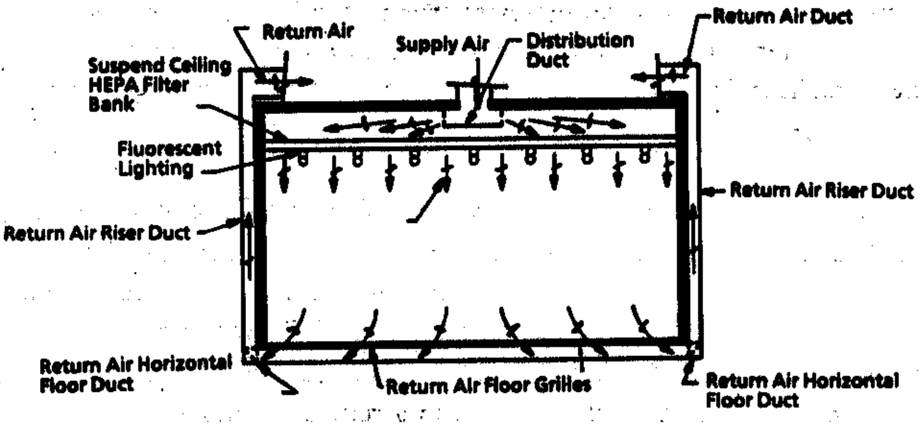
The prime requisite for a clean room is the filtration system. Prefilters are normally used to remove the larger particulates prior to the air being passed through the final HEPA or "absolute" filters. The actual arrangement of prefilters within the airflow cycle may vary,



a. Nonlaminar flow clean room



b. Horizontal laminar flow



c. Vertical laminar flow with floor grille return

Figure 21. Clean room airflow diagram.

but all are mounted in readily removable frames for cleaning and replacement. The HEPA filter has an efficiency of 99.97 percent or better on particles larger than 0.3 μm and is mounted in a metal frame, securely sealed against a gasket with clips for removal and replacement.

Air conditioning systems may vary, depending upon the purpose and requirements of the clean room. Typically, an air handling unit is comprised of a direct expansion refrigeration cooling coil, centrifugal blower and motor assembly, and air-cooled condensing unit. This system is capable of maintaining a condition of 72° ± 3°F and a relative humidity of 40 ± 10 percent. Lighting fixtures are specifically designed for clean rooms and use a recessed fluorescent fixture with a continuous hinge for servicing and relamping.

2.4.2 Manufacturing Equipment

Certain manufacturing faults give trouble, generally in the form of sticking. Sticking may occur because dust or hairs are trapped in the flotation and get into the gap between the gimbals and the inside case. This gap is as small as 0.005 in., or about the thickness of this paper.

The rotor must be precision-machined to ensure a uniform wall thickness, smooth surface finish, concentricity, and symmetry to ensure balance. The float and case must be precision-machined for a uniform gap for the flotation fluid. Ball bearings, gas bearings, or jewel bearings require the small precision-machining. Random torques produce unwanted random drifts affecting the precision of the gyro. Imperfect parts are a primary source of random torques.

Serial production of inertial guidance components requires a high-precision mechanical workshop, equipped with sophisticated machine tools (including numerically controlled machining units), using precision machine procedures in temperature controlled environments, employment of high-precision weights and measurement processes, and diligent quality control procedures during fabrication and assembly.

Dynamically tuned gyros may be a first choice for Third World countries because of the relative ease of manufacture compared to traditional gyros. Ring laser gyros and fiber-optic gyros also offer relatively low-cost manufacturing technology, because these gyros lend themselves to plastic and molded technology that produces components to final size, shape, and surface finish directly from the mold.

SECTION III

SOLID-PROPELLANT ROCKET PROPULSION

Chemical rocket propulsion is considered the only economical means of propulsion for SRBM use. Electric propulsion generates insufficient thrust, and nuclear propulsion is considered too advanced for Third World use. The fundamentals and requirements of solid-propellant chemical rocket propulsion are discussed in this section, and liquid-propellant chemical rocket propulsion is discussed in Section IV.

3.1 FUNDAMENTALS

3.1.1 Propulsion Systems

The propulsive force (thrust) created by the rocket is based on Newton's Third Law of Motion, which states that for every action there is an equal, but opposite, reaction. Figure 22 illustrates this principle.

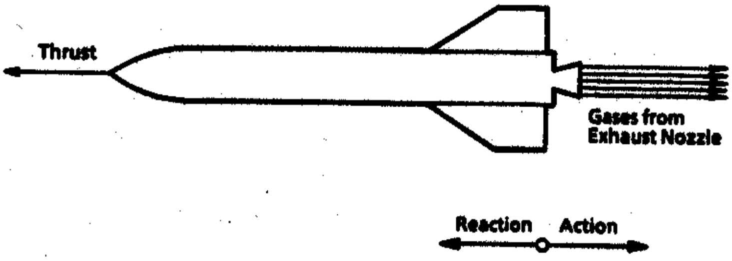


Figure 22. "Action/reaction" as applied to an SRBM.

The thrust generated by a rocket is given by

$$F = \dot{m} V_{ne} + (P_{ne} - P_a) A_{ne}$$

where

$\dot{m}$ = mass flow rate of rocket exhaust products
V_{ne} = velocity of exhaust products at the exhaust nozzle exit
P_{ne} = pressure at the exhaust nozzle exit
P_a = pressure of the surrounding (ambient) atmosphere
A_{ne} = area of exhaust nozzle at the exit

Most of the thrust typically produced by an SRBM is from the $\dot{m} V_{ne}$ or *momentum* term in the previous equation. For a rocket nozzle operating exactly at the design point, the pressure term is zero, and *all* the thrust is produced by the momentum term. The design point is defined as the nozzle exit area that has a static pressure equal to local atmospheric pressure. Local atmospheric pressure is a function of altitude, so the design point may be expressed in terms of altitude rather than static pressure. Since nozzle areas greater than the design point area cause a reduction in thrust, the SRBM launched from ground level will have relatively low nozzle area ratios (the ratio of exit area to throat area) with typical area ratios of about 10:1.

Specific impulse (I_{SP}) is a measure of the efficiency of the rocket propulsion system. It is the most used performance parameter in rocket technology. Specific impulse is the ratio of thrust to the mass flow rate of exhaust products. High specific impulse is desired because less propellant is required to perform a given mission.

In order to fly a minimum energy trajectory and achieve some minimum target-miss distance, thrust must be accurately terminated when the desired velocity has been attained during the ascent trajectory. Solid-propellant rocket motors are usually thrust-terminated by actuating explosive devices at designed ports in the forward end of the rocket motor case. Sudden depressurization is sufficient to stop burning. Residual gas flow through the forward ports effectively neutralizes normal thrust. Liquid-propellant rocket engines are thrust-terminated by simply closing the main bipropellant valve on the engine.

Some modern ballistic missiles allow the main propulsive stages to burn to completion and manage the flight trajectory by flight-path angle. At flight-path angles significantly different from the optimum cut-off angle, however, the target accuracy is highly sensitive to cut-off-angle errors. Complete main-stage burn missiles, therefore, employ some form of postboost propulsion vernier control. Thrust termination is considered the most viable alternative for the subject SRBMs.

3.1.2 Solid-Propellant Rockets

A solid-propellant rocket, also called solid rocket motor or SRM (Fig. 23), consists of a pressure vessel (case) partially filled with a combined fuel and oxidizer mixture, a case

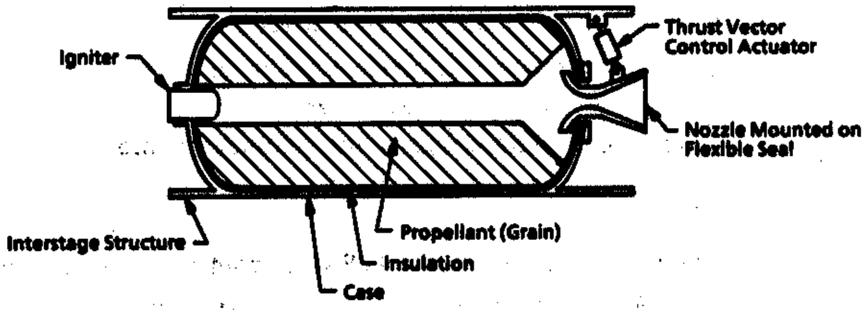


Figure 23. Typical SRBM solid-propellant rocket motor.

insulator, a converging-diverging exhaust nozzle, an igniter, and a thrust vector mechanism. The combined fuel and oxidizer mixture is called a grain. The fuel, which is a rubber-like substance, is the binder that holds the solids together and gives the grain mechanical properties sufficient to withstand thermal, pressure, and flight stresses. Ammonium perchlorate (AP) is the most popular oxidizer. Aluminum (Al) particles may be added to increase specific impulse and to enhance combustion stability. Total solids (AP and Al) approach 90 percent of the propellant mixture. The rubber-like binder is very similar to synthetic rubber used in automobile tires.

Some of the advantages of solid-propellant motors are the long storage life, high density (and therefore, smaller vehicles), and the relative ease of transportation and deployment. Solid-propellant rocket motors provide a subtle operational advantage not available from liquid-propellant rocket engines. The solid-propellant grain essentially burns to completion (in the first stage). The solid grain is a good insulator, and with proper design the internal case insulation can be minimized. Crude but effective solid-propellant motors can be built with minimum technical capabilities.

Some of the disadvantages of solid-propellant motors are (1) specific impulse is relatively low (compared to liquid propellants); (2) manufacturing imperfections tend to be catastrophic; (3) high performance is difficult to obtain with a solid propellant that possesses good mechanical properties over a wide range of operating temperatures; and (4) consistant and reproducible thrust termination is a difficult design challenge.

Solid-propellant rocket motor thrust cannot be independently modulated. The fixed grain geometry determines the thrust-time curve. Four typical samples are shown in Fig. 24.

Solid-propellant rocket motors require an ignition system consisting of a small rocket-type device inside the internal bore of the SRM. The igniter system generally includes a "safe-and-arm" device, which minimizes accidental ignition.

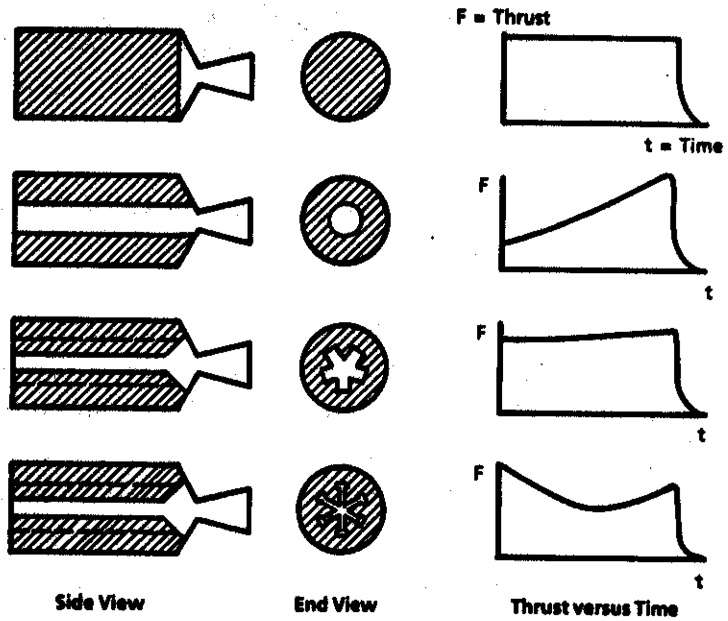


Figure 24. Geometry and thrust-time trace for solid-propellant rocket motors.

Solid-propellant rocket motors have widespread acceptance for tactical weapons, ballistic missiles, sounding vehicles, launch vehicle boosters, space orbit transfer vehicles, stage separation devices, airplane jet-assisted take-off power, and as gas generators. Gas generators are solid-propellant devices that produce a relatively low-temperature gas for a variety of uses such as turbine drives, start cartridges, tank pressurant, and auto safety air-bags.

3.2 REQUIREMENTS

Because of the advantages described in this section, solid-propellant rocket motors are obvious choices for the propulsion for a short-range ballistic missile. The primary attributes for this selection are the mobility and readiness allowed by solid propulsion. A two-stage missile capable of delivering a 1-metric-ton payload 1,000 km can be built with 1960s technology and have a launch weight under 7,000 kg (15,400 lbm). A missile with a single-stage SRM that could deliver the same payload the same distance would have a launch weight of 12,000 kg (26,300 lbm). Many of the requirements to design and develop the SRMs discussed in this report are adapted from Refs. 5 through 9. Manufacturing and testing are discussed in Sections 3.3 and Section VII.

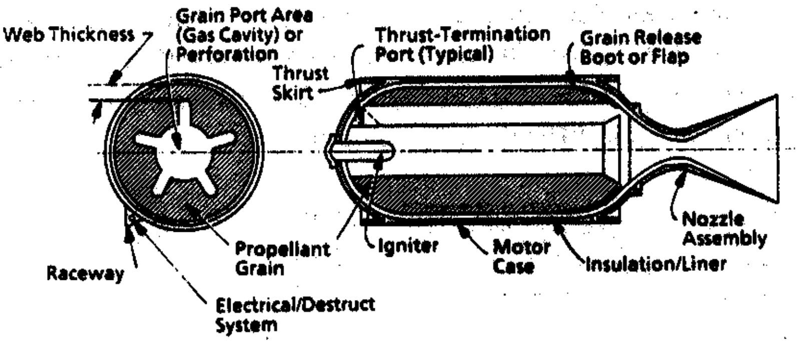


Figure 25. Simplified cross sections of a typical solid-propellant motor with case-bonded grain.

The principal components of a solid-propellant rocket motor, including propellant grain, igniter, motor case, exhaust nozzle, and mounting provisions, (which in this design are thrust skirts) are shown in Fig. 25. The metal motor case is lined with a rubber-like organic material, which ensures good bonding of the propellant grain and acts as a thermal insulator to the case. The thrust-termination blow-out diaphragms (not shown) allow stopping of the normal burning prior to the full consumption of all the propellants. Thrust termination is usually required on only the second stage of a two-stage vehicle.

3.2.1. Solid-Propellants Classifications

Solid-propellant rocket motors are classified in several ways; some typical classifications are listed in Table 3 with examples for each classification.

Any one solid propellant usually includes two or more of the following:

1. oxidizer — nitrates or perchlorates;
2. fuel — organic resins or plastics;
3. chemical compound combining fuel and oxidizer qualities — nitrocellulose or nitroglycerin;
4. additive to control the burn rate/catalyst, stabilizers, etc.;
5. inhibitors;
6. powdered metal, usually powdered aluminum.

Table 3. Classification of Solid-Propellant Rocket Motors

Basis of Classification	Examples of Classification
Propellant	Composite: Heterogeneous (Physical) Mixture of Crystalline Oxidizer, Polymeric Binder, and Powdered Metal
	Double-Base: Homogeneous Mixture (Colloidal) of Nitroglycerin and Nitrocellulose
	Composite Double-Base: Combines Composite and Double-Base Ingredients
Case Design	Steel Monolithic: Conventional One-Piece Steel Case
	Fiberglas® Monolithic: Filament-Wound (High-Strength Fibers) with a Plastic Matrix
	Segmented: Case (Usually Steel) Is in Segments That Are Bolted Together
Grain Configuration	Cylindrical: Cylindrically Shaped with Cylindrical or Star-Shaped Cavity
	Spherical: An External Sphere with an Interior Cavity
	End-Burning: Solid Cylinder Propellant Grain
Grain Installation	Case-Bonded: Adhesion Exists Between Grain and Insulation and Case. Propellant Is Usually Cast in the Case
	Cartridge-Loaded: Grain Is Formed Separately and Inserted in Case
Explosive Hazard	AFR 100-127 Class/Division 1.3 (Ref. 10): Catastrophic Failure Evidences Burning and Explosion, Not Detonation
	AFR 100-127 Class/Division 1.1: Catastrophic Failure Evidences Detonation
Thrust Action	Neutral Grain: Thrust Remains Essentially Constant During the Burn Period
	Progressive Grain: Thrust Increases with Time
	Regressive Grain: Thrust Decreases with Time
	Pulse Rocket: Two or More Independent Thrust Pulses or Burning Periods
	Step-Thrust Rocket: Usually Two Distinct Levels of Thrust
Toxicity	Toxic and Nontoxic Exhaust Gases

Processed or cured modern propellants fall into three general types: double-base, composite, and composite-modified double-base.

Double-base (DB) propellants form a homogeneous propellant grain, usually a nitrocellulose type of gunpowder (gun cotton) dissolved in nitroglycerin plus minor percentages of additives. Both the major ingredients are explosives and function as a combined fuel, oxidizer, and binder.

Composite propellants form a heterogeneous propellant grain with the solid oxidizer crystals and a powdered fuel additive (usually aluminum) held together in a matrix of synthetic rubber or plastic (organic polymer) such as polybutadiene. Neither item will burn satisfactorily without the presence of the other. Many composite propellants are less hazardous to manufacture and handle than double-base propellants.

Composite-modified double-base (CMDB) propellants, in one sense, are a combination of the double-base and composite propellants, usually a crystalline oxidizer (ammonium perchlorate) and powdered aluminum fuel held together in a matrix or binder of nitrocellulose-nitroglycerin. The hazards of processing and handling this type of propellant are similar to those of double-base propellants.

Composite propellants are by far the most common, consisting of an oxidizer, which is almost always (for reasons discussed later) ammonium perchlorate (AP) and a rubbery fuel-binder. The fuel-binder, as the name suggests, serves two purposes: It is a fuel that is oxidized by the AP oxidizer, and it serves as a rubbery matrix that binds the granular AP crystals into a cohesive mass of material with properties somewhat like those of a typewriter eraser.

Composite solid propellants may also contain aluminum powder. If aluminum is present, it serves as a fuel. It increases the combustion temperature of the solid propellant and, therefore, improves its performance while minimizing tendencies for combustion instabilities.

Aluminized conventional propellants produce aluminum oxide (Al_2O_3) as a combustion product. In the exhaust plume, aluminum oxide forms a distinctly white cloud that results in a highly visible plume, revealing the origin and flight path of the rocket motor.

Nonaluminized conventional propellants are often referred to as reduced smoke propellants. Since aluminum oxide is not a combustion product for these propellants, their plume tends to be less visible than that of aluminized propellants. However, since they use AP as an oxidizer, a major component of the combustion gas mixture is hydrochloric acid (HCl). Hydrochloric acid molecules tend to cause condensation of water molecules in the ambient air; as a result, motors that contain reduced smoke propellants may produce a visible plume (caused by water vapor condensation) if they operate in a low-temperature, high-humidity environment.

Strategic considerations clearly favor a reduction in visible plume where possible, requiring that HCl also be eliminated from the exhaust. One approach is to produce an energetic binder that uses an energetic plasticizer and contains solid particles that are themselves propellants; in other words, binder, plasticizer, and solids all contain both oxidizer and fuel elements. Propellants of this type are referred to as minimum-smoke propellants.

The simplest, and earliest, propellant that fits into the minimum-smoke category is a mixture of nitrocellulose and nitroglycerin called a double-base propellant. Each is said to be a monopropellant; in other words, if burned by themselves, they each would display relatively high energy. The distinction between oxidizer and fuel no longer applies.

Modern minimum-smoke propellants are somewhat more complicated in that they are cross-linked and contain solids (either HMX or RDX), which are also monopropellants; but the basic mechanism of burning and the factors controlling the burning rate are similar.

Another category of propellants (high-energy) results when oxidizing and reducing agents exist in discrete molecules. Thus, from the standpoint of energy potential, the best binders are cured cross-linked hydrocarbons (idealized chemical formula, CH_2) such as polybutadiene; the best fillers are inorganic oxidizers, such as AP; fuels, such as aluminum metal; some nitramine solid; and an energetic plasticizer. These propellants are formulated for the highest possible performance consistent with reasonable physical properties.

3.2.2 Propellant Contents and Ingredients

Several common propellant ingredients are tabulated in Table 4. Since it is common industrial practice to refer to the metal powders as a fuel, these powders are listed under "fuels." The binders are listed separately, although they too are fuels. Compositions for representative composite and composite-modified double-base (CMDB) propellants are also shown in Table 5.

SECTION V

STRUCTURES AND MATERIALS

The functions of missile structure and the materials used to satisfy these functions are discussed in the following paragraphs, concluded by a discussion of possible manufacturing processes.

5.1 FUNDAMENTALS

A ballistic missile must be designed to withstand operating conditions, flight environment, and ground-handling loads. Operating conditions are created by the propulsion system pressurization and external ambient temperature extremes. Flight conditions impose aerodynamic loads, inertia loads, high axial accelerations, and aerodynamic heating during both ascent and payload reentry. Ground-handling loads are created by transportation on rugged terrain and erection for launch. The aerodynamic loads are resolved as lift, drag, and moments about the body axes. Bending moments are created by lift, lateral component of thrust, and inertia loads. Wind and wind shear create both static and dynamic aerodynamic loads. The missile structure must also consider the maximum acceleration during flight. Maximum acceleration is generally achieved at the propulsion cut-off point.

The SRM cases and the LRE tanks often serve as structural elements. The solid-propellant motor case is designed to contain the maximum expected operating pressure with some margin of safety. The pressure-fed LRE requires tanks designed for operating pressures 20 to 30 percent greater than combustion chamber pressure. Typical tank design values would be around 600 psia for a rocket chamber pressure of 500 psia. Both the SRM and the pressure-fed LRE contain components that are sufficiently rigid to serve as primary structural elements. Propellant tanks of the pump-fed LRE are lightweight because they are designed to deliver relatively low pressure to the pump inlet. The pump-fed tank would be designed for an internal pressure around 30 to 50 psia, and would not provide structural rigidity until the tank is pressurized. Pump-fed systems would seem to obviate their advantage of lightweight structure by requiring external supporting structural elements, especially for mobile tactical applications.

The structure connecting various missile components is called the interstage structure. The interstage structure is typically dictated by maximum bending movement during flight, but may under some circumstances be designed to withstand some ground-handling needs. Erection for launch from the horizontal position is often a critical requirement.

The principle functions of the missile structure are (1) to provide an integrated framework combining the established general configuration with the various missile components and determines the propellant mechanical properties. The binder must be capable of bonding to plastic insulating materials and metal parts or lined metal parts of the motor. The binding ingredient, usually a polymer, has a primary effect on motor reliability, mechanical properties, propellant processing, storability, and costs.

Polymers can be grouped according to their effect on propellant processing as Group 1, plastisol binders; Group 2, oxygen-rich double-base propellant binders; Group 3, prepolymer or monomers for cast composite propellant binders; and Group 4, polymers from rubber gum stocks. Examples of each group are shown in Table 6.

Table 6. Typical Solid-Propellant Binders

Group 1, Plastisol Binders	Polyvinyl Chloride (PVC), Which Is a Commercially Available Thermo Plastic Polymer
Group 2, Double-Base Binder	Nitrocellulose (NC), Which Is a Relatively Low-Cost Commercial Material
Group 3, Composite Binders	Polybutadiene Acrylic Acid-Acrylonitrile (PBAN) Carboxy-Terminated Polybutadiene (CTPB) Hydroxy-Terminated Polybutadiene (HTPB) Butadiene Was (1985) the 36th Highest Volume Chemical Produced in the U.S.
Group 4, Rubber Gum Stocks	Neoprene and Butyl Both Are Widely Used Commercial Products, but Because of High Viscosity, Have Limited Applications for Propellant Binders.

Most current high-energy composite solid propellants are prepared with one of three castable binder systems. These are the chemically cross-linked polybutadiene and polyurethanes and the linear polycrystalline nitrocellulose plastisols.

Double-base propellants have been upgraded in recent years by the development of "double-base composites" in which the nitroglycerine-nitrocellulose system is used as the binder system with an additional oxidizer (AP) and a metallic fuel additive (Al).

In the double-base propellants, both ingredients have oxidizer and fuel groups in the molecule. In the case of composite propellants, a solid oxidizer (crystalline and inorganic) is suspended in a rubbery (organic) binder matrix. One of the first composite propellants consisting of potassium perchlorate oxidizer in an asphalt fuel binder was used in early bazookas and for airplane jet-assisted take-off units. Highly loaded asphalt physical properties were poor; the material was very hard and inflexible at low temperatures and flowed at high temperature (160°F).

Because of the constant desire for higher specific impulse and improved rocket motor performance, additional demands are continually being made on propellant technology. The addition of AP and Al to double-base compositions began in the early 1960s. These improvements and the use of nitramines such as RDX or HMX resulted in the use of composite-modified propellants.

Another propellant development concept started in the 1970s was the technology required to produce reduced smoke propellants. These propellants also used polyurethane technology with various combinations of AP, HTPB, HMX, RDX, selected nitroplasticizers, and polyisocyanates. Some of these formulations are used in contemporary tactical rockets.

HTPB is by far the most common binder used in U. S. composite propellants. HTPB is chemically a polyurethane because it is cured with isocyanates. The great versatility with which polyurethanes can be formulated compared with other nonenergetic polymers used as binders in solid composite propellants, is the primary reason polyurethane polymers have been used extensively throughout the years.

Several countries besides the U. S. have either acquired polyurethane technology through license and other agreements or have succeeded in developing their own technology. Italy, France, Germany, and Japan were licensed not only to produce the American propellant systems, but have continued very successfully with their own development. Other countries such as Norway, South Africa, Israel, Brazil, India, and Taiwan have embarked totally on their own and use their own raw materials such as HTPB, polyesters, and polyglycols. India is using a caprolactone prepolymer made from castor oil, a very inexpensive diol. Germany is using a hydroxy-terminated polyester together with nitrocellulose and nitroglycerin to produce a high-energy anti-tank weapon. Since this propellant contains aluminum powder and HMX, the exhaust is smoky but essentially corrosion free. Polyurethanes have been accepted in foreign countries primarily because most of the raw materials are easily accessible and the technology is widely known from other plastic and foam applications.

In conclusion,

- Polymers based on polyurethane chemistry are the most versatile binder for solid composite propellants. Polyurethane polymers as binders have been a cornerstone of solid-propellant rocket technology.
- Many materials are available to produce all types of propellants in a clean chemical reaction without side products.
- Hydroxy-terminated polyurethane (HTPB) is today's recognized workhorse propellant for almost all Class 1.3 propellants.
- Polyurethane propellants are now used internationally because of the ease of obtaining suitable raw materials and clean and reproducible cure chemistry.

Oxidizers. Selection of an oxidizer for composite solid propellants must necessarily be limited to those that are produced or can be produced in large quantities by the chemical industry. The best oxidizer for producing chemical energy for rocket propulsion should have its density as high as possible and its oxygen content as large as possible. The original oxidizer, potassium perchlorate, was replaced by ammonium nitrate, which has since been replaced (except for low-flame temperature gas generator and igniter propellants) by AP for higher-energy systems. Some of the important crystalline oxidizers are listed in Table 7. Note that they all have some undesirable property.

Table 7. Comparison of Crystalline Oxidizers

Oxidizer	Chemical Formula	Available Oxygen, Approximate Percent	Heat or Formation Kcal/mole	Molecular Weight	Remarks
Ammonium Nitrate	NH_4NO_3	19.5	−87.93	80.05	Smokeless/Medium Performance
Sodium Nitrate	$NaNO_3$	28.2	−106.6	—	Low Cost/Low Performance
Ammonium Perchlorate	NH_4ClO_4	34.0	−78.3	117.5	Low Cost, Readily Available, Exhaust Contains HCl
Potassium Nitrate	KNO_3	39.5	−118.78	101.1	Low Cost/Low Performance
Potassium Perchlorate	$KClO_4$	46.2	−99.24	138.5	Medium Performance
Sodium Perchlorate	$NaClO_4$	52.2	−100.6	122.4	Hygroscopic

These oxidizers are listed in order of increasing available oxygen as one selection criteria; another is heat of formation. The negative sign represents heat given off when the compound is formed from the basic elements; hence, the more negative the number, the more stable the oxidizer and the more heat required to decompose it. Another important consideration is molecular weight of the exhaust products: Lower molecular weight exhaust products result in higher specific impulse. AP has emerged as the most commonly used oxidizer.

Perchlorates. All of the perchlorates produce HCl and other chlorine compounds in their reaction with fuels. Their exhaust gases are not only toxic but also highly corrosive to many materials. The hydrochloric acid condenses in a moist atmosphere to form a dangerous fog. Ammonium and potassium perchlorate are only slightly soluble in water and, therefore, can be used for propellants that are exposed to moisture. The perchlorates are usually produced by the electrolysis of chlorides, which are naturally available materials. The oxidizing potential of the perchlorates is generally high, and for this reason they are often found in propellants of high specific impulse. Available in the form of small white crystals, perchlorates particle size influences the fabrication process and the burning rate. All perchlorate oxidizers are potential explosives. By using special high-purity material, special crystal processing techniques, and careful handling, it is possible to formulate high-energy propellants with these oxidizers.

Inorganic Nitrates. Inorganic nitrates are relatively low-performance oxidizers compared with perchlorates. Potassium nitrate and sodium nitrate produce undesirable smoke in the exhaust because of the solid material formed in the combustion products. Ammonium nitrate, has the advantage of a smokeless, relatively nontoxic exhaust; but its oxidizing potential is low. Its principal use, therefore, is with low-burning-rate, low-performance applications such as gas generators for turbopumps of liquid-propellant rocket engines or emergency starters for jet aircraft.

The nitrate salts are used in fertilizers and other industrial applications and are relatively cheap and naturally available. Ammonium nitrate can be produced from nitric acid and ammonia.

Sometimes one of two crystalline high explosives, HMX (cyclotetramethylenetetranitramine) and RDX (cyclotrimethylenetrinitramine), are included in a propellant formulation to achieve a specific performance characteristic. The percentage of the explosive can range from 5 to 50 percent in double-base smokeless (nonmetal) propellants depending on the specific impulse, burning rate, and other internal ballistic properties desired. Lower percentages are sometimes used in composite and composite double-base propellants, particularly in highly metallized formulations to ensure efficient combustion, increased burning rate, and high specific impulse.

Organic Nitrates. These are basically solid monopropellants capable of chemical energy release and are used as ingredients in homogeneous or double-base propellants. Some of the organic nitrates most commonly used in propellants are glycerol trinitrate or nitroglycerin, diethyleneglycol dinitrate or DEGN, and cellulose nitrate or nitrocellulose. All are basically unstable compounds, which are capable of oxidizing their organic material.

Nitroglycerin is a colorless, oily liquid, only slightly soluble in water but readily soluble in alcohol and ether. Nitroglycerin can detonate violently with only a slight shock. The molecule contains more than sufficient oxygen to convert the carbon and hydrogen to the corresponding oxides, and gaseous nitrogen is liberated. The generally accepted method of production is the nitration of glycerin using a mixture of nitric and sulfuric acids. Nitroglycerin is somewhat less sensitive in the solid form, and also when absorbed in such materials as diatomaceous earth, sawdust, and charcoal. Commercial dynamites usually contain nitroglycerin absorbed in sawdust, in which form it is sufficiently insensitive to shock to permit handling and shipping with comparative safety. A somewhat similar material is obtained when nitrocellulose is gelatinized with nitroglycerin, the resulting material having satisfactory stability. This is the basis of ballistic-type propellants, or so-called double-base propellants.

Commercial nitrocellulose has much the same appearance as ordinary cotton and consists largely of cellulose trinitrate. It is fabricated by the nitration of wood pulp or cotton liners. The degree of nitration influences the properties of nitrocellulose. Highly nitrated material, called gun cotton, contains 12.2- to 13.8-percent nitrogen and, thus, corresponds closely to pure cellulose trinitrate, the theoretical nitrogen content of which is 14.16 percent. An increase in nitrocellulose content generally increases the physical strength, and a high-nitroglycerin content tends to increase the performance and burning rate.

Aromatic Nitrocompounds. Several of the aromatic nitrocompounds that have been used in propellants are ammonium picrate, trinitrotoluene, or TNT, and dinitrotoluene, or DNT. The nitrocompounds contain the $-NO_2$ group, as distinguished from the $-ONO_2$ group in nitrates.

AP is the workhorse oxidizer of composite solid propellants. It is stable and compatible with the other propellant materials, relatively nonhygroscopic, provides reasonably high performance, has 34.0-percent available oxygen, is relatively safe to handle, is commercially available in large quantities, and can be produced with good quality and uniformity.

AP is supplied in the form of small, white crystals. AP oxidizer normally is received from commercial sources in the size distribution shown in Fig. 26.

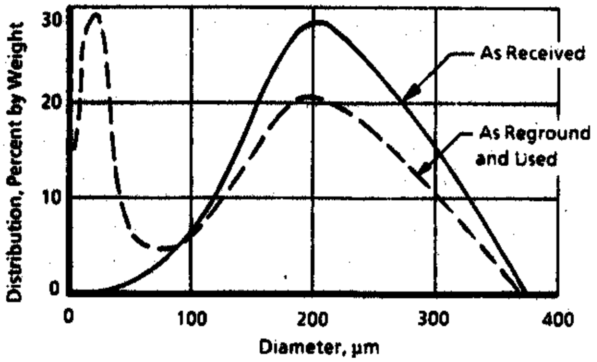


Figure 26. Particle size distribution of ammonium perchlorate.

Normally, the ground oxidizer crystals obtained commercially are graded according to particle size ranges as follows:

Coarse	300 to 600 μm ($1\ \mu m = 10^{-6}$ m)
Medium	50 to 300 μm
Fine	5 to 50 μm
Ultrafine	sub-μm to 5 μm

Coarse- and medium-grade crystals are handled as Class 1.3 (Ref. 10) materials, whereas the fine and ultrafine grades are considered as Class 1.1 (Ref. 10) high explosives and are usually manufactured on-site from the medium or coarse grades. Most propellants use a blend of oxidizer particle sizes obtained by grinding a portion to a finer distribution. This bimodal distribution, also shown in Fig. 26, lowers the viscosity and maximizes the weight of oxidizer per unit volume of propellant, with the small particles filling part of the voids between the larger particles.

Additives.

Metal Fuel (Inorganic Material). A rocket fuel is basically a reducing agent, which when oxidized, will yield high-energy and low-molecular weight gaseous products. Both requirements are not assured by a single fuel, necessitating the use of combinations. Metals are often used in unison with (organic) hydrogen-containing fuels to meet the energy/mass flow opportunities of a high specific impulse system. In fact, the discovery that metallic fuels could be incorporated into the binder-oxidizer mixture to provide higher energy and higher density propellants without compromising the mechanical properties of the system was a major advance in propellant technology. This paradoxical situation can be understood if it is realized that a hydrocarbon-oxidizer is balanced to produce carbon monoxide, carbon dioxide, and steam as combustion products. The metal additive can be considered to be oxidized by the steam, and therefore, it does not require additional oxidant.

The addition of fine particles improves the propellant by increasing the combustion temperature, by increasing the density of the grain, and by alleviating certain types of combustion instabilities. Powdered aluminum is usually present as irregularly shaped particles with an average particle size of 14 to 21 μm. In addition, spherical aluminum is used to lower propellant viscosity during processing. Total aluminum content is usually 14 to 18 percent of the propellant by weight. During combustion, the aluminum is oxidized into aluminum oxide (Al_2O_3). The Al_2O_3 particles tend to agglomerate and form larger particles. These oxidized particles solidify in the exhaust nozzle as the temperature drops and act as an abrasive on the wall of the nozzle.

Other metals, including beryllium (Be), boron (B), lithium (Li), magnesium (Mg), and zirconium (Zr) have been used from time to time. Boron has not proven to be a practical fuel because it has a high melting point (2,304°C) and is difficult to burn with high efficiency in combustion chambers of reasonable length. Beryllium burns much more easily than boron and improves the specific impulse of a solid-propellant motor but is a highly toxic powder when absorbed or inhaled by animals and humans. Beryllium use causes not only an increased combustion temperature but also a lower molecular weight, which assists in improved theoretical specific impulse. The technology with composite propellants using powdered beryllium fuel has been experimentally proven, but its toxicity makes its application unlikely.

Metal Hydrides. By adding metal hydrides to the fuel, the addition of hydrogen is beneficial to lower the gas molecular weight. Some of the hydrides cannot be allowed to remain in contact with the other propellant ingredients because they react. Encapsulating hydride particles with a metal or organic material membrane shows promise toward higher energy fuels but is currently beyond the capability of a typical Third World country.

Similarly, both aluminum hydride (AH_3) and beryllium hydride (B_3H_2) are attractive fuels because of their high-heat release and gas-volume contribution but are difficult to manufacture, and both deteriorate chemically during storage (loss of hydrogen). Again, these compounds are not practical for general use in fuel.

Propellants with metallic additives usually contain a condensed phase (liquid or solid) in the exhaust gas; this increases the problems of nozzle material erosion, heat transfer, and nozzle material compatibility. It also complicates the prediction of theoretical specific impulse.

3.2.3 Motor Case and Insulation

Motor case and case insulation requirements are discussed in this section. Manufacturing processes are discussed in Section 3.3. Problems arise when established technology is used improperly from improper design analysis, misunderstanding of the requirements, improper material and process control, or omission of nondestructive tests at critical points in the fabrication process. The motor case is a pressure vessel that must withstand starting surges, maximum operating pressure, and missile bending moments. The stress to which a motor case is subjected, is difficult to determine in practice, and must be determined from experimental data and iterated early in motor development. The case must be protected from the high internal temperature by the propellant and the case insulation.

Case design is usually governed by a combination of motor and vehicle requirements. Since the motor case frequently constitutes the primary structure of the missile as well as the propulsion mechanism, the optimization of a case design requires trade-offs between case design parameters and vehicle design parameters. Motor cases provide attachment joints for a nozzle, igniter, thrust termination ports, and interstage structure. High-strength steel, titanium alloys, and Fiberglas® -reinforced plastic (filament-wound) have been the most common materials in rocket motor cases. Filament-wound cases have been used since the Vanguard backup third-stage motor in the late 1950s. The recent trend is toward high-strength alloy steels and filament-wound reinforced plastics, including recently developed organic filaments (synthetic yarn) having strength-to-density ratios superior to glass filament. A typical steel motor case is shown in Fig. 27, and Fig. 28 shows a glass-filament-wound motor case in the winding process. Table 8 gives a comparison of motor case materials in terms of case wall material strength, density, and stiffness.

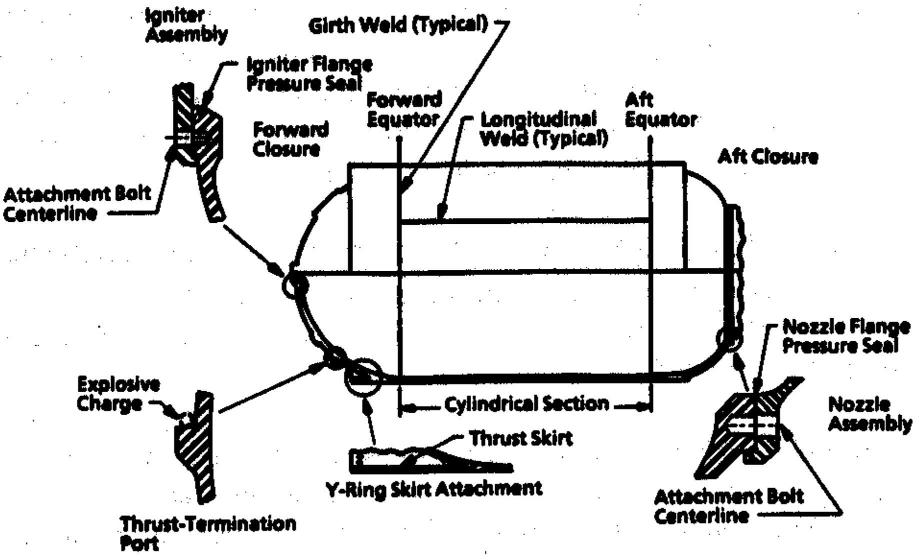


Figure 27. Typical solid-propellant rocket motor case made of steel.

Alloy steels commonly used in motor cases are discussed in Section V. The maraging steels discussed in Section 5.3 are attractive because of their toughness and resistance to tearing, a property important to motor cases and other pressure vessels since failures are less catastrophic. This toughness characteristic enables a "leak-before-failure" to occur, at least during hydrostatic proof testing.

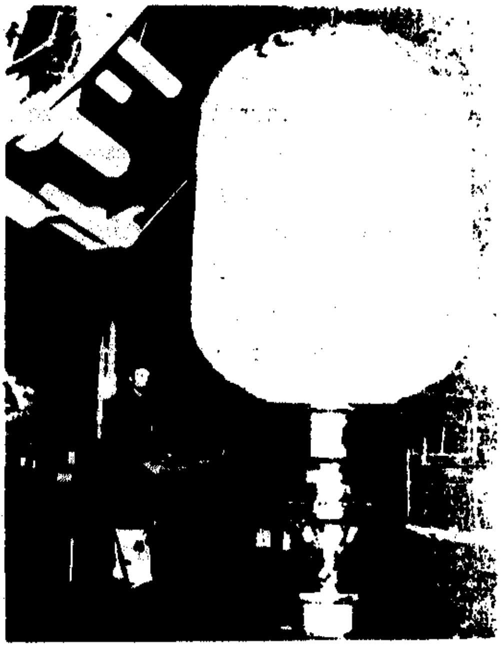


Figure 28. Glass fiber-resin-impregnated case.

Case-bonding of elasticized propellants is essential to development of the solid cast-in-case rocket motor for the SRBM. Case-insulation — lining the case with an inhibiting insulating and bonding material prior to pouring in the propellant — protects chamber walls from the combustion products. The case wall therefore does not experience adverse effects from internal combustion heat. Figure 29 indicates the relationship of the insulation to the case and the propellant. It is good design practice to limit heat transfer to the case by employing case insulation.

Table 8. Comparison of Motor Case Materials

	D6aC Steel	Maraging Steel	Titanium (6-percent Al, 4-percent V)	Glass-Filament Composite (2-901)*	Organic-Filament Composite (PRD-49)**
Tensile Strength, psi	230 × 10^3	250 × 10^3	140 × 10^3	170 × 10^3	250 × 10^3
Density, lb/in.^{3}	0.283	0.289	0.167	0.072	0.050
Strength/Density	813 × 10^3	865 × 10^3	875 × 10^3	2,360 × 10^3	5,000 × 10^3
Modulus, psi	29 × 10^6	27.5 × 10^6	16 × 10^6	4.6 × 10^6	11 × 10^6

* Typical Glass Filament-Wound Motor Case with Approximately 80-percent Owens-Corning Glass Filament No. 2-901 (600,000-psi Tensile Strength) and 20-percent Epoxy® Resin Matrix.

** Typical Organic Filament-Wound Motor Case with Approximately 70-percent Dupont PRD-49 (500,000-psi Tensile Strength) Filament and 30-percent Epoxy® Resin Matrix.

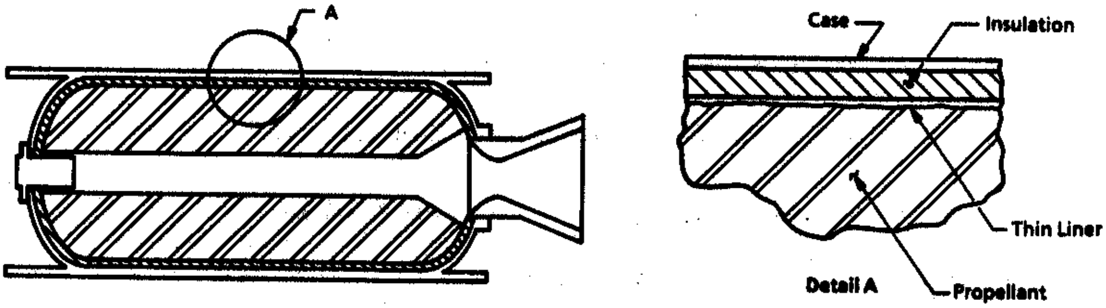


Figure 29. Typical case-bonded propellant grain.

The integrity of the propellant-substrate (liner or insulator) bond is vital to the reliability of case-bonded solid-propellant rocket motors. If the bond fails, propellant burning can occur in the unbonded areas causing a case overpressure condition and catastrophic failure. The bond must withstand stresses caused by thermal contraction of the propellant, weight of the propellant during motor storage, and inertia of the propellant (particularly in upper stages) during acceleration. The first two causes of stress, which involve slow stress buildup and low stresses of long duration, have usually been more troublesome than the third cause.

The case insulation is usually made of elastomers or plastics. These thermal insulators are often made from the same material as the polymerized binders and are sometimes reinforced with fibers or filled with inert materials. Typical insulator materials are listed in Table 9, and two typical formulations are given in Table 10.

Table 9. Insulator Materials

Insulator Materials

1. EPDM Rubber (Ethylene-Propylene-Diene Monomer)
2. Natural Rubber (Polyisopreme Plus Resins)
3. SBR Rubber (Styrene-Butadiene Rubber)
4. NBR Rubber (Nitrile Rubber)
5. Butadiene (Acrylonitrile Copolymer)
6. CR Rubber (Neoprene Polychloroprene)
7. Carboxy-Terminated Polybutadiene (CTPB)
8. Hydroxy-Terminated Polybutadiene (HTPB)

Filler Materials

1. Titanium Dioxide
2. Silicon Dioxide
3. Silica

Table 10. Typical Insulator Formulations

SBR Elastomer		EPDM Elastomer	
Ingredients	Percent by Weight	Ingredients	Percent by Weight
SBR Polymer	47	EPDM Polymer	53
Reinforcement	24	Neoprene Polymer	13
Polybutadiene Polymer	12	Silica Reinforcement	23
Plasticizer	9	Carbon Black	3
Curatives	5	Antioxidant	2
Processing Additives	0.5	Activator	3
Antioxidants (Aminox)	0.5	Curative	3
Carbon-Black	2		

Stress corrosion cracking of metals presents a unique problem that can result in spontaneous failure without any visual evidence of impending catastrophe. Emphasis given to lightweight, thin metal cases aggravates stress corrosion and crack propagation, often starting from a flaw in the metal, with failure occurring at stress levels below the yield strength of the metal. Adequate understanding of stress corrosion and fracture mechanics has yet to be attained for many of the newer high-strength steels.

3.2.4 Igniters

The igniter in a solid-propellant rocket motor is the principal component in the motor ignition system and functionally generates the heat and gas required for motor ignition. Solid-propellant ignition consists of a series of complex, rapid events in which the igniter is consumed in providing the transfer of heat to the motor grain surface to fill the chamber free volume (cavity) with hot, pressurized gas for igniting the grain surface. Motor ignition must be completed in a fraction of a second for SRBM applications. Igniters can be categorized as pyrotechnic, electrical, torch, hypergolic, and catalytic. Of these, the pyrotechnic type is the more widely used practical igniter. Conventional heat-releasing compounds are usually pyrotechnic materials, such as black powder, metal-oxidant formulations, and conventional solid propellant. Igniter cases are usually sealed to prevent absorption of moisture and to control the ignition at altitude. Some igniter cases are made of a plastic so that they will burn, and therefore, not form an obstruction to the gas flow. The igniters, like the propellant charge, must be resistant to moisture and capable of storage and operation over a wide range of operating environments.

The igniter is itself fired by receipt of an electrical signal into the initiator commonly called the squib or the primer charge, releasing the energy into the booster charge. Finally the main charge propellants are ignited. A typical igniter design is shown in Fig. 30.

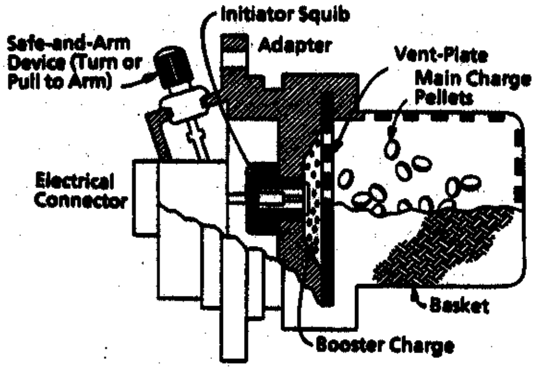


Figure 30. Typical pyrotechnic-type igniter (simplified).

Table 11 gives some of the more common igniter-material formulations; adjustment of the percentages shown is necessary in some formulations. Binder content usually varies from 1 to 5 percent and typically includes Epoxy resins, graphite, vegetable oil, nitrocellulose, and polyisobutylene. The initiator charge formulation is usually boron or a boron mixture since they are particularly easy to ignite and are self-sustaining at low pressure.

Table 11. Formulations of Typical Igniter Compounds for Pyrotechnic Igniters

Type	Fuel	Fuel Percentage	Oxidizer	Oxidizer Percentage
1	Aluminum	35	$KClO_4$	65
2	Boron	30	$KClO_4$	70
3	Boron	20	KNO_3	80
4	Magnesium	60	Teflon®	40

$KClO_4$, Potassium Perchlorate
KNO_3, Potassium Nitrate

Pyrogen igniters are similar except that heat transfer from the pyrogen to the motor grain is largely convective, with the hot gases contacting the grain surface as contrasted to a highly radiative energy emitted by pyrotechnic igniters. Figure 31 illustrates a typical pyrogen igniter; the initiator and the booster charge are very similar to the designs used in pyrotechnic igniters.

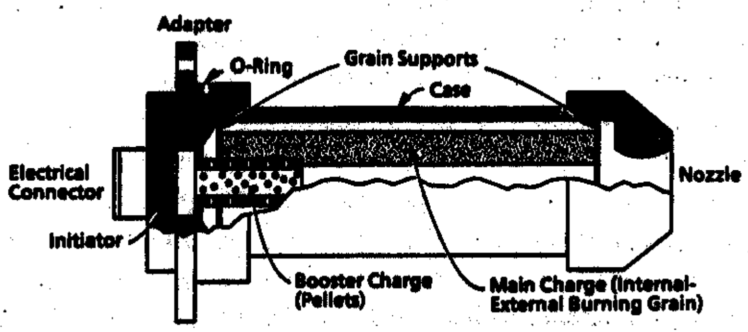
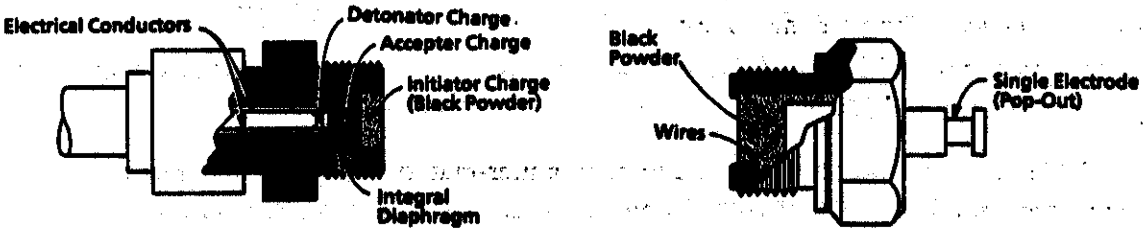


Figure 31. Typical pyrogen (rocket-type) igniter.

To safeguard against motor misfires or inadvertent motor ignition, two approaches are commonly used. One is use of the classical safe-and-arm device, and the second is the design of safeguards into the initiator. Functionally, the safe-and-arm device serves as an electrical switch to keep the igniter circuit grounded when not operating to avoid unintentional ignition caused by static electricity, induced current from electromagnetic radiation, such as radar, stray electrical currents, or heat, vibration, or shock from handling operations. Three typical initiator designs are shown in Fig. 32.

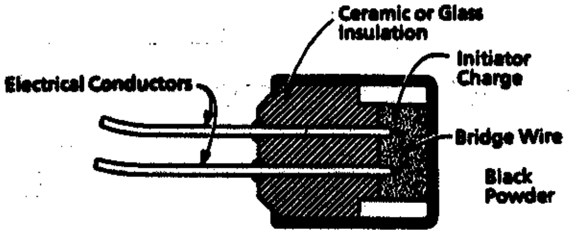


a. Integral diaphragm type

b. Header type, double bridge wire

3.2.5 Nozzles

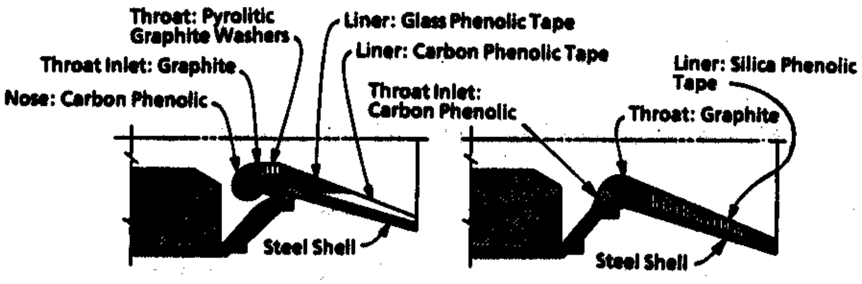
The nozzle must be designed to convert the combustion chamber thermal energy into directed kinetic energy and to restrict the gas flow so that a desired chamber pressure is maintained.



c. Exploding bridge wire type

Figure 32. Typical electrical initiators.

The nozzles of solid-propellant rocket motors, like the cases, are usually uncooled. The nozzle section of the rocket is subjected to severe conditions because of the relatively high heat-transfer rates and because of the mechanical erosion effects of the hot, high-velocity gases that contain entrained solid matter. Maximum heat-transfer conditions occur at the nozzle throat; material limitations of this area provide the major drawback to increasing specific impulse by increasing flame temperature.



Partially Submerged Nozzle

External Nozzle

Figure 33. Typical ablative nozzle sections and materials.

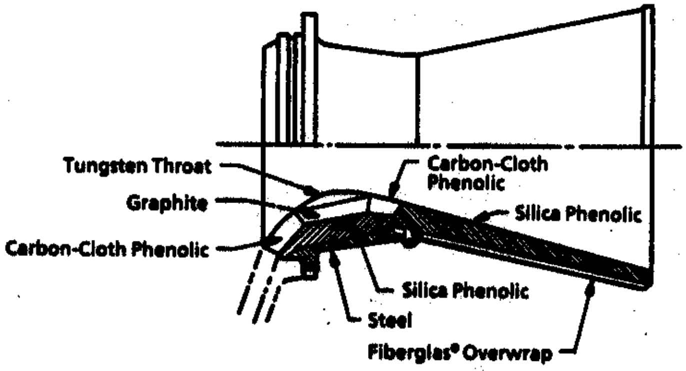


Figure 34. Nozzle design for solid-propellant motor employing heat-sink walls and complex throat inserts.

Nozzles in SRBM applications with solid-propellant rocket motors, require inserts of special materials for the throat section (tungsten, various carbides, carbon-carbon, or ablative material such as glass or reinforced plastic). Figures 33 and 34 show designs of typical ablative nozzles. Most of these nozzles use a simple 30-deg (total included angle) conical expansion section, since the bell-shaped contour popular in liquid-propellant rocket engines loses much of its benefit in the presence of mixed gas and solid-particle (Al_2O_3) flow. Compared to nozzles on liquid-propellant rocket engines, solid-propellant rocket nozzles (being uncooled) are relatively rugged and heavy.

Nozzle throat erosion is one of the most critical problems encountered in nozzle design. Usually, a throat-area-increase larger than 5 percent is considered unacceptable. Two successful materials used to resist the erosion are ATJ grade of molded graphite and pyrolytic graphite. Erosion rates for these materials are shown as follows:

	ATJ Molded Graphite	Pyrolytic Graphite
Erosion Rate (Typical Solid-Propellant Rocket, in./sec)	0.004 to 0.006	0.001 to 0.002

Carbon-carbon fiber fabrics are also used in state-of-the-art rockets, using labor-intensive layer processes. Table 12 groups various typical nozzle materials according to their usage.

Table 12. Motor Nozzle Materials and Their Functions

Function	Material	Remarks
Housing and Structure (Shell)	Aluminum or Filament-Reinforced Plastics	Lightweight; Limited to 400° to 500°F and Relatively Low Chamber Pressure
	High-Strength Steels, Including Udimet 500, René 41, Waspalloy	Good to 1,500°F, Relatively Rigid, Strong
Heat Sink (Throat)	Graphites (Pyrolitic and Molded)	Pyrolytic Graphite Has Anisotropic Conductivity
	Tungsten	Heavy, Expensive. Subject to Cracking
	Molybdenum	Good Strength; Subject to Cracking
Insulator (Divergent Section)	Ablative Plastics (Refrasil, Asbestos Phenolic, Graphite, Cloth Phenolic Impregnated)	Very Low Conductivity
	Pyrolytic Graphite	Crystal or Grain Orientation Controls Conductivity
	Ceramics (ZrO_2,Al_2O_3, etc.)	Subject to Cracking
Flame Barrier	Ceramic Coatings	Subject to Cracking, Flaking; Low Erosion Rates
	Graphite Coatings	Pyrolytic Has Best High-Temperature Resistance
	Ablative Plastics (Filament Reinforced)	Rugged; Relatively High Erosion Rates
	Refractory Metals (W, Mo)	Heavy, Strong; Low Erosion Rate but Subject to Cracking

Special reinforced plastics are satisfactory for the nozzle converging and diverging sections, where the heat-transfer rate is much lower than in the throat. Nozzles with several different ablative materials are shown in Figs. 33 and 34. Typical ablative materials usually consist of a high-temperature-resistant plastic or resin with reinforcement fibers. The material near the surface becomes rough and porous — a "char."

3.2.6 Thrust Vector Control (TVC) Methods

Capability to vary the thrust vector angle with respect to the motor's major thrust axis is a requirement for precision SRBM targeting. Gimballing of the entire solid-propellant rocket motor is much more complicated than with liquid-propellant rocket thrust chambers because of motor weight, size, and its structural integration with the vehicle.

Alternatives to motor gimballing are shown in Table 13. These TVC methods deflect the exhaust gas mechanically (such as the jet vane) or aerodynamically (fluid injection). Another method, using a gimballed or movable nozzle design, which uses flexible bearings without any sliding contact surfaces that need to be sealed, is shown in Fig. 35.

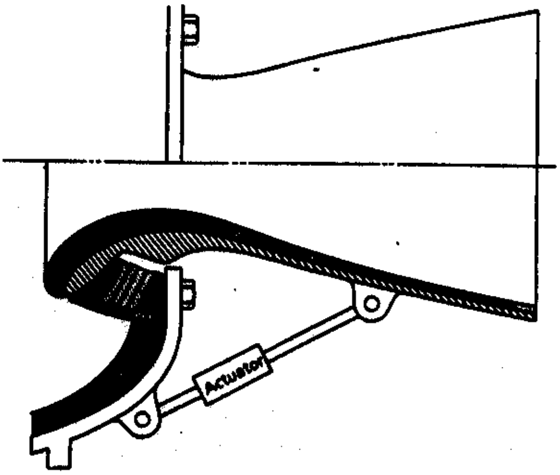


Figure 35. Movable nozzle using a flexible elastomeric laminated bearing.

Table 13. Common Types of Solid-Propellant Rocket Motor Thrust Vector Control

Types	Advantages	Disadvantages	Characteristics
1. Jet Vanes	Proven Technology; Low Actuation Power; High Slew Rate	Thrust Loss of 0.5 to 2 percent; Jet Vane Erosion	Four Vanes per Nozzle Gives Pitch, Yaw, and Roll
2. Jetevators	Proven Technology; Low Actuation Power; Lightweight	Similar to Jet Vanes; Induces Vehicle Base Recirculation.	One Jetevator Gives Pitch and Yaw; Two, Gimballed, Give Pitch, Yaw, and Roll
3. Movable Nozzle (Flexible Bearing)	Proven Technology; No Sliding Hot Parts; No Gimbal Ring; Reliable Gas Seal; Predictable and Uniform (Unit to Unit) Actuation Power	High Actuation Power Required; Complex Assembly	One Nozzle Gives Pitch and Yaw; Two Nozzles Give Pitch, Yaw, and Roll
4. Liquid Injection	Proven Technology; Minimum Requirement for Full-Scale Engine Tests; High Slew Rate; Easy to Adapt to Various Motors	Subject to Maintenance and Repeated Checkouts; Toxic Liquids Required for High Performance; Packaging of Tankage and Feed System	One Nozzle with Four Equally Spaced Sets of Injection Ports Gives Pitch and Yaw. Two Nozzles Give Pitch, Yaw, and Roll

In addition to thrust vector control for pitch and yaw, roll control will also be required. Actually, roll control is unnecessary if the onboard guidance computer is sufficiently sophisticated, but it is simpler to provide roll control than account for exact missile angular position when making pitch/yaw corrections to achieve the proper flight path/angle. Roll control can be achieved, as noted in Table 13, with multiple jet vanes or nozzles. Otherwise, auxiliary roll control from stored gas or a solid-propellant gas generator is required. Roll torque requirements are usually minimal, unless external air vanes are misaligned or the motor nozzle has a large thrust vector offset.

3.2.7 Thrust Termination

Applications of solid-propellant rockets in ballistic missiles require that the rocket thrust be precisely terminated in its trajectory at a specified flight velocity. Several thrust-termination schemes are shown in Fig. 36. The scheme using the opening of holes in the forward chamber closure provides rapid depressurization and flame extinguishment. Only the second stage of a two-stage SRBM needs to be equipped with thrust-termination capability.

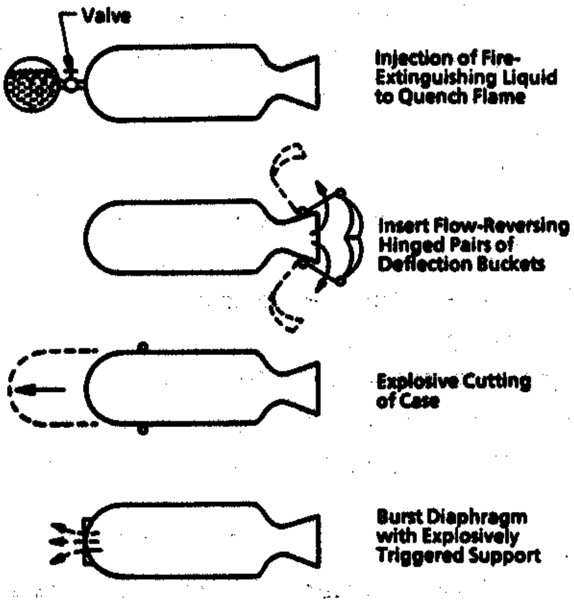


Figure 36. Schematic diagrams of several thrust-termination devices.

The most popular, efficient, and repeatable method of thrust termination is by case blow-out plugs or ports that are usually actuated by explosive devices, mainly rope/line charges whose action is initiated on receipt of an electric signal. Thrust-termination ports are usually located on the forward case closure (opposite the nozzle), and there are usually two or more such ports. In order to balance side forces, the thrust-termination blow-out devices and their ducts are designed in symmetrically opposed sets (two or more). Their action is twofold: (1) By producing a flow of mass in a direction opposite to the nozzle flow, the net thrust is close to zero; and (2) by increasing the effective nozzle area, the actual chamber pressure is quickly reduced to a value where sustained burning of the propellant ceases. Figure 27 shows the location of such thrust-termination devices in a metal motor case, and Fig. 28 shows the termination ports in a filament-wound case.

3.3 MANUFACTURING PROCESSES

The manufacture of solid propellant involves complex physical and chemical processes. In the past, propellant has been produced by several different processes, including the compaction or pressing of powder charges, extrusion of propellant through dies under pressure using heavy presses, and mixing with a solvent that is later evaporated. Even for the same type of propellant (e.g., double-base, composite, or composite double-base), the fabrication processes are usually not identical for different motor types, sizes, or propellant formulation. Much of the solid-propellant processing discussed in this section is adopted from Refs. 11 and 12. A generalized process flow sheet or fabrication technique is shown in Fig. 37.

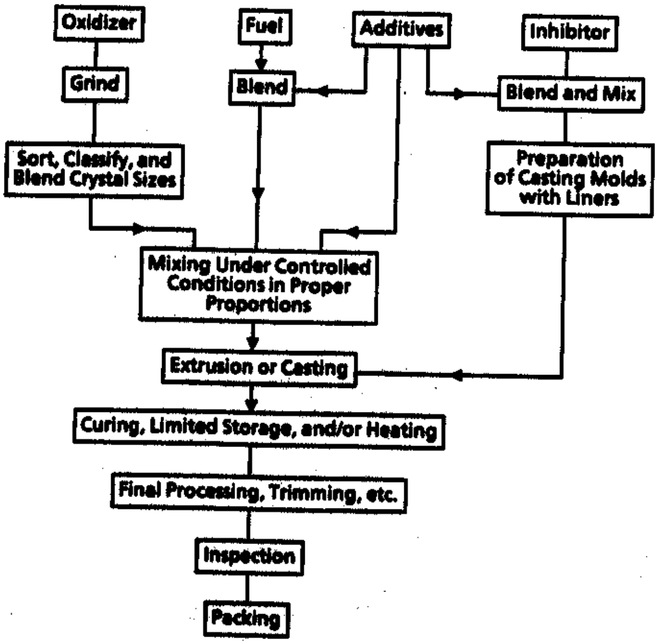


Figure 37. General processing sequences in the preparation of a fuel-oxidizer composite propellant.

Short-range ballistic missile (SRBM) propellants are mainly fabricated by casting the propellant into the motor case. Propellants can be extruded and sealed in the case as in Fig. 38. Either single-base or double-base propellants can be extruded, but the process is limited to propellant grains of about 1/2-m diam because of the large, heavy-duty, very expensive extrusion presses required.

Castable propellants are categorized into three types as briefly discussed in the following:

1. **Solvent Cast Double-Base.** The cast double-base process depends on the gelatinization of nitrocellulose granules with nitroglycerin and other plasticizers to achieve a single, solid mass of propellant.

   The nitrocellulose is prepared as small right circular cylinders about 0.30 in. long by 0.30 in. in diameter by extrusion, cutting, and drying of nitrocellulose that has been plasticized with an alcohol-ether solvent system. The small cylindrical

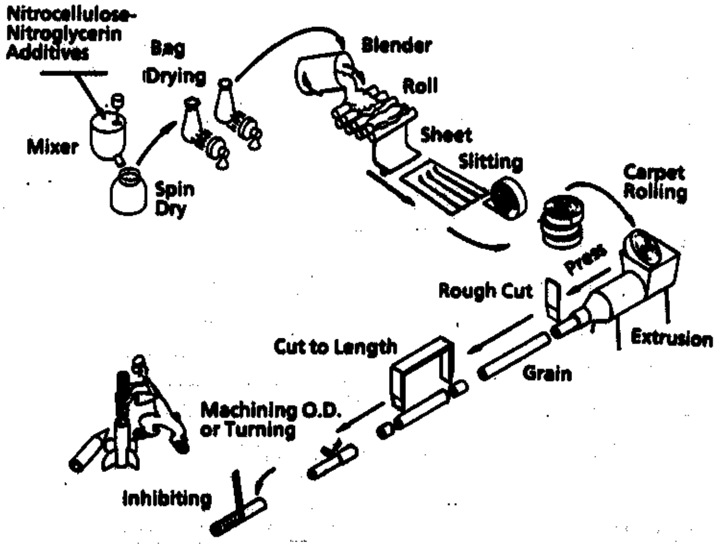


Figure 38. Diagram for manufacture of solventless double-base extruded propellant.

granules of nitrocellulose are loaded into a previously prepared rocket motor, and a suitable solvent system is forced into the bed of granules. This solvent system is nitroglycerin and selected plasticizers. The entire assembly is heated at 110° to 130°F for a period of time sufficient for the casting solvent to soften and swell the nitrocellulose to obtain a single, solid mass.

The interior burning surface configuration is formed by a mandrel that has been placed inside the motor, and this mandrel is withdrawn after the casting process is complete.

For cast composite-modified double-base propellant containing AP oxidizer and metal fuels, these solid materials can be incorporated in the nitrocellulose granules, or the oxidizer and metal can be blended with the granules of nitrocellulose.

2. **Slurry-Cast Double-Base Propellant.** This process also depends on the gelatinization of nitrocellulose with a suitable high-energy plasticizing material to obtain a single, solid mass of propellant.

   The nitrocellulose is prepared in the form of spheres of a 10-μm, or less, diameter by the emulsification of a nitrocellulose lacquer in a water suspension followed by removal of the lacquer solvent. With the nitrocellulose in this physical form, suitable ratios of nitrocellulose to plasticizer can be prepared directly in simple mixing equipment, and the result is a low-viscosity slurry, even when the slurry contains AP or other oxidizer and metal fuels. The slurry is poured directly into a motor chamber that has been prepared with suitable adhesives and liner, and after gelatinization at 110° to 130°F, the entire mass is found to be bonded to the motor chamber. Burning surface configuration is obtained by a suitably shaped mandrel that is removed after the gelatinizing step.

3. **Cast Composite Propellants.** The composite type of solid propellant depends on a chemical cross-linking of suitable binder containing AP or other oxidizer and metal fuel. Binders currently used are polybutadiene-acrylic acid cross-linked with Epoxy resins; polyurethanes; and polysulfides bonded through the mercaptan linkage. The polybutandiene-acrylic acid, or the polypropylene glycol and triols, or the liquid-polysulfide polymer is placed in a mixer, and the metal fuel is added initially. The oxidizer is added in increments with additional mixing, and finally the liquid Epoxy resin, to the tolylene diisocyanate; or the suitable polysulfide cross-linker is added just shortly before the end of the mixing cycle. The resulting slurry is poured into a previously prepared and lined motor chamber, and the entire motor is held at an elevated temperature sufficient to obtain the necessary chemical cross-linking. This casting process results in a single, solid mass of propellant that is bonded to the motor chamber. The burning surface configuration is obtained by conducting this casting and curing operation around a suitably shaped mandrel, which is later withdrawn.

A generalized manufacturing flow process for a composite and composite-modified double-base (CMDB) solid-propellant-type rocket motor is shown in Fig. 39.

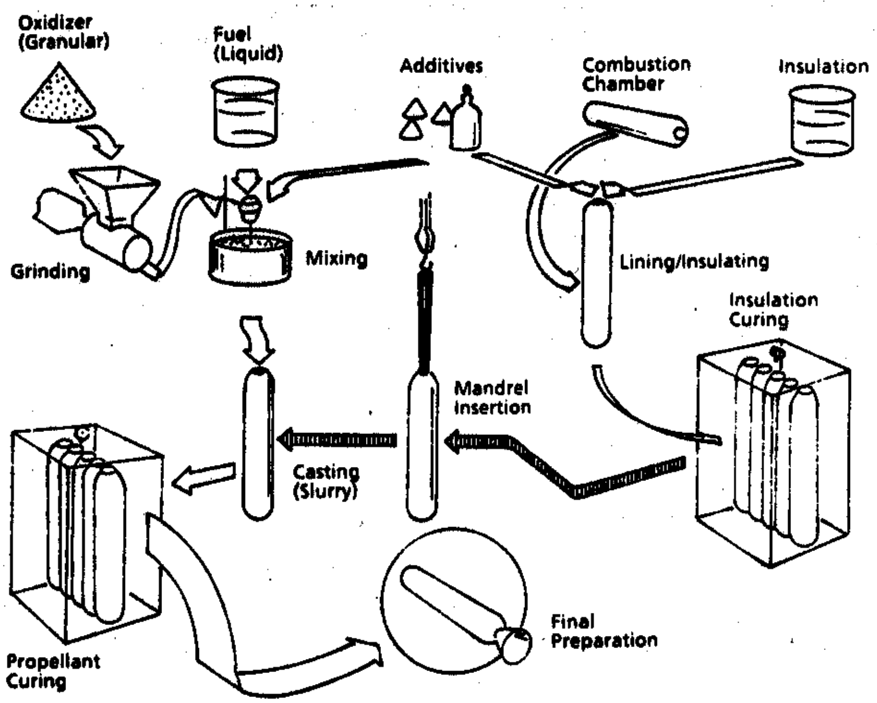


Figure 39. Manufacture of engine with internal-burning charge of castable composite propellant.

The rheological properties of the uncured propellant, i.e. its flow properties in terms of shear rate, stress, and time, are all important to the processability of the propellant, and these properties usually change substantially throughout the length of the processing line, especially in production lines that process the propellant in batches as contrasted to continuous-flow propellant processing lines. Batch-type processing of propellant, including the casting (pouring) of propellant into motors that serve as their own molds, is the most common method. Whether a continuous-flow or a batch process is employed in the manufacture of a motor, vacuum is almost always imposed on the propellant during the mixing and casting operations to remove air and other dispersed gases and to avoid air bubbles in the grain. Vacuum, temperature, energy input of the mixer, and time are some of the factors affecting the viscosity of the uncured propellant; time is important in terms of pot-life, that period of time the uncured propellant remains reasonably fluid after mixing before it cures and hardens. Short pot-life requires fast operations in emptying mixers, measuring for quality control, transporting, and casting into motors. Some binder systems, such as those using PVC, give a very long pot-life and avoid the urgency of haste in the processing line.

Mandrels are used during casting and curing to assure a good internal form. They are made in the shape of the internal bore (e.g., star or dog bone) and are often slightly tapered and coated with a nonbonding material, such as Teflon®, to permit the withdrawal of the mandrel after curing without tearing the grain. For complicated internal passages, a complex built-up mandrel, which can be withdrawn through the nozzle opening in smaller pieces or which can be collapsed, may be required. Some manufacturers have had success in making permanent mandrels (They are not withdrawn but stay with the motor) out of lightweight foamed propellant, which burns very quickly once it is ignited.

An important objective in propellant processing is to produce a propellant grain free of cracks, low-density areas, voids, or other flaws. In general, voids and other flaws degrade the ballistic and mechanical properties of the propellant grain. Even the inclusion of finely dispersed gas in a propellant can result in an abnormally high burning rate, one so high as to cause catastrophic motor failure.

Processing techniques that minimize the formation of flaws in the propellant grain include (1) application of vacuum during the mixing, transporting, and casting operations; (2) use of bayonet nozzle in casting; and (3) vibration of the motor during the casting operation. The bayonet nozzle withdraws as the propellant level rises in the motor case, the rate of withdrawal equaling the propellant-level rise rate. Often the nozzle exit is kept slightly submerged in the propellant during the casting process, and the nozzle and/or the case is vibrated to further minimize the formation of bubbles in the viscous, uncured propellant. The finished grain (or motor) is usually inspected for defects (cracks, voids, and debonds) using X-ray, ultrasonic, heat conductivity, or other nondestructive inspection techniques.

Samples of propellant are taken from each batch, tested for rheological properties, and cast into physical property specimens and/or small motors that are cured and subsequently tested. A determination of the sensitivity of motor performance, including possible failure, to propellant voids and other flaws often requires the test firing of motors with known defects. Data from the tests are important in establishing inspection criteria for accepting and rejecting production motors.

Rigid safety precautions must be observed during solid-propellant rocket manufacture to minimize potential hazards of explosion or fire. This includes such items as a limit on the number of persons allowed at any one time in a hazardous area, requirements for spark-proof tools and shoes, prohibition against use of matches, cigarettes or lighters, use of remote controls and handling mechanisms, close automatic surveillance of hazardous operations (e.g., mixing/pouring), or physical separation of building with potentially dangerous unit operations, and sources of sparking from electrostatic discharge of metal-to-metal contact.

Toxicity. The toxicity, both dermatological and respiratory, of some propellant ingredients, such as epoxide and imine cross-linking agents used with polybutadiene prepolymer binder systems, necessitates specific safeguards and training in handling and storing the ingredients and in processing the propellants.

3.4 PROCESSING EQUIPMENT AND OPERATIONS

Most of the ballistic missiles in production today use castable CMDB or composite-type propellants. Most available processing equipment is designed for these applications; therefore, the majority of the discussion will be focused in this area.

The processing of the propellant can be placed simply into these eight categories:

1. case and component preparation,
2. restrictor and copolymer binder preparation,
3. oxidizer preparation and grinding,
4. mixing,
5. blocking and extrusion or casting,
6. trimming and restricting,
7. curing,
8. final assembly.

Table 14 shows the composition of a typical nonaluminized composite propellant.

Table 14. Conventional Composite Propellant Composition

	Percent by Weight	
	Typical	Range
Synthetic Rubber	10.0	5 to 15
Carbon-Black	2.0	0 to 5
Plasticizer	2.0	0 to 5
Curatives	0.4	0 to 1
Age Resistor	0.3	0 to 1
Oxidizer	83.0	75 to 90
Burn-Rate Catalyst	2.3	0 to 4

The components in the propellant are generally used in the following manner:

1. The synthetic rubber serves as the major portion of the fuel and also serves as the matrix for holding the other ingredients together.
2. The carbon-black reinforces, or strengthens, the polymer and acts as part of the fuel system.
3. The plasticizer is a processing aid and serves as part of the fuel.
4. Curatives impart the necessary physical properties to the polymer system. The age resistor protects the polymer from atmospheric oxidation and other aging effects.
5. The oxidizer provides the oxygen required by the fuel for combustion.
6. The burning-rate catalyst provides a coarse control of the burning rate of the propellant.
7. The combined synthetic rubber, carbon-black, plasticizer, curatives, and age resistor are often referred to as the binder.

Caked oxidizer must be crushed into flowable prills (spherical form) before processing can proceed. This primary crushing operation is generally not difficult. Standard crushers such as the rotary crusher will readily reduce the clusters with little loss of usable oxidizer.

Propellant raw materials that would contribute significant quantities of moisture to the propellant must be dried. Water in propellant adds weight and is detrimental to storage properties. Generally, the moisture content of the propellant is held below 0.3 percent and preferably below 0.1 percent. In order to maintain the low level of moisture, those stages of processing where the oxidizer, the binder, or the propellant are exposed to the atmosphere, must be conducted under conditions of controlled temperature and humidity because of their hygroscopic (tendency to absorb water) nature. Propellant-processing room temperatures are controlled at approximately 85°F, and relative humidity is held to less than 30 percent.

Oxidizers may be dried in conventional drying equipment such as the tray, rotary, or vacuum dryer. When available, steam is generally the preferred source of heat for economy and safety. Drying temperatures range from about 179° to 255°F, and drying cycles vary from about 1 to 12 hr depending on the type of drying equipment and the initial moisture content of the oxidizer. At lower temperatures, the drying cycle is unduly long, and at higher temperatures, the danger of decomposition is increased. Initial moisture content of the oxidizer varies from 0.1 to 0.3 percent, and moisture content after drying varies from 0.02 to 0.05 percent. The oxidizer is dried before grinding to improve the flow properties for the grinding operation. When the drying operation is conducted in equipment such as a rotary dryer, special care must be taken to avoid undue attrition that would require an additional operation to screen out fine and irregular particles. These fine and irregular particles may cause serious bulk flow problems in the grinding operation.

After the oxidizer has been dried, it is ground to the particle size required to provide a propellant with the proper burning rate. It has been found that the particle size of the crystals has a major effect on the burning rate, the processing properties, and the physical properties of the propellant. In general, a decrease in particle size results in an increase in burning rate. The effects of crystal size are sometimes so significant that a whole series of propellant can be made with the same composition by merely varying the particle size. The grinding of the crystals to the proper sizes (and also to the proper distribution of particle sizes) under controlled atmospheric conditions is a mechanical process that is often difficult to control.

Because of the effect on the burning rate, rigorous control of the grinding operation is required. Particle sizes required range generally from about 5 to 300 μm (Fig. 26). Conventional grinding equipment such as the hammermill is used for the grinding operation.

Operating problems are associated with the poor flow properties of ammonium nitrate. If inadequately dried, the prills will bridge in the feed hopper, and the feed screw cannot pick them up. Fine particles aggravate this problem since they fill the voids between the prills, causing the oxidizer to pack. Pulsating panels have been used to break such bridges. Good hopper design can contribute to the prevention of the formation of the bridge. Hoppers with sides sloped at a minimum of 60 deg are used. Bridges that may form from all-ground oxidizer in later operations are much more difficult to break. Ammonium nitrate has a tendency to agglomerate on grinder parts and in pneumatic conveyor collectors. Shutdown for clean out does not contribute to a well-lined-out operation. Control of particle size, using sieve analysis, has not proved satisfactory. The particles agglomerate and the sieve analysis is not accurate for fine grinds. A subsieve sizer is accurate for the fine particles, but inaccurate for coarse grinds. Adequate process control has been developed by making microscopic analyses to determine particle size for specific hammer speeds and screen sizes. With such analyses over the range of operating conditions for the machine, particle size can be adjusted by setting the machine to operate at the conditions known to give the desired particle size.

Binder Preparation. Binder preparation includes drying of the rubber; breakdown of the rubber to reduce viscosity and improve plasticity; addition of carbon-black; and incorporation of age resistor, plasticizer, curatives, and other specific ingredients. Moisture content of the rubber as received may be as high as 1.0 percent. In order to maintain the desired moisture content of the propellant, the rubber is dried to about 0.1-percent moisture. Although other methods can be used, the drying operation is best conducted in a heavy-duty mixer of the type used in the rubber industry. Heat generated by the intensive action of the mixer blades in masticating the rubber readily drives off the moisture. The continuous exposure of fresh surfaces aids in releasing the moisture. Since viscosity of the rubbery mixture is very high, the viscosity is measured in a Mooney viscometer. Mooney scorch is a measure of the incipient curing characteristics of a rubber compound. Viscosity of the rubber may vary from about 20- to 50-Mooney scorch. The viscosity range is reduced to about 20 to 30 by blending or working in the mixer. The lower viscosity aids the propellant mixing process. The carbon-black content of the rubber may not be within the formulation specifications and is adjusted in the binder mixer by blending or addition.

Other ingredients may be added at this time or as a preliminary operation in the propellant mixing step. Curatives that are readily active at low temperature would not be added prior to propellant mixing. Although the preparation of the rubber binder may be conducted in an undehumidified atmosphere, after it is dried the binder must be protected or moved to a dehumidified atmosphere to prevent moisture pickup. Figure 40 shows a binder preparation setup with a mixer on top that discharges into an extruder below. Material extruded is cut into sections for transfer to the next process step.

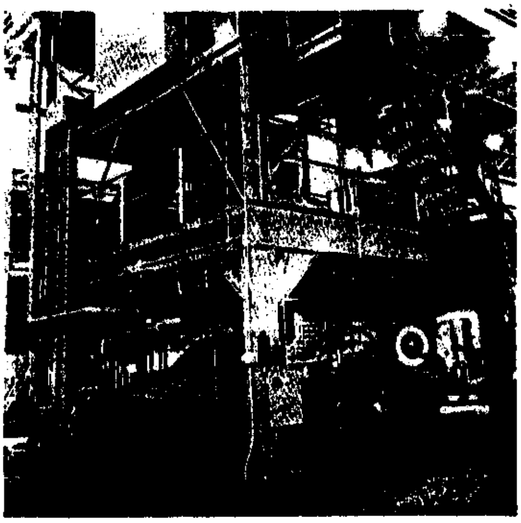


Figure 40. Mixer and extruder for copolymer preparation.

Mixing. Propellant mixing is the most critical step of the process. Adequate mixing demands the incorporation and dispersion of the oxidizer and burning-rate catalyst into the rubber binder, the rubber being the continuous phase. The propellant is then a rubber heavily loaded with oxidizer salt. The oxidizer (ammonium nitrate or AP) is added in increments, and the increment size is controlled to prevent the mixture from falling apart. The number of increments may vary from two to as many as six in extreme cases. Generally, three increments are adequate. After incorporation, mixing is continued to break up oxidizer agglomerate and achieve adequate dispersion. Burning-rate control is accomplished not only through oxidizer particle size and quantity of burning-rate catalyst but through extension of mixing time. Overall mixing time may vary from approximately 30 min to as long as 2 hr where high burning rates are desired.

Some fuel binders require elevated temperatures (for example, the use of steam-jacketed mixers) to attain sufficient fluidity to permit mixing. Other fuel binders (usually consisting of two or more basic ingredients) undergo a chemical change and release heat (for example, certain types of polymerizing plastics) to form the grain. With this last type of fuel, the grains must be cast, extruded (gives off heat), or formed within a prescribed time after mixing. If this chemical reaction is highly exothermic, the mixer may have to include cooling provisions.

Burning Rate. In some cases, low burning-rate requirements do not permit sufficient mixing time to achieve good incorporation and dispersion. Batch-to-batch reproducibility then suffers. This shortcoming can be overcome by adding a burning-rate inhibitor so that additional work can be put into the mix to obtain adequate incorporation and dispersion without exceeding burning-rate specification. Care must be taken to control the temperature of the mix to prevent scorching or incipient curing. Preferably, the mix temperature is controlled at a maximum of 140°F. The degree of scorch has a time-temperature relationship; consequently, extended mix time generally results in a stiffer, less plastic mix. Scorched propellant may cause poor consolidation, swelling, and distortion of the formed propellant from the extrusion process. Generally, a portion of the mixing step is conducted under vacuum to remove air bubbles from the mix. This may not be necessary if adequate evacuation is provided in the blocking and extrusion operations. Mixing is conducted in the rugged, heavy-duty-type mixers common to the rubber and plastic industries. These mixers usually range from a 100- to 300-gallon size, and occasionally a 600-gallon size is used for large-diameter solid-propellant rocket motors. The mixers employed in the process are usually either sigma-blade mixers or vertical planetary mixers. They are equipped with a compression ram to hold the propellant in the mixer bowl where the dispersion blades can get a good bite. A vacuum cover is provided to permit evacuation of air from the mix. The mixer bowl is jacketed for circulation of cooling water. Sometimes the blades are cored for circulation of water where additional cooling surface is required. Mixer performance may vary even between supposedly identical mixers, requiring minor modifications to mixing procedures to achieve comparable mixes. This effect is attributed to slight differences in blade-to-bowl clearances, blade contour, and metal-surface finish resulting in different mixing intensities. Blade-to-blade and blade-to-bowl clearance is critical;

it should be kept to a minimum to maximize shearing energy input, but no contact must take place between blade and bowl for safety reasons. A typical propellant mixer is shown in Fig. 41.

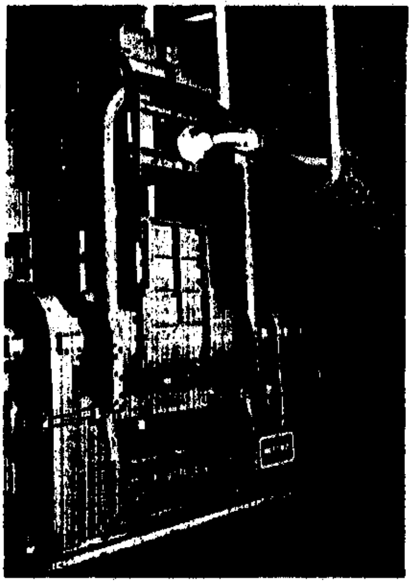


Figure 41. Propellant mixer.

Extrusion. Mixed propellant can be formed to the desired geometric configuration by extrusion with hydraulic extrusion presses. Preblocking the mix before charging the extruder is generally practiced with the use of hydraulic blocking presses capable of exerting up to 3,000 lb/in.^{2} on the propellant. Evacuation of the basket of the press before exerting force prevents heating of any entrapped air, which may cause an explosion. Blocking cycles run in the order of 10 min. Blocking may not be required but has the advantage of simplifying the loading of the basket of the extrusion press and also of permitting the higher loading required for extruding large pieces. Extrusion presses capable of exerting a force in excess of 2,000 tons have been used. After loading, the basket is evacuated to remove air before force is applied. Extrudability is affected by the hardness and flow characteristics of the propellant and the size and geometric complexity of the extrudate. Pressure on the propellant may vary from about 3,000 to 20,000 lb/in.^{2}. The basket can be jacketed and the die sections cored for circulation of cold or hot water. Cooling may be required to reduce the skin temperature of the propellant, and heat may be required to improve the flow properties at the friction surfaces.

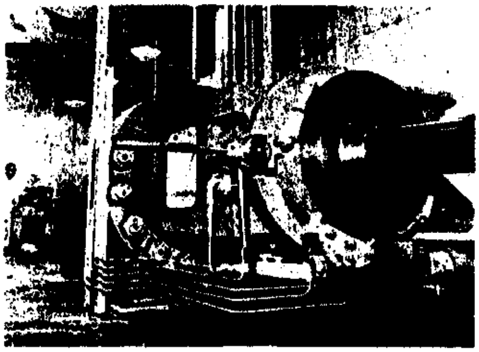


Figure 42. Propellant extrusion press.

Good die design is imperative to achieve a well-consolidated extruded stock. Contoured approach section, a polished surface, and adequate land length are mandatory. The more complex the design of the formed propellant, the more complex becomes the die design problems. Even with careful balance of die design factors, extrusion rates, and extrusion temperatures, the die may require several modifications before it meets all requirements. Extrusion rates may vary from a few in./min to as high as 50 in./min. Extrusion cycles may vary from about 20 to 60 min. Figures 42 and 43 show an extrusion press and schematic extruding a tube of rubber-base composite rocket propellant. Although the extrusion process requires costly equipment, it permits the exact control of grain size and shape.

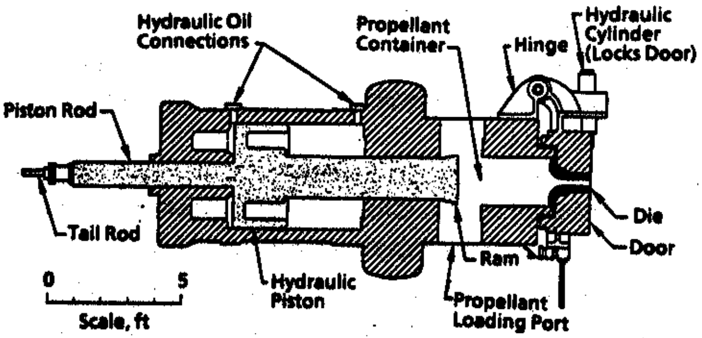


Figure 43. Schematic of large extrusion press.

Trimming. The formed propellant is cut from the extruder by one of several types of cutters, generally a guillotine type. The propellant at this stage is commonly referred to as a grain. Since the guillotine makes a rough cut, a final trimming operation is required to meet dimensional specifications. Trimming may be done before or after curing. Where dimensional control is critical, trimming is preferably accomplished after curing because of dimensional changes that occur during cure. Extrusions will usually shorten slightly, and the cross section will get larger. Both the green and the cured propellant cut and machine readily. Cutting has been conducted with a band saw and with rotary cutters. Machining has been accomplished with a lathe and with special contouring machines.

The surfaces of the grain that are not burning surfaces during the rocket firing are inhibited from burning by application of a restrictor. The restrictor being used with the rubber-base propellants discussed in this report is similar to the propellant binder. The formulation includes a polymer reinforced with a furnace black, a plasticizer selected to impart good processing and superior low-temperature properties, age resistors to ensure long life, and curing agents. It is prepared in the same type of equipment as is the binder and is sheeted on a three-roll calender. Sheeted restrictor is generally from 1/16 to 3/16 in. thick. The restrictor may be bonded to the propellant with or without adhesives. Normally, direct propellant to restrictor bond is adequate to withstand the temperature cycling and vibration tests to which the rocket will be subjected.

Severe problems, such as high-velocity gas flow past the joined surfaces require application techniques using adhesives. The restrictor may in some cases be subjected to high temperatures for relatively long durations, which require that the restrictor be insulated to prevent breakdown. As the restrictor bonds to the rubber on the propellant surface and the more oxidizer particles are exposed on the surface, the less the opportunity for a good bond. The periphery will usually have less oxidizer at the surface than the end of the grain. In addition to adhesives, the bond can be improved by pressure application of the restrictor. Special fixtures have been used in which the restricted grain can be placed, vacuum applied to remove entrapped air, and pressure applied to the restricted surface to make an excellent bond. In many cases, the restricted surface must also be bonded to a metal support that is part of the internal hardware of the rocket. The rubber-base restrictor is adequate for this purpose.

The grains are cured in an oven at an elevated temperature. The temperature at which the oven is operated and the time required to achieve curing depend on the cure system used in the propellant formulation and the physical characteristics desired. Temperatures used vary from 175° to 225°F, and curing times vary from 16 to 48 hr. Intricate grain shapes and grains made with soft propellant may require support to prevent slumping.

Final Assembly. Preparation of the rocket case and metal components includes degreasing, removing of strippable protective coatings, phosphatizing, painting, hydrostatic testing, application of insulation, and insertion of rupture disks. Finally, assembly includes insertion of the starter disk and related operations. Special jigs and fixtures are used to insert the grain in the proper position without disfiguring the surfaces.

Cast Propellant. Many of the propellants that have a crystalline oxidizing agent are cast into the proper grain shape. They are cast either directly into the combustion chamber (which has been prepared prior to casting by suitable cleaning processes and often the application of a liner) or into special molds. To form the required port area, a metal core or mandrel is inserted into the mold. This core is usually slightly tapered to permit easy withdrawal after hardening of the propellant. The mandrel is usually coated with Teflon to prevent the cast propellant from sticking to it.

Some typical rocket motor grain geometries are shown in Fig. 24. The geometry is dictated by the ballistic requirements of the motor, but the configuration is constrained by the mechanical properties of the propellant. Mechanical properties determine the maximum strain that may be imposed by operation and storage over a wide temperature range.

The solid-propellant grain is usually not cast directly into the insulated motor case because a better bond is obtained by using a 20- to 50-mil-thick layer of liner, a rubbery material that is painted on the inside of the motor case and partially cured. The uncured propellant is then cast against the partially cured liner, and the cure of both propellant and liner is then completed at an elevated temperature. Thus, some "chemical bonding" takes place across the propellant-liner interface. Generally, the liner is a carbon-filled rubber that is based on the same polymer system as the propellant binder and the case insulation.

Casting composite solid propellant for SRBMs is in many ways similar to the much older casting techniques used to shape and form metals. Almost all the available shapes and sizes of metals have their beginning in the form of a casting — that is, the metals all start from a liquid (molten) stage; the molten metal is poured into a suitable mold and allowed to solidify.

The three most common methods of propellant casting are bayonet casting, in which the propellant is introduced into the top of the motor through hoses; bottom casting, in which the propellant is forced by pressure through an opening in the bottom of the rocket case; and vacuum casting, in which the propellant is passed through a slit plate into a rocket case either enclosed in a vacuum bell, or serving as its own bell. The latter method, vacuum casting, is used most universally because it provides the surest method of loading propellant into the case without entrapping air, which would change the burning characteristics.

Bayonet Casting. Bayonet casting has been used to load rocket motors for many years. In this process, the air introduced into the propellant during mixing must be removed. Deaeration usually is accomplished immediately after mixing. This process is accomplished by "split deaeration" where the propellant is placed in a "slit can" with a "slit plate" bottom (i.e. casting can). From the casting can, the propellant is then forced into the motor case using pneumatic pressure. Propellant then flows through a hose and a casting bayonet, the tip of which is kept just below the propellant surface in order to avoid entrainment of air. Bayonet casting requires use of a pressure vessel to push propellant through the bayonets, using a driving force such as air or nitrogen. Equipment also is required to either lower the motor or to remove the bayonets as the propellant level rises. Facilities are relatively inexpensive, and although bayonet casting allows introduction of more voids in the grain than vacuum casting, it also eliminates the necessity of expensive vacuum bells and related tooling. However, propellant losses with this process are higher than with other casting techniques.

The bayonet casting technique (Figs. 44 and 45) has been used throughout the industry and is versatile enough to have been used for motors ranging in size from 1 lb in weight to a huge 260-in.-diam space booster motor.

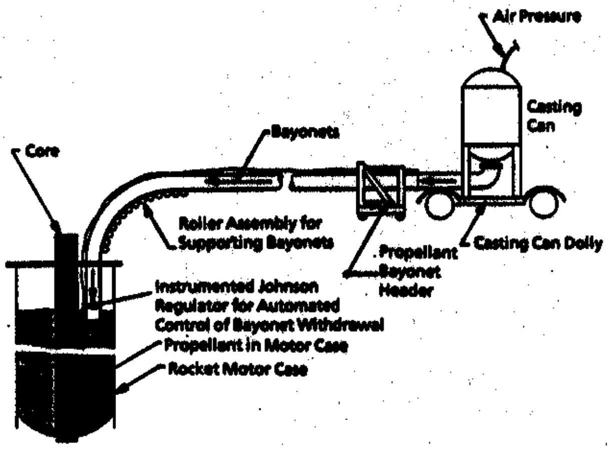


Figure 44. Bayonet casting technique.

Vacuum Casting. Casting the under-aerated propellant into a motor under vacuum is an extremely effective process. Since deaeration is part of the loading process, the possibility of voids in the finished grain is minimized. After mixing is complete, the propellant slurry must be deaerated, or the resulting propellant grain will contain voids. The usual technique is "slit deaeration" in which the propellant is placed in a "slit can," with a "slit plate" in the bottom. The propellant is then pulled through the "slit plate" under vacuum and pulled directly into the motor being cast. A vacuum casting arrangement is shown in Fig. 46. Rheological considerations are important because the only driving forces inabling the propellant to flow into the vacuum chamber through the narrow slits are the head of propellant and the differential pressure, which of course, cannot exceed atmospheric pressure; consequently, with some grain designs and/or extremely viscous propellants, vacuum casting could not be used. Vacuum casting also has the advantage of eliminating deaeration as a separate, time-consuming step after mixing. Comparative data clearly have established the improvement in quality (i.e. void reduction) of vacuum-cast propellant. Vacuum levels were studied as a process variable. Reproducible levels were important; but usually, best results were in the range not exceeding 0.75 psia, although the vacuum must not be too high or important volatile materials may be removed.

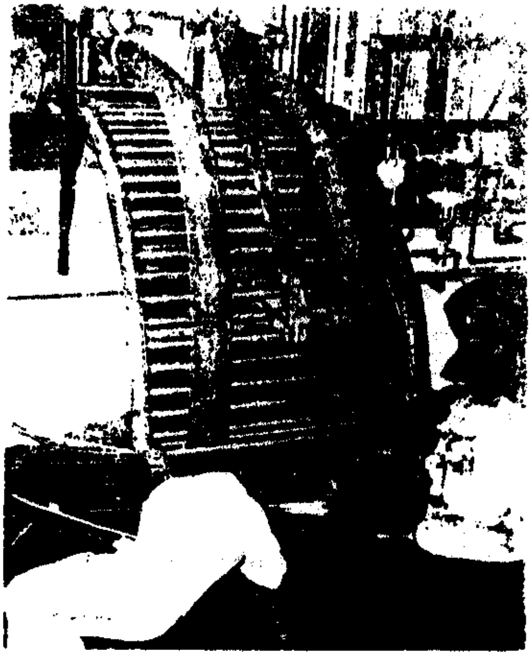


Figure 45. Casting bayonets extending into motor case.

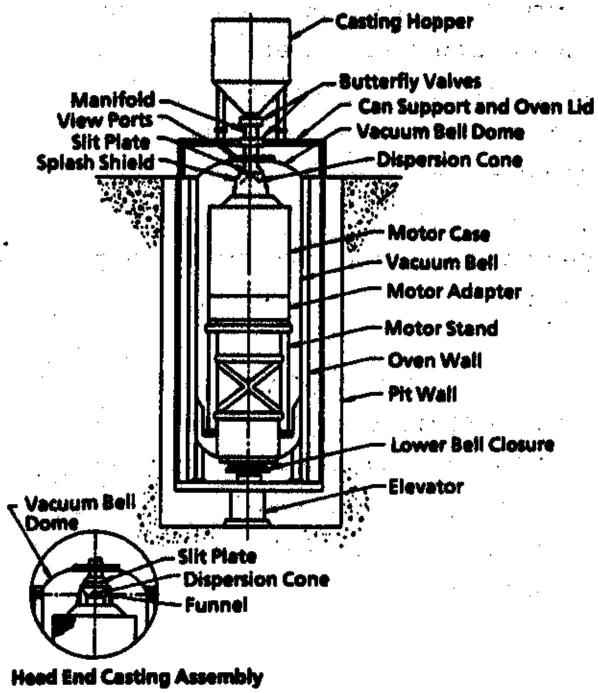


Figure 46. Vacuum casting schematic.

No significant changes in propellant physical properties are measured as a result of vacuum casting. Vacuum casting has reduced propellant wastage to an almost insignificant level.

The vacuum casting process sometimes produces foamy propellant on the top portion of the grain, which slumps to a 1- to 3-in.-deep area when the vacuum is removed. The frothy propellant, resembling Swiss cheese, is frequently removed by mechanical machining to final configuration after it has cured to the final hard, rubbery state. Formation of froth suggests an equilibrium between escaping traces of gas or air and the settling liquid propellant.

Unlike bayonet casting, vacuum casting produces virtually no intermingling of propellant batches. A vacuum-cast grain using different colors for subsequent propellant mixes showed distinct transition lines.

A vacuum casting rate of about 24 in./hr for the Minuteman and Poseidon first-stage motors produces a quality, void-free propellant. Somewhere between the extremes of 0 to 24 in./hr is a minimum rate for casting that produces void-free propellant. Studies with the polybutadiene acrylonitrile acrylic acid base, 86-percent solid-loaded propellants used in these motors have shown this limit to be 4 to 5 in./hr. Casting at a lower rate produces propellant filled with voids.

Bottom Casting. This method of loading propellant into motors is also one of the earliest, but is still advantageous with certain motor designs. The bottom casting process indicates only that the propellant will be pushed up into the motor from the bottom, usually by a bayonet or piping connection between a pressure casting can and the motor (Fig. 47). In this process, as with bayonet casting, deaeration must already have been accomplished.

Bottom casting is particularly advantageous with motor designs that do not allow adequate clearance from the top to drop in vacuum-casting propellants or to accept a bayonet.

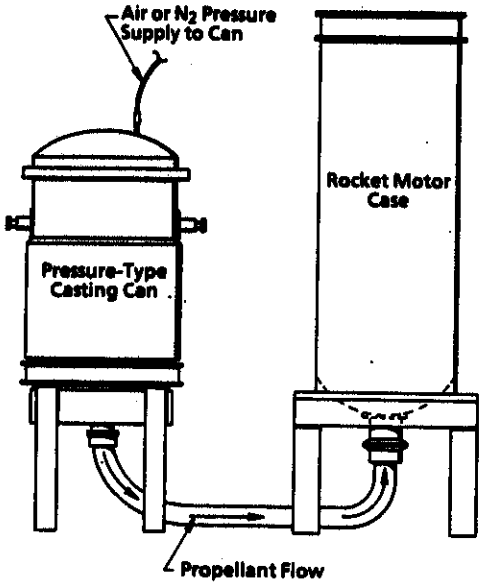


Figure 47. Bottom casting technique.

Curing. After casting, the propellant is cured. With some binders, this involves merely a slow and controlled cooling process; with others, it involves a chemical reaction in the propellant. The time required for this chemical process depends on the curing temperature — the higher the temperature, the faster the curing. Because the curing is often characterized by an exothermic reaction, the center of the propellant grain may be hotter than the outside.

Most composite propellant motors are cured at elevated temperature; generally, it has been found to be desirable to keep the temperature as nearly constant as possible throughout the mixing, casting, and curing process. The exact temperature used depends upon the particular polymer and cure system, but curing at 135°F for 5 or 6 days would be typical for a CTPB propellant. After cure is complete, the motor is allowed to cool. The mandrel used to form the inner bore is removed, and any necessary trimming of the excess propellant in the risers is done.

During the cure process, volume change takes place in the propellant because of absorption of the liquids by the solid and because of the polymerization process itself. After the cure has progressed to a certain point, this volume change can no longer be made up by flow of the propellant and shows up as "cure shrinkage" in the motor.

Final Assembly. After cure and cool-down, the motor is ready for final assembly, which includes installation of the igniter, the nozzle and ground test, flight test or operational instrumentation and control equipment. External insulation is often applied on the motor aft done to minimize exhaust gas radiation heat transfer to the case.

SECTION IV

LIQUID-PROPELLANT ROCKET PROPULSION

4.1 FUNDAMENTALS

A liquid-bipropellant rocket engine, also called a liquid rocket engine (LRE) (Fig. 48), consists of two propellant tanks, a tank pressurization system, propellant feed systems, a combustion chamber assembly and associated valving, piping, and controls. One of the tanks contains a liquid oxidizer, and the other contains a liquid fuel. Monopropellant LREs (such as those using the decomposition of hydrogen peroxide) are used in satellites for station keeping and could be used for roll control, but they do not provide enough specific impulse to be considered for ballistic missile primary propulsion application.

The LRE combustion chamber assembly consists of an injector for mixing the oxidizer with the fuel, a combustion chamber, and a converging-diverging nozzle. Since the combustion chamber is exposed to high temperatures, it is usually cooled. Most combustion chambers employ regenerative cooling in which the fuel is routed through passages in the chamber structure before it is injected into the chamber for burning as in Fig. 49. For nonreusable applications (such as ballistic missiles), chambers fabricated with ablative materials, said to

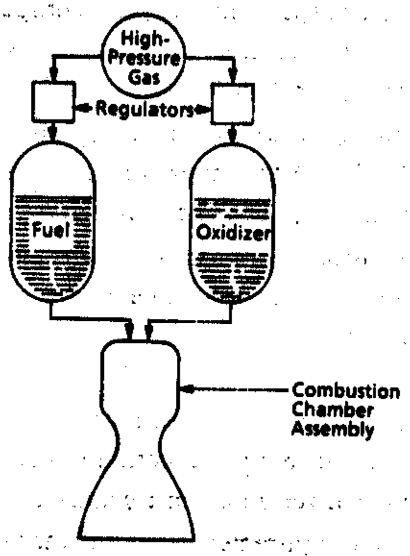


Figure 48. Pressure-fed liquid-propellant rocket engine.

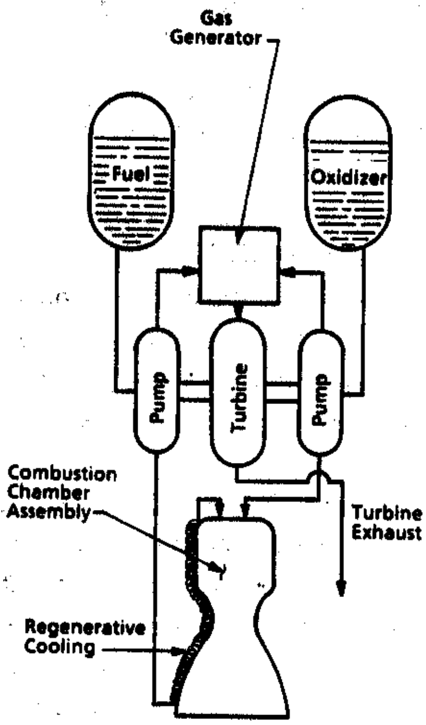


Figure 49. Pump-fed liquid-propellant rocket engine with regenerative cooling.

be ablatively cooled, could be used. The Apollo Service Propulsion Systems (SPS), The Lunar Excursion Module (LEM) Descent, and LEM Ascent engines are examples of long-duration-burn LREs that have successfully employed ablatively cooled combustion chambers.

The distinguishing characteristics of LREs are (1) the type of propellant-feed system and (2) the class of propellants. Both of these distinguishing characteristics are significant discriminators. An LRE may have either pressure-fed propellants (Fig. 48) or pump-fed propellants (Fig. 49).

A pressure-fed system is much simpler, although it is much heavier than a pump-fed system. It is heavier because the propellant tanks must be pressurized to about 100 to 200 psia above combustion chamber pressure, and the pressurant must be carried onboard. Pump-fed systems may use lightweight tanks but require a complex pump and pump drive system to feed propellants at high pressure to the combustion chamber. The pump driving system is not an insignificant component. The pump drive system, in fact, determines the LRE basic operating cycle, which is also a discriminating characteristic. The gas generator (gg) cycle, as shown in Fig. 49, is the most universally used cycle. The gg cycle employs a separate combustion device to provide the driving fluid for the turbomachinery. The turbomachinery pumps the propellants to a high pressure for delivery to the injector in the combustion chamber.

An LRE may use either cryogenic propellants or storable propellants. Cryogenic propellants are gases at normal pressure and temperature; they require cooling and insulated tanks and plumbing to maintain liquid conditions to the chamber injector. Liquid hydrogen (LH_2) and liquid oxygen (LO_2) are common cryogenic propellants. They are delivered to the injector at temperatures below −423°F (20 K) and −297°F (90 K) for hydrogen and oxygen, respectively. Although a cryogenic oxidizer (LO_2) was used on the German V2, cryogenic propellants are not a viable alternative for mobile ballistic missile applications. Storable propellants are liquid at normal pressure and temperature. Selective storable propellants can be prepackaged in a ready state for lengthy time periods.

The advantages of LREs are (1) the higher delivered specific impulse, and therefore lighter launch weight (but not smaller size) than solids; (2) the ease and repeatability of thrust termination, and (3) the relative safety. Disadvantages are lower bulk density and, therefore, larger size vehicle requirements and more complex logistics requirements. A two-stage liquid-bipropellant system always has some residual propellant remaining in the first stage, depending on the tolerances of the operational propellant mixture ratio.

4.2 REQUIREMENTS

A short-range ballistic missile fired by a Third World country today is likely to be powered by a liquid-propellant rocket engine even though the components and operational requirements are in many cases more detailed and demanding than for a corresponding solid-propellant rocket propulsion system. This is largely because much of the technology presently available to these countries is not state-of-the-art but of 1960s vintage before SRBM development focused on solid-propellant systems. Surplus, deactivated, or excess inventory items acquired from a First World power offer opportunities to build systems still very capable of potent tactical warfare for an aspiring regional power. This section discusses the necessary elements for such an opportunist to produce liquid-propellant SRBMs by any combination of new or retired missile hardware.

4.2.1 Propellants

The variety of propellants for liquid-fueled rocketry was explored early in this century by a number of pioneers. Although the range of options include hybrids of solids and liquids (or as in the German V2, a cryogenic oxidizer, liquid oxygen, combined with storable alcohol as fuel, a liquid hybrid), it is convenient to categorize propellant systems as either storable or cryogenic. Table 15 lists physical properties of several prevalent propellants, and Table 16 provides performance for certain combinations of these propellants.

Storable Propellants. The bulk of liquid propellants applied to missile propulsion systems has been storable propellants. Though advantageous because they need no complex conditioning and support equipment, storables do require close attention to compatibility of storage vessels and components with the various fuel and oxidizers. Storage conditions, including temperature, pressure, and stability of the propellant in its stored state, and proximity to other materials and ignition sources, are critical to equipment/personnel safety and operational readiness of the assembled missile system.

A typical storable propellant system available to Third World countries would (either by importation of subsystems or development of indigenous capabilities) incorporate well-documented oxidizers such as hydrogen peroxide, nitric acid, or nitrogen tetroxide. Fuels, similarly, would include hydrocarbons such as kerosene and methyl or ethyl alcohol, or one of the hydrazine class of propellants. Beyond storage and compatibility concerns, selection of a specific combination of propellants will be based on the specific and total impulse demanded, the ease and rate of ignition, energy and thermal characteristics of the combustion process, criticality of injector and motor design, complexity of feed and control system design, and incorporation of the system into an integrated SRBM package. Storables offer a number of advantages in these areas because of their commonly high-energy densities, simplified ignition systems (especially for hypergolic propellant combinations), straightforward combustion chamber and nozzle designs, and the predominant use of pressure-fed supply systems. Although hydrazine, in combination with many oxidizers, delivers high specific impulse, it is not a good candidate for tactical missiles. The freezing (melting) point is too high (Table 15). When mixed with equal parts of UDMH, the 50/50 blend produces high specific impulse, and the freezing temperature is adequate for middle latitude countries.

Table 15. Physical and Chemical Properties of Selected Liquid Propellants

	Liquid Oxygen, LO_2	Liquid Hydrogen, LH_2	Nitric Acid HNO_3	Hydrogen, Peroxide 80-percent, H_2O_2	Kerosene	Ethyl Alcohol, 100-percent, C_2H_5OH	Nitrogen Tetroxide, N_2O_4	Hydrazine N_2H_4	UDMH $(CH_3)_2N_2H_2$*	50/50 Blend, 50-percent N_2H_4, 50-percent UDMH
Relative Density**	1.14	0.07	1.50	1.34	0.80	0.78	1.45	1.0	0.78	0.9
Dynamic Viscosity Centipoise	1.9	0.01	0.9	1.3	1.5	1.2	0.41	0.9	0.50	0.8
Surface Tension, dynes/cm	13	2.3	40	76	25	22	—	28	28	—
Boiling Point, °C	−183	−253	86	131	153 to 288	78	21.15	113.5	63	63
Melting Point, °C	−218	−260	−42	−22	< −40	−117	−11.2	1.5	−57.2	−22
Molecular Weight	32.0	2.02	63.02	34.02	100	46.07	92.02	32.05	60.08	41.8
Heat of Formation, Kcal/gm mole	0	−1.90	−41.66	−45.20	−46.0	−69.90	8.0	12.0	12.7	11.8
Biological Effects	Bad Burns After Several Seconds Exposure	Bad Burns After Several Seconds Exposure	Very Toxic; Attacks Flesh Rapidly	Poison; Attacks Flesh	Mildly Toxic	Intoxicating	Toxic; Severe Respiratory Attack	Toxic; Skin Burns	Toxic; Skin Burns	Toxic; Skin Burns
Effect on Metals	Embrittles Most	Embrittles Most	Highly Corrosive	Corrosive Catalyzed by Many	None	None	Corrosive with H_2O	Corrosive	Corrosive	Corrosive
Effect on Organic Materials	Embrittles Many	Embrittles Many	Reaction	Reaction Often Spontaneous	Moderate Solvent	Solvent	Reaction	Reaction	Reaction	Reaction
Fire Risk	High	High	High but Easily Diluted	High but Easily Diluted	Moderate	Moderate	High	High	High	High

* UDMH: Unsymmetrical Dimethylhydrazine
** Water = 1.0

Cryogenic Propellants. Cryogenic propellants are propellants that are attractive from a combustion chemistry viewpoint but are high volume (gaseous) at normal temperatures and, therefore, volume-inefficient unless condensed through liquefaction. Liquid oxygen (LOX) is clearly the cryogenic oxidizer of choice, with liquid hydrogen and liquid ammonia as more common cryogenic fuels. LOX/hydrogen is most recognizable as the combination used in the space shuttle main engine (SSME), but the duo is surprisingly poor for "volumetric heat of formation," i.e., markedly inefficient in minimization of package size for a given total impulse. The density of liquid hydrogen is only 7 percent of the density of water.

Cryogenic propellants are normally produced at an off-site, central plant, transferred by truck or rail to a local storage site, and then onloaded into the missile immediately before

Table 16. Performance of Liquid-Propellant Rocket Engines

Propellants		Mixture Ratio		Sea Level Specific Impulse*, ~sec
Oxidizer	Fuel	By Weight	By Volume	
Liquid Oxygen	Liquid Hydrogen	5.0	0.22	334
Liquid Oxygen	Ethyl Alcohol	1.73	1.21	226
Nitric Acid	Kerosene	4.13	2.19	225
Nitric Acid	UDMH	2.6	1.38	241
Hydrogen Peroxide	Hydrazine	2.0	1.38	255
Nitrogen Tetroxide	50-percent Hydrazine + 50-percent UDMH	1.6	1.00	253

* 500 psia Expanded to 14.7 psia

the anticipated launch schedule. Delays of 2 to 4 hr usually necessitate refilling or offloading of propellants with corresponding turnaround tasks and schedules. Fixed launch sites and advanced notice launches are clearly the norm for missiles using cryogenic propellants. Add the necessary insulation, and operation and support equipment, including startup, feed system, and controls, and you have a poor candidate for SRBM applications. Cryogenic propellants are not considered to be a viable choice for the SRBM. The U. S. has no ballistic missiles using cryogenic propellants in its inventory.

Physical Properties. Desirable physical properties for liquid propellants, in approximate order of importance, are (1) the highest concentration by weight of chemical energy, (2) the greatest supply of energy per unit volume, (3) high specific heat corresponding to low burning temperature of the combustion process, and (4) optimum expansion and transformation of heat energy into kinetic energy, and (5) suitable operational characteristics (freezing temperature, boiling temperature, vapor pressure).

Other key properties include the ability of the propellant to absorb heat to avoid overheating, low ignition temperature for nonself-igniting fuels, or shortest possible delay times for self-igniting fuels, and tolerance of the propellants in storage and handling practices. Tolerance properties include freezing and boiling temperatures, vibration/shock, static discharge sensitivities, and hazards to both personnel and equipment associated with loading, firing, and recovery of components and systems.

It should come as no surprise that an ideal oxidizer/fuel combination does not exist, although a large number of acceptable candidates are readily available. The practical capabilities of some Third World infrastructures prioritize or eliminate many of the likely candidates, although heavy involvement by outside sources can drive the selection beyond the most readily available chemistry. The infusion of petroleum-related chemical processing has enhanced the capabilities of many Third World countires to develop hydrocarbon fuels and to refine distillation processes for related fuels and oxidizers. Most Third World countries have indigenous ammonia, urea, nitric acid, and sulfuric acid capabilities, which can lead to a potential for production of a wide range of propellants. The requirements for design of propellant-feed systems and ignition system selection will help clarify the range of choices for propellant system selection.

4.2.2 Propellant-Feed Systems

Feed systems are divided into two categories, displacement, or pressure-fed systems, and pump-fed systems. The pressure-fed system is by far the simpler of the two designs, although the size and mass of the pressure storage system has limited the versatility of its application. Pump-fed systems have predominated in large liquid-propellant engine systems and are well-suited for both storable and cryogenic liquids. The SRBM is well suited to the pressure-fed LRE. Pump-fed LREs are usually required on long-range (IRBM and ICBM) missiles in order to keep the empty weight within reasonable bounds.

Pump-Feed Systems. A pump-feed system for liquid-propellant rocket engines uses a turbopump — a combination of a gas turbine and a centrifugal pump — that generates the high horsepower and fluid delivery capabilities required for moving large volumes of propellant with only a minor weight penalty for the missile system. The driving force for the turbopump turbine is usually the exhaust gas from a gas generator burning the same propellants as the main engine (gas generator cycle). This gas generator cycle is started from a stored gas supply or the gas discharge from a small solid-propellant start cartridge. Other strategies use exhaust bleed from the thrust chamber to drive the turbine (tap-off cycle) or with cryogenics, use the chamber heat rejector to expand one of the propellants through the turbine (expander cycle). Turbopumps and their control systems are sophisticated devices requiring substantial development and testing to ensure success. Sealing of caustic materials and lubrication are additional challenges for turbopump technology. A bipropellant system may operate two pumps with a single turbine or may have a dedicated turbopump assembly for each constituent. The feed system may be operated until propellant depletion or thrust may be terminated upon command from the guidance system. A simplified schematic of a pump-fed system is provided in Fig. 50.

Pressure-Feed Systems. Pressure systems are basically a pressurized storage tank for helium, nitrogen, or air with a regulator and valving to distribute the displacing gas to each propellant tank on demand. The gas storage vessel (usually a sphere in order to optimize weight/strength

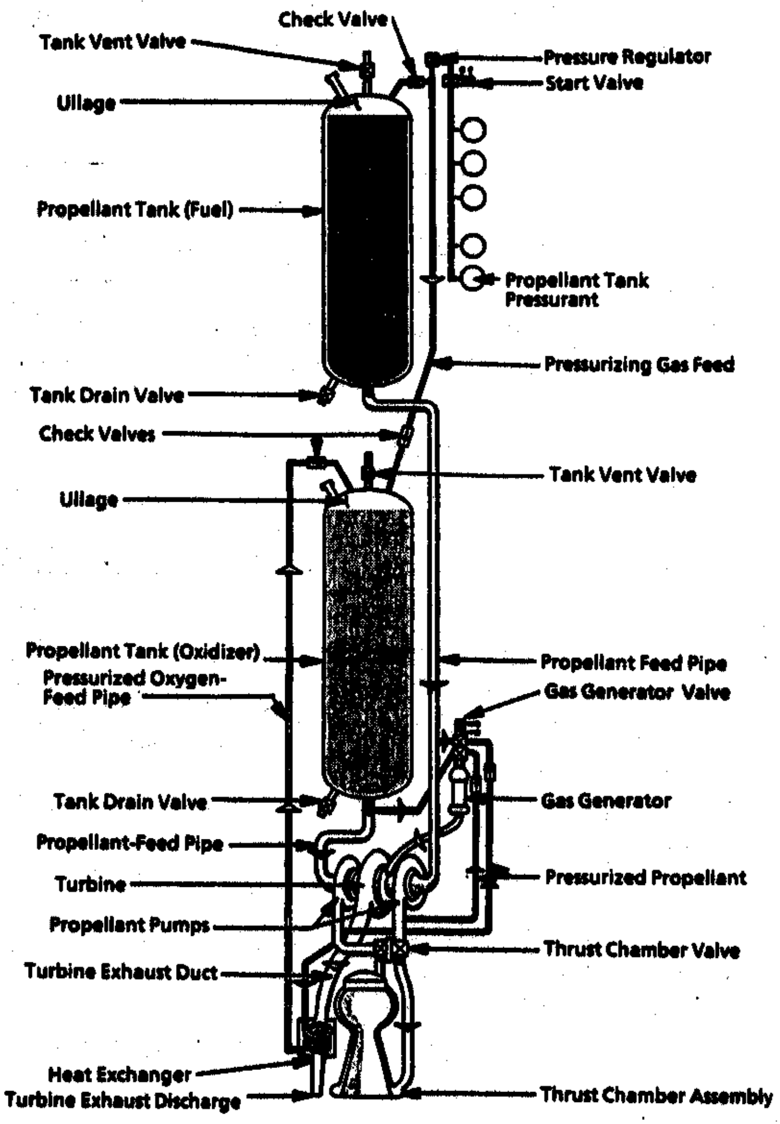


Figure 50. Turbopump-fed propellant system with gas generator fed from main propellants.

trade-offs) is typically pressurized at 3,000 to 6,000 psi. With conventional low-technology, welded fabrication, tanks will be massive and greatly decrease payload capability. The mass of the pressurant gas itself may be significant. Solid grain charges have also been applied as gas generators to produce a hot-gas source that effectively displaces the liquid in tankage for propellant feed. Widely available technology can produce weight-efficient spheres to provide acceptable feed of storable propellants. A typical pressure-feed system is illustrated in Fig. 51.

Propellant Tankage and Pressure Considerations. Propellant tanks for storable propellants are most often stainless steel, the grade depending again on chemical compatibilities. Other materials such as aluminum alloy or alloy steel are selected as appropriate for chemical compatability. Cryogenic storage tanks may be any of the mentioned alloys, or may be of a composite material that resists brittle failure at low temperature. In either case, tank pressure and load ratings are selected both for handling/erection operations and for actual launch/flight conditions. Buckling stresses on filled tanks during erection from horizontal to vertical often preclude the loading of propellants during prelaunch until the rocket has been positioned in the firing attitude. Pressures during operation would typically range from 15 to 30 psig for pump-fed systems and from 300 to 600 psig or more for pressure-fed systems. Stress concentration factors for heavier-walled vessels require more than simply scaling the thickness proportional to pressure factor; therefore, tank structural selection for a storable propellant can be seen as distinct from that for a cryogenic propellant system.

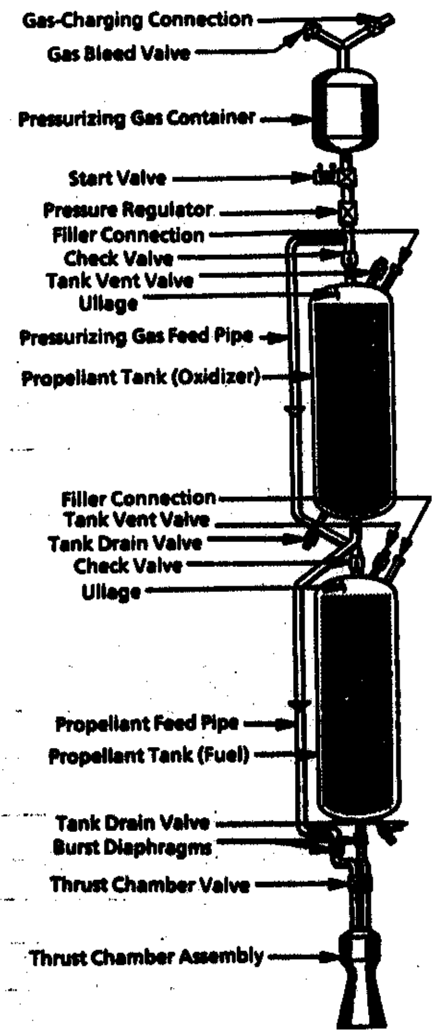


Figure 51. Pressure-fed propellant system.

As in pressurization spheres, tank specification is a trade-off between strength and mass penalties for a given volume. If the decision is made to load propellants immediately prior to launch for storables as is normal for cryogenics, the compatibility restrictions may be relaxed somewhat to optimize the tankage for extended payload or range capabilities. Assembly of an indigenous missile from acquired components rarely allows this degree of system "tuning."

4.2.3 Engine Components

The basic elements of the liquid-propellant rocket engine include the injector, the combustion chamber, and the nozzle as shown in Fig. 52. Additional requirements for the SRBM include thrust vectoring for directional control and targeting. All cryogenic and many storable engines require ignition systems, with precision valving and instrument components necessary for checkout, testing, and operational use.

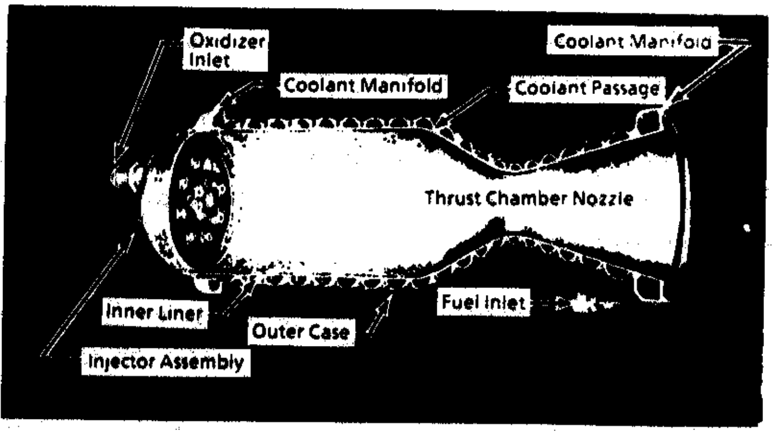


Figure 52. Major components of a regeneratively cooled LRE combustion chamber.

Injector. The task of the injector, in orchestration with the propellant-feed/pressure system, is to properly atomize and mix the constituents into a volatile mix that will efficiently combust to provide the required thrust. In reality, the injector design is linked to the size and shape of the combustion chamber so that the combustion occurs at a steady location, or flame front, within the chamber. If the flame front is too near the injector, its surface will degrade and fail; if it is allowed to progress to or through the nozzle throat, there is loss of thrust and the combustion process is not sustained. The injector must be designed to the propellants used and their combustion characteristics; it also reflects the selection of chamber pressure and the use of supplemental functions such as film cooling to prolong the life of the combustion chamber.

Combustion Chamber. The combustion chamber represents an equally delicate balance of functions as defined for the injector. The chamber, whether cooled or uncooled, must maintain an energy balance that sustains optimum performance without thermal damage to the chamber walls. A cooled chamber circulates incoming propellant (particularly in the case of cryogenics) or other coolant to prevent damage to the chamber surface. An uncooled chamber relies on a thermal equilibrium below its erosion temperature or, with the use of film cooling, by insulating the chamber walls with a curtain of cool fuel to protect the wall material from the destructive action of the oxidizer and heat. Chamber walls may be copper, stainless steel, or specialty alloys, or may be lined with a glass or ceramic compound to resist the severe environment. Since an SRBM represents a single-use device, it is normal to expect degradation of the chamber within acceptable limits.

Nozzles. The nozzle is the converging-diverging section of the combustion chamber. The nozzle contains the throat, which is the minimum flow area and the region of highest heat transfer. The nozzle may also be fabricated from metal or composite material and may be integral with or attached to the chamber. The expansion ratio (ratio of nozzle exit area to throat area) is nominally 10:1 for a single-stage SRBM. A two-stage missile might have a first-stage area ratio of 10:1 and a second-stage area ratio of 16:1. The design points are altitudes of 60,000 and 75,000 ft for the first and second stages, respectively (with 500-psia chamber pressure). The contour of the nozzle from throat to exit is not a critical design parameter for the SRBM and may be a simple conic section. Nozzles are cooled or uncooled depending on the combustion chamber design.

Thrust Vector Control (TVC). Vehicle attitude control is provided by a thrust vector control mechanism in conjunction with auxiliary roll control. Pitch, yaw, and roll control could be achieved from jet vanes immersed in the nozzle exhaust. LRE TVC is generally provided by gimballing of the entire thrust chamber assembly, which requires flexible propellant flow ducts between the fixed structure and the gimballed engine. Pump-fed LRE roll control is often obtained by selective discharge of the gas generator (turbine drive) exhaust gas. Pressure-fed LREs need auxiliary roll control similar to the SRM.

For a missile to be guided and provide vehicle stability, it must have a feedback-controlled thrust vectoring system. Liquid-propellant engines are often gimballed from a universal-joint mounting arrangement (gimbal block) so that vectoring may be accomplished in combinations of pitch and yaw direction, with the movement originating from cylinders or screw actuators within the feedback control loop. Jet vanes may alternately be mounted at the nozzle exit and servo-controlled to modify the direction of thrust. Fabricated of graphite or other heat-resistant material, these remain functional within a range of erosive loss. More recent use of liquid-injection thrust vectoring (LITVC) has been proven effective by injecting dense, thrust-axis-altering liquid into sets of holes within the nozzle at four 90-deg locations. Finally, auxiliary thrusters can provide pitch, yaw, and roll impulses to alter the missile attitude and direction while in flight.

Ignition System. Ignition systems for liquid-propellant rocket engines are often spark-initiated using battery-operated plugs to ignite the primary flow. It is essential that ignition be timed precisely with propellant flow initiation to avoid "hard starts," i. e., sudden ignition of an excessive quantity of propellant that has entered the chamber prematurely, causing explosive firing. A small pyrotechnic charge can accomplish the same function; for many propellant combinations, it is not necessary that the igniter remain functional throughout the duration of the firing.

The hypergolic propellant combinations need only be introduced into the injector concurrently to produce combustion and thrust, eliminating the need for an external ignition system. Hard starts are still possible, however, because of variations in mixture ratio or timing of the fuel and oxidizer valving operation.

Valving and Instrumentation Devices. Valve sizing and operation to initiate the flow of propellants into the injector and thrust chamber should be selected based on well-defined criteria. It is normal to provide a fuel-rich mixture of propellants in recognition that combustion is never completed and to protect the motor surfaces from the erosive effects of raw oxidizer. The fuel is often made to "lead," or precede the flow of oxidizer for similar reasons. The precise control of valve timing is often added to the difficulties of turbopump operation for pump-fed systems but more often handled directly through the use of a bipropellant valve for pressure-fed systems. The bipropellant valve is actuated by a single operating shaft and lead or lag functions are designed into its operation. Thus, the predicted performance of the engine start/stop functions can be readily maintained.

Instrumentation, in the form of pressure transducers, thermocouples, and strain gages, is often applied to provide information during assembly, testing, and storage. Transducers can confirm the correct pressure of isolated tankage and give indication of loss or leakage. Thermocouples and strain gages supplement thermal and structural stresses during development and testing. Instrumentation used in flight hardware is minimized to reduce complexity, but devices used in testing are often carried over to production systems to avoid configuration changes. Flight tests of LRE systems would require chamber pressure, two tank pressures, engine gimbal position, and pressurant tank pressure for pressure-fed engines, or two pump speeds for pump-fed engines. On-board transducers are an integral component of leak checks and functional checks when a missile is removed from storage and made operational and can be monitored during transportation and fill operations. Tank level indicators are rarely used since filling is accomplished with positive displacement ground support systems.

4.3 MANUFACTURING PROCESSES

The required manufacturing processes for liquid-propellant SRBMs is similar to that for solids in the areas of guidance and staging; less alike for structure, nozzle design, and thurst vectoring capabilities; and completely dissimilar for propellants and feed systems, combustion chambers, valving, ignition, and other engine-specific parameters. Skills developed in and for other industries, however, may be used to bridge gaps that exist in dedicated SRBM and engine technologies.

4.3.1 Propellant Manufacture

Manufacturing of storable oxidizers and fuels are discussed, but cryogenic propellants have been eliminated from the scope of study (Section 4.2.1) since their suitability fails practical tests of portability and responsiveness.

Oxidizers. The storable oxidizers described in Section 4.2.1 — hydrogen peroxide, nitric acid, and nitrogen tetroxide — are within the realm of capability of most Third World infrastructures that produce basic chemical feedstocks. Hydrogen peroxide, used by early rocket pioneers and still acceptable for both bipropellant primary motors and monopropellant gas generators, is produced by concentration of commercial (30-percent) hydrogen peroxide, the remainder being water. An advantage of H_2O_2 is that it can decompose as a monopropellant to produce a large quantity of gas and steam, making it a good candidate as a gas generator source. In its concentrated state, however, it is somewhat unstable and potentially explosive and is not a good candidate for long-term storage applications. Its use has therefore diminished since the mid-60s. Nitric acid, HNO_3, is a readily available oxidizer acid used in several successful propulsion systems. It is aggressively corrosive, particularly in the impure (water-added) state, requiring appropriate stainless steel or aluminum alloys for storage and operational componentry. It is commonly produced as a feedstock for fertilizer and dyes as well as for explosive or propellant applications.

Nitric acids of low water content are known as "fuming," and when they are manufactured to contain dissolved oxides of nitrogen (NO_2 + N_2O_4), they are called red fuming nitric acids (RFNA). An inhibitor (1-percent hydrogen flouride) can be added to reduce the corrosive action on stainless steels and aluminum to a negligible amount. Inhibited red fuming nitric acid (IRFNA) allows the storage and pressure vessels and lines to be aluminum for a substantial cost and weight advantage. The addition of NO_2 in either mixture provides additional oxygen to improve efficiency and enhance the combustion process.

N_2O_4, or nitrogen tetroxide, is a more specialized oxidizer still widely used in state-of-the-art propulsion systems, usually in combination with one of the hydrazine fuels. Particularly toxic, N_2O_4, has a very narrow liquid range, freezes at a relatively high (12°F) temperature, and therefore, requires particular care in handling and operation. Its material compatibility is similar to the nitric acid compounds, and its density (89.3 lb/ft^3) is an advantage in minimizing flight tankage sizing. It can be manufactured by the same technology base used to manufacture nitric acid.

Fuels. A number of fuels have already been mentioned including gasoline, kerosene, hydrazine, ethyl alcohol, and methyl alcohol, to review the most common. Fuels that are derivatives of petroleum distillation are seen to be readily available; alcohol compounds, either wood or grain, are equally producible by low-technology means.

The hydrazine class of fuels, including monomethyl hydrazine (MMH), unsymmetrical dimethylhydrazine (UDMH), and the various mixed hydrazine fuels (Aerozine 50, for instance) represent the state-of-the-art in both bipropellant and monopropellant fuels. They are toxic materials and are reactive to all but a few of the stainless steels and aluminum compounds. Extensive use has allowed them to be well characterized; however, production of propellant-grade hydrazines has been limited to only a few manufacturers worldwide (the U. S. and

France are noted suppliers). The technology to achieve indigenous manufacturing capability of hydrazine-class fuels is, however, only a short step for countries with extensive chemical, petrochemical, and fertilizer capabilities.

4.3.2 Feed Systems and Tankage Manufacture

Correlation can be made between tankage requirements for a bipropellant, liquid-propellant pressure-fed rocket and the motor case for a solid-propellant rocket motor; both are pressure vessels for which strength and corrosion resistance are key qualities and weight minimization is a necessity. Information supplied in Section 3.2.3 should be referred to in conjunction with materials discussed here; pump and pressurization material is also complemented by information contained in Section V.

Pumping Subsystem Manufacture. A turbopump, as previously described, consists of an assembly that marries the function of a small, high-speed gas-driven turbine and a centrifugal or vane-type pump. Of the pair, the turbine is the more sophisticated device, but both can be manufactured using automotive or aircraft-grade technology. The turbomachinery manufacturing requirements rival the guidance component requirements for sophistication. The relative short operating time of the SRBM reduces the risk, but not by much. Both the pump and the turbine require precision casting and machining. Sealing and lubricating require small tolerance production and clean room assembly. Most Third World countries would elect pressure-fed systems instead of turbomachinery systems unless the intention is to provide an SRBM with growth capability for a much longer range.

Pressure Subsystem Manufacture. Pressurant spheres for propellant-feed systems as described in Section 4.2.2 are usually cold-gas canisters with 3,000- to 6,000-psi nitrogen or other inert gas charges. Wall thickness of a typical sphere to contain the required 200 lb of GN_2 for propellant expulsion would be only 0.37 in. using 100-ksi steel, a relatively common, low-tech grade. The sphere weight would then be only 300 lb, scarcely more than the weight of the gas itself. Aluminum alloys commonly used in pressure fabrication are tabulated in Table 17. Alternate materials including the maraging steels, ultra-high-strength alloy steels, and ultra-high-strength stainless steel are discussed in Section V. A higher strength steel, such as the 200- to 350-ksi-strength steels would certainly reduce the corresponding material weight by factors of 2 or more, but would not diminish the required gas volume and mass to any appreciable amount. In other words, the ultra-high-strength steels offer a weight advantage but are not essential to the design and assembly of an SRBM. This fact also suggests that, except in cases of dire need for long-range or high-payload capability, one would not be expected to use gas heaters or solid-fueled gas generator canisters to supply the expulsion gas. Each increment of sophistication can improve performance by the one or two percentage points, but a desire to field a system as quickly as possible can supersede the desire to produce a missile with all of the state-of-the-art "bells and whistles."

Table 17. Typical Aluminum Alloys for High-Pressure Applications

Designation	Maximum Yield Strength 10^3 psi (kbar)	Maximum Tensile Strength 10^3 psi (kbar)
Non-Heat-Treatable		
3003-H18	27 (1.9)	29 (2.0)
3004-H38	36 (2.5)	41 (2.9)
5154-H38	39 (2.7)	48 (3.4)
5454-H34	35 (2.5)	44 (3.1)
5456-H321	37 (2.6)	51 (2.6)
5056-H18	59 (4.2)	60 (4.2)
Heat-Treatable		
2014-T6	60 (4.2)	70 (4.9)
2218-T72	37 (2.6)	48 (3.4)
6061-T6	40 (2.8)	45 (3.2)
6262-T9	55 (3.9)	58 (4.1)
7001-T6	91 (6.4)	98 (6.9)
7079-T6	68 (4.8)	78 (5.5)
7178-T6	78 (5.5)	88 (6.2)

Propellant Tankage Manufacture. The technology required to produce propellant tankage is a moderate extension of that required for a pressurant canister. Fabrication techniques can be as simple as roll and weld sheet stock, with purchased or in-house-formed domes welded to the cylindrical section. Explosive forming and hydrospinning (Section V) are within the capability of most Third World countries. Propellant compatibility considerations require that a corrosion or reaction-resistant grade of material be used, particularly when medium or long-term storage is inherent in the design. Many materials, including noncorrosion-resistant alloys may be considered for SRBMs that are loaded immediately prior to launch. UDMH, for example, may be stored in mild steel drums for up to a year with minimal chemical effects. Though oxidizers are somewhat less forgiving, especially when a percentage of water is present, a number of alloys are suitable for both short- and long-term storage.

The larger initial volume of propellant compared to pressurant would suggest that tank material be selected with more attention to weight reduction. At least one aluminum alloy, 2014-T6, with moderate strength properties (60-ksi yield strength when heat-treated) has been widely used for fuel tankage; both aluminum and stainless steel alloys are available for oxidizers. Since pressure-fed tankage is an order of magnitude lower in operating pressure than pressurant canisters (about 600 psi compared to 5,000 to 6,000 psi), the lower strength alloys do not cause severe weight penalties on total tank weight. In the model developed for this study, a wall thickness of 0.125 in. is sufficient with 100-ksi material; the 60-ksi aluminum would require nominal 1/4-in. thickness but require less mass overall. Further, significant reductions in weight by the use of exotic materials have questionable value since the operational aspects of handling, including buckling during erection or rotation, puncture resistance, and attachment of fittings may obviate apparent advantages of mass minimization. It may be said in general that short-range ballistic missiles may benefit from, but are not limited by, the lack of state-of-the-art structural metals as would be a medium or long-range missile. Tankage for pump-fed systems, similarly, operate an order of magnitude lower in pressure than do pressure-fed tanks — perhaps 30 to 60 psig — but wall thicknesses are limited more by the aforementioned operational considerations than by simple yield-strength calculations on the selected alloy.

4.3.3 Engine Component Manufacture

Design technology on the various subcomponents of an LRE is well documented in the public literature. Injector plates, chambers, nozzles, and thrust vector systems have been developed openly for several decades with only the most recent technology remaining proprietary in its availability. As with other componentry within the propulsion system, careful subcomponent testing is the key to successful SRBM system design and manufacture.

Injector. Injector plate design is an entire field within the broader field of LRE design, with a number of diverse approaches to solving the basic challenge to mix the two propellant components to obtain desirable combustion characteristics. Named to describe their function, the four basic types are impinging, nonimpinging, spray, and aeration. Within each major heading are a number of subtypes that accomplish their tasks through often subtle techniques.

In simplest form, an injector has connections for both the fuel and oxidizer with lines sized for the selected flow rate. (These may not be equal, however, depending on the chemistry; the fuel-to-oxidizer-mass ratio may vary up to 4:1 or more.) Both fuel and oxidizer are then routed through individual manifolding to a quantity of small, precisely sized holes or nozzles to achieve the desired mixing effect upon ejection as shown in Fig. 53. Injector components can be cast, forged, or stamped, then machined and welded. Injector orifices can be drilled in the face or drilled in inserts welded in the face. The most troublesome manufacturing requirement is that of providing uniform fuel film-cooling orifices, if required, in the injector face near the chamber mounting flange.

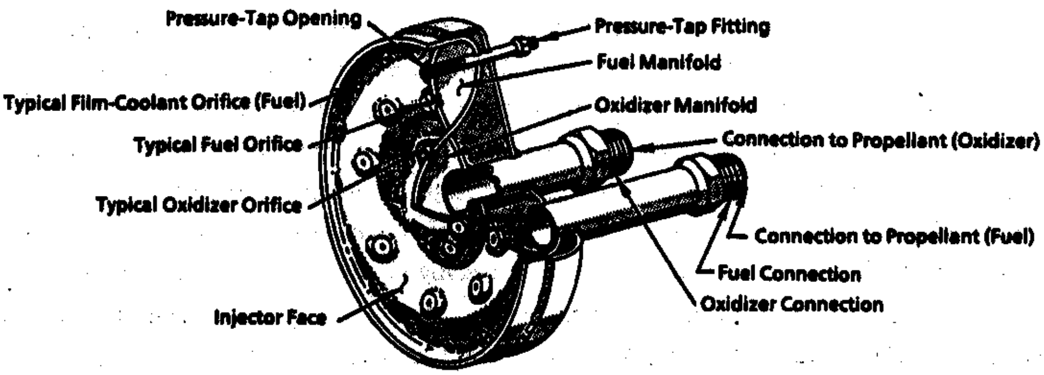


Figure 53. Simplified illustration of a bipropellant injector assembly.

Combustion Chamber. The combustion chamber is bolted directly to the injector face or flange, but is designed to very different environmental demands. Thermal conditions change rather rapidly as one follows the axial direction of propellant flow, and the chamber must be fabricated to withstand high differential and ultimate temperatures.

Chambers are usually cold-formed in production but may be forged, cast, or machined, with machining almost always used for prototyping. Inconel or stainless steel is typically used, but high-strength steel may be equally acceptable. The high-heat conditions of the chamber are usually shielded by the use of regenerative cooling (Fig. 54) or by lining with a heat- and erosion-resistant material. Since an SRBM is a one-time-use device, substantial erosion can be anticipated and even designed into the chamber wall, but prototype testing is the only way to be sure that performance will be maintained throughout the needed duration.

State-of-the-art materials used for ablative chambers as well as throats and nozzles may be organic fibers, but many less-sophisticated materials may be expected to perform acceptably within a properly selected thermal design. Among these are silica phenolic, one of the glass composites, silicon carbide, and alumina, silica, or asbestos-fiber-reinforced pressed composites. Even a furnace liner refractory may succeed, although shock resistance must exceed normal liner capabilities. These may be cast integral to the throat, but a higher temperature, more erosion-resistant composite is usually applied to the most highly stressed throat region. The chamber is essentially a pressure vessel (with pressures nominally 50 to 100 psi lower than the propellant supply) and should be designed accordingly. Thermal equilibrium is not a design requirement; however, the insulation is selected to protect the metal structure from the highest temperature reached during the firing interval.

Nozzles. Because of the low area ratio requirements for the SRBM nozzles (about 10:1 for the first stage and about 16:1 for the second stage), no separate nozzle extensions are

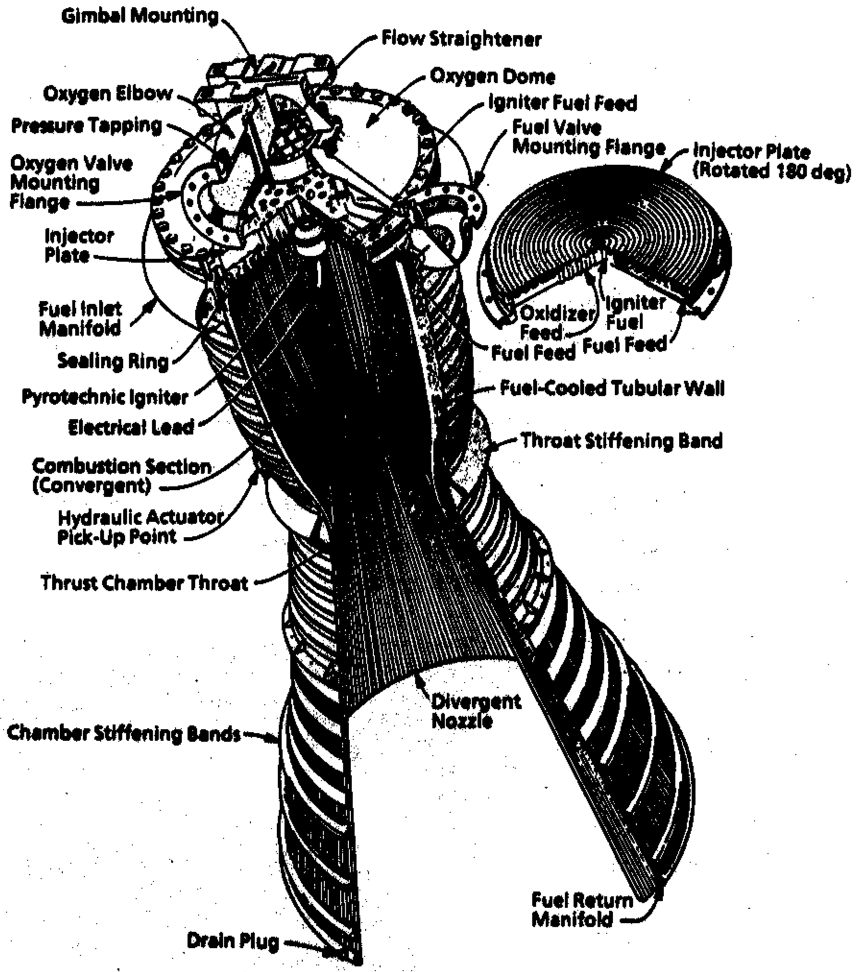


Figure 54. Construction of a regeneratively cooled tubular combustion chamber assembly.

required. The combustion chamber, throat, and nozzle for the SRBM are fabricated as an integral unit as shown in Fig. 55. Regenerative cooling is typical of many proven systems but is not mandatory for an SRBM. Thermal insulation, however, is still required, particularly in the transition regions immediately downstream of the throat. As with the chamber and throat, a good knowledge of composite lay-up and bonding is needed to produce a

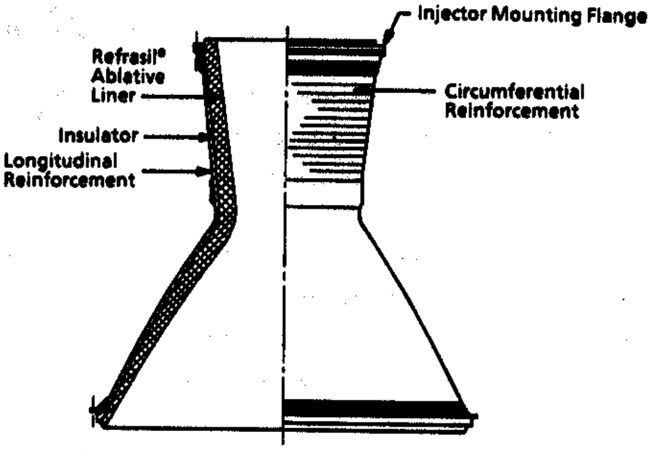


Figure 55. LRE ablative combustion chamber.

successful nozzle design that balances heating transients with composite lay-up and bonding to maintain performance over the relatively short thrust interval. Unless an existing design were copied precisely, it is doubtful that a nozzle system could be considered developed without prototype testing. Pressure requirements within the nozzle are significantly lower than for the chamber, and backing material strength is not a critical need. Shock and erosion resistance are the more critical design and fabrication elements that must be proven in sea-level testing.

Thrust Vector System. Of the vectoring mechanisms described in Section 4.2.3, gimballing and internal vanes are considered the logical choice. The gimballing device used to pivot the liquid engine is merely an oversized universal-joint mount of relatively low-tech challenge. Actuation and feedback of the vectored engine is the higher technical achievement; either pressure cylinder or screw-jack actuation are acceptable methods. Both require precise position feedback sensors to interact with the guidance system. Conventional systems use pitch- and yaw-mounted actuators that are tested with square and sinusoidal wave inputs that translate into precise directional measurement and control.

Jet vanes (Fig. 56) are often fabricated of graphite, either machined or hot-pressed, which are then assembled with solenoid actuators mounted external to the nozzle. Feedback control is the critical element of this method as well, and its success is essentially a subelement of the guidance control system. Development testing for both vectoring system types requires multicomponent thrust stands to measure angular thrust feedback and control.

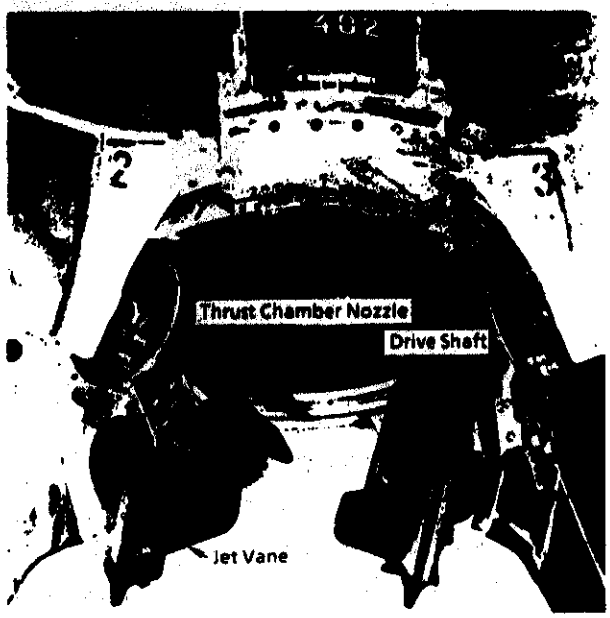


Figure 56. Jet vanes mounted at the nozzle exit used for thrust vector control.

Ignition System. Development and fabrication of the ignition system is possibly the only trivial element for most of the missile system combinations described previously. As defined, the hypergolic combinations of propellants only need to be mixed to achieve combustion; the nonhypergolics can be ignited using a simple spark igniter system with on-board electric power.

Valving. Bipropellant valving is intricate primarily because of the microsecond sequencing of the respective fuel and oxidizer flows to produce clean actuation while avoiding hard or erratic starts. Simple in concept, the bipropellant valve design and fabrication is integral to the overall fuel system design and balancing. Other valves, including rupture-type explosive isolating devices, are used to protect the system from contaminants or pressure during the assembly and storage functions. Regulator valving is also essential to maintain steady flow of propellants and smooth performance. Any of these valve requirements (with the exception of explosive isolation valves) can be adapted from off-the-shelf, precision valving as might be used in precision refinery equipment or aircraft-grade assemblies. Indigenous capability to produce all valving, including isolation valving, may be reverse-engineered from devices obtained in quantities as few as one.

Instrumentation. Instrumentation for a production SRBM is minimal and is usually limited to that required to assist the guidance system in following a programmed trajectory. Chamber pressure is the most important measure of engine performance and is usually measured with redundant devices. Once performance characteristics are established, even this elemental pressure measurement can be replaced by axial acceleration. Pressure transducers are widely available; off-the-shelf devices and axial acceleration is a guidance system parameter. Other instrumentation needed for system development and validation include thermal transducers, accelerometers, strain gages, and possibly, optical observers including radiometers and spectrometers, flowmeters, and load cells. These are in fact the instruments that form the bulk of ground test instrumentation and can be used in flight development with appropriate telemetry devices as discussed in Section VI.

4.3.4 LRE Production

A scenario is conceived for the production of a single-stage pressure-fed LRE. As shown in Fig. 57, the LRE

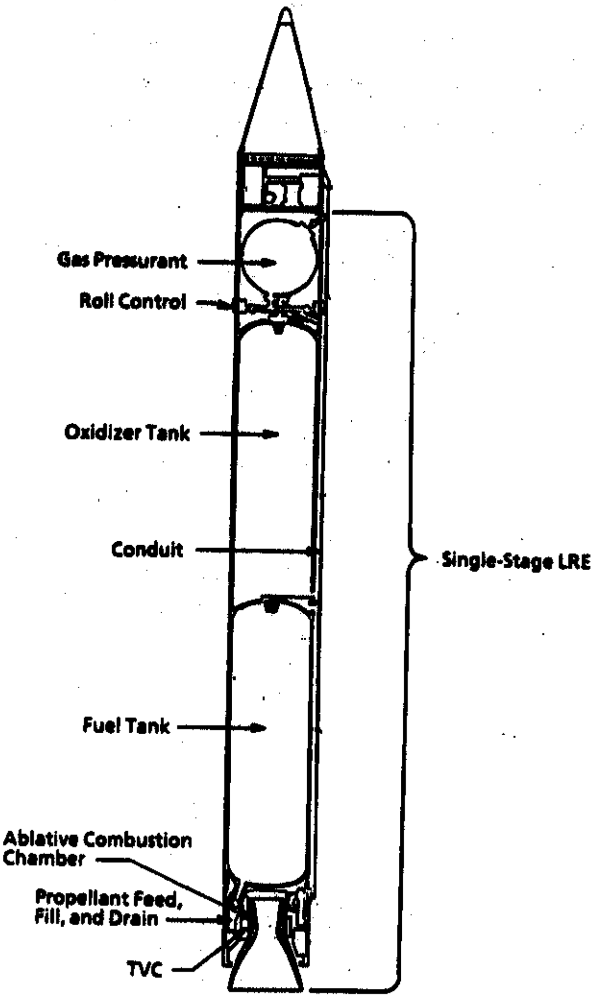


Figure 57. Components of a single-stage pressure-fed LRE.

consists of a gas pressurant sphere (which also provides roll control gas), two propellant tanks, a combustion chamber assembly (which uses an ablatively cooled chamber), thrust vector control actuators, tubes, pipes, and other associated minor components. Production would be housed in eight to ten industrial buildings. There would be no distinguishing characteristics in the outward appearance of these nondescript industrial buildings.

The flow chart for the production process is shown in Fig. 58. Small precision parts are cast, machined, assembled, cleaned, and bench flow checked where appropriate. Bench flow checks and leak checks are required for injectors, valves, and cylinders. Figure 58 shows that the casting shop is supported by a tool and pattern shop and a machine shop. The valve shop is supported by a clean room and bench check facility. Each combustion chamber assembly is given a 10-sec green run, and orifices are resized if necessary to meet mixture and injector pressure drop specifications. The two large buildings are the sheet-forming/tank-fabrication building and the LRE assembly building. Process flow for LRE assembly is shown in Fig. 59.

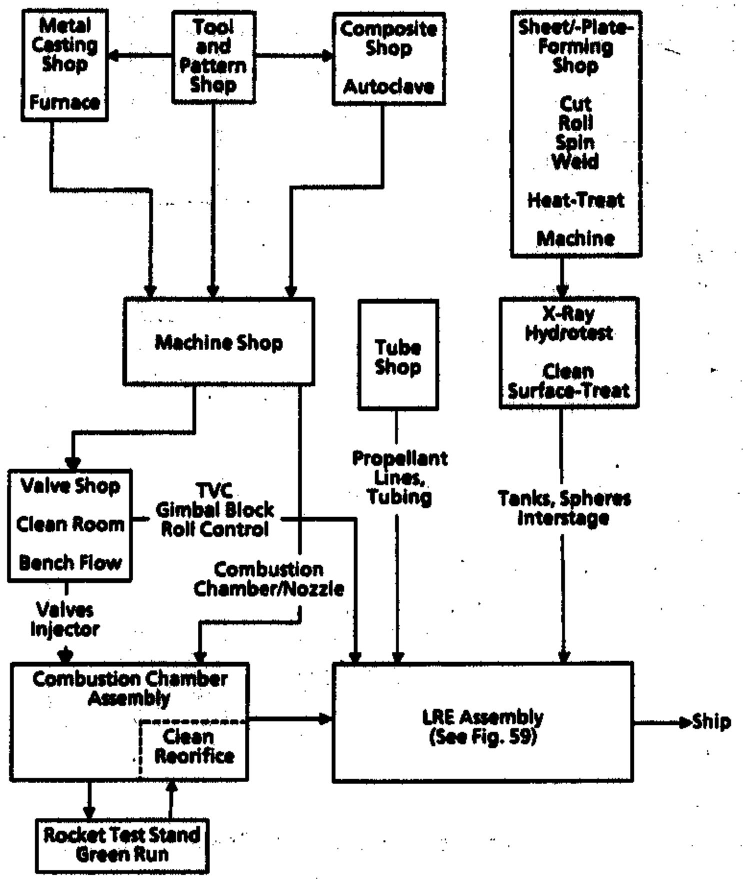
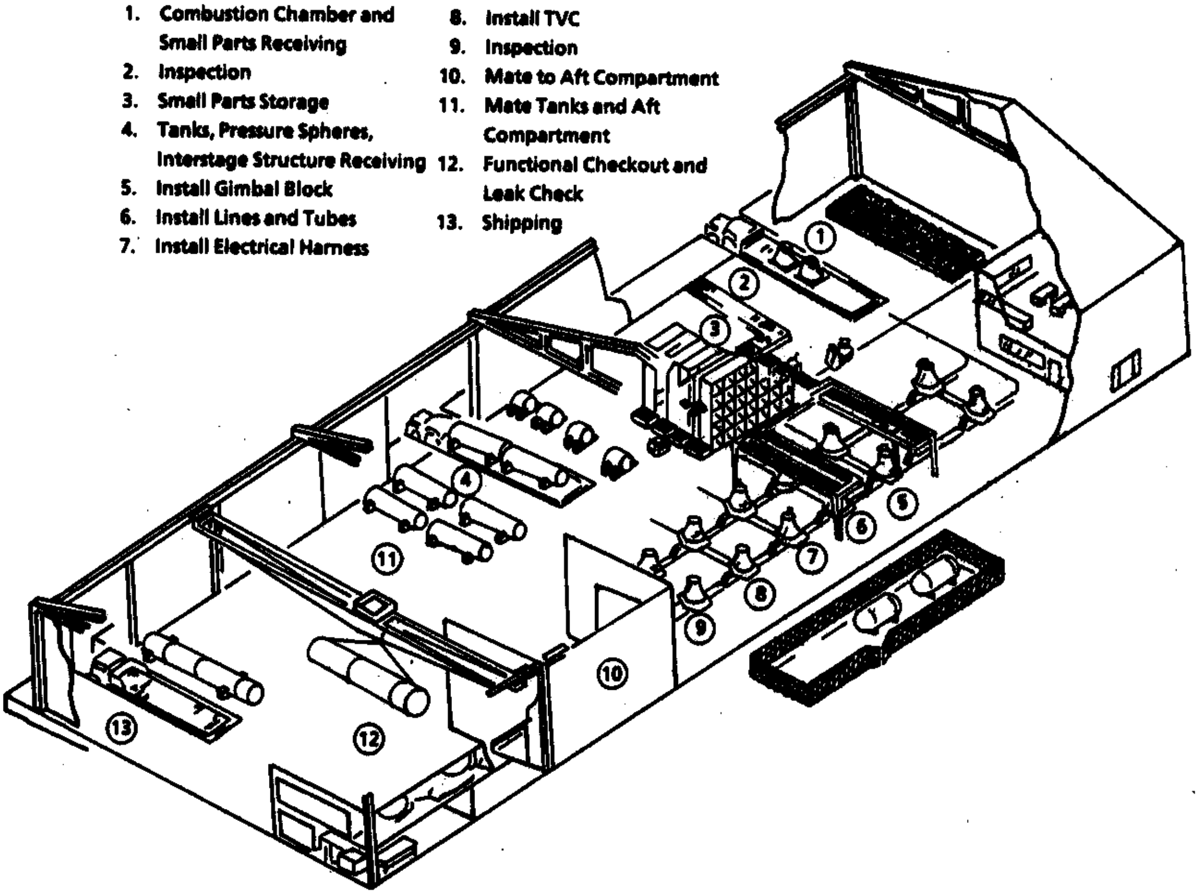
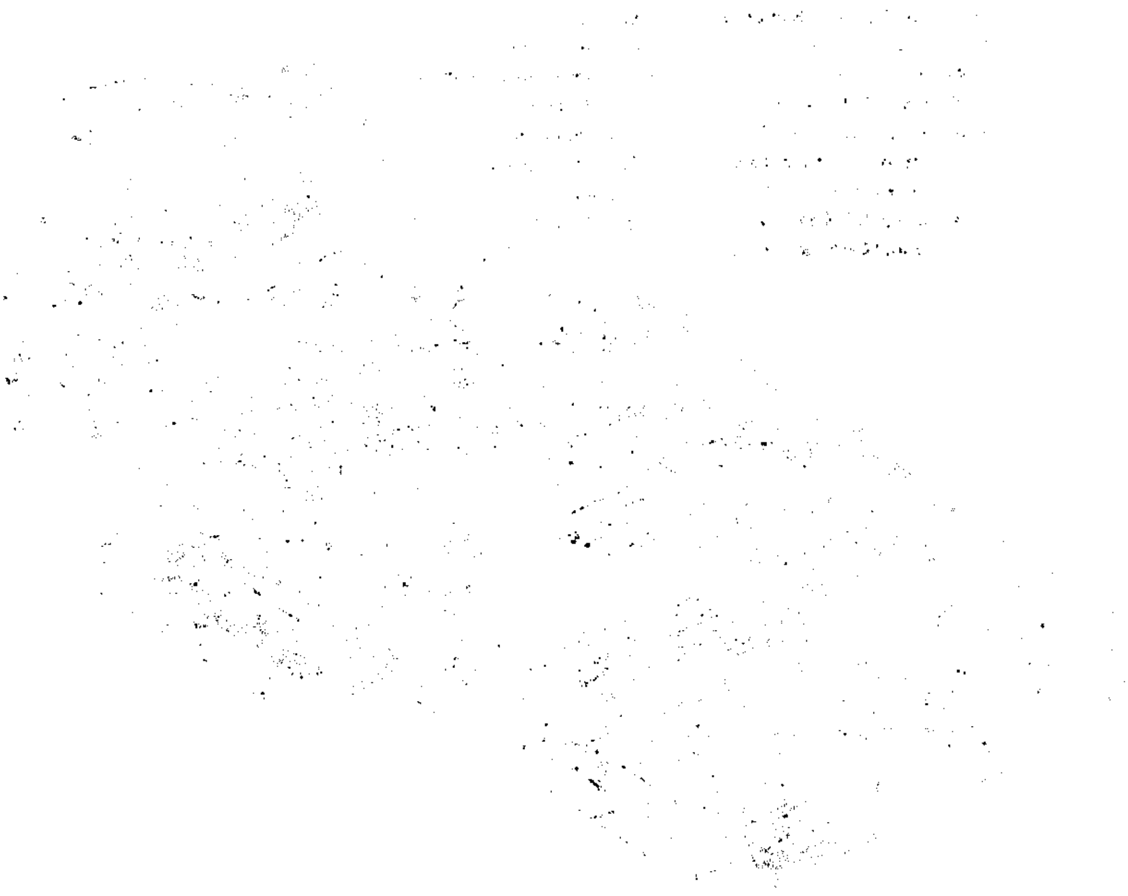


Figure 58. LRE production flow chart.



1. Combustion Chamber and Small Parts Receiving
2. Inspection
3. Small Parts Storage
4. Tanks, Pressure Spheres, Interstage Structure Receiving
5. Install Gimbal Block
6. Install Lines and Tubes
7. Install Electrical Harness
8. Install TVC
9. Inspection
10. Mate to Aft Compartment
11. Mate Tanks and Aft Compartment
12. Functional Checkout and Leak Check
13. Shipping

Figure 59. Typical LRE assembly building and process.



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SECTION V

STRUCTURES AND MATERIALS

The functions of missile structure and the materials used to satisfy these functions are discussed in the following paragraphs, concluded by a discussion of possible manufacturing processes.

5.1 FUNDAMENTALS

A ballistic missile must be designed to withstand operating conditions, flight environment, and ground-handling loads. Operating conditions are created by the propulsion system pressurization and external ambient temperature extremes. Flight conditions impose aerodynamic loads, inertia loads, high axial accelerations, and aerodynamic heating during both ascent and payload reentry. Ground-handling loads are created by transportation on rugged terrain and erection for launch. The aerodynamic loads are resolved as lift, drag, and moments about the body axes. Bending moments are created by lift, lateral component of thrust, and inertia loads. Wind and wind shear create both static and dynamic aerodynamic loads. The missile structure must also consider the maximum acceleration during flight. Maximum acceleration is generally achieved at the propulsion cut-off point.

The SRM cases and the LRE tanks often serve as structural elements. The solid-propellant motor case is designed to contain the maximum expected operating pressure with some margin of safety. The pressure-fed LRE requires tanks designed for operating pressures 20 to 30 percent greater than combustion chamber pressure. Typical tank design values would be around 600 psia for a rocket chamber pressure of 500 psia. Both the SRM and the pressure-fed LRE contain components that are sufficiently rigid to serve as primary structural elements. Propellant tanks of the pump-fed LRE are lightweight because they are designed to deliver relatively low pressure to the pump inlet. The pump-fed tank would be designed for an internal pressure around 30 to 50 psia, and would not provide structural rigidity until the tank is pressurized. Pump-fed systems would seem to obviate their advantage of lightweight structure by requiring external supporting structural elements, especially for mobile tactical applications.

The structure connecting various missile components is called the interstage structure. The interstage structure is typically dictated by maximum bending movement during flight, but may under some circumstances be designed to withstand some ground-handling needs. Erection for launch from the horizontal position is often a critical requirement.

The principle functions of the missile structure are (1) to provide an integrated framework combining the established general configuration with the various missile components and assemblies while retaining their proper spatial relationship; (2) to resist the internal and external loads imposed during ground-handling, launch, and flight; and (3) to maintain the designed external aerodynamic characteristics. Overall weight of the structure is an important parameter of missile performance, and therefore, materials with high strength-to-weight ratios are of prime consideration. However, trade-offs must be made with other factors involved in the selection of structure design and materials, which include

1. relative ease and reliability of fabrication,
2. availability of sheets and shapes,
3. strength at elevated temperatures,
4. strength and ductility at subzero temperature,
5. erosion resistance,
6. corrosion resistance,
7. aging characteristics,
8. availability in quantity, and
9. nominal cost.

Nonavailability of some or most of the materials with the desired properties, however, only results in a less efficient missile and may not be a detriment to obtaining an indigenous missile capability.

5.2 MISSILE STRUCTURE

5.2.1 Motor Cases and Propellant Tanks

The basic structure of a solid-propellant missile consists of the motor case, insulation, and propellant. A simplified cross section of a solid-propellant motor is seen in Fig. 27. The SRM motor case is the unifying cylindrical structure designed to provide the structural integrity and to support the SRBM components under dynamic, aerodynamic, handling, storage, and transportation loads. The combustion chamber is contained within the motor case and may be subjected to internal pressures up to or exceeding 1,000 psi. The materials used in the construction of motor cases are discussed in Section 5.3.

The basic structure of a liquid-propellant missile consists of external skin and missile body, liquid oxidizer and fuel tanks, propellant feed system, guidance systems, payload, and interstage structure. The design and material thickness of the LRE tanks depends on the type of propellant-feed system used.

Since the basic pump-fed LRE body is not a pressure vessel, the missile may be constructed as a monocoque or semi-monocoque structure. The former construction consists of an unstiffened shell with very few transverse frames and is relatively simple to manufacture with a minimum of detail parts and few manufacturing operations. The semi-monocoque structure consists of shell, stiffened longitudinally by stringers or longerons, with transverse stability provided by transverse frames and bulkheads. A large number of detail parts and assembly operations are required to manufacture this type structure. In addition to the body construction, liquid fuel and oxidizer tanks may be incorporated with the shell to provide the necessary structural integrity. Pump-fed liquid-propellant tanks are usually a monocoque shell of 6061 aluminum, stainless, or steel alloy and, dependent upon the chemical compatibility with the particular propellant, may be internally lined. Structural frames and bulkheads provide lateral stability to resist side loads during storage, transportation, and launch operations.

Pressure-fed LRE tanks are pressure vessels similar to the structural rigidity of SRM cases. They are generally suitable as load-carrying members. A possible structural configuration of a single-stage pressure-fed liquid-propellant SRBM is shown in Fig. 60.

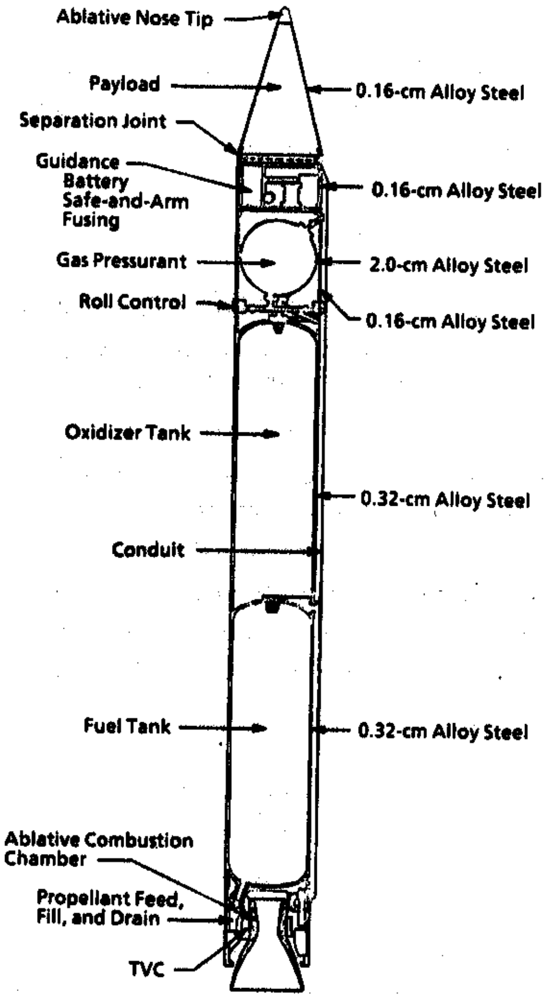


Figure 60. Structural configuration of a single-stage pressure-fed liquid-propellant SRBM.

5.2.2 Interstage

An interstage is a structural member that attaches the stages (i.e. first and second stage) together. A typical interstage is shown in Fig. 61. The interstage is designed to withstand flight/aerodynamics, handling, environment, and thrust loadings and, therefore, is much lighter in construction than the rocket motor structure and case.

During the two-stage rocket motor powered flight portion, the first- and second-stage sections must be separated. This separation operation takes place in the interstage portion of the SRBM, prior to or concurrent with ignition of the second-stage rocket motor.

This separation operation is critical and must be accomplished efficiently and accurately to prevent missile control and structural failure problems. Separation at the interstage is usually performed by separation/release devices such as frangible bolts and nuts or shaped charges. The later device is the most popular and efficient.

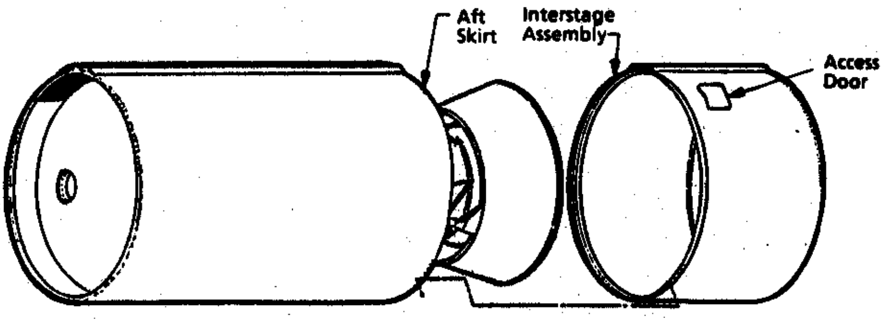


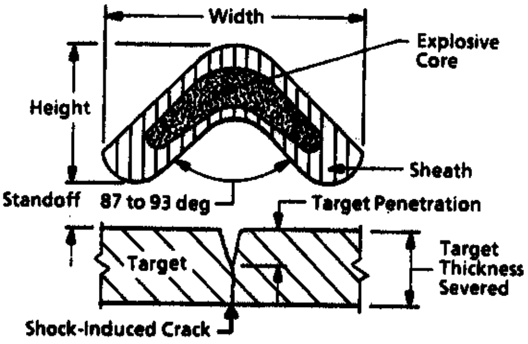
Figure 61. Typical rocket motor and interstage assembly.

Shaped Charges. Shaped charges are a form of pyrotechnics that controls the direction of and concentrates the explosive energy. In many instances, the energy intensity of an explosive can be increased more than a thousand times. Shaped charges can be subdivided into three classifications: conical-shaped charges (CSC), linear-shaped charges (LSC), and flexible, linear-shaped charges (FLSC).

Their primary purpose is to supply a source of heavy molecules that can be accelerated toward the target by the high pressure and shock waves generated by the high- or secondary-explosive core. RDX, PETN, HNS, and DIPAM are the most often used core explosives. Upon impact with the target, these high-velocity molecules transfer tremendous amounts of kinetic energy to the target, causing it to deform and fail. With the advent of linear-shaped charges, it soon became apparent that there was a need to sever targets whose surfaces were contoured such as pipes, tubing, tanks, spheres, etc. of all diameters, thicknesses, and materials. Flexing a length of LSC without precise tooling can result in degradation of its performance. Even with close-tolerance tooling, very little LSC with explosive core loadings in excess of 500 grains/ft (106 gm/m) is flexed. Therefore, the FLSC is the normally used shape charge in interstage separation operations.

The vast majority of FLSC used today falls within explosive core loadings of 5 to 150 grains/ft (1 to 32 gm/m). Like the smaller sizes of LSC, FLSC is fabricated by incrementally filling a tube of sheath material with compressings of the desired explosive, sealing the ends, and then drawing it through a combination of swagging and forming dies. Figure 62 presents an FLSC cross section and tabulates the linear loading, and Fig. 63 shows representative samples of the continuous standoff spacers employed with FLSC devices. Typical installation in a missile separation joint is shown in Fig. 64.

Separation/Release Devices. As the name implies, these devices are pyrotechnic cartridge-actuated separation or release devices that may structurally attach two adjacent components together and when initiated, separate or release them. A more complex device may use a



Core Load, grains/ft	Height, in.	Width, in.
7	0.07	0.14
10	0.08	0.16
15	0.10	0.19
20	0.12	0.22
25	0.13	0.24
30	0.15	0.25
40	0.17	0.30
50	0.20	0.33
75	0.23	0.36
100	0.26	0.43

Figure 62. Geometric characteristics of flexible linear-shaped charges.

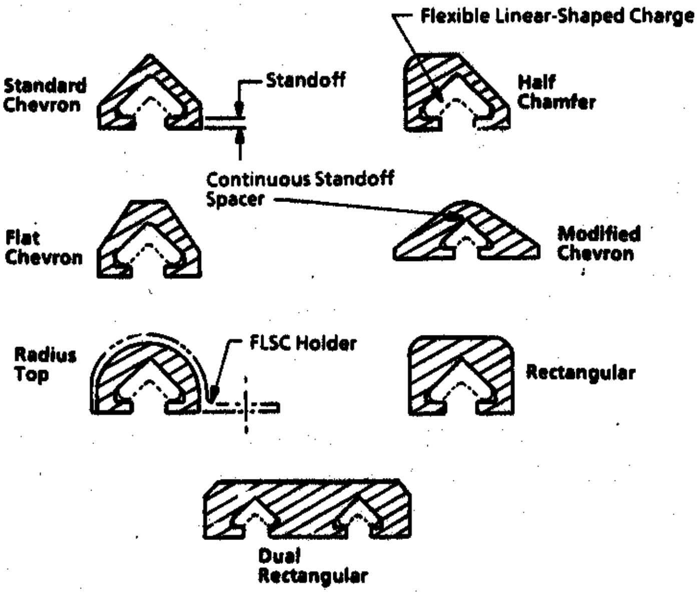


Figure 63. Typical FLSC continuous standoff spacers.

pyrotechnic device somewhat as a toggle stage, which upon initiation, allows a mechanical device to perform the actual separation (or releasing) function.

Pyrotechnic cartridge-actuated devices have several distinct advantages over other types of power systems, such as hydraulics, pneumatics, electrical, etc. Their main advantage is their being extremely lightweight. This is because of the relative higher operating pressure of pyrotechnics versus hydraulic or pneumatics; namely 10,000 to 12,000 psi (703 to 844 kg/cm^2) versus 2,000 to 4,000 psi (141 to 282 kg/cm^2), respectively. All these components are generally made of steel or aluminum that permit relatively thin cylinder walls. To perform equal amounts of work, hydraulic or pneumatic actuators would require pistons with two to six times the area of a comparable pyrotechnic actuator, and hence, would be considerably heavier too. Additional system weight saving is realized when hydraulic or pneumatic tubing and pumps (or compressors) are replaced with a pair of pyrotechnic firing wires.

Another distinct advantage of cartridge-actuated devices is their simultaneity of actuation for multiple devices. This feature becomes extremely important when two or more attachments must be released at the same time, such as aircraft fuel tanks or multistage booster rockets.

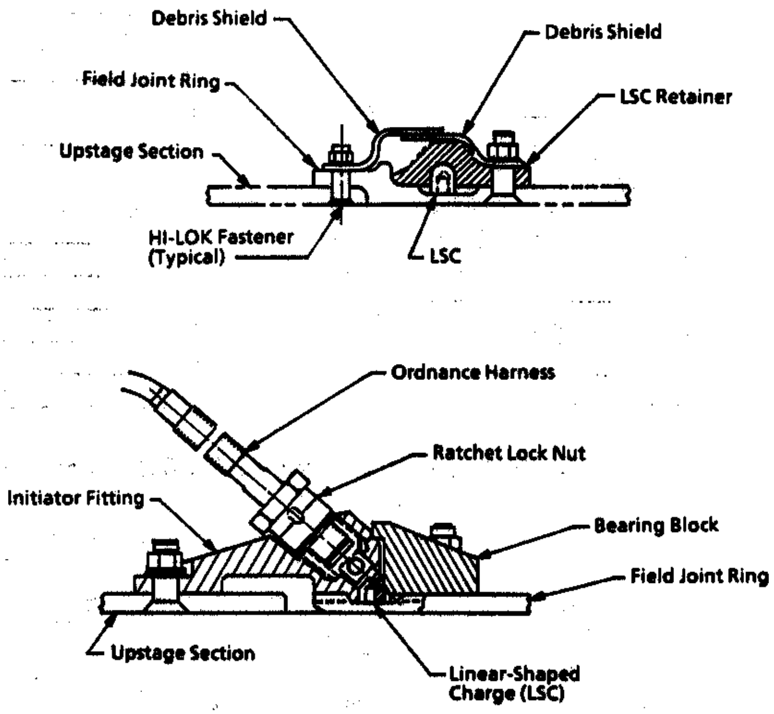


Figure 64. Interstage assembly joint showing ordnance device.

Frangible Devices. These devices are the most reliable of all pyrotechnic separation devices because they are, by far, the ultimate in simplicity of design. They are load-carrying structural members that are fractured by the explosive output of their pyrotechnic cartridges.

Frangible Nuts. The simplest of all frangible devices are frangible nuts. These devices consist only of a conventional structural nut that has been modified to accommodate redundant, conventional output detonator cartridges as shown in Fig. 65.

a. Conventional detonator **b. End-firing detonator**

Figure 65. Detonator outputs.

Frangible nuts are based upon the principle of minimizing the amount of material required to retain together two integral halves of a nut when loaded to a predetermined maximum tensile load. Radial loads are imposed on each nut half when a tensile load is imparted by a mating stud along the bevels of the nut/stud interfacing threads. The thin webs holding the two halves of the frangible nut together are broken when one or both of the detonator cartridges are initiated. When only one detonator fires, it breaks the adjacent webs and spreads the two halves of the nut apart, causing the two webs on the opposite end to also break because of the fulcrum effect of the spreading nut halves. Even when both detonators are fired simultaneously, one detonator always precedes the other because of differences in firing circuits and detonator characteristics. Instrumented tests have shown the nuts to be completely separated within 3 to 4 msec after the onset of current flow in the bridge wire of the detonator.

Frangible Bolts. The main advantage of frangible bolts over frangible nuts is that the former do not require such massive blast and fragment containers as do the latter. Blast and fragmentation can be virtually eliminated in the frangible bolt, and yet fracturing of the primary load-carrying structural member, to effect a separation, can be accomplished. A typical separation joint using frangible bolts is shown in Fig. 66.

5.3 STRUCTURAL MATERIALS

5.3.1 Steel Identification

As the unifying element of an SRBM, the missile structure material properties make the ultra-high-strength steels and maraging steels of particular interest. This section discusses those commercial ultra-high-strength steels capable of a minimum yield strength of 200 ksi and some of the more recently developed steels, such as the family of maraging steels, used in the aerospace and missile industries. The various grades, industry names and designations, and viable substitute steels are identified. The remelt and reuse of maraging steel from scrap and the manufacturing processes are also discussed.

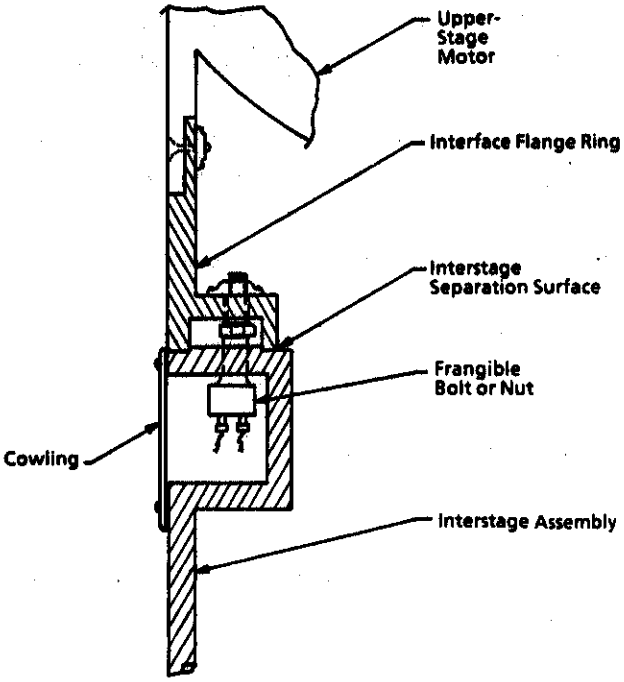


Figure 66. Separation joint using frangible bolts.

The mechanical, physical, or chemical properties, usually in combination, determine the usefulness of a product for a given application. Recognizing a need for a method to accurately identify these properties, the steel industry developed a systematic arrangement or division of steels into groups on the basis of some common characteristics. The classification of steels can be on the basis of (1) composition, as carbon or alloy steel; (2) finishing methods, as hot-rolled or cold-rolled steel; or (3) product form, such as bar, plate, sheet, strip, tubing, or structural shape.

Common usage has further subdivided these broad classifications. Carbon steels are often loosely and imprecisely classified according to carbon content as low-, medium-, or high-carbon steels. Depending on the deoxidation practice used in producing them, steels may be classified as rimmed, capped, semikilled, or killed. Alloy steels are often classified according to the principle alloying element(s) present. For example, there are nickel steels, chromium steels, chromium-vanadium steel, etc. The most common classification systems used in the U.S. are those of the American Iron and Steel Institute (AISI) and the Society of Automotive Engineers (SAE).

"Grade," "type," and "class" are terms used to classify steel products. Within the steel industry, "grade" is used to denote chemical composition; "type" is used to indicate deoxidation practice; and "class" is used to describe some other attribute, such as strength level or surface smoothness. In the American Society for Testing and Materials (ASTM) specifications, these terms are used somewhat interchangeably.

Designation is a specific identification of each grade, type, or class of steel by a number, letter, symbol, name, or suitable combination thereof unique to a particular steel. Chemical composition and mechanical-property specifications are the most widely used systems. The most commonly used system of designation is that of the SAE and AISI.

The term "quality" in a product description, as used in the steel industry, implies special characteristics that make the mill product particularly well suited to specific applications or subsequent fabrication operations. It does not imply that the mill product is better material, is made from better raw materials, or is more carefully produced than other mill products (Ref. 13).

A specification is a written statement of the requirements, both technical and commercial, that a product must meet. There are nearly as many formats for specifications as there are groups writing them. Engineering societies, associations, and institutes whose members make, specify, or purchase steel products publish standard specifications. Some of the important specification-writing groups are listed in Table 18.

Table 18. Principal Specification-Writing Groups in the United States

Association of American Railroads	AAR
American Bureau of Shipping	ABS
American Petroleum Institute	API
American Railroad Engineering Association	AREA
American Society of Mechanical Engineers	ASME
American Society of Testing and Materials	ASTM
United States Government Dept. of Defense	MIL and JAN
Society of Automotive Engineers	SAE
Aerospace Material Specification (of SAE)	AMS

Other specifications for steel products have been prepared by various corporation and governmental agencies to serve their own special needs. They are used primarily for procurement by that corporation or agency.

Many manufacturers of steel mill products publish compilations of their standard manufacturing practices. These data represent the dimensions, tolerances, and properties that might be expected in the absence of specific requirements that indicate otherwise. Although standard manufacturing practices are not specifications, they are good indicators of what restrictions and tolerances many producers of steel products will accept and should, whenever possible, be incorporated into proprietary specifications.

5.3.2 Ultra-High-Strength Steels

Structural steels with very high-strength levels are often arbitrarily referred to as ultra-high-strength steels; however, there is no universally accepted strength level set for this term. For this report, those commercial structural steels capable of a minimum yield strength of 200,000 psi (hereafter, 200 ksi) will be considered. Table 19 lists the compositions of some of the ultra-high-strength steels.

Table 19. Compositions of the Ultra-High-Strength Steels

Designation or Trade Name	Composition(s), wt percent							
	C	Mn	Si	Cr	Ni	Mo	V	Others
Medium-Carbon Low-Alloy Steels								
4130	0.28 to 0.33	0.40 to 0.60	0.20 to 0.35	0.80 to 1.10	—	0.15 to 0.25	—	—
4140	0.38 to 0.43	0.75 to 1.00	0.20 to 0.35	0.80 to 1.10	—	0.15 to 0.25	—	—
4340	0.38 to 0.43	0.60 to 0.80	0.20 to 0.35	0.70 to 0.90	1.65 to 2.00	0.20 to 0.30	—	—
AMS 6434	0.31 to 0.38	0.60 to 0.80	0.20 to 0.35	0.65 to 0.90	1.65 to 2.00	0.30 to 0.40	0.17 to 0.23	—
300M	0.40 to 0.46	0.65 to 0.90	1.45 to 1.80	0.70 to 0.95	1.65 to 2.00	0.30 to 0.45	0.05 min	—
D6A	0.42 to 0.48	0.60 to 0.90	0.15 to 0.30	0.90 to 1.20	0.40 to 0.70	0.90 to 1.10	0.05 to 0.10	—
6150	0.48 to 0.53	0.70 to 0.90	0.20 to 0.35	0.80 to 1.10	—	—	0.15 to 0.25	—
8640	0.38 to 0.43	0.75 to 1.00	0.20 to 0.35	0.40 to 0.60	0.40 to 0.70	0.15 to 0.25	—	—
Medium-Alloy Air-Hardening Steel								
H11 Mod	0.37 to 0.43	0.20 to 0.40	0.80 to 1.00	4.75 to 5.25	—	1.20 to 1.40	0.40 to 0.60	—
H13	0.32 to 0.45	0.20 to 0.50	0.80 to 1.20	4.75 to 5.50	—	1.10 to 1.75	0.80 to 1.20	—
9Ni-4Co Steels								
HP 9-4-20	0.16 to 0.23	0.20 to 0.40	0.20 max	0.65 to 0.85	8.50 to 9.50	0.90 to 1.10	0.06 to 0.12...	4.25 to 4.75 Co
HP 9-4-30	0.29 to 0.34	0.10 to 0.35	0.20 max	0.90 to 1.10	7.0 to 8.0	0.90 to 1.10	0.06 to 0.12	4.25 to 4.75 Co

1. P and S Contents May Vary with Steelmaking Practice. Usually, These Steels Contain No More than 0.035 P and 0.40 S; 9Ni-4Co Steels Are Specified to Have 0.10 Max P and 0.10 Max S.
2. ASTM A681; Composition Ranges Utilized by Some Producers Are Narrower.

AISI/SAE 4130 steel is a water-hardening alloy steel of low to intermediate hardenability. It retains good tensile, fatigue, and impact properties up to about 700°F; however, it has poor impact properties at cryogenic temperatures.

AISI/SAE 4140 steel is similar to 4130 steel except for a higher carbon content. It is used in applications requiring a combination of moderate hardenability and good strength and toughness, but in which service conditions are only moderately severe. This steel can be welded by any of the standard welding methods provided that proper procedures are employed. For welding, preheating temperatures of 300° to 500°F and postheating at 1,100° to 1,250°F followed by slow cooling are recommended.

AISI/SAE 4340 steel is considered the standard to which the other ultra-high-strength steels are compared. It combines deep hardenability with high ductility, toughness, and strength. It has high fatigue resistance and is often used where severe service conditions exist and where high strength in heavy sections is required. 4340 steel has good welding characteristics, and it can be readily gas or arc welded. However, welding rods of the same composition should be used. Welded parts should be either annealed or normalized and tempered shortly after welding.

Alloy 300M is basically a silicon-modified 4340 steel, but has slightly higher carbon and molybdenum contents and also contains vanadium. This steel exhibits deep hardenability and has ductility and toughness at tensile strengths of 270 to 300 ksi. This alloy has many of the properties similar to those of 4340 steel. Although alloy 300M can be gas or arc welded, welding is generally not recommended for critical applications.

Ladish D6A and D6AC, produced by air-melting (D6A) in an electric furnace or by air melting followed by vacuum-arc melting (D6AC), are low-alloy ultra-high-strength steels developed for high-performance aircraft structures and solid-propellant rocket booster case applications. This alloy has good ductility and high resistance to impact loading and retains its high strength at elevated temperatures. Welding is accomplished using techniques and controls normally required for welding medium-carbon, high hardenability steel alloys. Welding rods should be of the same composition.

AISI/SAE 6150 steel is a tough, shock-resisting, shallow-hardening chromium-vanadium alloy with high fatigue and impact resistance in the heat-treated condition. Welding is readily accomplished using standard welding techniques and methods. Welded parts should be normalized, then hardened and tempered to required hardness.

AISI/SAE 8640 steel was developed to provide maximum hardenability and best combination of properties possible with minimum alloying additions. Welding may be performed using standard welding procedures; however, preheating, postheating, and stress relieving is recommended.

Table 20 presents a list of some of the ultra-high-strength steels with their commercial and alternate designations.

Table 20. Cross Index of Alloys

Ultra-High-Strength Steel Designation and Alternate Designations

4130
4130H
AISI 4130
AMS 6350F
AMS 6351C
AMS 6370J
SAE 4130
UNS G41300
UNS G93103
UNS H41300

4140
4140H
AISI 4140
AMS 6395B
SAE 4140
UNS G41400
UNS J14046

4335 Modified
4335V Mod
AMS 6433C
AMS 6434C
AMS 6435C
UNS K33517

4337
4340
4340H
AISI 4337
AISI 4340
AMS 6359D
E4340
SAE 4337
SAE 4340
UNS G43400

AMS 6438C
Crucible D6 Alloy Steel
D6A, D6AC
D6AC Electric Furnace
D6AC Vacuum Degassed
Ladish D6A
Ladish D6A (Consumable Electrode VacMelt)
MIL-S-47036
MIL-S-8949
UNS K24728
UNS K24729

Crucible 422
Crucible HY-Tuf
Hy-Tuf
MIL-S-7108
UNS K32550

5Ni-Cr-Mo-V
HY 130/140
UNS K51255
USS Airsteel X-200

300-M
AISI 4340M (Obsolete)
AMS 6417C
AMS 6419B
Inco Ultra-High-Strength Steel
MIL-S-8844C
TRICENT (Obsolete)
UNS K44220
UNS K44540

5Cr-Mo-V Aircraft Steel
5Cr-Ultra-High-Strength Steel
882 Mel-Trol
AISI No. 610
Alcodie
AMS 6437A
Atlas 59
Castdie
Cr-Mo-V (Low V)
Crucible 218 (Halcomb 218)

Dica B Modified
Dyecast No. 1
Dynaflex
Firedie
H-11
H-11 Mod
HWD 2
Megal
Modified AISI Type H-11 Steel
Mod Holform No. 2
Potomac A
Pressurdie 3-L
Type H-11
Type H-11 Modified
Unimach 1 (Thermold A)
Vascojet 1000

9Ni-4Co
AMS 6523B
AMS 6524B
HP-9-4-20
HP-9-4-30
Republic HP 9-4-25
Republic HP 9-4-XX
UNS K91283

17-4PH
17-7PH
AMS 5528A
AMS 5529A
AMS 5864
PH-13-8Mo

AISI No. 635
Stainless W
USS "W"

Almar 455
AMS 5617A
Carpenter Custom 455
Custom 455 Stainless Steel
UNS S45500

5.3.3 Maraging Steels

Maraging steel is a series of wrought high-nickel alloys developed in 1959 to combine superior toughness and resistance to crack propagation with high strength. This combination is achieved by aging to promote complex precipitation reactions in a low carbon iron-nickel martensite. Maraging is defined as a precipitation-hardening treatment applied to a special group of iron-base alloys to precipitate one or more intermetallic compounds in a matrix of essentially carbon-free martensite. The term "maraging" is thus derived from "martensite age hardening." In the 18-percent nickel (18 Ni) maraging steels, the transformation from austenite to martensite occurs just above "room" temperature (200° to 400°F). In the martensitic condition, the steels are soft and ductile. They can be easily fabricated and subsequently strengthened by age-hardening at 900°F. A high degree of dimensional stability is maintained throughout heat treatment (Ref. 14).

Four grades of maraging steels have been specified according to their approximate yield strengths in ksi. These are grades 200, 250, 300, and 350, with the 250 grade being the most widely used. The nominal amounts of cobalt, molybdenum, and titanium vary in these four grades. For optimum strength and toughness, carbon, silicon, manganese, sulfur, and phosphorus are held to low levels (Ref. 14). The 350 grade is made in limited quantities for special applications. Maraging steels with yield strengths as high as 500 ksi have been produced experimentally. These experimental steels typically have very high nickel, cobalt, and molybdenum contents and very low carbon contents (Ref. 13).

18 Ni (200) Maraging Steel. 18 Ni (200) maraging steel is one of the 18 Ni maraging types in which a relatively low yield strength of approximately 200 ksi is chosen because of its accompanying high ductility and exceptional toughness. This alloy differs from the other higher strength 18 Ni maraging grades primarily in its lower molybdenum and titanium content. Mechanical properties can be varied over a wide range by heat treatment and processing, and by variations in composition, within the specified limits, while still falling within the general designation of "200 Grade." The major experience with this steel has been obtained in two major yield strength ranges: from 175 to 200 ksi, developed principally for deep-submergence submarine applications, and from 200 to 235 ksi used principally for solid-propellant rocket motor cases. Table 21 shows compositions of the 18 Ni maraging steel for various motor case applications.

Table 21. Maraging Steel Compositions for Rocket Case Applications

Alloy	Fe-18Ni-8.5Co-Mo-Ti-Al(200)						
Form	Plate Cameron Iron Works		Forward Y Ring		Weld Wire Heat No. 08950		Plate Lukens
	Mill	Sun Ship[1]	Ladish	Sun Ship[1]	Armet Co.	Sun Ship[1]	Sun Ship[1]
Aluminum	0.08	0.095	0.12	0.104	0.065	0.075	0.07
Carbon	0.022	0.021	0.02	0.024	0.01	0.016	0.02
Cobalt	7.51	7.49	7.68	7.51	7.80	7.88	7.82
Hydrogen	—	—	—	—	2.5*	1.3*	—
Manganese	0.05**	0.029	0.08	0.052	0.02	0.007	0.07
Molybdenum	4.25	4.38	4.36	4.29	3.68	3.74	4.25
Nickel	18.37	18.23	17.99	18.14	17.88	17.82	18.11
Nitrogen	—	—	—	—	35*	51*	—
Oxygen	—	—	—	—	15*	37*	—
Phosphorus	0.006	0.005	0.009	0.003	0.002	0.007	0.008
Silicon	0.05**	0.021	0.07	0.014	0.01	0.008	0.08
Sulfur	0.009	0.008	0.005	0.004	0.007	0.003	0.007
Titanium	0.16	0.21	0.23	0.22	0.29	0.28	0.17

1. Sun Ship Building and Dry Dock Co.
* ppm
** Maximum

The resistance to hydrogen embrittlement is much superior to that of conventional low-alloy steels, and its corrosion characteristics are somewhat better than 4340 steel. Because of its good corrosion resistance and outstanding fracture toughness, it is currently under intensive investigation for such high-performance applications as deep-submergence submarines, special aircraft forgings, and large solid-propellant rocket motor cases. Care is still required in the choice of composition, heat treatment, and processing variables despite its apparent desirable features. Welding may also require special precautions since the toughness of the weld deposit may not be as high as that of the parent metal.

Product forms available for this 200 grade steel are bars, sheet, plate, tubing, and forging stock in the hot-worked or annealed condition. Sheet is also available in the annealed and cold-worked condition. Hot-working by conventional rolling and forging operations is readily accomplished, whereas cold-working is easily done by conventional procedures in the annealed condition.

Welding may be done without preheat in both the fully heat-treated and solution-annealed conditions. Postweld heat treatment is accomplished by the normal aging procedure. Virtually no problems are encountered with gas tungsten-arc welding. Occasional porosity is encountered with gas metal-arc welding and can be controlled by closer control of welding technique and composition of filler metal. Pure helium shielding is often required during arc welding.

18 Ni (250) Maraging Steel. 18 Ni (250) maraging steel is currently the most widely used steel among the maraging steels. The actual strength level and toughness can vary considerably with composition variations within the specification limits and also depends strongly on processing history. A properly processed sheet product has higher fracture toughness than standard low-alloy quenched and tempered steels. Heavy section toughness and impact properties are also superior to those of conventional medium carbon, low-alloy high-strength steels heat-treated to comparable strength levels. Heavy section fracture properties, however, can be directional. This directionality is influenced by melting and processing conditions. Modern practice requires vacuum induction melting (VIM) plus consumable vacuum arc remelting (CVM) or vacuum arc melting (VAR).

18 Ni (250) is weldable in both the solution-annealed and fully heat-treated condition. The gas metal arc (GMA), often called MIG (metal inert gas), and gas tungsten arc (GTA), often called TIG (tungsten inert gas), welding processes are suitable for the grade. By proper techniques and close control, joint efficiencies of 90 to 100 percent are obtainable for aged welds in sheets and heavy sections. Submerged arc welding is not recommended because of a tendency for hot-cracking, low-fracture toughness, and severe embrittlement in the heat-affected zone.

Electron beam welding techniques have been developed for thinner gauges, although, the close fit-up required for satisfactory joints is a disadvantage. Other joining methods such as resistance welding, inertia welding, and brazing have been investigated but are not in general use.

T-250 Maraging Steel. T-250 maraging steel is a maraging steel that contains no cobalt. Cobalt has been considered as a strategic element because of uncertain supply coupled with a high and volatile price. The strength of the cobalt-free alloy is essentially equal to that of the conventional cobalt-containing 250 grade maraging steel. This equivalent strength has been obtained by a substantial increase in the titanium content with the alloy properties being significantly influenced by variations in titanium within the composition limits. T-250 maintains many of the desirable characteristics of the cobalt-containing alloy including excellent hot- and cold-formability, simple heat treatment with very small dimensional change, high fracture toughness, and good weldability.

Welding is readily performed using the electron beam or GTA processes. Minimal preheat is required to avoid condensation of moisture, with temperatures of 200° to 250°F being recommended. This alloy is very susceptible to hydrogen embrittlement, and care should be taken to employ low-hydrogen filler wire (4 to 5 ppm) and to take suitable precautions to avoid hydrogen contamination from other sources.

Applications to date have been primarily in the production of relatively small rocket motor cases by high cold-reduction shear forming. Demonstration projects have shown that very large cases (e.g. solid-propellant rocket motor case segments for the Space Shuttle) can be successfully produced by the same processes.

18 Ni (300) Maraging Steel. Of the three commercially produced maraging steel strength grades (200, 250, and 300), the 300 grade has a higher titanium range level (0.5 to 0.8 percent) and slightly higher cobalt range level (8.0 to 9.5 percent) than the other two grades. As with all the grades within the 18 Ni maraging steel family, strength levels and toughness vary considerably within the composition limits and can also depend strongly on the processing history. The toughness and impact properties of heavy sections are superior to those of conventional medium-carbon, low-alloy ultra-high-strength steels heat-treated to strength levels in excess of 250 ksi. The fracture properties of heavy sections can be directional, which is influenced by the melting and processing conditions. Corrosion and oxidation resistance is somewhat better than 4340 steel. Resistance to environment-assisted crack propagation is also better than 4340 steel at an equivalent strength level. Hydrogen embrittles maraging steels; however, they exhibit a greater tolerance for hydrogen than conventional low-alloy steels. Formability is excellent in the annealed condition. It is readily machined in the annealed condition and can be machined in the fully aged condition.

This alloy is hot-worked readily by conventional rolling and forging operations and is easily cold-worked by conventional procedures in the annealed condition. Hot-forming and bending should be performed at temperatures under 1,800°F to prevent grain coarsening. Machining is most easily performed in the solution-annealed condition. After aging, its machinability is comparable to 4340 at equal hardness levels.

The 18 Ni (300) maraging steel is weldable in both the annealed and fully heat-treated conditions. Gas-shielded processes (gas metal arc, GMA and gas tungsten arc, GTA) are suitable for this alloy. Argon is recommended for use with either GMA or GTA process. Joint efficiencies from 90 to 100 percent are obtainable, using proper techniques, for aged welds in sheets and heavy sections. Submerged arc welding is not recommended because of the pronounced tendency for hot-cracking, low-fracture toughness, and severe embrittlement in the heat-affected zone.

VascoMax 350 CVM is the steel designation used by Teledyne Vasco to identify a 350-grade 18 Ni maraging steel product produced in its mill. It has a high yield strength range of 340 to 360 ksi combined with superior toughness and ductility. The consumable vacuum-melted process is used in production. The cobalt and titanium content is considerably higher in this grade than in the other maraging steels. The 350 grade is readily machinable in the solution-treated or annealed condition, but rather difficult to machine in the fully hardened condition. Machinability corresponds to that of 4340 steels at equal hardness levels. Welded joints are best accomplished by the GTA process with the base metal in the annealed condition. The 20 Ni and 25 Ni maraging steels differ from the 18 Ni maraging steels in the hardening elements used in the chemical composition. The 18 Ni steels use mainly cobalt-molybdenum additions with small amounts of titanium and aluminum, whereas the 20 Ni and 25 Ni use columbium and higher ranges of titanium and aluminum to obtain the high-stress levels. A comparison of the composition of nickel maraging steels is listed in Table 22.

Table 22. Compositions of Nickel Maraging Steels

Designation	C Max	Mn Max	Si Max	S Max	P Max	Ni	Co	Mo	Ti	Al	Cb
25 Ni		0.10	0.10	0.01	0.01	25.0 to 26.0	—	—	1.3 to 1.6	0.15 to 0.30	0.30 to 0.50
20 Ni	0.03	0.10	0.10	0.01	0.01	19.0 to 20.0	—	—	1.3 to 1.6	0.15 to 0.30	0.30 to 0.50
18 Ni (300)	0.03	0.10	0.10	0.01	0.01	18.0 to 19.0	8.5 to 9.5	4.6 to 5.2	0.5 to 0.8	0.05 to 0.15	—
18 Ni (250)	0.03	0.10	0.10	0.01	0.01	17.0 to 19.0	7.0 to 8.5	4.6 to 5.2	0.3 to 0.5	0.05 to 0.15	—
18 Ni (200)	0.03	0.10	0.10	0.01	0.01	17.0 to 19.0	8.0 to 9.0	3.0 to 3.5	0.15 to 0.25	0.05 to 0.15	—

The 20 Ni grade is lower in toughness, in resistance to stress-corrosion cracking, and in dimensional stability during heat treatment by comparison with the 18 Ni grades. In contrast with the 18 Ni and 20 Ni grades, the 25 Ni grade, to reach the high-strength levels, must be conditioned at 1,300°F for 4 hr after forming or cold-worked at least 25 percent and then refrigerated at −100°F (Ref. 15).

The identification of maraging steels uses many of the classification systems previously listed. In addition, some of the maraging steels use designations of the individual steel producers. Table 23 lists the designations and alternate designations of commercially available maraging steel. Some U. S. producers of maraging steels are

Carpenter Technology Corp., Reading, PA
Latrobe Steel Co., Latrobe, PA
Republic Steel Corp., Cleveland, OH
Special Metals Corp., New Hartford, NY
Teledyne Vasco, Latrobe, PA

Table 23. Maraging Steel Designations and Alternate Designations

200 Grade

18 Ni Maraging Steel
18 Ni (200) Maraging Steel
18 Ni CoMo (200 Grade)
18-8-3
Almar 18 (200 Grade)
RSM 200 (200 Grade)
Vascomax 200 CVM

250 Grade

18 Ni 250 Grade Maraging Steel
18 Ni Maraging (250 Grade)
18 Ni CoMo (250 Grade)
18 Ni (250) Maraging Steel
18-7-5
250 AM
Almar 18 (250 Grade)
AMS 6512B
AMS 6520A
ASTM A538 (Grade B)
ASTM A579 (Grade 72)
Marvac 250
MIL-S-46850
Nimark 250
RSM 250 (250 Grade)
RSM 250
Udimar B-250
UNS K92890
UNS K92940
Vascomax 250 AM
Vascomax 250 CVM

T-250 Grade

AMS 6518
AMS 6591A
Maraging Free-Co
Maraging MS 250
Maraging T-250
MIS 36275

300 Grade

18 NiMaraging (300 Grade)
18 Ni CoMo (300 Grade)
18 Ni (300) Maraging Steel
18-percent Nickel Precipitation Hardening Steel
18-9-5
300 Grade Maraging Steel
Almar 18 (300 Grade)
Grade C-MAR-18-300
Marvac 300
RSM 300
Vascomax 300 CVM

5.3.4 Composite Materials

The idea of combining two or more dissimilar materials, bonded together, to act as a homogeneous structure, is not a recent development. Steel-reinforced concrete is a well-known example. Fiber-reinforced composites have been developed over the last 30 yr, primarily because of the accelerated pace of the aerospace technology needs. Composite materials exhibit an excellent strength/weight ratio that is a requirement in most aerospace applications. Modern high-performance composite materials consist of high-strength fibers, natural or synthetic polymers or metal, intimately mixed with a matrix, which must be able to infiltrate or bond to the fibers, and then be solidified. Table 24 (from Ref. 16) compares some of the fiber material properties. It is to be noted that while the metal wires have higher strengths and moduli than most of the polymers, when the specific strengths (strength/density) are compared, the polymers are competitive. There are many candidate materials, in either elemental form or as compounds, that possess the desired properties of high modulus of elasticity (or simply modulus) and low densities. The three major reinforcing fibers used with thermosetting resins for aerospace applications are glaze, aramid, and carbon fibers.

Table 24. Fiber Material Strength

	Material	Density, $Mg\ m^{-3}$	Strength, GPa	Modulus, GPa
Natural Polymers	Cotton	1.50	0.35	1.1
	Flax		0.9	110
	Silk	1.25	0.5	1.3
	Wool	1.3	0.36	6
	Wood (Kraft Paper)	~1.0	0.9	72
Synthetic Polymers	Cellulose (Fortisan)	1.52	1.1	2.4
	Polyester (Terylene)	1.38	0.6	1.2
	Nylon	1.14	0.8	2.9
	Kevlar 49®	1.45	3.6	130
Metals	Beryllium	1.8	1.3	315
	Molybedenum	10.3	2.1	343
	Nickel Alloy (Rene 41)	8.2	2.3	220
	Steel	7.9	4.2	210
	Tungsten	19.3	3.9	411
	Titanium Alloy	4.6	2.2	120

Glass fibers were developed for particular fields of application. "A" glass is now obsolete but was the original fiber, being made from standard window glass. "C" glass was developed to provide resistance to acids used in the chemical industry. The requirement for a low dielectric constant and good transparency to radar frequencies led to the development of "D" glass. "E" glass was the result of a need for better electrical insulation properties. About 90 percent of the total production, circa 1979, was this product. "S" glass was developed for high strength. "R" glass is a European alternative to "S" glass with similar properties but easier to produce. Continuous glass filaments used in composites are drawn to diameters of 6 to 15 μm with a tendency towards the larger diameters to improve production efficiency (Ref. 17).

Designation of continuous glass fiber reinforcement differs in the U. S. and Europe. The European system lists the filament diameter in microns (μm), strand count in tex (grams per kilometer), and roving count as strand count multiplied by the number of strands. The U. S.

designations use code letters for type and diameter of the filaments, yards (in hundredths) per pound for strand count, and yards per pound for roving. Glass yarn designations are similar to rovings. A typical glass yarn may be identified as *ECG-150-3/2*. The first letter designates the type of glass ("E" glass). The second letter (C) indicates continuous fiber (versus "S" for staple or cut fibers). The third letter defines the filament diameter in inches (See Table 25).

Table 25. Filament Size Designation

Letter Designation	Fiber Diameters, in.
A	Over 0.00006 to 0.00010
B	0.00010 to 0.00015
C	0.00015 to 0.00020
D	0.00020 to 0.00025
E	0.00025 to 0.00030
F	0.00030 to 0.00035
G	0.00035 to 0.00040
H	0.00040 to 0.00045
J	0.00045 to 0.00050
K	0.00050 to 0.00055
L	0.00055 to 0.00060

The number following the letters is called the "count of individual strands." This number represents the hundreds per pound of the strand. For example, the number 150 represents a strand of 15,000 yards per pound. The final set of numbers (as in example 3/2) designates the yarn construction and consists of two numbers separated by a diagonal line. The first represents the number of strands twisted together to form unbalanced yard. The second, after the slash, represents the number of plies of this unbalanced yarn needed to make a plied yarn. The designation 3/2 is used for yarn consisting of three strands twisted together to form a yarn, two of which are then combined to form a plied yarn (Ref. 17).

An aramid fiber of particular interest in the field of fiber-reinforced composites for rocket motor cases is Kevlar®, a trademark for an aromatic polyamide fiber of extremely high tensile strength and greater resistance to elongation than steel. In 1970, the DuPont Company introduced an aramid fiber of high strength and exceptionally high modulus under the experimental name of Fiber B for radial reinforcement of tires. A second-generation fiber of considerably higher strength than that of Fiber B was later introduced. An even higher modulus fiber intended for use in rigid composites was introduced under the experimental name of PRD-49. Upon announcement of construction of commercial facilities for these fibers, the trademarks Kevlar®, Kevlar -29®, and Kevlar -49®, respectively, were introduced. In early 1975, the Netherlands firm Akzo AG announced their intention to commercialize an aramid fiber under the name Arenka; this fiber is probably based on the PPD-T monomer as are Kevlar-29 and Kevlar-49 (Ref. 18).

Carbon fibers, often called graphite fibers, are usually made from polymer fibers by careful heat treatment. They can also be made from tar or bitumen. Of the three carbon forms, diamond, graphite, and amorphus (noncrystalline or glassy), only the crystalline forms have high modulus. Of the crystalline carbon, the only fibers to be produced resemble graphite. Although amorphous carbon fibers can be produced, the relatively low modulus eliminates them from consideration for this report.

The main precursor is polyacrylonitrile (PAN) with pitch or rayon as the alternate. These polymer fibers are first heated at relatively low temperature (about 220°C) in air under tension to oxidize the fibers and to stabilize them. The fibers are then heated at temperatures up to 2,500°C, usually under tension. After the initial conversion to carbon, some recrystallization occurs, so that the graphite planes are oriented along the fiber axis.

Carbon fibers may be conveniently arranged in four classes: ultra-high modulus (UHM); high modulus (HM); very high strength (VHS); and high strength (HS). Table 26 lists the classification and typical properties of PAN carbon fibers. As the manufacturing technology has advanced, both the strength and consistency have been increased for all classes. One important development has been away from the original 10,000 filament tow to fiber tows for weaving and heavier tows for pultrusion. Finer tows, up to 12,000 filaments, can be woven into carbon fabrics (tapes or broadcloths) or, in combination with glass, aramid, and other fibers in roving or yarn form, into hybrid fabrics. Table 27 (from Ref. 17) lists some of the carbon and hybrid fabrics manufactured in the 1980s.

Table 26. Classification and Typical Properties of Carbon Fibers

Property/Class	Units	UHM*	HM*	VHS*	HS
Filament Modulus	GPa	400+	300 to 400	200 to 250	200 to 250
Filament Strength	GPa	1.7+	1.7+	2.76+	2.0 to 2.75
Filament Density	kgm^{-3} ($\times 10^3$)	1.95+	1.8 to 2.0	1.73 to 1.82	1.73 to 1.82
No. in Class		1	10	15	9
Typical Properties					
Filament Modulus	GPa	517	375	234	216
Filament Strength	GPa	1.86	2.23	2.97	2.42
Coefficient of Variation (Strength)	Percent	—	10	7	12
Elongation	Percent	0.38	0.60	1.27	1.12
Filament Diameter	μm	8.4	7.5	8.0	8.5
Filament Density	kgm^{-3} ($\times 10^3$)	1.96	1.85	1.75	1.76
Filament/Tow	10^3	0.384 × 30 Tape	1,3,6,10,12,40	1,3,6,10,12,20,40	10,12,40,160
Electrical Resistivity	μΩ/m	6.5	8	14	25
Coefficient of Thermal Expansion	10^{-6} K^{-1}	—	−1	−0.7	—
Thermal Conductivity	Wm^{-1} K^{-1}	140	100	20	10
Specific Heat	Jkg^{-1} K^{-1}	—	710	710	—
Surface Area	m^2 g^{-1}	—	0.5	1.0	—
Carbon Content	Percent w/w	99.8	99.0	96.5	94.5
Oxidative Resistance (Weight Loss 70 h at 590 K)	Percent	0	0.1	0.8	2

Properties of Selected Carbon Fibers

Class/Property	Units	UHM	HM	HM	VHS	HS
Tradename		Celion®	Thornel®	Fortafil®	Torayca®	Grafil®
Type		GY 70	P	5	300	E/AS
Filament Modulus	GPa	517	379	331	226	200
Filament Strength	GPa	1.86	1.72	2.76	2.94	2.55
Elongation	Percent	0.38	0.5	0.83	1.3	1.27
Filament Diameter	μm	8.4**	11	9.1**	7	8.2
Filament Density	kgm^{-3} ($\times 10^3$)	1.96	2.02	1.8	1.74	1.82
Filament/Tow	10^3	0.384	2	40	1,3,6	10
Electrical Resistivity	μΩ/m	6.5	—	10.5	16	26

* UHM = Ultra-High Modulus; HM = High Modulus; VHS = Very High Strength; HS = High Strength.
** Nonround section, equivalent diameter.

5.4 MANUFACTURING PROCESSES

The basic infrastructure for manufacturing processes to provide an indigenous tactical ballistic missile capability is presented herein. Although the process of obtaining and refining the raw materials from naturally occurring ore deposits or resources is not considered to be within the scope of this report, the manufacturing process or conversion of basic products and materials into SRBM components, the assembly, and transportation are described.

5.4.1 Steel Production

The production of steel is an extensive industrial process that ranges from the basic mining operations, preparation and processing of the ores and minerals, through the reduction and

Table 27. Selection of Carbon and Hybrid Fabrics

Weave	Area Weight, gm^{-2}	Wrap Ends (Length)		Weft (Fill* Ends Width,		Widths, cm	Notes
		Material	No./cm	Material	No./cm		
Unidirectional	165	Carbon 3K**	6.7	Glass Yarn 44 Tex	3.9	7.5,15,60,105,120	Plain Weave
	220	Carbon 3K	10	Carbon 1K	10	100	
	220	Carbon 6K	2.3	Glass Yarn 44 Tex	4	7.5, 15,60,105,120	Plain Weave
		Glass 600 Tex	2.3				
	90	Carbon 1K	7.4	Glass 22 Tex	9	100	2 Carbon: 1 Glass Warp Ends
		Glass 22 Tex	3.7				
Plain	90	Carbon 1K	2.75	Carbon 1K	2.75	100	
	192	Carbon 3K	4.7	Carbon 3K	4.7	100	
	247	Carbon 6K	3.15	Carbon 6K	3.15	100	
	249	Carbon 6K	3.2	Carbon 6K	3.2	100	1 Carbon: 1 Glass Warp and Weft
		S Glass	3.2	S Glass	3.2		
Twill	500	Carbon 6K	1.2	Carbon 6K	1.1	7.5,15,60,105,120	2 × 2 Twill Weave
		Glass 600 Tex	3.5	Glass 600 Tex	3.3		1 Carbon: 3 Glass Warp and Weft
Satin 8	210	Carbon 1K	16	Carbon 1K	16	100	8 Harness (8 Shaft)* Satin Weave (Weft Passes Over 7 Warp Ends Before Passing Under One)
	517	Carbon 6K	5.9	Carbon 6K	6.3	100	
	291	Carbon 3K	9.5	Carbon 3K	9.5	100	1 Carbon: 3 Kevlar 49®
		Kevlar® 127 Tex	28.5	Kevlar® 127 Tex	28.5		
	339	Carbon 3K	4.7	Carbon 3K	4.7	100	1 Carbon: 1 Kevlar 49®
		Kevlar® 158 Tex	4.7	Kevlar® 158 Tex	4.7		
Satin 5	112	Carbon 1K	9.4	Carbon 1K	7.5	100	5 Harness (5 Shaft) Satin
	374	Carbon 6K	4.7	Carbon 6K	4.7	100	
	312	Carbon 3K	16.5	Kevlar 49®	2.3	100	
Satin 4	386	Carbon 6K	4.7	Carbon 6K	4.7	100	4 Harness (4 Shaft) Satin

* The Terms *Weft* and *Fill*, and *Harness* and *Shaft* Are Used Interchangeably.

** 3K = 3,000 Filaments.

conversion into steel products. An indigenous capacity to produce iron and steel products represents a large capital investment. Historically, the direct-reduction (DR) processes by which metallic iron is produced by removing most of the oxygen at temperatures below the melting point of the materials, were used prior to the advent of the blast furnace. The direct-reduced iron is then refined to steel by any commercial steelmaking process. Because the direct-reduction processes could not be carried out on a large scale, these DR processes were supplanted by the higher capacity indirect processes based on the blast-furnace process in the industrialized countries. The four principal DR processes are the fluidized-bed, moving-bed shaft, fixed-bed retort, and rotary-kiln processes. The major uses of the direct-reduction iron products are for steelmaking in electric-arc furnaces, open hearths, basic oxygen furnaces, and induction furnaces.

The modern blast furnace is extremely complex in construction as well as in operation and is capable of producing three to five thousand tons of pig iron in a day. As in the DR process, the primary use of the pig iron resulting from the blast furnace is in the production of steel. Figure 67 is a flow diagram for the production of pig iron through the production of mill-product end forms. The products in largest demand for SRBM production are plates, sheets, bars, and tubes, which are among the products shown in Fig. 68.

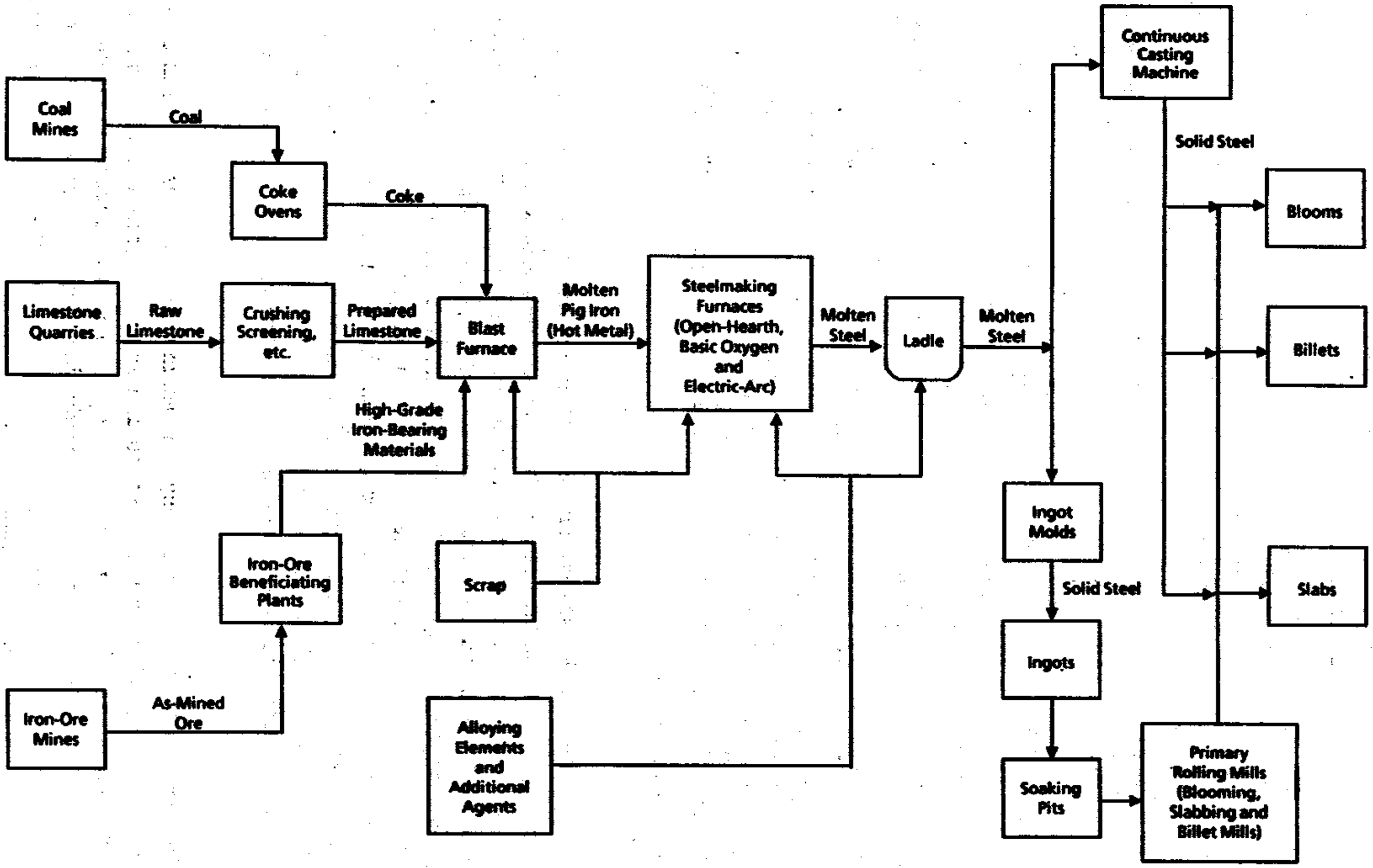
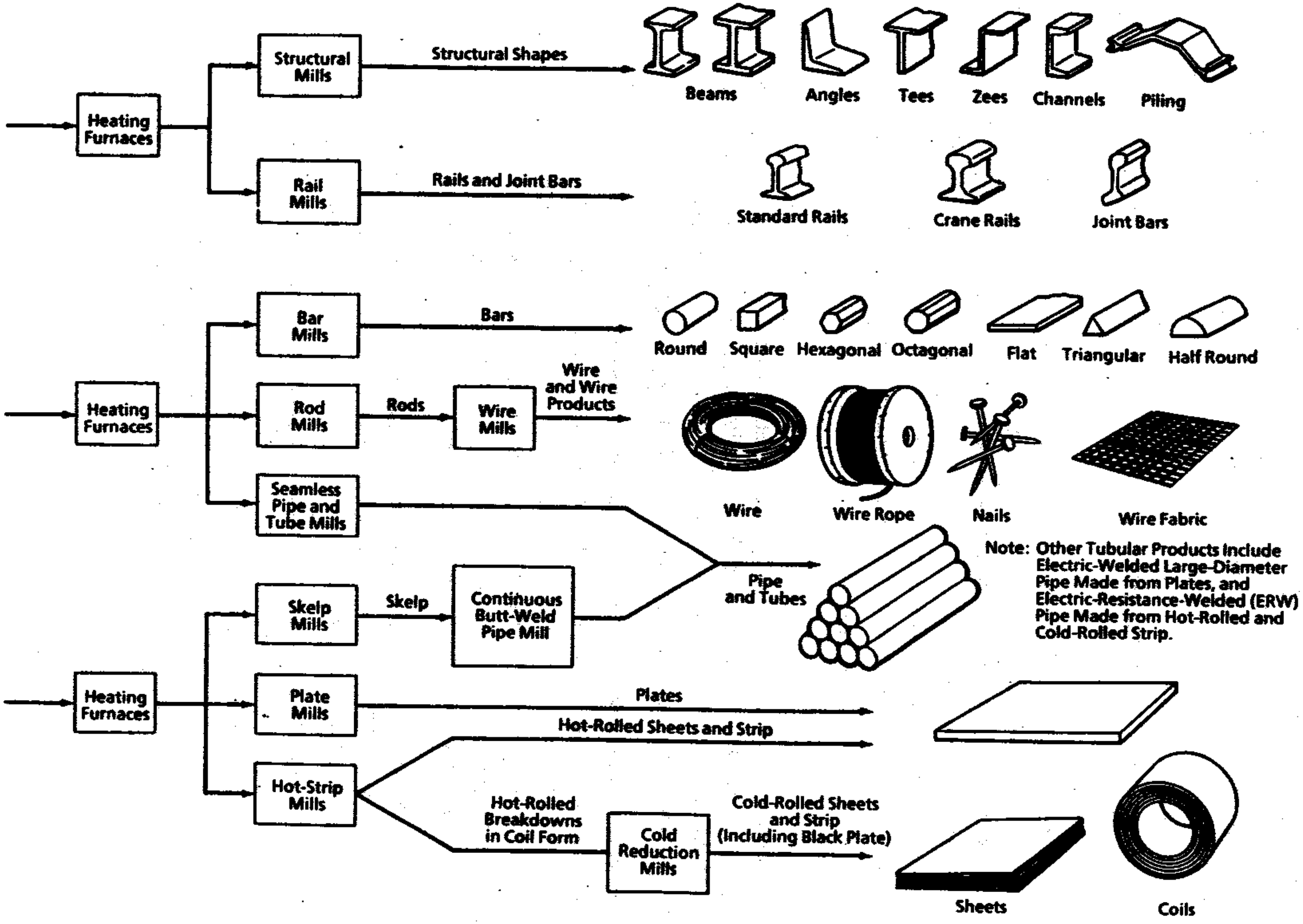


Figure 67. Flow diagram for production of pig iron and steel.



Note: Other Tubular Products Include Electric-Welded Large-Diameter Pipe Made from Plates, and Electric-Resistance-Welded (ERW) Pipe Made from Hot-Rolled and Cold-Rolled Strip.

Figure 68. Process of converting raw steel into mill-product forms.

The open-hearth process of steelmaking most commonly uses the basic open-hearth furnace or the acid or basic electric furnace. The open-hearth furnace (lined with either basic or acid refractory material) is charged with a mixture of molten pig iron, solid pig iron and steel scrap (in almost any desired proportion), and fluxes. The fuel burned in the furnace is necessary to melt the solid ingredients and maintain the proper operating temperature for the time period required to produce a heat of steel. The size and expense of this type furnace usually limits its use to large steel-producing facilities.

Of the several types of electric furnaces used in the manufacture of steel, the electric-arc furnace is used most extensively, whereas the induction furnace is generally used in the production of relatively small quantities of specialty steels or for remelting and refining special steels. Although the electric-arc furnace is usually built to operate in air, the induction and other type furnaces can be built to operate in air or as vacuum furnaces. Electric furnaces can be built to a small-scale convenient for small-scale steelmaking operations, and since they do not require molten pig iron in the charge, the facilities do not need to be located near blast furnaces.

The basic oxygen process uses the basic oxygen furnace and is the principal method of high-tonnage steel production. Because of the large quantity of molten pig iron in the charge (65 to 75 percent), together with scrap steel and fluxes, the furnace is normally used in conjunction with blast furnaces and large steel manufacturing facilities.

The high-strength levels, toughness, and resistance to crack propagation of maraging steels are greatly affected by variations in chemical composition, most notably the low levels of carbon, phosphorus, sulfur, silicon, and manganese. The refining and remelting processes recommended in the production of maraging steel are the vacuum induction melting (VIM) plus consumable vacuum arc remelting (CVM). Although early heats of maraging steels were produced in an air-melting process, current technology uses vacuum induction furnaces.

Reprocessing of Scrap Steels. Within the context of this report, the term *scrap* is used to denote recoverable metal. There are two principal sources of this type of material. Generally termed *processing scrap*, this recoverable metal is generated from the processing of steel in the form of turnings, borings, punchings, skeletons, trimmings, drops, sprues, risers, and gates. The second principal source consists of scrap from used or worn-out products. Examples of these two sources indicate the importance of scrap recycling. Within many foundries, as much as 50 percent of the total tonnage melted becomes reprocessing scrap. Recovery of metal from worn-out or obsolete products is typified by the recycling of cast iron engine blocks of worn-out automobiles and the recovery of worn (out-of-dimensional-tolerance) railroad rails. A survey of the industry in 1976 indicated that the superalloys produced in the U. S. were melted using an average of 42-percent in-house scrap, 17-percent purchased scrap, and 41-percent primary metal.

Where large steel mill facilities are not available and materials are not covered by export controls, Third World countries will satisfy the requirements for maraging and ultra-high-strength steels by acquisition on the world markets or through trade and barter agreements. The product forms purchased may not necessarily be in the form of intended use. Frequently, because of the high cost and/or periodic shortages of these steels and the difficulty in detection, purchases of scrap metals will help fulfill the requirements.

In the processing of recyclable metals, it is important to properly identify the composition of the scrap materials being used to reduce or eliminate the undesirable constituents in the required chemical composition heat. This is especially true in the production of maraging steels and ultra-high-strength steels. The problem of composition identification is not as difficult in scrap generated from in-house processing as it is from purchased scrap.

The best method of composition identification of scrap metals is by quantitative chemical analysis. Chemical or spectrographic analysis requires extensive, time-consuming procedures and expensive equipment. The common methods of rapid identification of metals (magnetic properties, weight, spark testing, and chemical spot testing) are not considered appropriate for identification of maraging steels. These rapid methods, although able to identify the presence of certain constituents in a sample, are unable to determine chemical composition or the microscopic grain structure.

The refining and remelting processes recommended for the production of maraging steels and most of the ultra-high-strength steels are argon-oxygen decarburization (AOD), electroslag refining (ESR), vacuum arc remelting (VAR), and vacuum induction melting (VIM). Early production of maraging steel used electric-furnace air melting; however, vacuum melting is recommended. The most flexible vacuum melting process is VIM because it allows for independent control of temperature, pressure, and mass transfer by means of stirring, thus providing the greatest control over alloy compositions of all the melting processes. Mechanical roughdown pumps and ejector-type diffusion pumps reduce the pressure to the operating range. Steam ejectors have been used in the larger size furnaces; however, because of very low thermal efficiency of the steam ejector, the trend is back to the mechanical booster combination using high-speed blowers. Figure 69 shows a schematic of the VAR furnace, and Fig. 70 (from Ref. 19) shows a schematic of the VIM furnace.

5.4.2 Filament Winding Production

The general process used for manufacturing glass fiber (Fig. 71) is that of melting glass marbles, approximately 19 mm in diameter, or various forms of chipped glass, and drawing it through a platinum bushing. The marbles are electrically melted and stirred and then allowed to fall through 1- to 2-mm-diam orifices in the bushing. The emerging glass filaments are rapidly pulled away to draw the fibers down to about 6- to 15-μm diam. The platinum bushing contains several hundred holes, and the fibers are all drawn together. To obtain strong, continuous fibers, it is essential that the fiber surfaces do not touch anything, even another fiber. Therefore, prior to being drawn together, they are coated with a "sizing," usually a starch-oil emulsion or other special coating to ensure good bonding between the fiber and matrix. Immediately after the sizing and drawing of filaments, they are bundled together into a single compact unit without twist identified as a strand. Usually a strand consists of 51, 102, or 204 filaments bundled together in the forming operations. Continuous glass reinforcing is ordinarily supplied in the form of roving or yarn. The production of glass roving only requires the plying together of the desired number of untwisted strands. Within the glass fiber roving, each strand is called an end, with the more common roving being 20 or 60 end counts. Rovings are generally the lowest-cost reinforcement for filament winding. If twisted yarn is desired, the 204 filament strand is put through a twisting machine. The principal reason for the twisting of yarns is to prevent separating when tension is relaxed (Ref. 17).

The methods used in the manufacturing of composite materials from filament winding are essentially the same as the well-established techniques already applied to other areas of the fiber plastics industry. These methods include (1) compression molding, (2) vacuum bag/autoclave molding, (3) mandrel wrapping, (4) pultrusion, (5) filament winding, and (6) adhesive bonding. Of the many contributing factors to be considered in

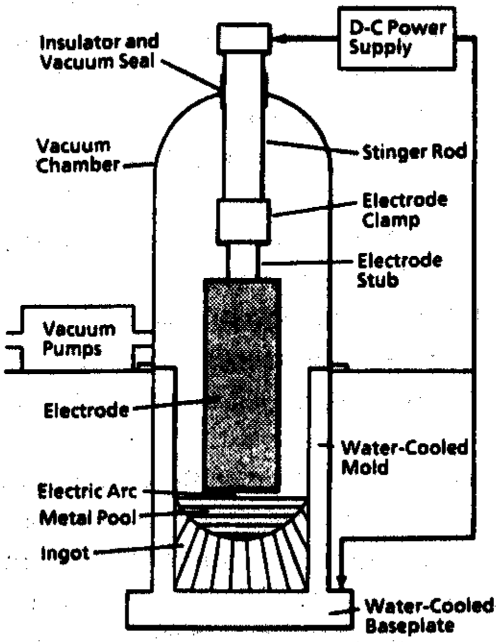


Figure 69. Schematic diagram of a typical vacuum arc remelting (VAR) furnace.

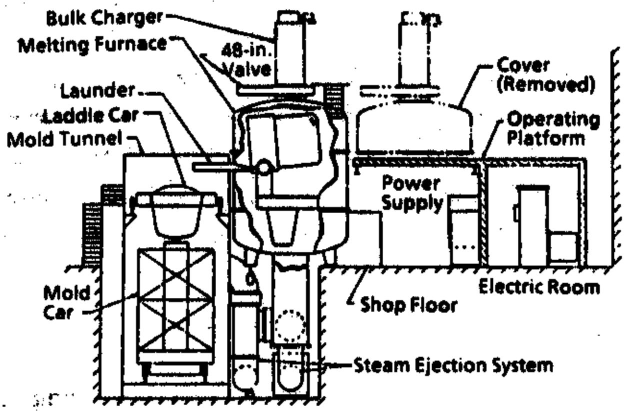
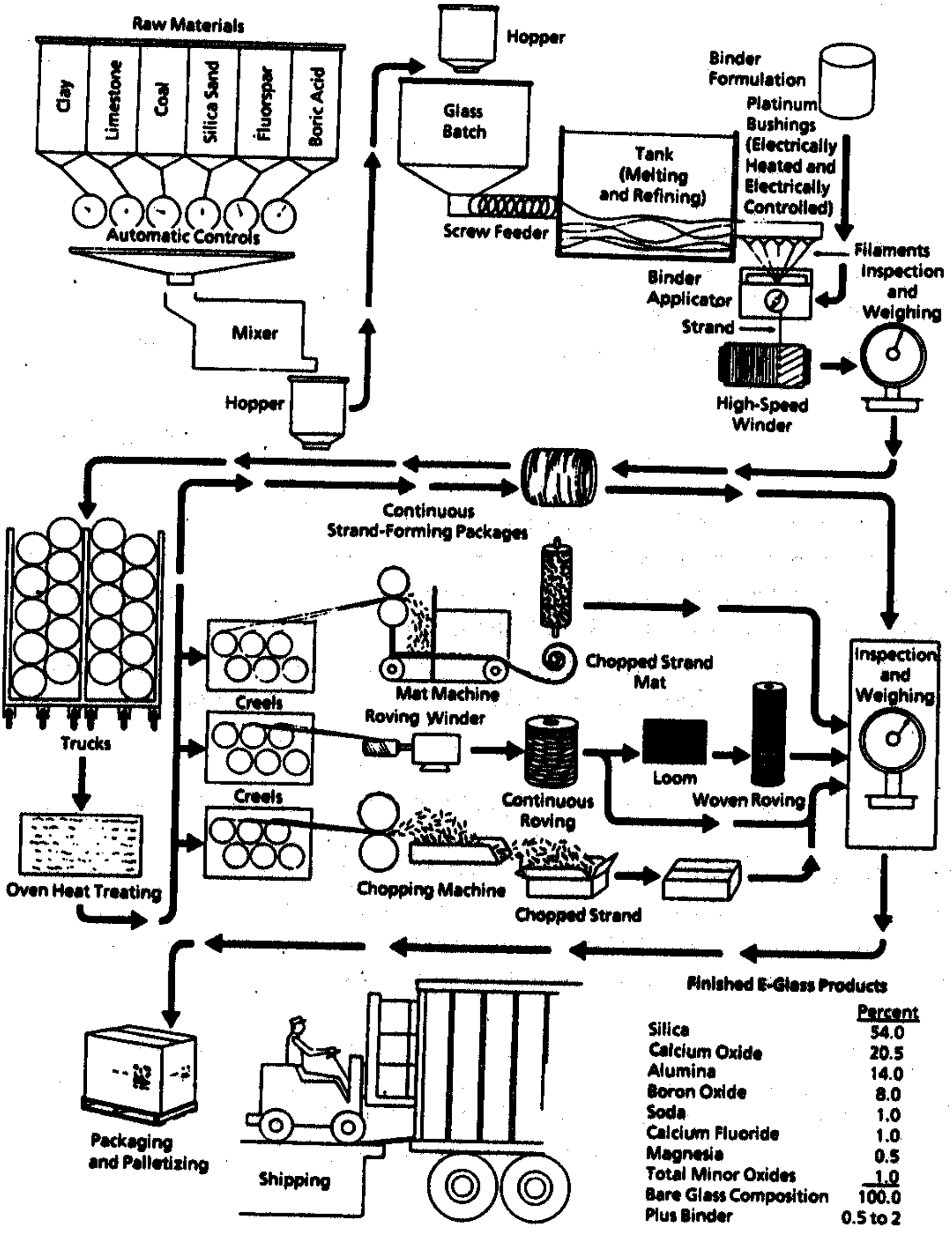


Figure 70. Schematic view of a 15-ton vacuum induction melting (VIM) furnace.



Finished E-Glass Products

	Percent
Silica	54.0
Calcium Oxide	20.5
Alumina	14.0
Boron Oxide	8.0
Soda	1.0
Calcium Fluoride	1.0
Magnesia	0.5
Total Minor Oxides	1.0
Bare Glass Composition	100.0
Plus Binder	0.5 to 2

Figure 71. Glass fiber production process.

the selection of any one or combination of methods for a given application, filament-wound structures are particularly adaptable in the production of SRM cases as well as many basic components of the LRE.

Filament winding is carried out on specially designed automatic machines. Precise control of the winding pattern and direction of the filaments are required for maximum strength, which can be achieved only with controlled machine operation.

Filament winding machines are designed to undertake a specific manufacturing operation and are classified mainly on the basis of their winding pattern—the principal ones being helical, circumferential, polar, and continuous circumferential machines (Fig. 72). In all cases the machine is designed to lay down onto a mandrel reinforcing fibers in a controlled pattern, although their mode of operation varies.

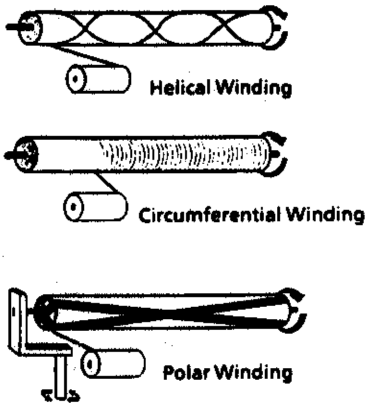


Figure 72. Basic patterns used in filament winding.

The winding machine consists essentially of a mandrel and a reinforcement feeding head. These components can be made to operate by either simple or relatively complex techniques. One of the more basic techniques simulates the operation of a lathe with the mandrel. The mandrel rotates, and the feeding head traverses back and forth along the length of the mandrel. In the lathe-type machine, helical winding patterns ranging from 5 to 85 deg can be accurately positioned. Circumferential windings can be included with the helical windings.

Winding is also accomplished in machines where the axis of the mandrel is in the vertical position. These planetary-type machines generally have the mandrels rotating at very slow speeds. This technique is preferred for the larger mandrels in order to eliminate or reduce its deflection. In operation, a rotating arm passes over the forward and aft poles of the mandrel while it rotates. For large units, filaments are fed through a series of rollers to produce desired wide tapes in order to lay down more glass during each rotation.

Machines are also being used with mandrels rotating in a tumbling motion. They basically rotate perpendicular to the main longitudinal axis with its longitudinal axis offset by an angle equal to the desired helical winding pattern to be used. These tumbling-type machines permit filaments to be placed very easily over the complete surface of the mandrel with an overall high accuracy of control.

Another technique employs a rotating mandrel traversing backwards and forwards while the feed head remains stationary. Other complex systems use the feed head moving circumferentially and longitudinally around a mandrel. In this latter case, the mandrel can also be rotating. Computer numerical control (N/C) equipment can be used with the winding machines to simplify and properly orient complex operations.

In developing extremely efficient structures, filaments are generally applied to a mandrel by one of two basic methods of winding. These are circumferential winding and helical winding. Circumferential winding does not involve complex techniques. The impregnated reinforcement, in either single or multiple strands, is laid down on a rotating mandrel at approximately a 90-deg angle with the axis of rotation. The movement of the carriage directing the reinforcement to the mandrel advances the material at a predetermined amount depending on the thickness of wrap desired.

Circumferential windings are capable of resisting hoop stresses only. In order to make parts that will also withstand longitudinal loading, it is necessary to place material in the longitudinal direction. In general, longitudinal winding material is laid down by machine operation techniques between layers of circumferential material. For applications where integral ends are required or where angles of more than 30 deg are to be wound, the helical method of winding is employed. This method is similar to the circumferential technique in that the mandrel rotates while an advancing feed places the reinforcement in the proper position. However, the feed advances at a much faster rate. Depending on the ratio of the mandrel speed to the feed rate, reinforcements are laid down at angles anywhere between 25 and 85 deg. By varying the angle of winding, any ratio of hoop to longitudinal fibers can be obtained.

Helical winding requires very precise control to distribute the material uniformly over the mandrel. The design for this type of a winding machine is much more complex than it is for a circumferential machine. This complexity is further extended when parts with changing cross sections are to be wound. However, only helical winding techniques can be used to produce this kind of part.

In order to obtain the ultimate strength properties from a filament-wound structure, it is desirable to have all the loads acting along the path of the reinforcement. In some instances, this can be accomplished readily, e.g., in parts in which there are only hoop loads. In other cases, such as in closed pressure vessels, this can be accomplished only by a proper design of the vessel itself. For this reason, the majority of wound pressure vessels are designed to have an end shape that is a modified ellipse. This shape not only loads the fibers properly but also can be converged by only one angle of winding rather than the several that are required for a hemispherical end shape.

Some winding techniques are employed in which the mandrel does not rotate. Systems can be set up whereby the feed moves around the mandrel. Other variations involve the mandrel rotating perpendicular to the polar axis. Basically, the circumferential winding machines can be built with minimum effort, whereas helical machines are more costly and require more technical knowledge. A number of machines specifically built for filament winding are not on the open market. The equipment can produce parts ranging from 3 to 35 ft in diameter and 6 to 90 ft in length, depending on their application. Predominantly, equipment ranges in diameter from 5 to 8 ft and in length from 10 to 40 ft. Laboratory filament-winding equipment is also available for research and development. The size of this type of equipment is in the range of 3 ft in diameter by 8 ft in length.

In certain applications, such as solid-propellant rocket motor cases, an inside thermal insulator on the filament-wound structure is desired. It is sometimes feasible and advantageous to apply this insulation material around the mandrel prior to the wrapping operation. In this way, the cure of the insulator as well as the filament structure can be accomplished at the same time. This type of cure cycle results in an integrated insulation with the case wall. The insulators can be made of homogeneous rubber-plastic sheet or reinforced plastics. The types of reinforced plastics include high resin-treated glass tape, phenolic-asbestos tapes, etc.

Integral case winding is a manufacturing process well worth the consideration of the designer of pressure vessels for SRMs. This process compresses the integration of the propellant grain, the insulating components, and end-closure details.

The disadvantages of this type of system are the hazardous nature of this winding operation plus the difficulty and hazard of curing the thermosetting resin after winding. However, it is generally considered that the winding operation is perhaps a safer procedure than the technique of machining solid-propellant grains. The winding operation suffers no particular disadvantage if isolated. Various resin systems are now available that permit curing of the filament-wound structure below the hazardous temperature (generally from 160° to 210°F).

The major advantage of this procedure is the ability to inspect the propellant casting prior to providing the unit with the necessary insulation and rocket motor case. At the present time, the propellant is cast into a completed case. This procedure requires elaborate inspection techniques and expensive methods to remove and recast any reject castings. With the integral case-winding method, only acceptable castings are completed by filament-winding the required rocket motor case.

Another advantage gained by this technique is the absence of internal strains in the propellant when it is cast into a fixed-size rocket motor case. With a fixed case, an adhesive is used to fix the propellant to the case to prevent the formation of a gap between the two. The inability of the propellant to shrink or reduce in size during casting sets up internal strains in the propellant. These strains, when augmented by the strains caused by the differential thermal response, have often proved catastrophic. With an integral system, the casting shrinkage has occurred before the case is filament wound over the cast propellant. In addition, the filament-wound system can be fabricated to shrink on the propellant and thus minimize the differential strain between the propellant and the rocket motor case at low service temperatures.

Filament winding uses one of two basic methods for pretreating or impregnating the filament with resin. The first, commonly referred to as the "wet" system, involves the impregnation of the filaments with liquid resin prior to winding around the mandrel. A second method uses preimpregnated (wet or dry) filaments that have been wetted and dried with partially cured resin.

In the past, the wet system was used almost exclusively. At present, the major usage is the preimpregnated system. The trend for the future is that the preimpregnated system will be used exclusively as major production programs are developed.

As the term implies, the wet method applies a liquid resin to the filament before winding, while still wet, around the mandrel. Selection of the resin is limited to resins that are adaptable to liquid application, that is, epoxies and polyesters. In addition to creating an untidy working environment on and around the winding machine, the low rate of speed at which the filaments can be impregnated with liquid resin is a drawback. The filaments may only be wound around the mandrel as fast as they can be thoroughly penetrated with the resin. The wet winding method is dependent upon low viscosity resins and thereby eliminates the use of many resins. The main advantage of the wet system is economy, being less costly than the preimpregnated system of the same resin and filament.

The preimpregnated dry system is suitable for a number of resins that do not readily lend themselves to direct application in liquid form. These are the resins that are normally solid or thick, and that require the addition of a diluent to thin them for practical use. The removal of these diluents requires gentle heat and large volumes of dry air, which cannot easily be included in the winding operation, but which can be accomplished when preimpregnating the filaments in a tower operation. This preimpregnated or "dry" system can be used with resins that are essentially the same as (or very similar to) those resins commonly referred to as "wet" resins.

In addition to the higher cost of the impregnated supply stock, the preimpregnated dry system requires more expensive tooling and winding machinery. For example, to afford a degree of plasticity to the resin sheath, the filament should be heated between the supply spool and workpiece. In addition, the mandrel should be heated or warmed throughout the winding operation to further assure wetting of the applied filament by the resin matrix through gentle migration of the softened resin into areas immediately adjacent.

The primary advantage in the use of a "dry" or "wet" preimpregnated system is not related to physical performance, but to the rate of application, which is limited only by the performance of machinery at reasonable velocities. As part of the filament-winding process, the design of the mandrel is dependent upon the type of resin system being used, the wet or the preimpregnated dry system. The primary difference is the need to heat the mandrel during the winding with a dry system. This is not the case with the wet system. In addition, any mandrel must sustain the working loads incident to winding, maintain a reasonable dimensional integrity throughout its operational life, withstand curing temperatures without degradation, and be subsequently removable.

Materials used in mandrels for the wet resin systems are eutectic salt soluble plaster, and eutectic metal. The eutectic salt is melted by heating and slush-cast to provide a shell. Removal is by dissolving with hot water and agitation. The plaster is cast to provide a shell predried before use. It is mostly dissolvable with water, usually coming out as a milky liquid with chunks of undissolved plaster. The eutectic metal is heated to melt and slush-cast or skin-chilled to provide a hollow shell. It is removable with live steam. Vessels with small openings require final X-ray to detect unmelted inclusion still clinging to the inner wall.

The dry system, for which the mandrel must be heated during winding, generally needs some sort of heating element imbedded in the mandrel. This element may be either tubes for steam, superheated oil, etc., requiring swivel joints for entering and exhausting fluids from the revolving mandrel, or electrical-resistance heating parts, requiring commutator-type slip rings to provide an electrical connection to the revolving mandrel. They are all potentially troublesome. The expense of the revolving heat-energy connection itself can be minimized by integrating this joint with the winding machine design.

Dry system mandrels have been made using eutectic metals, soluble plaster, and cast aluminum. Using an eutectic metal, flexible, insulated wires are tied in place in the casting mold, after which the liquid metal is cast to form a shell including the wires. Flexible tubes or metallic hose can also be used. Either medium must, of course, be sufficiently flexible to allow removal after the mandrel shell has been melted out. In soluble plaster mandrels, heating members are treated in the same manner as the eutectic metals. Care must be taken to avoid large temperature gradients between heating elements and the plaster matrix, which will cause thermal-stress cracking and spalling. Using cast aluminum if it is geometrically possible, half-shells are cast form nearly pure aluminum, for example, 1100. Heating members are cast integrally but with the provision to bridge the parting line. Half-shells are thereafter put together to provide a hollow mandrel. Following cure, the aluminum is simply eaten away with a caustic solution. In order to protect the laminate, a barrier, such as rubber, is required on the outer surface of the mandrel. This method gives excellent heat transfer and is structurally sound throughout the life cycle. It is, however, costly and has a very high coefficient of thermal expansion, according to the authors of Ref. 20.

5.4.3 Machine Tools

The acquisition of, or the indigenous capability to provide a manufacturing base for the production of a missile system is a function of several basic controlling factors, i.e., national priority, cost, labor force, production rate, current manufacturing capacity, export restrictions, and current world technology. Given the national priority, the capability is only time-dependent. Machine tool requirements can best be presented by identifying the manufacturing processes. The machine tools listed under each process are not all required, but are intended to show alternates that are capable of performing the process.

Drilling, Reaming, and Related Operations. The process of producing circular holes is one of the oldest and most widely used manufacturing processes and includes drilling, reaming, counterboring, and punching. Holes serve a wide variety of needs, including mechanical connections, reduction of part weight, penetration ports through a surface, flow passages for fluids (coolants, fuels, etc.), and maintenance of proper alignment of parts, etc. In addition to drilling operations, drilling machines perform operations such as facing, counterboring, chambering, countersinking, tapping, and reaming. Drilling machines may be classified by the following general types: sensitive, upright or vertical, radial, gang, multiple-spindle, automatic, horizontal, and deep-hole (gundrilling and gunboring) drilling machines.

Gundrills are of particular importance in the drilling of long, deep holes. Length of holes that can be drilled by gundrills range from less than two to more than 125 times the drill-tool diameter. Special hole-pattern configurations such as intersecting, crossing, and overlapping holes, as well as drilling of stacked parts, can be drilled effectively. Almost any material can be economically drilled from wood and plastic to titanium and Inconel.

Turning and Boring. Turning is a machining process for generating external cylindrical forms by removing metal, usually with a single-point cutting tool. Boring is essentially internal turning, normally using a single-point cutting tool, forming internal shapes. Most machines capable of turning operations will also perform boring operations. Turning machines include engine lathes, horizontal turret lathes, single-spindle automatic lathes, single-spindle automatic screw machines, Swiss-type automatic screw machines, and multiple-spindle automatic bar and chucking machines.

The engine lathe is the general all-purpose machine tool of the metal-fabricating industry. Arbitrary classifications by size, function, and degree of precision mark the distinction between engine lathes with the regular engine lathe being the general-purpose shop machine. The gap-lathe is basically an engine lathe with the provision for turning large-diameter work.

The horizontal turret lathe differs from the engine lathe by the mounting of a square turret on the cross slide (in place of the compound rest of the engine lathe), and a multisided turret takes the place of the engine lathe tailstock. Even though the selection of a turret-lathe operation (versus other types of operations) is usually based upon lot sizes (normally from 10 to 500 pieces) and complexity of operation, economic considerations may be outweighed by national priority.

The single-spindle automatic lathe is designed to meet the demands of mass production requiring primarily turning and facing operations. The single-spindle automatic screw machine is designed to produce finished parts from bar stock at high production rates and has many tooling and operating principles similar to the horizontal turret lathe, single-spindle automatic lathe, and multiple-spindle automatic bar and chucking machine.

The Swiss-type automatic screw machine was born out of the watch industry and is completely cam-controlled. Although this method is old, it is proven and assures repeatability and reliability. This machine is particularly useful for producing long, slender parts.

The principal advantage of the multiple-spindle automatic bar and chucking machine over the single-spindle machine is the reduction of time required per piece. The multiple-spindle machine is capable of having all turret faces working on all spindles at the same time.

Boring machines are machine tools for heavy production, i.e., heavy cuts beginning with average 3-in.-diam finished-size holes. Machines used in heavy boring are horizontal boring, drilling, and milling machines; traveling-head or bar-type horizontal boring machines; engine lathes; vertical turret lathes and horizontal boring mills; and large radial drills.

Milling, Planing, Shaping, and Slotting. The process of machining flat and contoured surfaces on a workpiece may be accomplished by the use of planers and shapers. This equipment uses a single-point cutting tool. Several types of planers have been available to meet the needs of industry that use two cross rail heads with a side head on one or both sides. However, because of the technical advances in the cutting tool blades and materials, the single-point tool has been replaced by the multitoothed rotary milling cutter. The planers and shapers, because of the cutting tool, were a relatively slow operation. Milling machines, capable of performing the same operations previously done by planers and shapers at a faster rate, begin to replace the slower machines approximately 20 to 30 yr ago. It is conceivable that the older technology machines have found their way to less technologically advanced countries.

Milling machines are available in many sizes and power capacities and are broadly classed as either standard or special. Milling machines in the standard classification are further classified according to structure, these being the knee-and-column-type or the bed-type milling machine. The former type permits greater flexibility or versatility of operation, whereas the latter is potentially more rigid. Special milling machines are basically the standard machine that is modified resulting in approximately 50 percent or more change in the basic standard design. A very desirable feature that may be included is a tracer-controlled capability whereby a complex part requiring shaping and contouring may be produced by tracing a model or master. The model or master may be obtained from a disassembled system.

Sawing and Filing. Sawing is a universal method of cutting short lengths from long stock bars or rods. All machinable metals are capable of being cut by power hacksawing, horizontal or vertical high-speed bandsawing, and circular sawing. Filing is a method of machining or smoothing surfaces from which only a minimum amount of material is to be removed. The common techniques of filing are band filing and rotary filing or burring. Grinding or abrasive machining is the process of material removal in the form of small chips by the mechanical action of abrasive particles that are used loose, in bonded wheels or stones, or on coated belts. Grinding is considered a precision finishing process, whereas abrasive machining usually connotes heavier stock-removal applications. Of particular interest to the missile industry are cylindrical surface and internal grinders, form grinders, and jig grinders.

Hot-Working Process. The hot-working process is that manufacturing procedure in which a metal is plastically deformed under the influence of an applied external force to produce a change in shape by working the metal above the recrystallization temperature. In many cases, hot-working is the only means by which certain "brittle" metals can be worked. The hot-working process includes hot-rolling, forging, extrusion and hot-spinning, and shear-forming.

Hot-rolling consists of passing a hot material between two rolls that are driven to rotate in opposite directions, reducing the thickness equal to the gap between the rolls. The products produced in this process are flat sections such as sheets, plates, and hot-rolled strips and formed sections such as rails, bars (flat and round), structural shapes, and other more complex configurations. There are three principal-type rolling mills: two-high, three-high, and four-high mills.

Forging is the controlled deformation or working of metals into useful shapes by means of pressure, impact blows, or a combination of both. Forging refines the structure of the material with the following advantages:

1. A completely integral part is produced eliminating stress concentration points, and a more uniform heat-treatment response can be achieved.
2. Forging eliminates voids in the material that may have occurred during casting and provides a more uniform chemistry and finer grain size.
3. Forged material possesses the full density that sintered-powder parts lack and can be provided in larger sizes.
4. When compared with most other product processes, the maximum strength potential of the material is developed, notch effects are avoided, and impact and fatigue strength is improved.

Most forgings are produced in closed dies by forging hammers (gravity, double-acting, and counterblow), forging presses (mechanical and hydraulic), and horizontal forging machines, often called upsetters or hot-heading machines.

Extrusion is the process of forcing a material, at an elevated temperature, through a die or set of dies and may be classified into two main groups, direct and indirect extrusion. The direct process consists of forcing the entire hot billet, by a ram, through the dies. The extrusion exits in the same forward direction as the ram. The indirect process requires the hot billet to remain stationary while the die is pushed into the billet by a hollow ram, and the extrusion exits in a direction opposite to the direction of the ram. The equipment used in this process is of two large categories, self-contained presses and accumulator-type presses. Typical products of the extrusion process are seamless pipe, tubing, and structural shapes. Most of the aerospace and missile industry materials can be extruded, including aluminum, steel, stainless steel, titanium, tungsten, molybdenum, and reinforced fiber materials.

Metal spinning is a point-deformation process in which one or more rollers move along a rotating mandrel and metal blank (part being formed) in the axial direction, thus forming axisymmetrical curvilinear shapes by rotation. This spinning process (Fig. 73) is classified into two basic types, conventional spinning and shear forming.

Some metals and alloys exhibit low ductility at room temperatures, i.e. tungsten and beryllium, and must be spun at elevated temperatures, whereas other metals and materials can be spun at ambient temperatures (cold spinning). The basic equipment and process are essentially the same as those required for cold-spinning operations. Hot spinning is accomplished by injecting heat from an external heat source such as a gas torch or radiant-heat source into the mandrel and metal blank. Typical materials requiring the hot-working process are as follows:

2024-T3
PH15-7Mo
AM-350
A286
René 41
L-605
TI-8-1-1
TI-13-11-3
TZM Mo
Cb-752
Tungsten
Beryllium
Vascojet 1000
USS 12 MoV
Columbium (10Mo-10Ti)
Molybdenum (0.5 Ti)

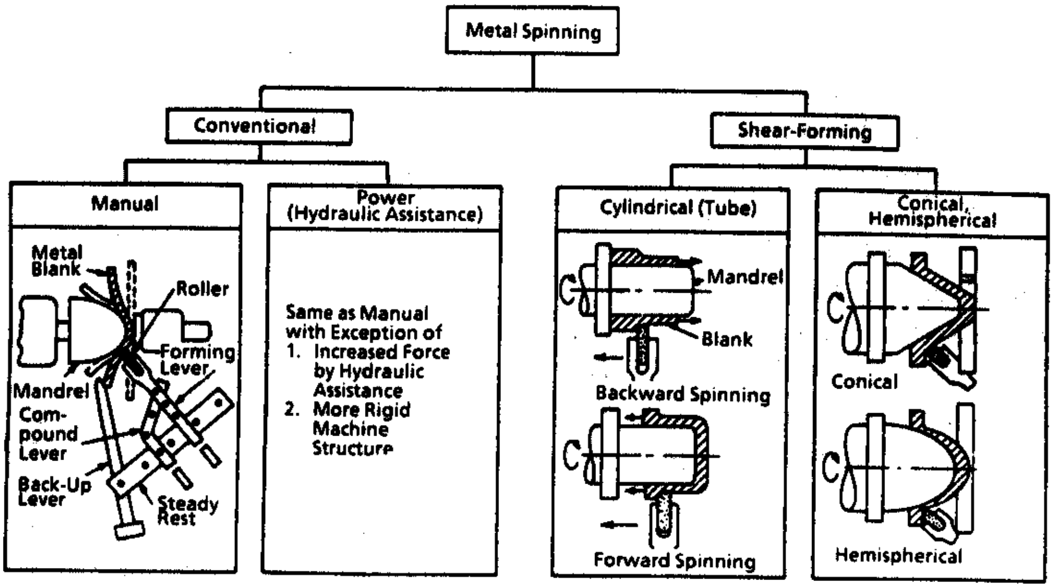


Figure 73. Metal spinning processes.

Conventional spinning is essentially a "semi-art" depending in a large part upon the skill of the operator. The basic machine used for the process is an engine lathe and, with the addition of hydraulic power, permits the forming of thicker, higher-strength materials. Conventional spinning may be used to produce pressure-tank heads, containers for electronic components, and other aerospace shapes. The deep-drawing process is an alternative to metal spinning.

Shear-forming, sometimes known as shear-spinning, floturning or flow-turning, roll forming, hydrospinning, roll extension, or power spinning, is a rotary point-extrusion process with high-shear stresses in the short transverse (thickness) direction, which results in significant reductions in thickness (up to 85 percent). The radial position of each element in the blank does not change during the forming operation.

The shear-forming process is ideal for manufacturing conical parts and cylindrical shapes. Hemispherical, elliptical, and other nonconical-shaped parts can be produced with a uniform wall thickness; however, a rather elaborate preform operation is required.

Two problems that are present in the hot shear-forming process are (1) the cooling action of mandrels and tools, and (2) the adverse effect of heat on the lubricants. A commonly used method of heating the blanks is to heat the blank locally by gas-torch flames directly ahead of the roller. For hot shear-forming cylinders, an induction coil can be used to heat the band of material directly ahead of the roller. Radiant tube heaters, and reflective burners are occasionally used. Lubricants employed depend upon the forming temperature and, are in general, the solid-film-type such as graphite, molybdenum disulfide, and mica suspended in a suitable viscous vehicle. Mandrels for hot shear-forming are cast A11 tool steel.

The manufacture of cylindrical rocket-motor cases, motor case heads, and nozzles is one of the most successful production applications of hot shear-forming. Machine specifications of three major manufacturers are listed in Table 28. Special equipment capable of shear-forming cylinders in 10-ft-diam and more than 15-ft lengths is available. The sequence of flow-turning a one-piece SRM case is shown in Fig. 74.

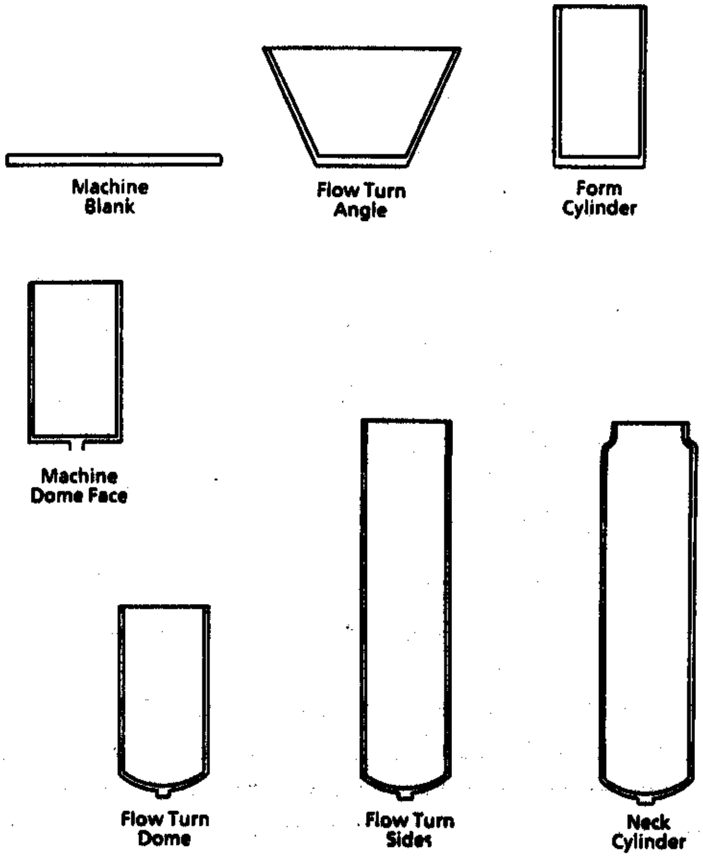


Figure 74. Flow-turning process for one-piece case.

Table 28. Typical Available Spinning and Shear-Forming Machine Size

Part Diam, in.	Part Length, in.	Spindle, hp	Forces			Production Machine		Number of Rolls
			Roller, lb	Carriage, lb	Tailstock, lb	Rate, piece/hr	Weight, lb	
12	15	15	4,000	5,000	2,000	75 to 100	8,750	1 Horizontal
12	15	40	14,000	12,000	3,000	90 to 125	26,000	2 Vertical
24	30	75	32,000	54,000	8,000	30 to 80	52,000	2 Vertical
40	50	20	15,000	—	7,500	8 to 30	41,000	1 Horizontal
60	70	90	40,000	—	15,000	1 to 15	100,000	1 Horizontal
70	84	150	70,000	70,000	35,000	1 to 15	195,000	2 Horizontal
42	50	20	50,000	50,000	35,000	—	53,970	1 Horizontal
42	50	20	50,000	50,000	35,000	—	78,970	2 Horizontal
62	50	20	50,000	50,000	35,000	—	145,500	2 Horizontal
70	72	30	70,000	70,000	50,000	—	235,000	2 Vertical
60	60	200	225,000	225,000	200,000	—	—	2 Vertical
60	120	200	225,000	225,000	200,000	—	425,000	2 Vertical

Heat Treatment. Heat treatment is that process whereby metals are better adapted to desired conditions or properties by means of controlled heating and cooling in their solid state without alteration of their chemical properties. There are several factors to be considered in the selection or use of the heat-treatment process and equipment. In addition to the desired properties required in the fabrication process (i.e., ductility, machinability, formability, bending quality, etc.), the necessary properties of the finished parts must be considered (i.e., improved tensile strength, toughness, wear resistance, corrosion resistance, magnetic properties, etc.). The size and shape, type of steel and materials used, the quantity of pieces, surface finish, and production rate also affect the selection of equipment in the heat-treatment process. Methods employed in the heating processes are atmospheric furnace heating, induction heating, vacuum heating, flame heating, and salt-and-metal-bath heating.

Atmospheric heat-treating furnaces are either the batch furnace, used for small lots or complex alloy grades, and the continuous furnace used for straight-line or flow-through process. The most common material for furnace construction is firebrick. Furnaces may be either gas-fired or electrically heated. Electrically heated furnaces may use either metallic, commonly 80-percent nickel and 20-percent chromium wire or rod, or nonmetallic, commonly bonded silicon carbide-resistor elements.

Induction heating is accomplished by flowing a high-frequency alternating electric current through an inductor or heating element. The three basic types of equipment for induction hardening are the motor generator, the vacuum-tube, and the spark-gap types.

Vacuum heat treating is the process of heat-treating a material in a chamber at pressures much below room pressure or near-vacuum condition to avoid contamination of the material. Some of the materials using the vacuum heat-treating process are M2 and M11 tool steel, 310, 347, 321, 410, and 440-C stainless steels, titanium and titanium alloys, beryllium, tantalum, columbium, and Zircoloy. This is a batch process.

Flame heating is a practical method of developing general or local surface hardness and may include equipment as simple as a single torch or a more elaborate apparatus that automatically indexes, heats, and quenches parts. This process of surface hardening is most suitable for short production runs with its greatest potential being surface treatment of massive parts, which are beyond the capacity of induction-hardening equipment. Typical fuels include acetylene, city gas, hydrogen, natural gas, and propane.

The salt-bath furnace is basically a ceramic or metal container filled with molten salt in which the work is submerged. The molten bath consists of one or more salts such as nitrates, chlorides, carbonates, cyanides, and caustic soda, heated either electrically or by gas. Temperature control is accurate and automatic, with no auxiliary equipment to regulate.

Unskilled labor with minimum supervision is capable of handling thousands of pounds of work per hour. Limitations of this process are that it is not suited for intermittent operations; buoyant parts are difficult to handle; blank cavities with trapped air or salts are a problem; work must be thoroughly dry before immersion; and bright surfaces cannot be maintained.

Nondestructive Testing and Inspection. Nondestructive testing (NDT) is essential in the manufacturing of missiles to detect internal or surface flaws, measure and ensure uniform thickness, and determine material structure or composition. The basic tools and equipment of NDT have been radiography (X-rays and gamma rays), ultrasonics, dye penetrants, magnetic particles, eddy currents, and electromagnetics. More recent methods exhibiting NDT potential include neutron radiography, color radiography, flash radiography, microwaves, ultrasonic imaging, lasers, holography, liquid or cholesteric crystals, and infrared-thermal.

Radiography uses X-rays and gamma-rays to penetrate the material(s) to be inspected with the resulting shadow pattern being recorded on photographic film or fluoroscopic screens. The equipment consists of radioisotopes or X-ray generators and recording devices. This method is particularly important to detect cracks, incomplete bonding, cavities and voids, etc., in the SRM grain and case. Supporting equipment is required to lift, handle, and move the article being inspected as well as jigs and fixtures to hold, position, and/or rotate the article during the inspection. Table 29 lists the radioactive isotope source and type of emission.

Table 29. Nondestructive Testing Radioactive Source Characteristics

Radioactive Source	Type of Emission and Energy, MeV	Half-Life, years*
Cobalt 60	Gamma 1.33 and 1.17	5.25
Cesium 137	Gamma 0.66	33
Radium 226	Gamma 0.188	1,620
Promethium 147	Beta 0.30	2.25
Strontium 90	Beta 0.54	25
Krypton 85	Beta 0.72	9.4
Americium 241	Alpha 5.4	475
Polonium 210	Alpha 5.3	0.3

*The Half-Life Is the Time Required for Emission to Decay to One-Half Its Original Value.

The ultrasonic testing technique uses mechanical vibrations of very high frequencies, generated in the form of well-defined beams of small cross section, to detect and locate hidden flaws, measure thickness, and determine the dynamic elastic module of the test object. NDT uses very low amplitude vibrations that do not permanently affect the specimen, whereas very high amplitude vibrations are used for fatigue testing. There are two basic methods or equipment types in general use, classified as pulse-echo and resonance. The ultrasonic beam is produced by a transducer that converts the electrical voltages generated in the equipment oscillator and are introduced into the test specimen.

The dye penetrant NDT involves the application of a penetrant to the surface being tested and removing the excess. A developer is then applied that draws back the penetrant that has concentrated in discontinuities of the specimen. The developer, in action with the penetrant, colors or stains the surface at the flaw providing a visual indication of the discontinuity. Prior to penetrant testing, the specimen must be cleaned of all foreign deposits. Degreasing, sandblasting, and alkaline cleaning may be used, depending upon the physical and chemical properties of the specimen. The penetrants used may be either visible dye or a fluorescent type.

The magnetic particle process involves the application of a low-voltage, high-amperage electric current through or around (by means of a coil) the tested part, thereby creating a magnetic field in the specimen. Finely divided magnetic particles are then dusted on the part, resulting in a disrupted pattern in the filings in the area of surface discontinuities. After the article has been magnetically inspected, the work normally has to be cleaned and demagnitized by subjecting the piece to an a-c field and slowly removing it from the field.

Numerical and Computer Controls. Automated machine control is beneficial for production operations because component parts can be fabricated more uniformally and with less waste than with manually controlled machines. Although the automated tools are not an absolute requirement for SRBM production, a Third World country would attempt to procure numerical and computer-controlled machines.

Various machine-tool controls have been designed to increase productivity and reduce or eliminate the human factor. Modifications to existing equipment and machines or the procurement of new or replacement machines would place a high priority on machines with control systems. Some of the process control systems currently available include feedback gaging, numerical, computer, and adaptive controls.

The adaptive control system automatically and continuously monitors the online performance, compares this information with pre-established limits, and modifies the process by automatically adjusting the machine operations. This type of control system is effectively used on milling machines, multispindle profilers, and lathes. Another type of automatic control method is copying or tracing in which a profiled template or master controls the cutting tool motions. This is effectively used on special-purpose machines such as cam-operated lathes and bar and chucking machines.

Another control system involves the use of gages. Impulses from the gaging equipment are amplified and fed back to an indicator and a controller that adjusts the machine operation. Grinding machines use the automatic feedback gaging system effectively.

Computers have been used effectively in control systems in the manufacturing process. Computer-aided design (CAD) is being widely used to increase creativity and reduce product-development cost and time. Using mathematical models, and with controls added by designers, numerical control (N/C) tapes can be produced to control machine tool operations. Computer-aided manufacturing systems integrate the basic functions of manufacturing — design, production, and management. An integrated CAD/CAM system is required to assure a successful product. This control system is most likely at least a decade away for Third World countries.

In any machine-tool manufacturing process, the common practice is to pre-establish only a general description of the machine operation sequence. This requires the machine operator to do the detailed operation planning regarding the type of setup and work-holding devices to be employed, the cutting-tool configuration, and the operating feeds and speeds. These often depend upon the operator's skill and experience together with his knowledge of the workpiece requirements and the capabilities of the machine and cutting tools. The N/C system provides a machine tape that transfers a substantial amount of the planning from the operator. This system provides a permanent record, through tapes, that can be used for repeated runs. The three major elements of an N/C system, input media, information processing, and servo-loop, are shown in Fig. 75.

5.4.4 Conversion of Existing Facilities

Conversion and upgrading of existing facilities for the various manufacturing processes within the missile industry will range from minor or minimal adaptation of facilities (i.e. storage of components, materials, and subassemblies), rearrangement or expansion of existing capabilities (i.e. fertilizer plants and ammunition factories), to new construction of production plants. Existing petrochemical facilities are capable of producing low-tech asphaltic fuels and fuel binders without major modifications. These products are packaged and shipped to the propellant plants, usually in 55-gal containers.

5.4.5 Assembly

The short-range ballistic missile is designed to be assembled in the field (or at the flight test station). Each stage would be shipped in a shipping container designed to minimize shipping damage. Each missile would be assembled from four packages, (1) first stage, (2) second stage, (3) guidance package, and (4) payload.

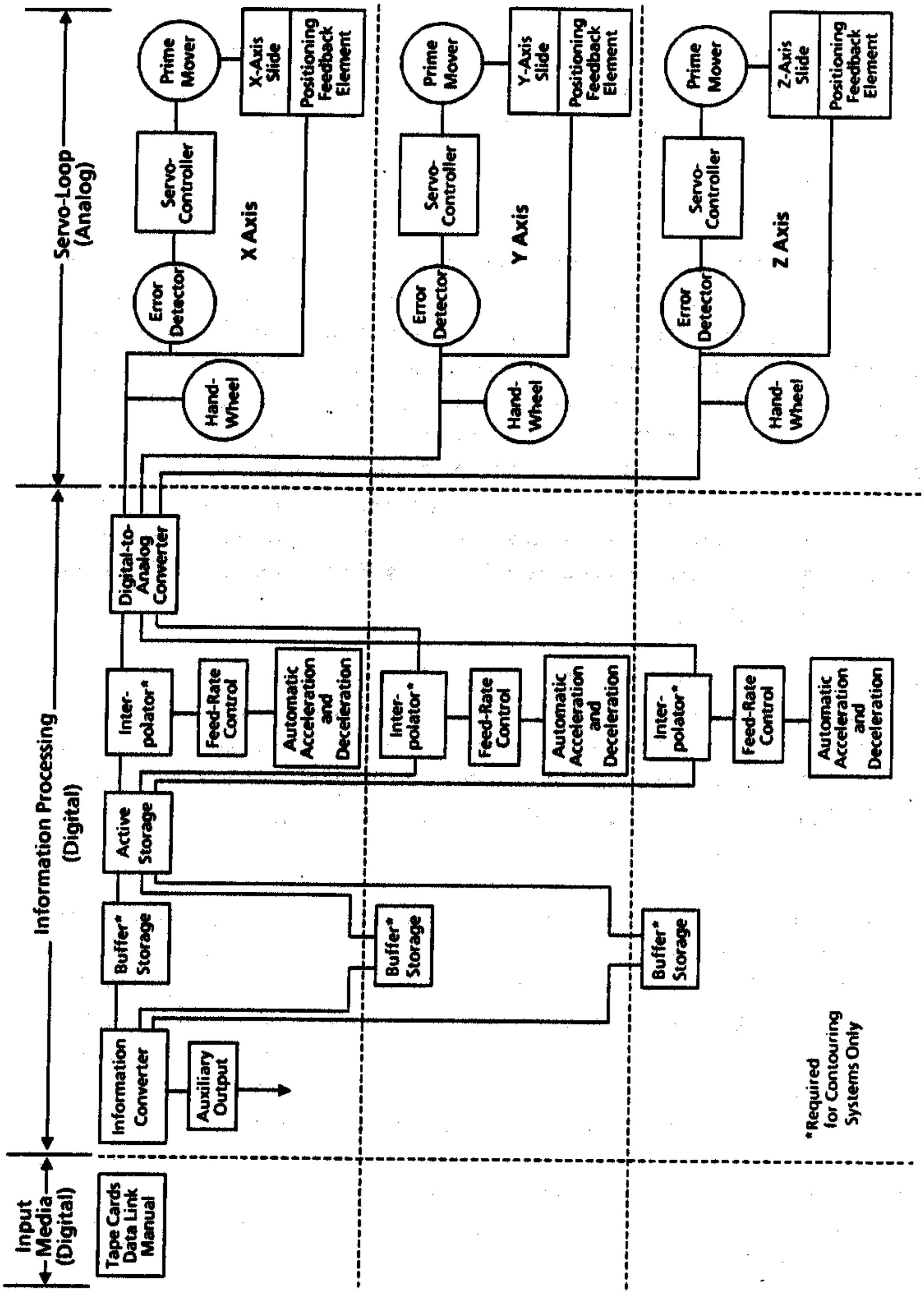


Figure 75. Basic numerical control system elements.

5.4.6 Quantities

A Third World country serious about developing an SRBM would have large serial production numbers in mind. Total production would probably be in the range of 500 to 2,000, with a production rate starting at one per day and building to three per day.

5.4.7 Transportation

An important criteria of a successful tactical missile system is the timely delivery of the missile from a storage depot to the launch area. Depending upon the military strategy, the greatest tactical advantage would be gained from a mobile infrastructure capable of evading detection and providing a larger selection of target areas for a given missile range. Whether a fixed or mobile launch system is used, transportation is a key element. This includes all the ground-handling activities from the manufacturing plant, to storage depot, to delivery in the general deployment area. (Launch area deployment is addressed later in this report.) Although air transportation is a possible alternate to ground transportation, to remain within the objective and scope of this report, only ground delivery will be discussed. The logistical process for air transportation would contain essentially the same equipment except for the obvious aircraft requirement.

Ground-handling, storage, and transportation procedures are established for safety to personnel and surrounding facilities and for the reduction of shock loads to the missile components. Special equipment may be necessary in the onloading, offloading, and transportation of liquid fuels because of the toxicity and unstable sensitivity of many propellants and oxidizers. The following is a list of equipment used in the transportation and ground-handling of missiles:

Ground Transporter. Solid-propellant rocket motors require an environmental control unit to maintain temperatures within a 40° to 100°F range. They can be transported in a commercial-type semi-trailer as shown in Fig. 76. Liquid-propellant rocket engines may be transported on heavy-duty flatbed trucks and normally do not require environmental control. Under pressing conditions, extendible pole- or beam-type trailers may be used. During ground transit, it is desirable to maintain a shock loading of less than 5 g, and for that and safety reasons in the U.S., highway speed is limited to approximately 45 mph.

Engine/Motor Dolly. Wheeled carts shown in Figs. 77a and b are used for on- and off-loading of rocket motors and short distance (in-plant) hauling. The nominal turning radius of the first-stage dolly in Fig. 77a is approximately 34 ft, and the turning radius of the dolly in Fig. 77b is approximately 16 ft.

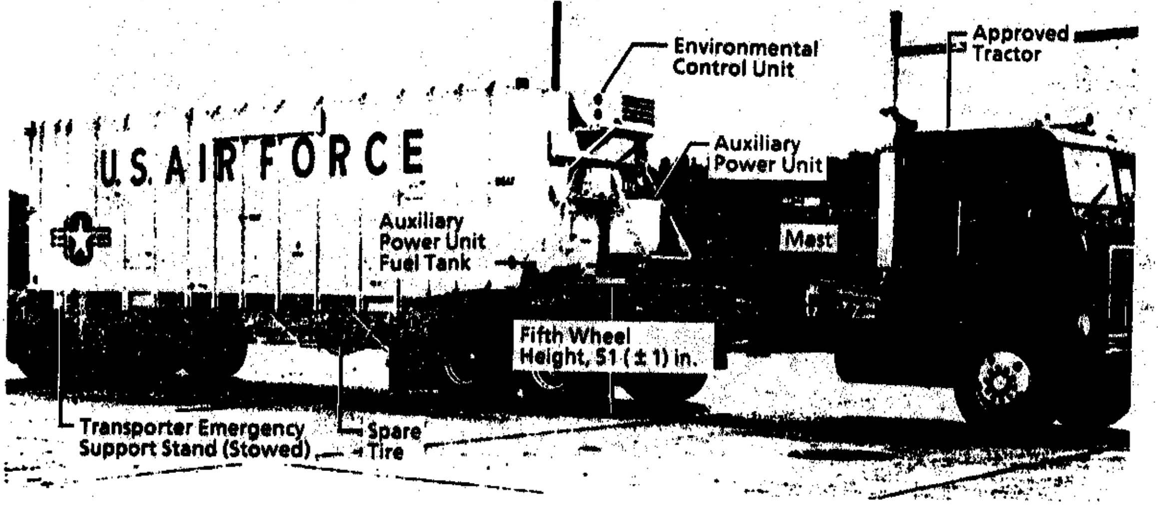
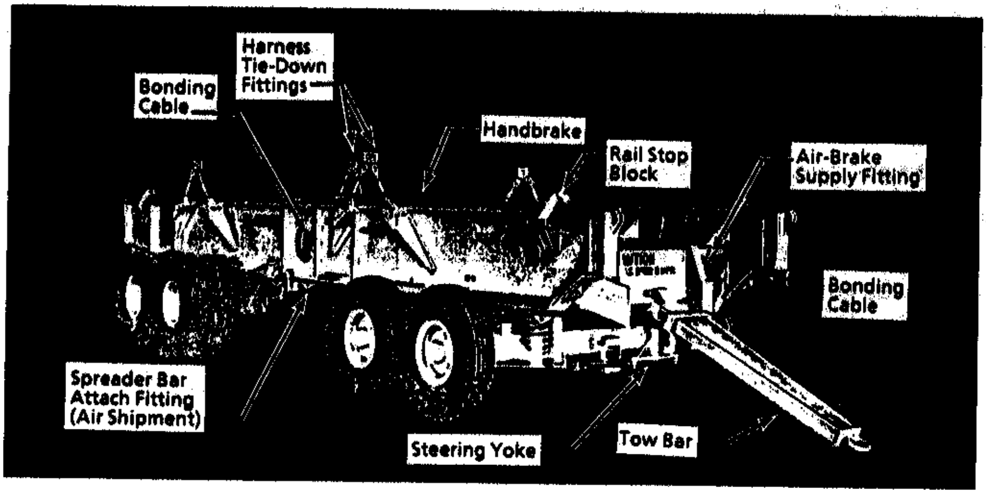
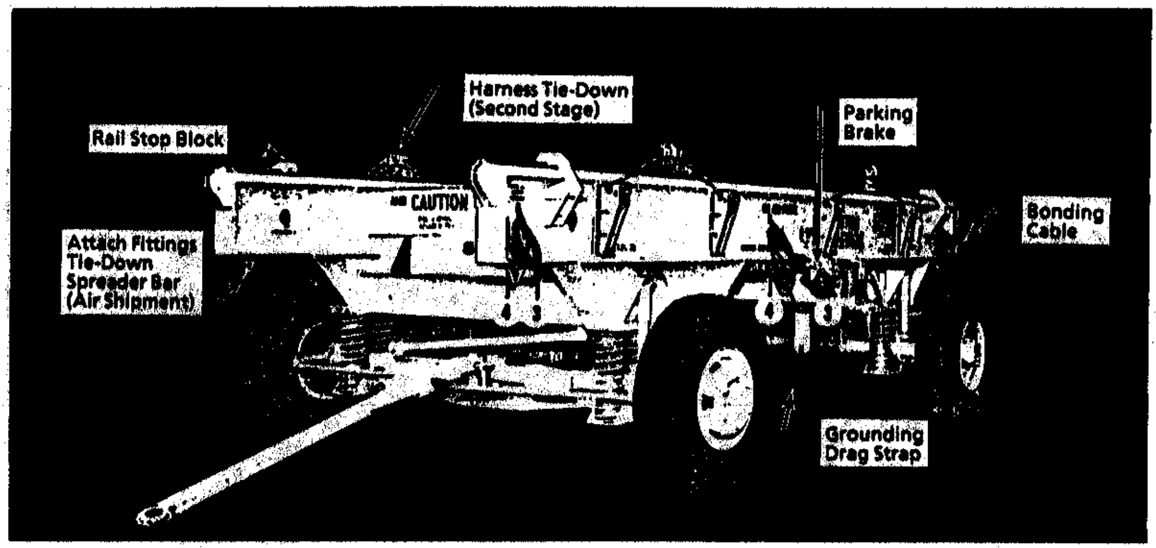


Figure 76. Transporter van.



a. First stage

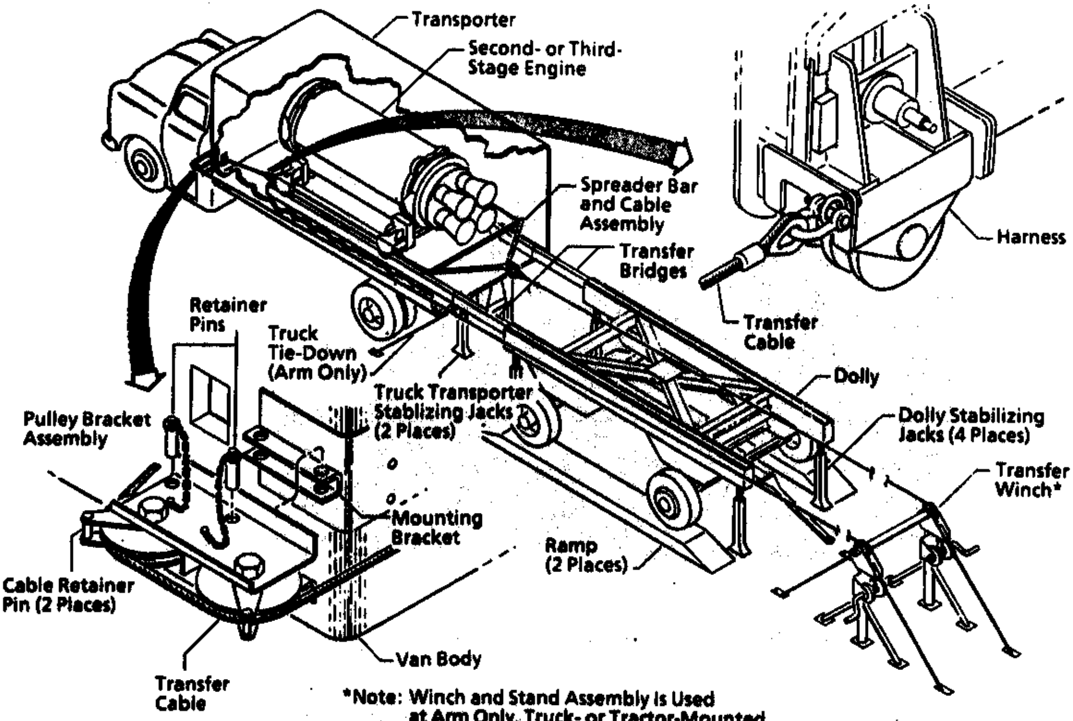
Figure 77. Rocket handling dolly.



b. Second stage
Figure 77. Concluded.

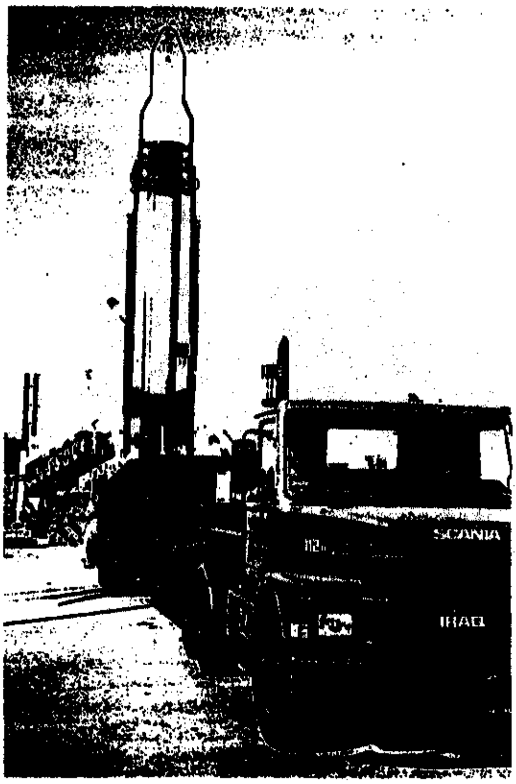
Truck or tractor-mounted power winches as shown in Fig. 78 are used to transfer from the dollys into a truck. Hand-winches and manual labor may be substituted under certain conditions. Fabricated structures called transfer bridges provide smooth transition between the dolly and the transporter.

Transporter-Erector-Launcher (TEL). The TEL is a specially adapted transporter designed for ground transportation of the missile with hydraulic or pneumatic pistons for the elevation of the missile to the firing attitude. It also serves as the launching base. Several TELs are shown in Figs. 79a, b, and c.



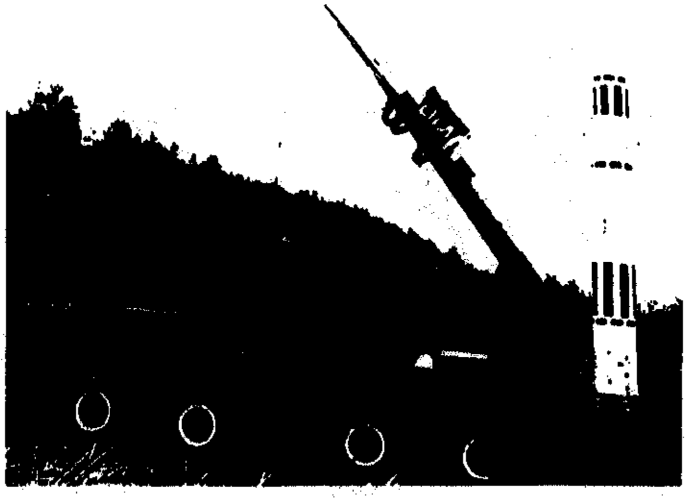
*Note: Winch and Stand Assembly Is Used at Arm Only. Truck- or Tractor-Mounted Power Winch Will Be Used at Other Locations.

Figure 78. Roll transfer operation.



a. Iraqi Al-Husayn on an indigenous Al-Waleed TEL

Figure 79. Transporter-erector-launcher.



b. Chinese M11 missile on a wheeled TEL

c. French Hades missile being launched from
a container on the articulated trailer.
Figure 79. Concluded.

SECTION VI

TESTING AND DEPLOYMENT

The usual purpose of a test is to gain technical information that will contribute to a future design, refine a design, and/or lead to a better understanding of the performance characteristics and limitations of a system. Operability, reliability, survivability, and qualification are important test objectives.

The use of proper ground testing at the component level and flight testing at the system level is essential in the development cycle of a ballistic missile system, especially where cost and schedule are important. The need for testing in ballistic missile systems development is greater than in most other system developments for two main reasons, (1) the relatively small design safety factors used, and (2) the magnitude of the potential hazards in case a failure occurs.

The expense and time involved in flight testing is great; therefore, in most instances, many component ground tests are required in order to minimize the probability of flight failures. A certain amount of flight testing is, however, always required since simulation of all the flight effects on the ground is extremely difficult, if not impossible.

6.1 GROUND TESTING

Ground testing is defined as any component or systems test performed before flight. This ground testing may be categorized into three stages of testing, (1) research, (2) development, and (3) production. Research testing is the most basic type of testing and is required to demonstrate operability and proof of new design concepts. Once the basic design concepts have been established, developmental testing of the prototype unit is required. Design refinement, demonstration of reliability, and documentation of performance are characteristically the objectives of this phase of testing. Once the system is fully developed, production tests must be performed to investigate aging characteristics of production units and to verify the maintenance of production quality.

6.1.1 Ground Test Facilities

Ground testing can range from factory tests to high-speed track tests, to wind tunnel tests, to static propulsion system operation tests. Factory tests are usually inspections, pressure tests, leak checks, and/or operational checks of missile subsystems such as valves, electronic components and inertial instruments. Simulated flight and guidance tests are conducted on the ground with computers. These type tests are usually not complex and require little or no sophisticated hardware or facilities.

Early in the development stage of ballistic missile systems, a wind tunnel is required to test a model of the missile structure in a controlled airstream to simulate atmospheric flight conditions, determine the aerodynamic and structural characteristics of the missile, and provide data for design of the final configuration. Discussions of various types of wind tunnels and their descriptions are beyond the scope of this report. For further information, the reader is referred to Refs. 21 and 22.

High-speed sleds may be used for missile component testing to subject the components to acceleration comparable to flight. Guidance systems tests may be conducted as part of the sled tests.

Space Simulation Facilities. Space simulation facilities are enclosures that expose the space vehicle to a simulated space environment for the purpose of determining space vehicle characteristics. Tests are designed to simulate outer space conditions as required for the vehicle mission. Tests may be structured to simulate zero gravity, plasmas, electromagnetic fields, ozone, high-energy particles, sensor targets, adversary confusion measures and offensive weapon characteristics and to investigate thruster plume flows and the resultant surface contamination.

Space simulation tests involve the simulation of pressure down to less than one-millionth of an atmosphere. In tests where thermal control of the vehicle is important, surrounding surfaces are usually cooled to less than −300°F to simulate radiation to space conditions while one surface is heated to simulate the sun. Tests that might be conducted on ballistic missiles in space simulation facilities include shock and vibration testing, stage separation, radiation effects on electronic on-board systems, and vernier rocket performance.

Space simulation testing is time-consuming and expensive because of the cleanliness required and the equipment involved. SRBMs can be developed with very little or no use of these type facilities. These facilities are usually required for vehicles that remain in space for extended periods of time.

Dynamics Test Facilities. The requirement to qualify the structural design and fabrication of ballistic missile systems by dynamic tests is of prime importance to their successful, cost-effective deployment. Dynamic loadings on ballistic missiles can result in solid-propellant defects such as cracks, voids, and propellant/case separations or damage to critically stressed structures such as high-pressure systems with welded joints and rocket nozzles. The detection and evaluation of rocket dynamic structural problems in ground level tests will permit the necessary design changes to be made before flight testing. Accelerated life-cycle testing can help prevent future problems that often occur during the service life of operational rocket propulsion systems. A typical dynamics test facility has the capability for vibrational testing, shock testing, and acceleration testing. Some facilities may simulate temperature and pressure as well during dynamics testing.

Vibrational testing is required to simulate continuous vibration forces over a wide frequency range. These forces are normally random forces occurring during powered flight or during transportation of the vehicle. Testing is accomplished by shaking the test specimen while it is mounted on a rigid table using electrodynamic and/or hydraulic vibrational simulators mounted to a seismic mass.

Shock testing is required to simulate sudden shock loads lasting for a short duration of time. An example is pyrotechnic separation in space vehicle staging. Shock testing requires a device such as a drop system or a parallel pendulum to provide reaction motion for shock loading and the velocity vector for impact loading.

Acceleration testing is required to simulate forces caused by constant or variable acceleration of the flight vehicle at lift-off and/or staging. Acceleration testing is usually accomplished by mounting the test article on a centrifuge.

A dynamics test facility is usually comprised of a test area, a data/facility control center, and a test control building. These units are remotely sited and discreetly separated to protect personnel, equipment, and utilities in the event of a mass detonation of the test article during evaluation. An example of a dynamics test facility is shown in Fig. 80.

Propulsion system ground test firings require specially designed test facilities because of the hazards of high-energy propellants. Safety regulations must be strictly observed for protection of personnel and test facilities.

Rocket Propulsion Test Facilities. Two types of ground test firing facilities may be required in the development of ballistic missile systems, depending on the system to be developed and its uses, (1) sea-level test facilities, and (2) altitude test facilities. Sea-level facilities subject the propulsion system to local ambient pressure during the test firing. Altitude facilities subject the propulsion system to low pressures to simulate the conditions at high altitudes. Sea-level facilities are adequate for developing single-stage short-range ballistic missile systems. Two-stage short-range ballistic missile systems may be developed without the use of altitude testing but not without risk. The second-stage propulsion system should be tested at simulated

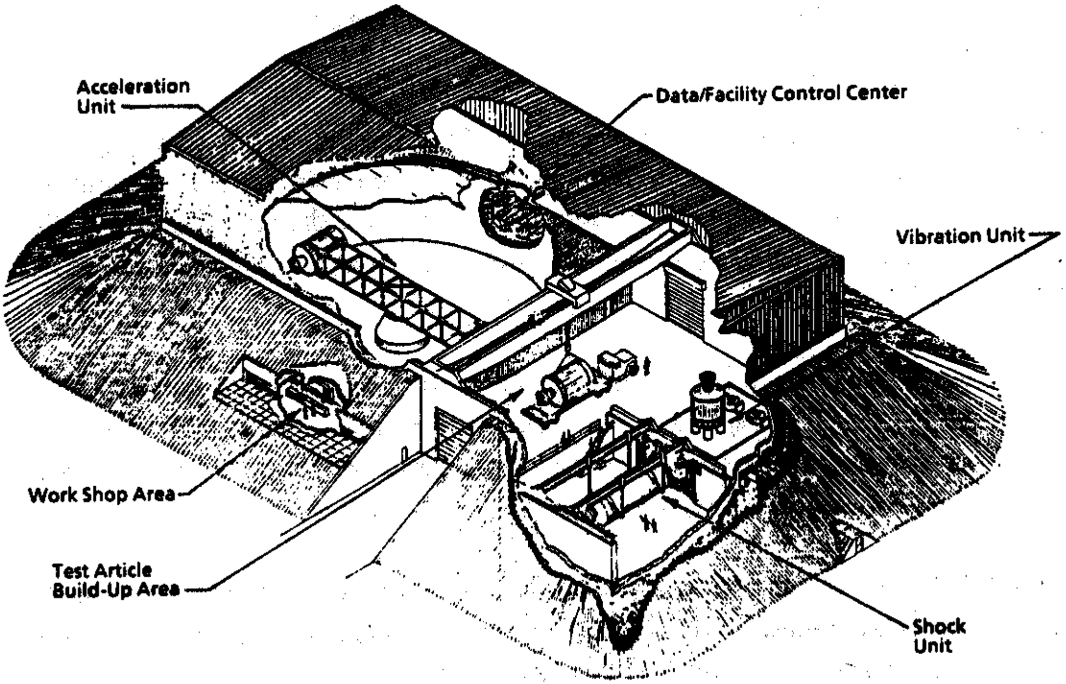


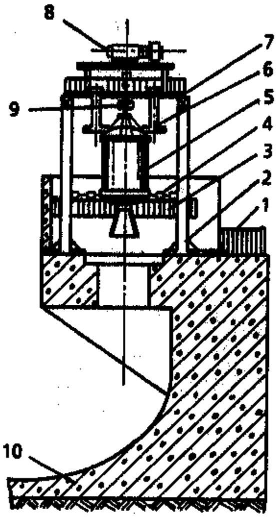
Figure 80. Dynamics test facility.

altitude pressure to uncover potential altitude ignition problems, to determine the heat-transfer characteristics of the missile components in the absence of convection, and to determine the performance characteristics of the rocket system.

A typical sea-level propulsion engine test facility is depicted in Figs. 81a, b, and c. Three features characterize the

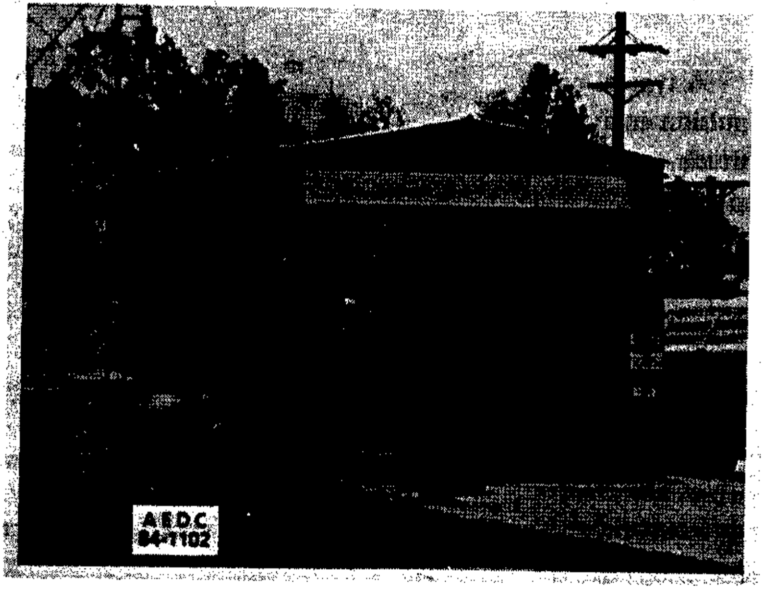
a. Photograph

Figure 81. Typical sea-level rocket engine test stands.



1. Foundation
2. Thrust Stand
3. Work Platform
4. Side-Force Train
5. Rocket Motor
6. Suspension
7. Thrust Butt
8. Hoist
9. Axial-Force Train
10. Exhaust Deflector

b. Typical sea-level vertical rocket test stand



c. Typical sea-level horizontal rocket test stand

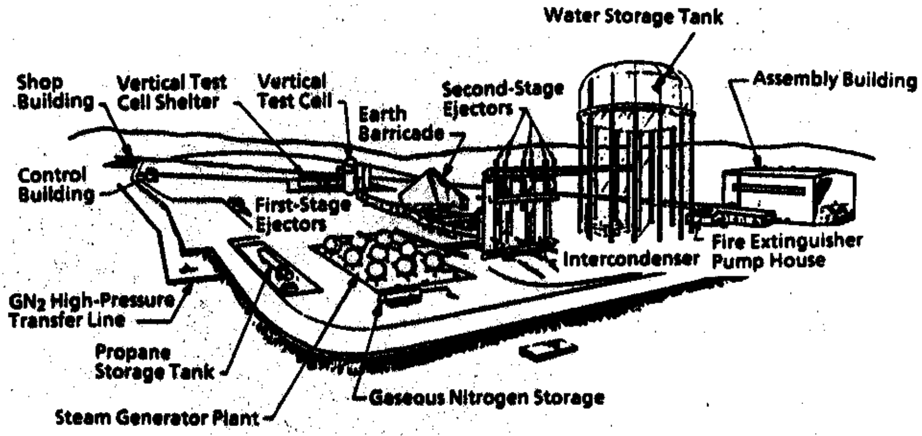
Figure 81. Concluded.

design of such a facility: (1) The crew is well protected; (2) the damage from a propulsion system explosive failure is minimized; and (3) civilians in the vicinity of the test facility are protected from danger.

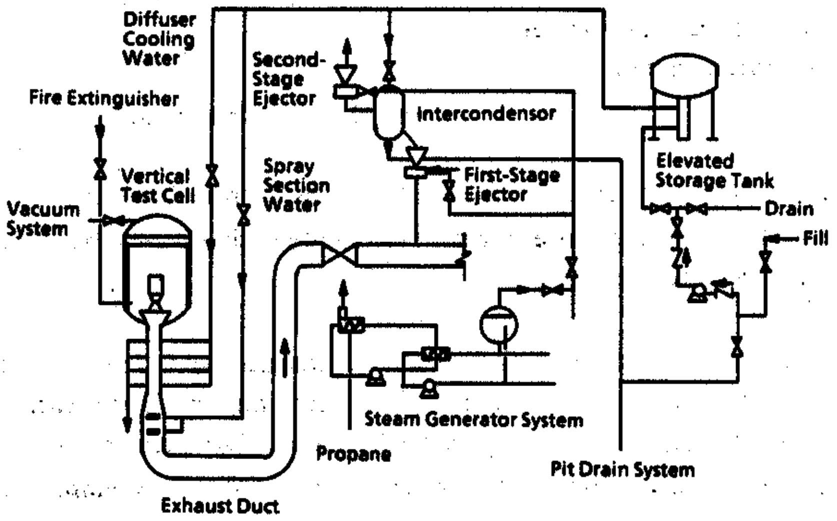
The simplest form of test facility is characterized by the motor being tested out in the open, a good distance from other buildings and inhabited areas, with the propellant supply tanks separated from the motor by a blast wall. Enhancements to this basic facility may include a control and viewing room near the test area and inside a reinforced concrete shelter, a simple shelter for the test position to protect it from the weather, and various other support equipment usually protected from the test article by blast walls. When thrust measurement is not important, the motor may be mounted on rigid iron construction. Where thrust measurement is desired, a specially designed, slightly moving motor-restraining mechanism, called a thrust stand, is required.

A major drawback to this type facility in populated or space-limited areas is that when an explosion occurs, fragments and blast are scattered in all directions. In cases such as this, the test stand may be surrounded on three sides and on top by strong enclosures. In case of an explosion, the fragments and blast are directed in only one direction to minimize hazards. Rocket test stands may be constructed to contain an explosion should one occur; however, for even small motors, the expense of containment can be prohibitive.

A typical propulsion engine altitude test cell is shown in Figs. 82a and b. Many of the same features found at the sea-level facility will be noticed at the altitude test facility. The major difference is in the handling of the propulsion system exhaust gases. Even though the exhaust gases in the sea-level facility may be handled very simply with an exhaust gas deflector, the altitude test facility is characterized by an exhaust gas management system capable of safely collecting and pumping the exhaust gas from the low simulated altitude pressure to atmospheric pressure.



a. General arrangement



b. Schematic

Figure 82. Typical rocket altitude test cell.

The exhaust gas management system consists of a rocket exhaust gas diffuser, water spray cooler/scrubber, and auxiliary pumping system. In some cases where the required simulated pressure is not so low, the auxiliary pumping system is not required.

Rocket test facilities are usually characterized by nearby high-pressure tanks storing gases (such as nitrogen for valve actuation and/or propellant tank pressurization), water tanks for fire fighting and/or exhaust gas cooling, and crane or transporter systems for handling heavy or awkward assemblies.

6.1.2 Ground Test Instrumentation

A reliable method for recording instrumentation readings must be provided for solid-propellant rocket testing because the motor is completely expended during each test. Electronic recording is most commonly used today, although simpler methods such as photographing meters and manometers can be used.

Some of the physical quantities required to be measured or recorded in rocket testing are pressures, temperatures, forces, flows, event timing, vibrations, displacements, and visual recordings. Research and developmental testing presents special demands on instrumentation that is not as important in production testing. Engine pressure transients must often be recorded since their signatures can be very important in identifying failure modes and thus lead to design fixes.

Required instrumentation components and their descriptions are as follows:

Pressure Transducers — sensors that convert pressure levels to analog or digital electronic signals.
Propellant Flow Rate Meters — instruments that measure rate of flow of gases or liquids.
Temperature Probes — sensors that return an electronic signal indicative of the temperature at the probe position.
Computers — information-handling devices capable of recording and storing large amounts of data, controlling complex test sequences, and making predetermined decisions based on measured current events.
Accelerometers — devices capable of sensing acceleration and returning an analog signal indicative of the sensed level of acceleration.

Further information may be obtained from Refs. 23 through 26 on different types of instruments, sensors, computers, and analyzers.

6.2 FLIGHT TESTING

Flight tests are specially instrumented flights of a special flight test vehicle or production vehicle on a flight test range. Flight tests, in most instances, will bring to light problems not uncovered in ground testing. The reason behind this is that some of the flight effects, such as acceleration of the flight vehicle, are impossible to duplicate in ground tests. Acceleration effects can cause such difficulties as valve failures and combustion chamber burnouts attributable to injection pattern upset or solid-propellant slumping, which can go totally undetected in ground tests.

Flight test ranges are required to test the guidance, controls, and ground support as well as the flight operability of the integrated missile system. They are characterized by radar and telemetry equipment and sophisticated tracking systems and can extend over large areas, often over the oceans. The ability of the ballistic missile system to deliver a payload to a certain location within an expected tolerance is, of course, the final test.

One of the more challenging problems associated with flight testing is the gathering of measured data from the flight vehicle. The ballistic missile must be observed in its trajectory throughout the entire flight, and it must provide methods of sending information to the ground test observer.

Radio telemetry consists of sensing the desired physical measurement of interest, converting the data to a variation in an electrical parameter (such as voltage, current, or resistance), using the electrical variation to modulate a radio signal, sending the radio signal, receiving the signal at the command center, and converting the radio signal back to meaningful physical measurement data. Information on telemetry methods may be found in Ref. 27.

6.3 DEPLOYMENT

The SRBM consists of three or four major subassemblies depending on whether it is a single- or two-stage missile. For a two-stage SRBM, these major assemblies are (1) the first stage with interstage separation pyrotechnics, (2) the second-stage assembly, (3) the guidance assembly, and (4) the warhead assembly with warhead separation pyrotechnics. The major component assemblies are transported to military depots for missile assembly and checkout. Storable liquid-propellant tanks are filled, pressurant tanks are pressurized, and the liquid-propulsion system becomes a prepackaged unit treated the same as a solid-propellant system.

Typically, mobile SRBMs are carried and launched from transporter-erector-launcher (TEL) vehicles. A TEL is usually custom-designed for a particular missile system, has an hydraulically actuated mechanism for erecting the missile, and has a launch platform with rotational capability and self-contained leveling jacks. Auxiliary equipment may include compressed air or inert gas containers for pressurizing the propellant tanks (for liquid-propellant SRBMs) and starter fuel tanks for those missiles requiring such fuels. Figure 83 is a photograph of a Soviet Scud B missile on its TEL vehicle. As can be noted in the photograph, this TEL is operating from an unimproved roadway.

The depot checkout consists of electrical circuit checkouts of ignition, safe-and-arm, separation pyrotechnics, thrust vector control, fusing, guidance components, and chamber pressure staging command.

The assembled SRMs are moved to the combat area in transportation vehicles as discussed in Section 5.4.7. The SRMs are then loaded onto TELs by combat battery personnel. The battery will be characterized by the presence of TELs, cranes, checkout vanes, surveying instruments, and the firing crews.

Figure 83. Soviet Scud B on transporter-erector-launcher.

For newly developed SRBMs, the TEL will transport the SRM to a presurveyed launch site, install a charged battery, spin up the gyros, input the launch site and target coordinates, erect the missile, and fire on command. Firing operations consume a few minutes compared to about an hour for the older technology. The shorter time is the consequence of (1) the ready response of solid-propellant rockets and prepackaged liquid-propellant rockets, (2) a guidance computer capable of commanding a roll to the proper azimuth immediately after launch but prior to pitching to the proper flight-path angle, and (3) modern aids in surveying launch sites including the "borrowing" of information from the NAVSTAR global satellite positioning system.

For older technology SRBMs (e.g., 1950s and 1960s), deployment operations, including launch preparations, may require many support vehicles and personnel. Briefly summarized, a typical list of support equipment consists of

- meteorological van,
- air compressor truck,
- decontamination van (if liquid propellant),
- fire fighting truck, and
- oxidizer truck (if liquid propellant),

- fuel truck (if liquid propellant),
- survey team van, and
- command and control vehicle.

The time required to complete all the prelaunch procedures can be lengthy. For example, the time required to prepare a Scud B for launch is about 1 hr (Ref. 28). The meteorological van is required to obtain, primarily, wind speed and direction as a function of altitude. The decontamination van is required in case of a toxic propellant spill. Also, special protective clothing must be worn when loading toxic propellants. The location of the launch pad must be known, and for older technology, the missile must be positioned in the proper direction prior to launch. Hence, a survey team and special surveying equipment are required. Some launch sites can be presurveyed, but more may be needed as the TEL attempts to avoid counterattack by immediately moving to another location after each missile launch.

SECTION VII

BUILDING THE INFRASTRUCTURE

Design, development, production, test, assembly, and deployment of the SRBM would begin with a small cadre responsible for developing a concept and recruiting a work force sufficient to implement the weapon system. The process would be a difficult one for a Third World country. This section describes how implementation might take place.

7.1 CADRE

The core cadre would develop a 10-yr plan for the deployment of a ballistic missile capable of delivering a 1-metric-ton payload up to 1,000 km. The cadre would initially consist of a small group, perhaps two dozen, chosen for their expertise in accomplishing difficult jobs and with some knowledge of artillery and tactical military concepts. They would have two early objectives, developing the hardware concept, and recruiting and training a task force. They would grow to about 2,000 persons in about 3 yr and consist of diverse disciplines.

7.2 CONCEPT

A first priority of the cadre would be to select the preliminary design of the missile and the transporter-erector-launcher (TEL). Both solid- and liquid-propellant rocket propulsion, both single- and two-stage missiles, various thrust vector control techniques, the employment of external air vanes, self-contained inertial guidance or ground-assist guidance, stage and reentry vehicle separation, thrust-termination techniques, the use of reentry decoys at the expense of warhead weight, the types of warheads applicable, and fabrication, assembly, testing, and evaluation philosophies all would be explored in order to intelligently build the weapon system and its required infrastructure.

7.3 WORK FORCE

The work force would be developed under the SRBM task force and would be implemented in a laboratory environment. A brief discussion of the expected laboratories and their initial efforts follows.

7.3.1 Propulsion Laboratory

Various formulations of composite solid propellants would be investigated for uniformity in manufacturing, performance, mechanical properties, burn rate and burn-rate exponents, and ease of bonding. These formulations would be tested in subscale test facilities that would also develop instrumentation techniques.

Storable liquid propellants would be evaluated for storage and handling properties, performance, and material compatibility. Literature on turbomachinery would be studied before the laboratory eliminates pump-fed propulsion as a viable alternative because it would be too large a risk to undertake at this early stage of development. Compatible materials would be investigated with emphasis on high strength-to-weight ratios and durability in the presence of high flame temperature erosive environments. After about 3 yr of developing and learning, the laboratory would be ready to present their recommendation (with justification) for the propulsion system for the 1,000-km-range SRBM. The presumed results of the performance studies are shown in Table 30 and indicate that the simplest vehicle is a two-stage solid-propellant vehicle. It employs thrust vector control by nozzle gimballing and would not have external fins. Second-stage thrust termination would be by rapid decompression through blowout ports in the head end of the second-stage rocket motor case. The propellant binder would be polybutadiene developed by the laboratory's own polymer and rheology chemist, who would have years of experience in the synthetic tire business. The propellant would use AP as the oxidizer and include 10-percent aluminum powder. The igniter would use the same propellant as the motor except that aluminum would not be used in the igniter. Motor cases fabricated from commercially available 4130 alloy steel would be used for the initial production lot while the structures laboratory would be improving their heat-treatment, machining, and welding processes for the future employment of maraging steel.

Table 30. Launch Weight and Rocket Parameters for an SRBM

		First-Stage			Second-Stage				$I_{sp_{SL}}$	
Propulsion System	Launch Weight, lbm	Propellant Weight, lbm	Inert Weight, lbm	Propellant Density, lbm/in^3	Propellant Weight, lbm	Inert Weight, lbm	Propellant Density, lbm/in^3	C* ft/sec	Stage 1 $\epsilon = 10$, sec	Stage 2 $\epsilon = 16$, sec
Single-Stage Solid*	26,300	19,660	4,315	0.0635	—	—	—	4,940	223.3	—
Two-Stage Solid*	15,400	7,934	1,741	0.0635	2,788	612	0.0635	4,940	223.3	204.9
Single-Stage Liquid**	23,850	17,220	4,305	0.0445	—	—	—	5,396	237.3	—
Two-Stage Liquid**	14,940	7,468	1,877	0.0445	2,422	604	0.0445	5,396	237.3	215.4

* Polybutadiene Binder, AP, 10-percent Al:Pc = 500 psia

** N_20_4/50/50 Blend: P_c = 500 psia

Nominal operating chamber pressure for both first- and second-stage motors is 500 psia. With this pressure, the nozzle area ratios would be a modest 10:1 for the first stage and 16:1 for the second stage. Most of the development testing could be conducted in sea-level test facilities; however, the second stage would also be evaluated in a simple altitude test rig. The altitude test rig would consist of a canister enclosing the motor and exhausting through a constant area diffuser discharging to local atmospheric pressure. The altitude facility would have the capability of being pumped to 60,000-ft altitude pressure for qualifying the altitude ignition. Steady-state operating pressure would also be about 60,000 ft and would be capable of evaluating the aft closure and nozzle durability in the presence of reduced convective heating.

7.3.2 Guidance Laboratory

The guidance laboratory would be responsible for the development of accelerometers, gyroscopes, computer, and the battery used in the guidance system as well as peripheral equipment such as on-board electronics, servo-feedback control systems, and instrumentation. They would also be responsible for testing and qualification of this equipment.

Much of the early effort of the guidance laboratory would be devoted to the reverse engineering of accelerometers, gyros, and gyro airbearings secured from outside sources. It would take 6 to 7 yr to build the indigenous expertise required for effective military tactical ballistic weapons and another few years of flight testing and perfection. With the laboratory approach, however, the hard lessons would be learned, and an indigenous capability would result.

The laboratory would design an inertial system and computer so that the mobile missile could be moved from any site for which the coordinates (and altitude) were known to any other remote launched site and launched as soon as erection was completed.

This laboratory would also be responsible for the guidance algorithms including rotating Earth (coriolis force) effects and would, therefore, require the knowledge of rigid-body physics, and orbital mechanics as well as the expertise of instrument makers. Some form of ascent and reentry atmospheric perturbation correction would also be required in the guidance algorithm.

7.3.3 Structures Laboratory

The structures laboratory would be responsible for pressure vessel, interstage structure, piping, valving, burst diaphragm, and overall configuration design. In order to fulfill this responsibility, the structures laboratory would be staffed with engineers knowledgeable about lightweight structures, airloads, transportation and ground-handling loads, dynamics, aerodynamics, reentry heating, and missile weight and balance.

This laboratory would also be responsible for most of the fabrication and, therefore, would require manufacturing personnel who are familiar with airframe-type structures. It is probable that the first operational, deployed missiles would be fabricated from commercially available material such as 4130 alloy steel, but by the end of the first 10-yr period, they would have progressed to fabrication with ultra high-strength alloys and composite structures. This laboratory would also be responsible for testing and qualification of all vehicle structural elements and for conducting the wind tunnel tests necessary to define configuration design, airloads, and aerodynamic stability derivatives required for control constants.

7.3.4 Armament Laboratory

The armament laboratory would be responsible for development of the high-explosive warhead, stage-separation pyrotechnics, reentry body design, warhead fusing, safe-and-arm, and rocket ignition systems. Reentry body design would offer some challenging possibilities. The reentry body must be made to be statically (aerodynamically) stable so that it rights itself during atmospheric reentry. A deployable aft fairing might be required to effect aerodynamic stability. Every vehicle must exhibit a repeatable ballistic coefficient.

7.3.5 TEL Laboratory

The transporter-erector-launcher (TEL) laboratory would be responsible for the vehicle used to move the missile into combat situations, elevate the missile to the vertical position, and launch the missile. The TEL may be either a wheeled or a tracked vehicle suitable for off-road transportation while carrying a 7-metric-ton weapon system. Auxiliary power would be supplied to the missile for checkout, battery charging, and for maintaining inertial coordinate position and target coordinates prior to launch. The TEL must present a stable and level platform and must withstand the rocket exhaust during launch. It is expected that most countries with ballistic missile expectations would be experienced with similar but smaller vehicle types.

7.4 PROJECT MANAGEMENT

A laboratory environment appears to be the appropriate organizational structure for a Third World country to build an SRBM capability. There are, as shown in Fig. 84, many technical and disciplinary interfaces requiring an authoritarian approach. A project management office is responsible for ensuring interface compatibility.

7.5 MATERIALS ACQUISITION

During the 10-yr period that a country would be building its indigenous ballistic missile capability, various supply sources would have to be developed. Many of these sources would be developed internally by normal expansion such as liquid oxidizers from the fertilizer factory, synthetic rubber from the tire plant, and liquid fuel from the alcohol industry. Many would

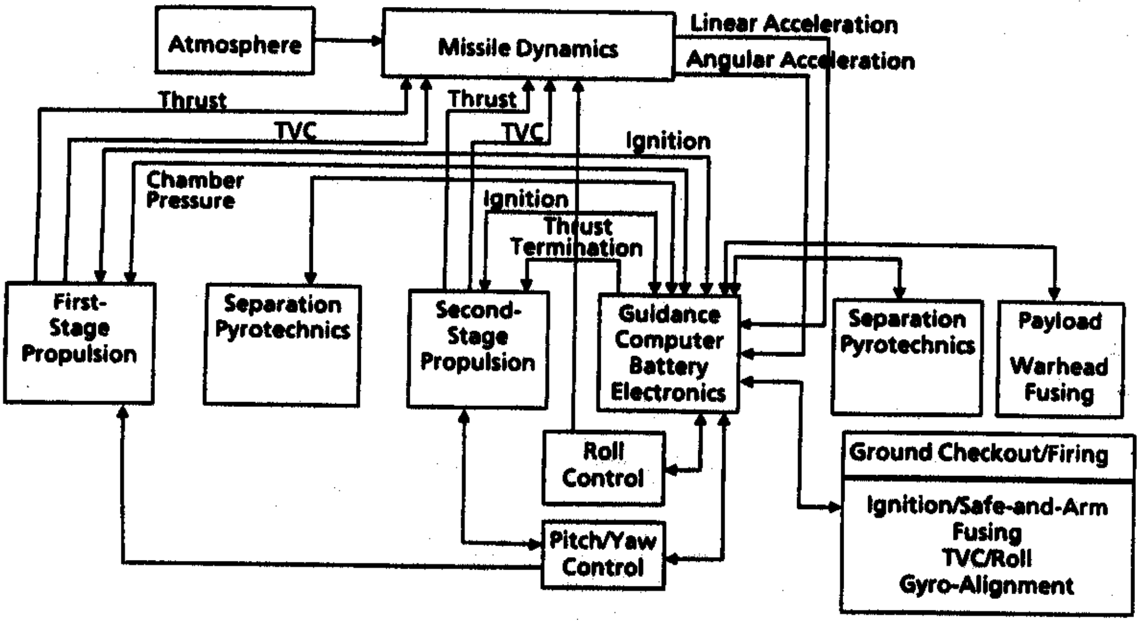


Figure 84. Short-range ballistic missile system interfaces.

have to be purchased on the world market and might become subject to sanctions. The successful country would develop legitimate markets for their purchases, such as automotive uses for aluminum and commercial shipping for integrating accelerometers.

Where statements were made in the previous paragraphs that a laboratory would be responsible for fabrication, the statement does not mean that the laboratory would produce the item. Much of the production would be done under contract by existing industrial organizations that would have world-wide procurement contracts and contacts.

7.6 SRBM INFRASTRUCTURE OVERVIEW

The infrastructure necessary to produce SRBMs could be developed indigenously in a Third World country with the desire to have the capability. The infrastructure would be fashioned from existing industries and institutions, recruitment and training, and purchases on the open commercial market. Some countries would have intrinsic capability for liquid-propellant rockets; others would ease into solid-propellant rockets; and some countries would develop both. Figure 85 provides a general overview of the indigenous infrastructure that must be in place to support both a liquid- and a solid-propellant SRBM.

If the enabling industry, shown in Fig. 85, does not exist in the country, that particular capability must be bought or developed. Inertial guidance components are thought to be critical path items for indigenous capability. These components (gyros, accelerometers, on-board

computer) could be developed in 7 to 10 yr depending on the amount and quality of mercenary technology procurable. Reverse engineering of purchased systems and components would ease the burden of transition into SRBM production.

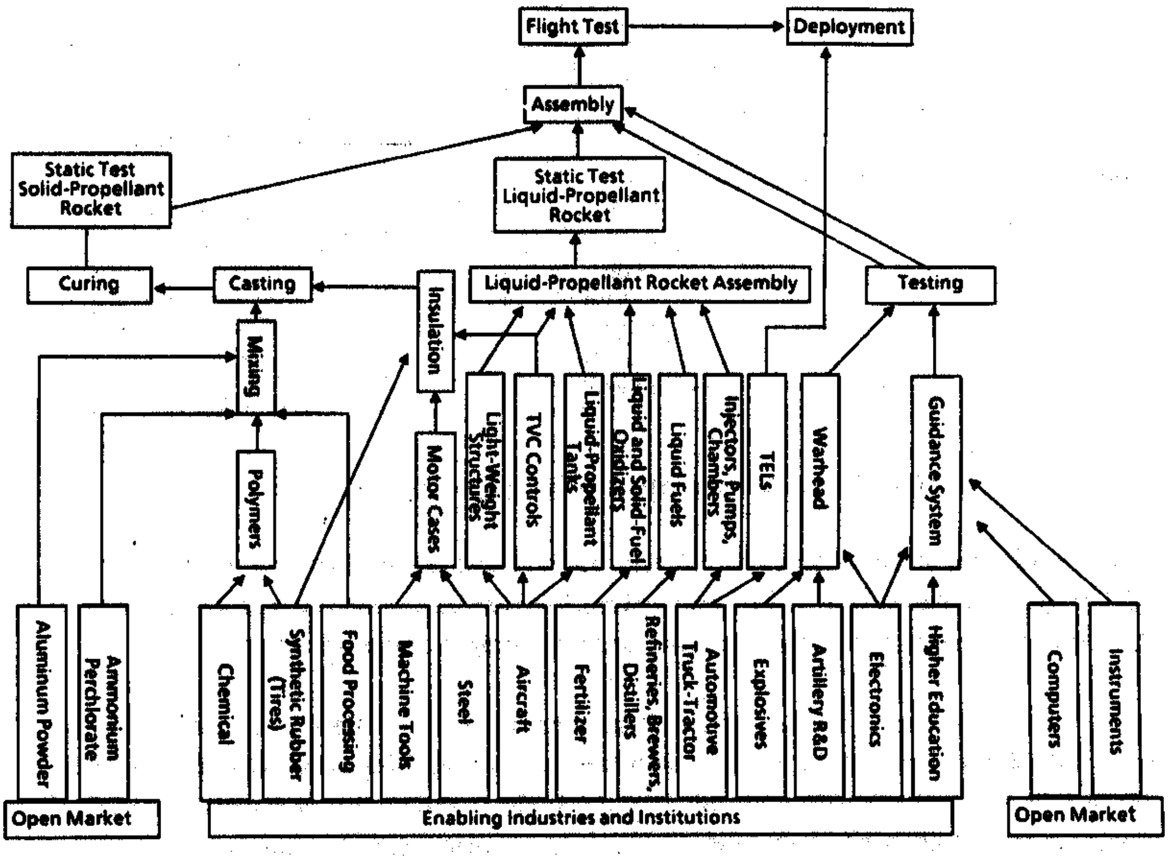


Figure 85. Indigenous ballistic missile infrastructure.

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GLOSSARY

anisoelasticity A nonuniform elastic deformation varying with the applied load and in the direction of the applied load.

annealing The process of holding a solid material at an elevated temperature for a length of time in order to eliminate any metastable conditioning; usually softens the material.

AP Ammonium perchlorate, a solid-propellant oxidizer.

Autosyn® An electrical servo for producing precise rotational positions. The commercial tradename of Bendix Aviation Corporation derived from the words automatic and sychronous. This device is also called Synchro®, Selsyn®, or any of several other names when manufactured by other companies.

azimuth The horizontal direction expressed as the angular distance from a reference direction, usually north, clockwise through 360 deg.

ballistic coefficient The ratio of reentry vehicle weight to the product of drag coefficient and area (W/C_DA) with the units of kg/m^2 or lbm/ft^2.

ballistic missile A self-propelled guided missile for surface targets that depends primarily on the thrust of its propelling system and its momentum, rather that on aerodynamic lift, for its support during flight; and on jet reaction, rather than aerodynamic reaction, for its control. A ballistic missile is driven and guided during a portion of its flight, usually the upward portion, and is under no thrust from its propelling system during the latter portion of its flight; it follows a trajectory similar to that of an artillery shell.

ballistic trajectory The vehicle path traveled after propulsive force has ceased, when gravity and possibly atmospheric friction are the only forces acting on the vehicle; also known as coasting flight, free flight, or ballistic flight.

bipropellant A type of rocket propellant consisting of two unmixed substances fed to the combustion chamber separately.

body axes Three mutually perpendicular axes intersecting at a reference point on the missile. The usual orientation is so that the longitudinal axis is known as the roll axis, normal is known as the yaw axis, and lateral is known as the pitch axis.

C* Characteristic velocity; measure of combustion chamber performances, with units in m/sec or ft/sec.

caprolactone A cross-linking agent for polyurethanes; an intermediate in the manufacturing of plasticizers and elastomers.

circular error probable (CEP) Measure of the accuracy with which a missile can be guided; defined as the radius of the circle at a specific distance or range in which 50 percent of the reliable shots will land. Also called circle of equal probability or circle of probable error.

Class 1.1 Propellant safety hazard class/division: Catastrophic failure evidences detonation.

Class 1.3 Propellant safety hazard class/division: Catastrophic failure evidences conflagration (not detonation).

CMDB Composite-modified double-base; a solid propellant, usually castable.

coriolis acceleration Acceleration caused by motion relative to rotating axes; used in guidance algorithms to acount for the Earth's rotation.

diol Synonym for dihydric alcohol, which collectively is called glycol.

directional gyro Flight instrument incorporating a gyroscope that holds its position in azimuth and so indicates deviation from a heading.

DTG Dynamically tuned gyro.

ϵ Nozzle area ratio. The ratio of the rocket nozzle exit area to the nozzle throat area. Also ellipse eccentricity.

exothermic A chemical reaction that gives off heat.

fairing A structural member used to provide a smooth surface and reduce aerodynamic drag.

FLSC Flexible linear-shaped charge.

gimbal Mechanical frame containing two mutually perpendicular intersecting axes of rotation that allows free movement through 360 deg in the plane of each axis. It is often used as a mechanical mount for a gyroscope. By means of the gimbal mounting, the gyroscope is given three degrees of freedom so that it can pick its own space orientation.

gimballed chamber Rocket combustion chamber mounted on a gimbal, i.e., on a contrivance having two mutually perpendicular and intersecting axes of rotation to permit pitch and yaw correction moments.

gimballed platform An inertial measurement system in which the three orthongonal axes are fixed with repsect to the "fixed" stars. See also **strapdown system.** Also called stabilized platform.

gravity turn A ballistic trajectory in which the flight-path angle is adjusted by the gravity vector perpendicular to the missile flight path.

gyrocompass Any compass that depends on the conservation of the angular momentum of a spinning body for its action (See **gyroscope**). In the usual gyrocompass, a motor-driven wheel is mounted on an axis in gimbals. Combined friction and gravitational-restoring torque ensure that the equilibrium position of the axis of rotation is along the north-south horizontal line, so that the gyrocompass indicates true north regardless of the orientation in which it started.

gyroscope Also called gyro. An instrument that maintains an angular reference direction by virtue of a rapidly spinning, heavy mass. All applications of the gyroscope depend on a special form of Newton's second law: A spinning body resists being disturbed and tends to react to a disturbing torque by precessing (rotating) in a direction at right angles to the direction of torque.

gyroscopic drift rate Progressive deflection of the axis of a gyroscope from four general sources: (1) unbalance caused by asymmetry of manufactured parts, temperature, etc.; (2) bearing friction; (3) gimbal inertia; and (4) anisoelasticity, a nonuniform elastic deformation varying with the angle at which a load is applied.

gyroscopic inertia Property of a gyroscope that resists any force tending to displace the rotor from its plane of rotation; also called rigidity or strength.

gyroscopic precession Movement of the axis of a spinning gyroscope resulting from Newton's second law of motion, whereby the time rate of change of angular momentum of a body about any given axis is equal to the torque applied about the given axis. Precession always tends to align the direction of rotation of the rotor with the direction of rotation of the applied torque (See **gyroscope**).

gyroscopic torque Process of applying external control to the gimbals of a displacement gyroscope to program the position of the reference axes.

gyrostabilized platform In inertial guidance, a gyroscopically stabilized platform for mounting accelerometers to keep them fixed either in a space- or Earth-based reference system despite changes in missile position and attitude.

HE High-explosive, e.g., TNT.

heat of steel A single, complete operation of heating at a forge or in a furnace; the quantity so heated.

HIG Hermetically sealed integrating gyro.

HTPB Hydroxy-terminated polybutadiene. A solid-propellant binder in which the polymer chain is terminated by an OH radical. Polybutadiene is a synthetic thermoplastic polymer.

hygroscopic A substance that absorbs moisture from the air.

hypergolic Self-igniting; capable of spontaneous ignition on contact.

ICBM Intercontinental ballistic missile; ballistic missile with a range greater than 5,500 km (3,400 miles).

IGS, inertial guidance system A missile guidance system independent of information obtained from outside the missile, having sensitive elements that use Newton's second law of motion. Its sensors are accelerometers and gyroscopes that provide input to a computer used to calculate velocity and distance and thus establish position. Both stabilized platforms and strapdown systems are used.

indigenous Produced in or native to a country.

INS, inertial navigation system (See also **IGS, inertial guidance system**). System functionally the same as the position-determining portion of an inertial guidance system. It is essentially a form of a dead-reckoning device. This means that the geographic position (latitude and longitude or equivalent) or both the starting point and destination must be known and must be set into the equipment. An inertial navigation system usually requires two or three accelerometers to sense aircraft or missile motion in the north-south direction, the east-west direction, and in some applications, the vertical direction.

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Newton's laws of motion (1) Every body either remains at rest or moves with constant speed in a straight line unless it is acted on by a force. (2) A force applied to a body accelerates the body by an amount proportional to and in the direction of the force. (3) Every action is opposed by an equal and opposite reaction.

nitration The introduction of the nitro group (NO_2) into an organic compound.

PAN A precursor for manufacturing carbon fibers.

PIGA, pendulous integrating gyroscope accelerometer Gyroscope capable of sensing and integrating a linear acceleration to obtain the resultant velocity. It is unsymmetrically suspended so that acceleration produces a precession force resulting in an angular displacement of the gyroscopic axis proportional to the time integral of the acceleration (i.e., velocity).

plasticizer Ingredient added to modify the properties of a plastic, usually to soften and make it moldable.

plastisols Mixtures of resins and plasticizers that can be molded or cast by the application of heat.

polymer An organic compound composed of large molecules built by the repetition of a monomer or from mixed monomers, e.g., polybutadiene.

polymerization A chemical reaction, usually with a catalyst of heat or light, in which several hundred or even several thousand monomers combine to form a large molecule with very high molecular weight. The macromolecules so produced are of broad (nonuniform) character.

precursor Chemicals used as raw materials in a reaction(s) to produce a desired compound.

prill An absorbent spherical form of a product.

propellant mass flow rate Mass flow rate of propellant with units of kg/sec or lbm/sec.

pultrusion Raw material or finished shape made by a process combining pulling through a die and extrusion under back pressure.

rad; radian An angular measurement unit. There are 2π radians in 360 deg.

rate gyroscope Gyroscope mounted in a single gimbal so that rotation about an axis perpendicular to the axis of the gimbal and to the axis of the gyroscope produces a precessional torque proportional to the rate of rotation. Rate gyros can be set up to register angular velocities or accelerations about the sensitive axis. Some rate gyros use the principle of gyroscopic presession, rather than the precessive force on a restrained axis, as the source of rate information.

reducing agent Agent capable of supplying electrons to another substance; opposite of oxidization.

reentry body; reentry vehicle (RV) That portion of a space-traversing missile that usefully reenters the atmosphere. In a long-range ballistic missile, the separable reentry body contains the warhead and the heat shield, and the attitude-stabilizing provisions and fuzing equipment needed to (1) reenter the Earth's atmosphere without self-destructing, (2) reduce the dispersion, and (3) explode the warhead.

rheology The science that treats the deformation and flow of matter, e.g., the flow properties of uncured solid propellant.

roll Angular displacement about an axis parallel to the longitudinal axis of a missile or vehicle. The angle of roll is the angle through which the missile has rotated about its longitudinal axis, as measured from some reference plane.

roll control Control of missile rotation about its longitudinal axis. Missiles are stabilized in appropriate axes to permit resolution of guidance signals. Intelligence is obtained from a reference system (e.g., gyros), and control is obtained from aerodynamic surfaces, jet vanes, or differential gas discharge.

roving Multiple continuous strands of glass fibers.

separation In multistage missiles, the discarding of a burned-out stage as the remaining missile continues on its way; the time or place at which the burned-out stage is discarded.

specific impulse The rocket thrust produced per unit expenditure of propellant. It is the price paid to obtain propulsive force. Units are Newton-sec/kg or lbf-sec/lbm. English units are commonly shortened to just sec.

SRBM, short-range ballistic missile Land-based, rocket-propelled vehicle capable of delivering a warhead through space to a target at ranges up to about 600 nautical miles or 1,000 km. The U. S. Pershing and Lance, and Soviet Scud are tactical missile systems classified as SRBMs.

SRM Solid-propellant rocket motor.

SSM Surface-to-surface missile.

stability In aerodynamics, the adherence of a missile to its desired attitude during its flight. Stability is most important in vertically launched missiles having slow take-off accelerations. Early stability is achieved by thrust-direction control devices. These may be gimballed motors, jet vanes, or other devices. These devices merely deflect the propulsion system's thrust vector.

stabilized platform Space-fixed reference framework often used to mount guidance accelerometers so they can integrate and thus yield positions and velocities from an unchanging reference plane. Two or more gyros (stable elements) usually maintain the attitude of the stabilized platform, one gyro monitoring sometimes two degrees of freedom. Sensors detect motions of the gyro gimbals with reference to the stable elements, and these detected errors are fed back into the platform's servo system to control the attitude of the platform. The space rigidity of the gyros is the basis for this control. Once the stabilized platform is established, sensitive accelerometers mounted on it, in a predetermined coordinate orientation, measure accelerations in each of the selected coordinate directions. These accelerations are integrated to yeild the instantaneous velocities and the distances traveled, and these data are then used in the missile's computers to determine the time for motor cut-off and path-control maneuvers.

strapdown system An inertial measurement system in which the three orthogonal axes are fixed with respect to the vehicle. See also **gimballed platform**.

TEL Transporter-erector-launcher.

telemetry; telemetering system Essentially, a system of devices in a flight vehicle that can pick up or sense conditions to be measured and convert the indications for transmission by a radio transmitter installed in the vehicle; the radio receiver and recording device installed at the location where the information is to be received.

Third World The underdeveloped countries of the world.

thrust Force furnished by a rocket propulsion. Thrust (F) has units of Newton or lbf.

thrust vector control (TVC) Means of controlling a missile by use of jet deflection devices (i.e., a movable nozzle, jet vanes, etc.), which in response to appropriate signals from the autopilot, maintain proper attitude and path control.

UDMH Unsymmetrical dimethylhydrazine; a storable rocket propellant (fuel).

velocity at cut-off Velocity of a missile when propulsion ceases, especially important in ballistic missiles.

warhead The effective military payload carried by a missile.

yaw An angular displacement usually about the vertical axis. Yawing causes the vehicle to turn crosswise in flight, causing increased air resistance and, if it proceeds too far, disturbs the flight path. Yaw is controlled by a thrust vector control device.

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