Solid Rockets

Solid Rocket Motors
• Oldest rocket technology

1941 demonstration of Jet Assisted Takeoff (JATO)

Fire Arrow launcher from 14th century Huǒ Lóng Jīng (developed before 1230)

Boxer Rocket (1855), two-stage, used for rescue operations

– powder based propellants (black powder, amide* powder for JATO)

*no sulfur and ammonium nitrate added
Solid Rocket Motors

- Compared to LREs

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple (less system components)</td>
<td>Lower Isp</td>
</tr>
<tr>
<td>Reliable (few moving parts)</td>
<td>Harder to test (no subcomponent tests) and sensitive to environmental temp.</td>
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<td>Reduced storage volume (high ( \rho ))</td>
<td>Hard to actively throttle</td>
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<tr>
<td>Storable (especially compared to cryogenics)</td>
<td>Manufacturing defects (e.g., cracks) and degradation at extreme storage conditions</td>
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<td>Easier to start (vs. pump fed LREs)</td>
<td>No restarts</td>
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<tr>
<td>Easily(?!) scalable (to high and low thrust)</td>
<td>Emissions (HCl and chlorinated compounds) and signature (smoke) for popular propellants</td>
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Solid Rockets - Major Applications

- High thrust
  - boosters
  - high acceleration missiles

- Simplicity, storability
  - hobbyists, weapons systems
  - novel programmable micro-thrusters
Solid Motor Components

- Segmented high-strength steel case to promote reusability
- 88% solids, 19% Al HTPB propellant (see Sec. 6.4)
- Kevlar-loaded EPDM insulation (see Sec. 6.3.6)

Nozzle assembly
Carbon phenolic, silica phenolic, and steel construction (see Sec. 6.3.7 and 6.3.8)

Fig. 6.2. Schematic of ASRM (Advanced Solid Rocket Motor). Courtesy of Aerojet Corporation. From Humble

Solid Propellants

- Two basic types
- Homogeneous
  - reactants (fuel, oxidizer) mixed at molecular level
  - e.g., double-base propellants
- Heterogeneous
  - fuel and oxidizer are “macroscopically” separated
  - e.g., composite propellants
Double-Base Propellant

- Nitrocellulose + Nitroglycerine
  - see Table 12.6 Sutton
- Used in early modern rockets, e.g. at JPL
  - replaced gun/black powder
  - used in WWII JATOs and early Sidewinders

Composite Propellants

- “Oxidizer” particles held together in polymer (fuel)
- Ground oxid. crystals
  - materials
- Binder
  - materials
- Curing agents
- Other fuels (metals) and catalysts
  see Table 12-7 Sutton
Mass “Production” Rate

- Propellant converted to gas at rate given by
  \[ \dot{m} = r \rho_s A_b \]  
  \tag{VI.1} 
  \text{(VI.1) ~ Propellant converted to gas at rate given by}

- (Surface) Regression Rate \( r \)
  \[ r = \frac{dx}{dt} \text{ sometimes } \dot{r}_b \]
  – standard model (Burning Rate “Law” or St. Robert’s “Law”)
  \[ r = a \rho_o^n \text{ with } a = f(T, ...) \]  
  \tag{VI.2} 
  \text{– also, } \dot{r} = c + b \rho_o^n \text{ etc.}

Solid Propellant Burning Rate

\[ \ln r \cong \ln a + n \ln \rho \]  
\text{FIGURE 11.6. From Sutton}
Motor Internal Ballistics

- What governs motor internal conditions?
- Examine mass conservation

\[
0 = \frac{dm_{CV}}{dt} + \int \rho(\vec{u} \cdot \hat{n})dA
\]

\[
0 = \frac{d}{dt}\left(\rho_o V_o + \dot{m}_{exit} - \dot{m}_b\right)
\]

\[
V_o \frac{dp_o}{dt} + \rho_o \frac{dV_o}{dt}
\]

Assuming:
1) uniform gas prop's. in CV
2) TPG, CPG
3) \(T_o = \text{constant} \) (e.g., \(T_{ad}\))
4) \(p_o, A_b, r \) given at time \(t\)

Internal Ballistics (con’t)

- Solve for rate of pressure change

\[
\frac{V_o}{RT_o} \frac{dp_o}{dt} = r A_b (\rho_s - \rho_o) - p_o A_i \left(\frac{\gamma}{RT_o} \left(\frac{2}{\gamma + 1}\right)\right)^{\frac{\gamma + 1}{\gamma - 1}}
\]

- For steady (neutral) burning

\[
\frac{dp_o}{dt} = 0 \Rightarrow p_o = r A_b (\rho_s - \rho_o) c^* \quad (VI.4)
\]

- using standard burning rate law

\[
p_o = a p_o^n A_e (\rho_s - \rho_o) c^* \Rightarrow p_o = \left[aK(\rho_s - \rho_o)c^*\right]^\frac{1}{n} \quad (VI.5)
\]

For steady burning (if \(a, n, T_o, \gamma, \) and \(A_i, \text{constant}\)) then \(A_b \) must be constant
Pressure Histories

- Motor designer can adjust pressure profile ("history") of a solid motor by arranging how burning area changes with time (grain geometry)
- Thrust given by $\tau = p_0 A_t c_\tau$
  - so thrust history of motor essentially follows motor's pressure history
- Characterize pressure/thrust histories as generally
  - progressive: increase with time
  - neutral: constant with time
  - regressive: decrease with time
  - combinations

Grain Geometries and Thrust History

From Hill and Peterson

**FIGURE 12.17** Internal-burning charge designs with their thrust-time programs. (Courtesy Shafer [18])

From Hill and Peterson
SSRB (Space Shuttle Rocket Booster)

- SRBs are largest solid propellant motors ever flown and first designed for reuse
  - Diameter = 12.17 ft
  - Length = 149.16 ft
- Sea Level Thrust: 3,300,000 lb
- Weight
  - With propellant: 1,300,000 lb
  - Inert: 192,000 lb
- Provide ~ 71% of thrust at lift-off and ascent
- Propellant composition (mass fractions)
  - AP: 69.6%, Al: 16%, Fe₂O₃ (catalyst): 0.4%, HTPB (binder): 12.04% epoxy (curing agent): 1.96%
- Four segments
  - 11 point star shape in forward segment
  - double truncated cone in 3 aft segments

Motor Stability

- Recall mass conservation for steady operation ($p_o =$constant)
  \[ \dot{m}_{exit} = \dot{m}_b - \rho_o A_b r = A_b (\rho_s - \rho_o) r = \Delta m_{incr} \]
  \[ \dot{m}_{exit} \propto p_o \]
  \[ \Delta m_{incr} \propto p_o^n \]

- Is this condition (point) stable?
  - only if $n \leq 1$
  - normally use $0.3 < n < 0.7$
Combustion Limits

- If \( n \) or \( p_o \) too low
  - do not get stable combustion
  - after ignition, propellant soon stops burning (\( r \rightarrow 0 \))

- At high \( p_o \)
  - possibility of erratic, unpredictable burning (usually > 5000 psi)

Design of an End-Burning Motor

- Start with end burning motor
  - easiest to analyze
  - constant thrust straight-forward
  - used in some small motors and gas generators

- Requirements
  - \( \Delta t_b = 100 \text{ s}, \tau_{\text{vac}} = 500 \text{ kN} \left( 10^5 \text{ lb} \right) \)

- Constraints
  - \( p_o = 4 \text{ MPa} \) (assume uniform)
  - nozzle: \( c^* = 1.85 \) (\( \epsilon \sim 30-50 \))
  - propellant: \( c^* = 1500 \text{ m/s}, \gamma = 1.2, \text{MW} = 24, \rho_s = 1800 \text{ kg/m}^3, \)
  - \( r = 0.40 \left( p_o (\text{MPa}) \right)^{0.3} \text{ cm/s} \)

- Design Variables
  - \( D_t, D_b, \ell_{\text{web}} \) (assume axisymmetric-cylindrical geometry)
End-Burning Motor Example

• Nozzle throat size, $D_t$

\[
A_t = \frac{\tau}{p_0 c_t} = \frac{5 \times 10^5 N}{(4 \times 10^6 N/m^2) 1.85} = 0.0676 m^2
\]

\[\Rightarrow D_t = 29 cm (~ 1 ft)\]

• Motor length, $\ell_{web}$

\[
r = \frac{dx}{dt} \quad \text{steady burning}
\]

\[= \frac{\ell_{web}}{t_b}
\]

\[
\ell_{web} = r t_b = 0.4(4)^{0.3} \text{ cm/s} (100 s)
\]

\[= 0.61 \text{ cm/s} (100 s)
\]

\[\ell_{web} = 61 \text{ cm}
\]

\[\Rightarrow \ell_{web} / D_t \approx 2
\]

$D_t = 29 \text{ cm}$
End-Burning Motor Example

- Motor diameter, $D_b$
  - recall for steady-burn

\[
p_o = r \frac{A_b}{A_i} \left( \rho_i - \rho_o \right) c^* \]

\[
\frac{A_b}{A_i} \equiv K = \frac{p_o}{r(\rho_i - \rho_o)c^*} \geq \frac{p_o}{r \rho_i c^*} = \frac{4 \times 10^6 \text{ N/m}^2}{0.0061 \text{ m/s} \left(1800 \text{ kg/m}^3\right) \text{1500 m/s}} = 243
\]

\[
\Rightarrow D_b = \sqrt{243(29 \text{ cm})} = 4.57 \text{ m} \Rightarrow \frac{D_b}{\ell_{web}} \approx 7.5!!!!
\]

Huge end-burning motors to produce high thrust