Solid Propellant Fundamentals

Solid Design Team

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Basic Solid Rocket Motor

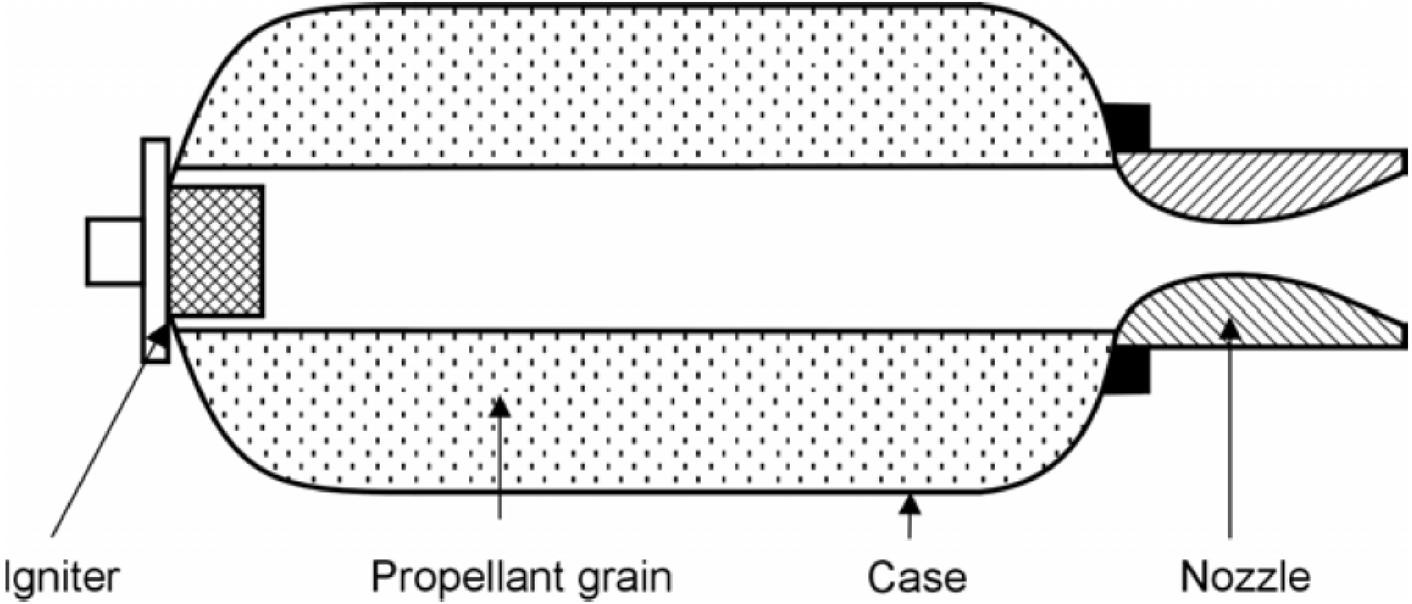


Figure 1: Basic Solid Rocket Motor.

(1)

Burning Rate Relation with Temperature

- Conditioning
- Acceptable temperature limits
  - 219 K (-65℉)
  - 344 K (160℉)
- Variations
  - Pressure
  - Operating time

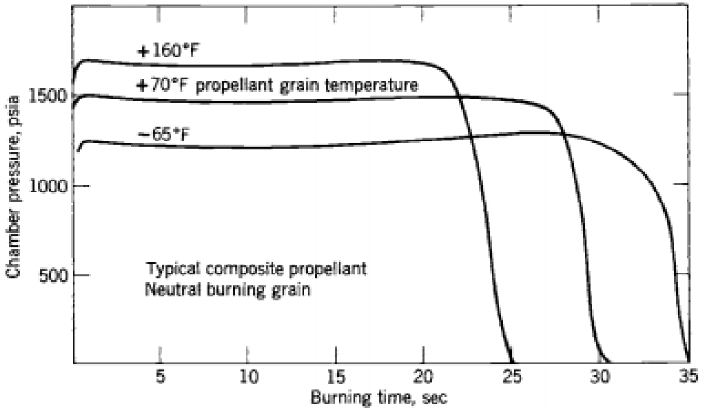


FIGURE 11–8. Effect of propellant temperature on burning time and chamber pressure for a particular motor. The integrated areas under the curves are proportional to the total impulse, which is the same for the three curves.

Temperature Coefficients

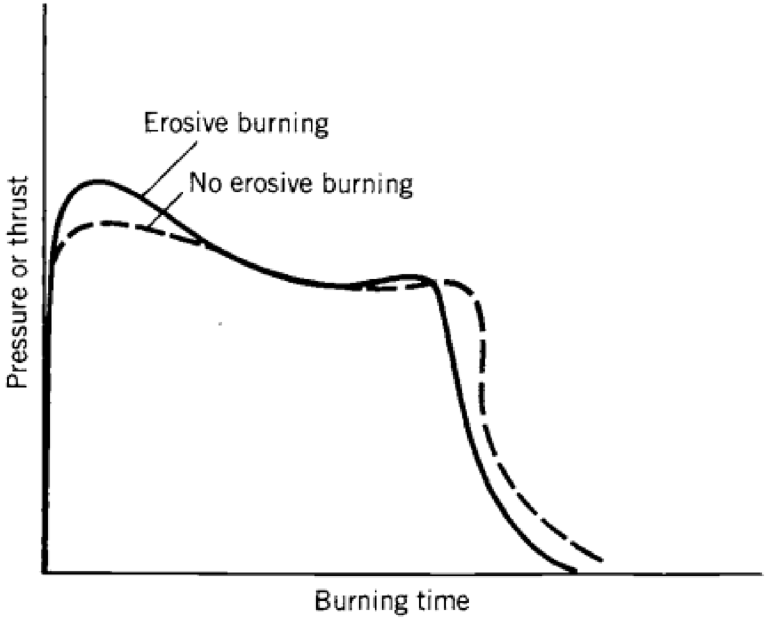
- Temperature sensitivity of burning rate
- Temperature sensitivity of pressure

$$\sigma_p = \left(\frac{\delta \ln r}{\delta T}\right)_p = \frac{1}{r}\left(\frac{\delta r}{\delta T}\right)_p$$

$$\pi_K = \left(\frac{\delta \ln p}{\delta T}\right)_K = \frac{1}{p_1}\left(\frac{\delta p}{\delta T}\right)_K$$

$$\pi_K = \frac{1}{1-n}\sigma_p$$

Burning Enhancement by Erosion



- Occurs in port passages
- More likely when port area is small relative to throat area
- Turbulent mixing increases heat transfer
- Propellant consumed more rapidly
- Early burnout of the web

Erosive Burn Equation

- 1956 by Lenoir and Robillard
- Based on adding 2 burn rates
  - r_0: function of pressure and T_b
  - r_e: increase due to erosion

$$r = r_0 + r_e$$

$$= ap^n + \alpha G^{0.8} D^{-0.2} \exp(-\beta r \rho_b / G)$$

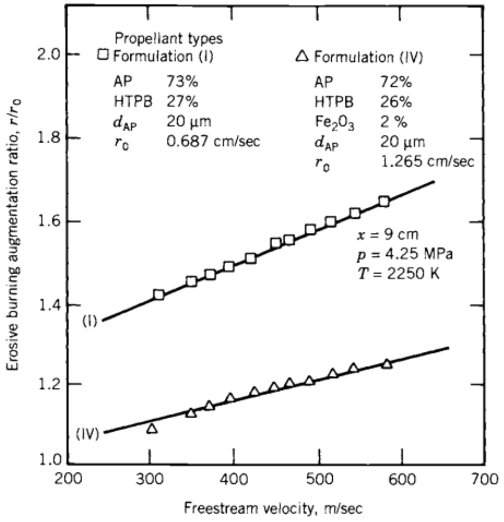


FIGURE 11–10. Effect of gas velocity in the perforation or grain cavity on the erosive burning augmentation factor, which is the burning rate with erosion r divided by the burning rate without erosion r_0. (Reproduced with permission of the AIAA from Chapter 10 of Ref. 11–3.)

Other Burning Rate Enhancements

- Spinning
- Embedding of wires
- Wire staples

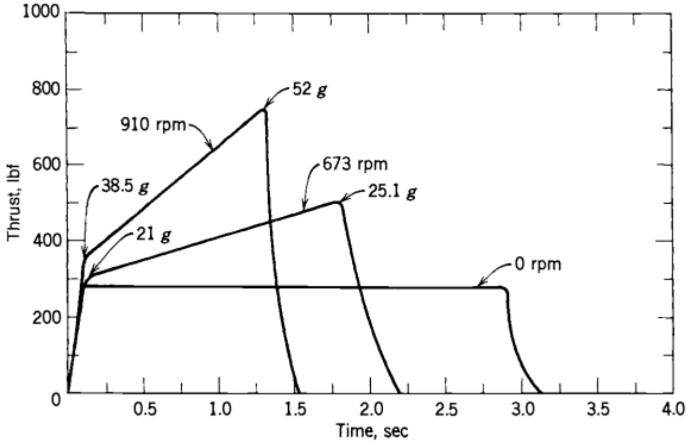


FIGURE 11–12. Effect of axial spin on the thrust–time behavior of a rocket motor with composite propellant using aluminum and PBAN (polybutadiene acrylonitrile) as fuels. (Adapted with permission from Ref. 11–7.)

Performance Issues

Overall Performance Parameters

Solid only Performance Parameters

Overall Performance Parameters

- Thrust (Ch. 2 & 3)
- Effective exhaust velocity (Ch.2)
- Specific impulse (Ch. 2 & 3)
- Propellant mass fraction (Ch. 2)
- Flame Temperature (Ch. 5)

Total Impulse

$$I_t = \int_0^{t_b} F\, dt = \overline{F} t_b$$

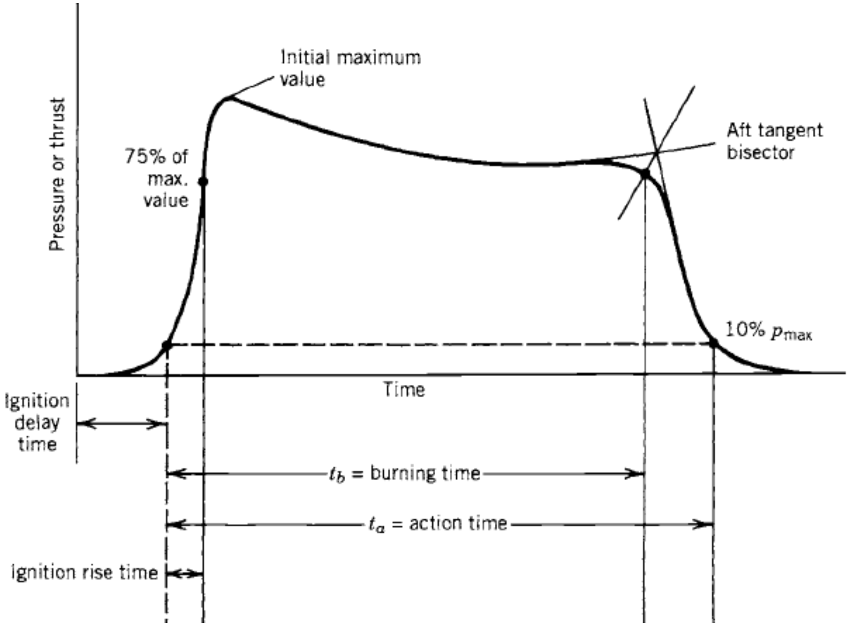


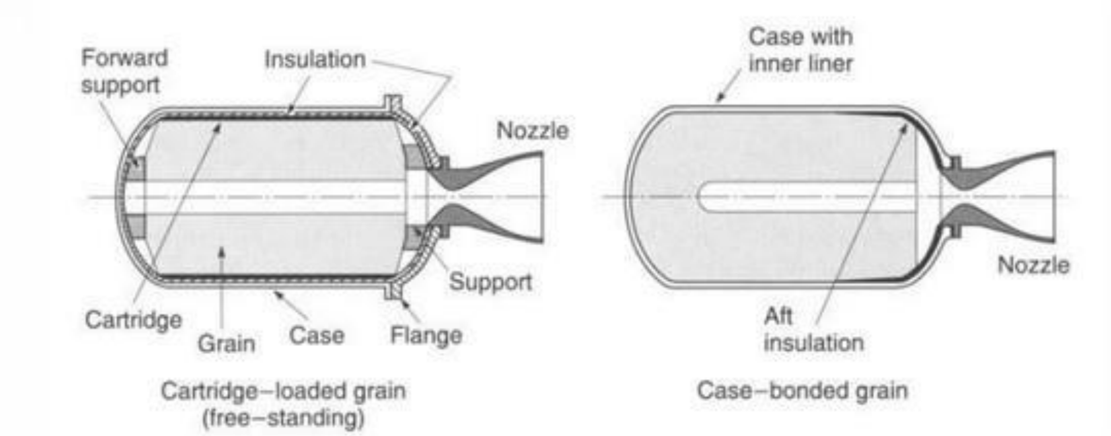
Figure 12-13

Solid Performance Parameters

- Ideal nozzle exhaust velocity $v_2 = \sqrt{2(h_1 - h_2)}$
- loaded weight w_G
- Total-impulse-to-loaded-weight-ratio I_t / w_G
- Volume impulse I_t / V_b
- Thrust-to-weight-ratio F / w_G
- Temperature limits

Propellant Grain and Grain Configuration

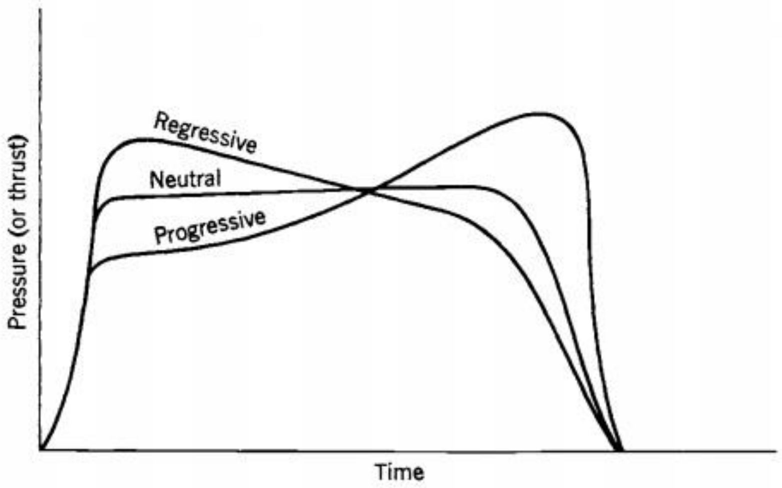
Grain: shaped mass of processed solid propellant inside the rocket motor



(2) **FIGURE 11–14.** Simplified schematic diagrams of a free-standing (or cartridge-loaded) and a case-bonded grain.

Propellant Grain and Grain Configuration

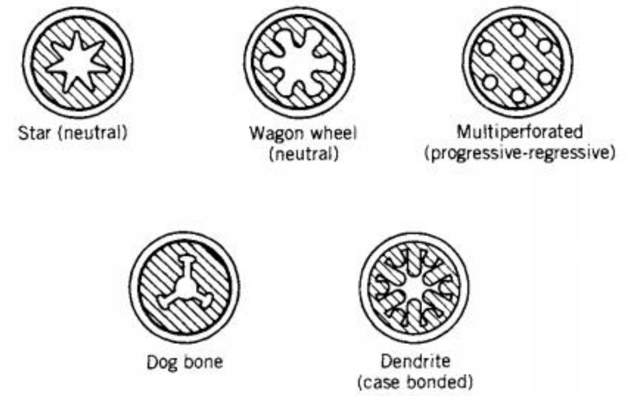
Grain Configuration Performance



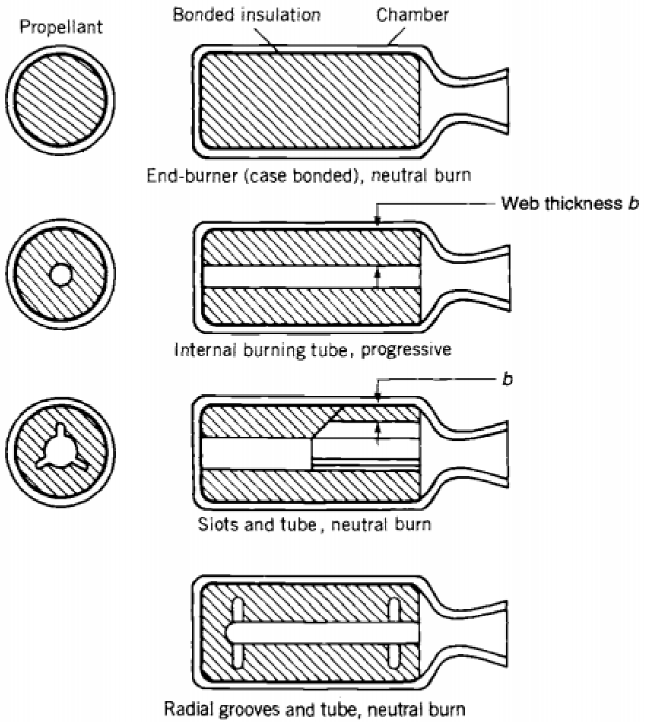
(2) **FIGURE 11–15.** Classification of grains according to their pressure–time characteristics.

Propellant Grain and Grain Configuration

Single Grain Configuration

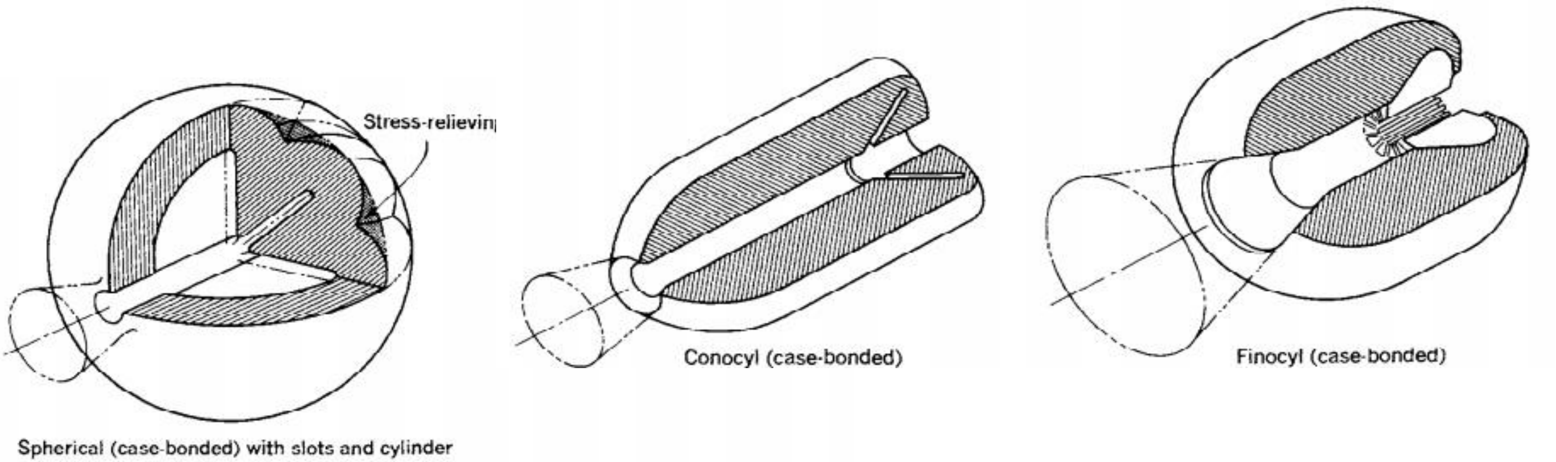


(2) **FIGURE 11–16.** Simplified diagrams of several grain configurations.



Propellant Grain and Grain Configuration

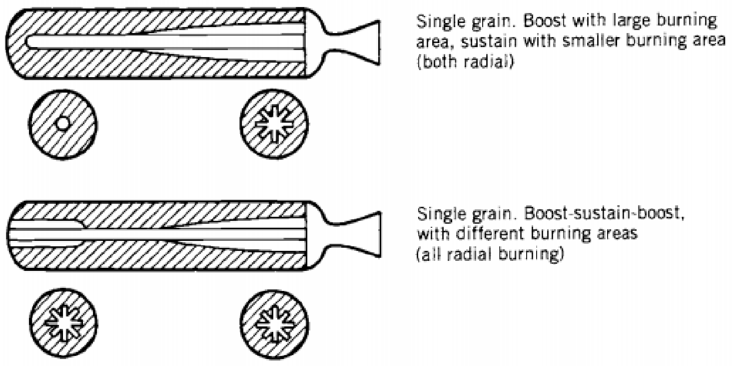
Three Dimensional Grain Configuration



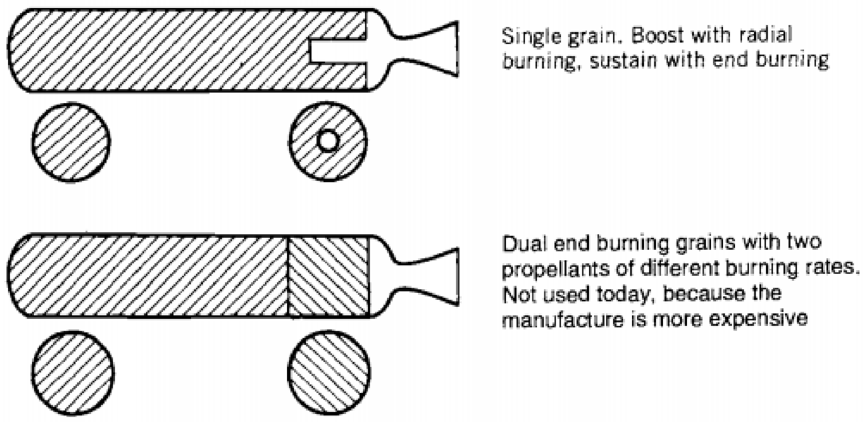
(2) **FIGURE 11–17.** Typical common grain configurations using combinations of two basic shapes for the grain cavity.

Propellant Grain and Grain Configuration

Grain Configuration Dual Thrust

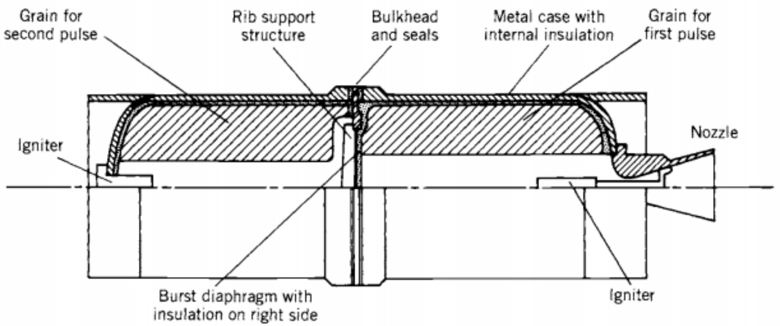


(2) **FIGURE 11–19.** Several simplified schematic diagrams of grain configurations for an initial period of high thrust followed by a lower-thrust period.



Propellant Grain and Grain Configuration

Grain Configuration Dual Thrust and End Burning Grain Coning Effect



(2) **FIGURE 11–20.** Simplified diagram of one concept of a two-pulse experimental rocket motor with two grains separated by a bulkhead. During the first pulse operation the metal diaphragm is supported by a spider-web-like structure made of high temperature material. Upon ignition of the second stage, the scored diaphragm is loaded in the other direction; it breaks and its leaves peel back. The bulkhead opening has a much larger area than the nozzle throat.

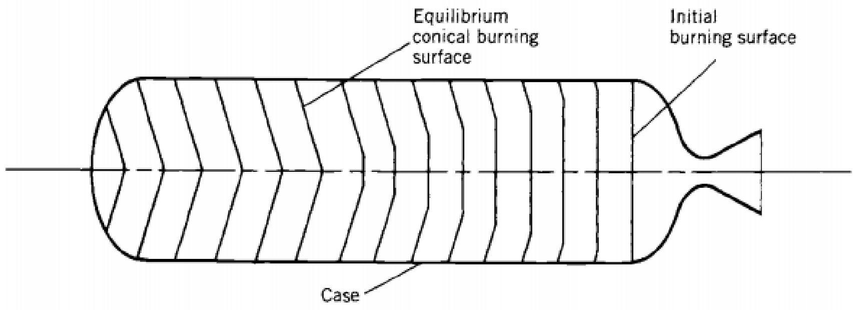


FIGURE 11–18. Schematic diagram of end-burning grain coning effect. In larger sizes (above approximately 0.5 m diameter) the burning surface does not remain flat and perpendicular to the motor axis, but gradually assumes a conical shape. The lines in the grain indicate successively larger-area burning surface contours.

Solid Propellant Handling and Storage

WHY?

- Avoid inconsistent burn rates as a result of grain damage

WHEN?

- During manufacture of propellant
- Transport
- Storage
- Operation

Factors that Induce Grain Deformations

- Thermal cycling and/or external heat through the case
- Cooling Rate after manufacturing causing compressive stress and strain
- Vibrations during transport/handling
- Undergoing high acceleration: including flight maneuvers
- Gravity slump: storage (Mostly for large motors)
- Imperfections during manufacture

Propellant Grain Stress and Strain

(2)

- Undamaged propellant
    - High max stress and strain
- Damaged propellant
    - Reduced max stress and strain
- Results in grain fractures and cracks, grain debonding from case line and insulation.

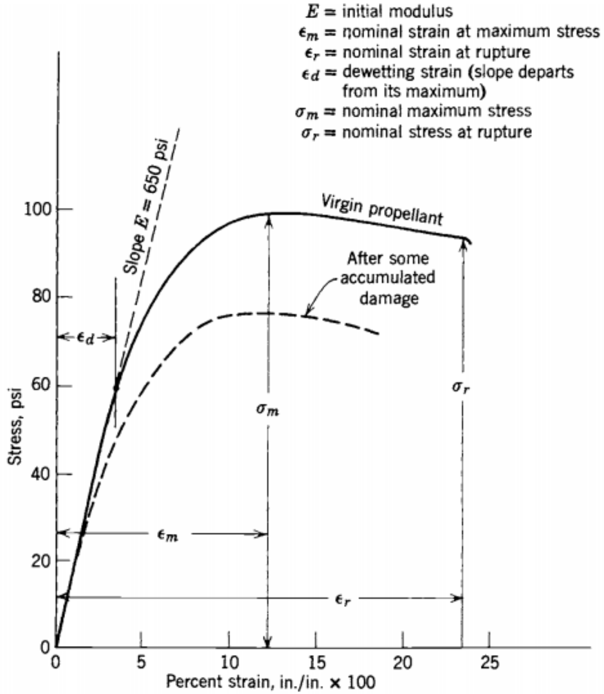


FIGURE 11–21. Stress–strain curves for a typical composite-type solid propellant showing the effect of cumulative damage. The maximum stress σ_m is higher than the rupture stress σ_r, of the tensile test sample.

Grain Damage Plot

11.4. PROPELLANT GRAIN STRESS AND STRAIN **465**

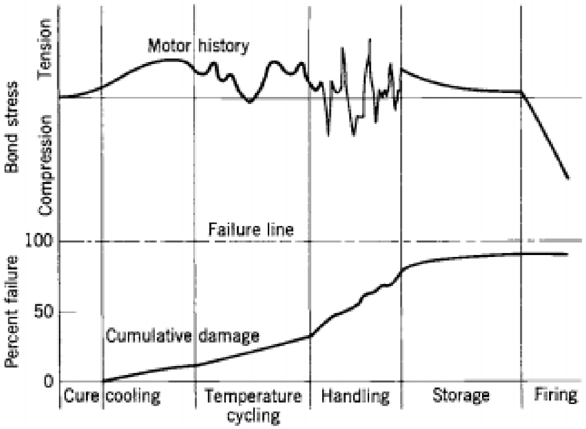


FIGURE 11–25. Representation of the progress in cumulative damage to the bond between the grain and the case in a case-bonded rocket motor experiencing a hypothetical stress history. (Adapted from Ref. 11–30.)

TABLE 11–6. Summary of Loads and Likely Failure Modes in Case-Bonded Rocket Motors

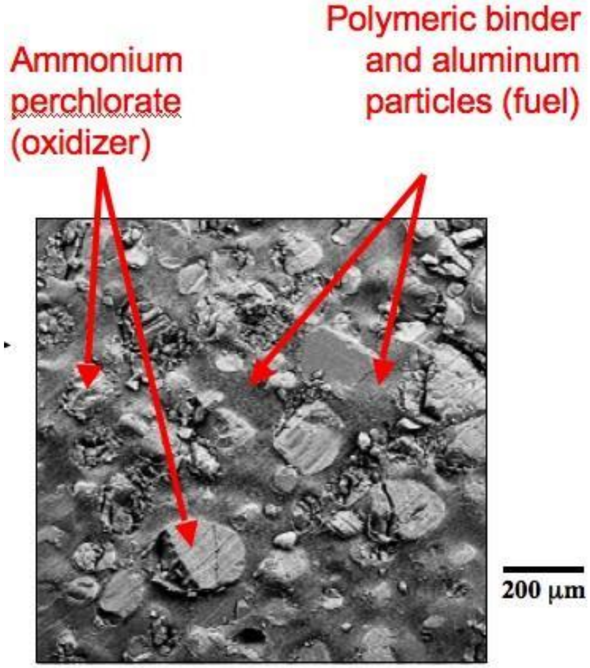
Load Source	Description of Load and Critical Stress Area
1. Cool-down during manufacture after hot cure	Temperature differential across case and grain; tension and compression stresses on grain surfaces; hot grain, cool case
2. Thermal cycling during storage or transport	Alternative hot and cold environment; critical condition is with cold grain, hot case; two critical areas: bond-line tensile stress (tearing), inner-bore surface cracking
3. Improper handling and transport vibrations	Shock and vibration, 5 to $30g_0$ forces during road transport at 5 to 300 Hz (5 to 2500 Hz for external aircraft carry) for hours or days; critical failure: grain fracture or grain debonding
4. Ignition shock/pressure loading	Case expands and grain compresses; axial pressure differential is severe with end-burning grains; critical areas; fracture and debonding at grain periphery
5. Friction of internal gas flow in cavity	Axially rearward force on grain
6. Launch and axial flight acceleration	Inertial load mostly axial; shear stress at bond line; slump deformation in large motors can reduce port diameter
7. Flight maneuvers (e.g., antimissile rocket)	High side accelerations cause unsymmetrical stress distribution; can result in debonding or cracks
8. Centrifugal forces in spin-stabilized projectiles/missiles	High strain at inner burning surfaces; cracks will form
9. Gravity slump during storage; only in large motors	Stresses and deformation in perforation can be minimized by rotating the motor periodically; port area can be reduced by slump
10. External air friction when case is also the vehicle's skin	Heating of propellant, liner and insulators will lower their strengths causing premature failure. Induces thermal stresses

Handling

- Manufacturer to WSU
- Inspection and handling on campus
- Over 800 miles
- About 13 hours trip to Green River, UT
- Pre launch

Grain damage

- Most propellants are viscoelastic i.e non-linear viscoelastic behavior
- Adhesive between individual solid particles and binder gets broken down
  - Caused by cyclic load/thermal stress
  - Maximum stress/strain diminishes with each cycle
- Varies between space motor to tactical missile to ballistic missile

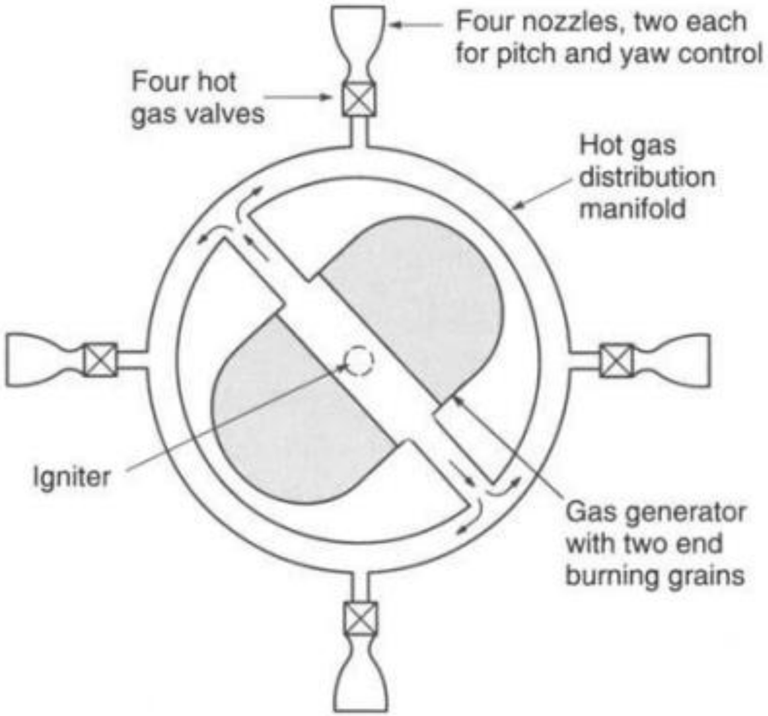


Micrograph of solid propellant

(3)

Reaction Control Systems

- 2 types of RCS
  - Main exhaust RCS
  - Monopropellant RCS
- Main exhaust RCS used during mid-flight maneuvers
- Monopropellant RCS used for orbital maneuvers for finer maneuvering



Orion Launch Abort System (LAS)

Summary

- Knowing how burning rate relates and changes with mass flow, pressure, and temperature is key to solid motor design.
- Grain configuration is necessary in large scale motors, but can be neglected in our design case.
- For our case, handling is a big deal since we’ll be driving it down to competition.
- RCS won’t be used in the competition rocket since our rocket will have roughly a 2 second burn time.

Bibliography

(1) www.dtic.mil/cgi-bin/GetTRDoc?AD=ada425146
(2) Rocket Propulsion Elements by George P. Sutton and Oscar Biblarz, 8th ed.

http://www.csar.illinois.edu/rocstar/