Rocket Propulsion

Solid Rocket Motors

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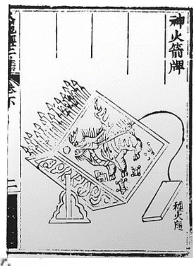
Background

Solid Rocket Motors

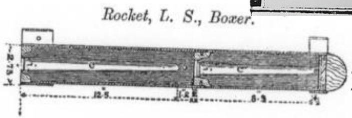
- Oldest rocket technology

credit: National Air and Space Museum

1941 demonstration of Jet Assisted Takeoff (JATO)



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



cyber-heritage.co.uk /rocketrocket/rockets.htm

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

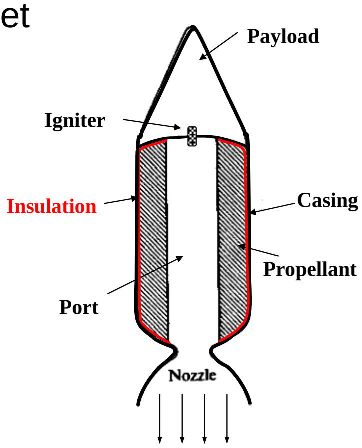
Advantages	Disadvantages
Simple (less system components)	Lower Isp
Reliable (few moving parts)	Harder to test (no subcomponent tests) and sensitive to environmental temp.
Reduced storage volume (high ρ)	Hard to actively throttle
Storable (especially compared to cryogenics)	Manufacturing defects (e.g., cracks) and degradation at extreme storage conditions
Easier to start (vs. pump fed LREs)	No restarts
Easily(?) scalable (to high and low thrust)	Emissions (HCl and chlorinated compounds) and signature (smoke) for popular propellants

Solid Rockets - Major Applications

- **High thrust**
  - boosters
  - high acceleration missiles
- **Simplicity, storability**
  - hobbyists, weapons systems
  - novel programmable micro-thrusters

SRM Components/Nomenclature

- Basic parts of a solid rocket motor (SRM)
  - casing
  - insulation
  - propellant (grain)
  - port/bore (not for end burning)
  - igniter
  - payload
  - nozzle



SRM Launch Booster Example

Titan IV

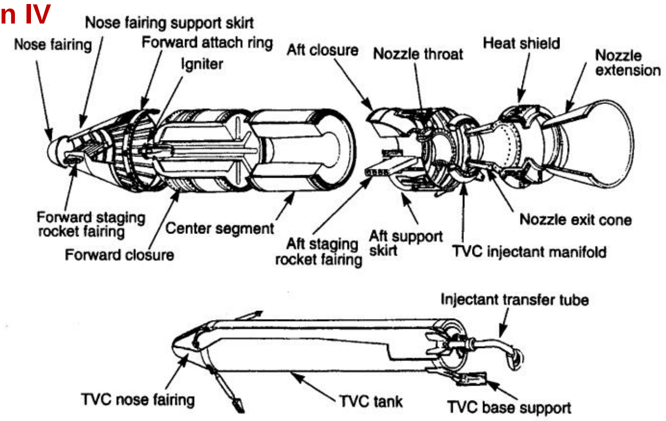


Fig. 6.3. **Schematic of Titan IV Motor.** (TVC = Thrust Vector Control) Courtesy of United Technologies Chemical Systems.

From Humble

SRM In-Space Example

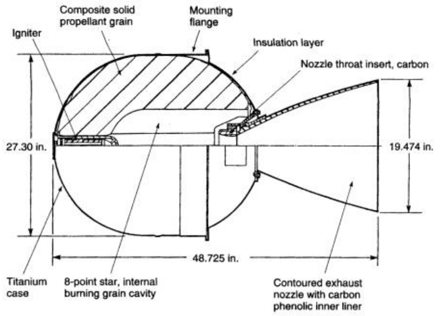


FIGURE 11–1. Cross section of the STAR^{TM} 27 rocket motor, which has been used for orbit and satellite maneuvers. It has an altitude thrust of 6000 lbf, nominally burns for 34.4 sec and has an initial mass of 796 lbm. For more data see Table 11–3. (Courtesy of Thiokol Propulsion, a Division of Cordant Technologies.)

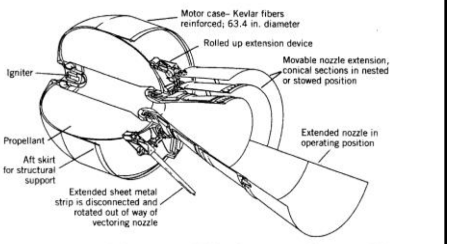


FIGURE 11–3. Inertial upper stage (IUS) rocket motor with an extendible exit cone (EEC). This motor is used for propelling upper launch vehicle stages or spacecraft. The grain is simple (internal tube perforation). With the EEC and a thrust vector control, the

STAR (apogee kick motor): CTS, GMS, BS, GPS, GOES satellites

from Sutton, Rocket Propulsion

Inertial Upper Stage (IUS): used in Titan, Space Shuttle launches

Solid Propellants

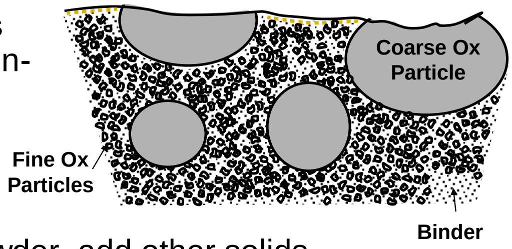
- Two basic types
- **Homogeneous**
  - reactants (fuel, oxidizer) mixed at molecular level
  - e.g., double-base propellants
- **Heterogeneous**
  - fuel and oxidizer are “macroscopically” separated
  - e.g., composite propellants

Double-Base Propellants

- Typically combination of explosive liquid and self-burning powder
  - e.g., nitroglycerine and nitrocellulose (gun cotton, flash paper)
  - powder absorbs liquid explosive, molecularly mixed
  - other additives (opacifier, stabilizers, burn-rate modifiers, flash suppressors)
- Can be extruded or cast
- Used in early modern rockets, e.g. at JPL
  - replaced gun/black powder
  - used in WWII JATOs and early Sidewinder
  - weapons systems

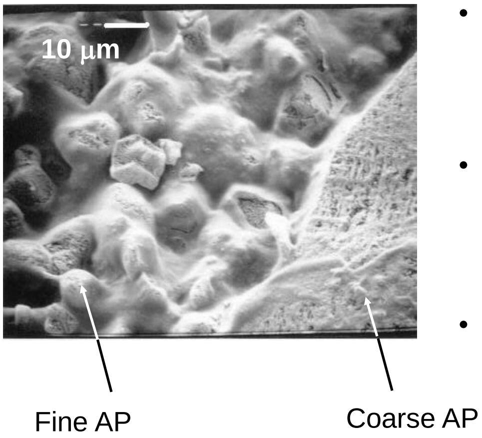
Composite Propellants (CP)

- “Oxidizer” particles held together in non-energetic polymer binder (fuel)
- Manufacture
  - grind oxidizer crystals into powder, add other solids (e.g., catalysts)
  - mix liquid binder with liquid curing agents, crosslinkers, plasticizers, stabilizers, bonding agents
  - mix solids and liquids, cast and cure



Cleaved Composite Propellant Sample

Scanning Electron Microscope (SEM) image



- 10μm and 400μm ammonium perchlorate (AP) particles
  - self-burning oxidizer
- HTPB binder
  - polymer (like a synthetic rubber)
  - fuel
- 92% solids
  - relatively high solids loading

Rocket Propulsion

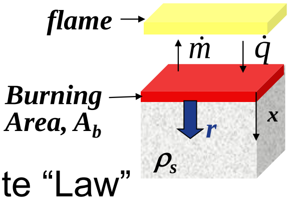
Solid Rocket Motors

Regression Rate and Internal Ballistics

Mass "Production" Rate

- Propellant converted to gas due to heat feedback from flame at rate given by

(IV.26) $\boxed{\dot{m} = r\rho_s A_b}$



- (Surface) **Regression Rate *r***

$r = dx/dt$ *sometimes* $\dot{r}_b$

  - standard model (Burning Rate "Law" or St. Robert's "Law")

(IV.27) $\boxed{r = a p_o^n}$ *with* $a = f(T_{solid}, \ldots)$

  - also, $r = c + b p_o^n$ etc.

Solid Propellant Burning Rate

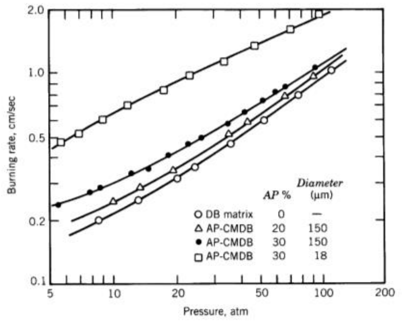
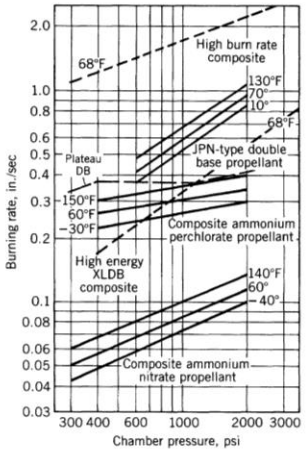


FIGURE 11–7. Measured burning rate characteristics of a double-base (DB) propellant and three composite-modified double-base (CMDB) propellants which contain an increasing percentage of small diameter (159 µm) particles of ammonium perchlorate (AP). When the size of the AP particles is reduced or the percentage of AP is increased, an increase in burning rate is observed. None of these data form straight lines.



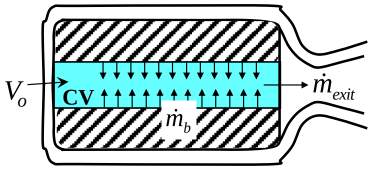
$$r = a p_o^n \Rightarrow \quad \ln r = \ln a + n \ln p$$

FIGURE 11–6.

From Sutton

Motor Internal Ballistics

- What governs motor internal conditions?
- Examine mass conservation



$$0 = \underbrace{\frac{dm_{CV}}{dt}}_{\dot{m}_{store}} + \int \rho(\vec{u}\cdot\hat{n})dA$$

$$0 = \underbrace{\frac{d}{dt}(\rho_o V_o)} + \dot{m}_{exit} - \dot{m}_b$$

$$V_o \frac{d\rho_o}{dt} + \rho_o \frac{dV_o}{dt} \qquad r\rho_s A_b$$

$$\underbrace{\frac{1}{RT_o}\frac{dp_o}{dt}}_{\dot{m}_{store,p}} \qquad \underbrace{\rho_o(A_b r)}_{\dot{m}_{store,V}} \qquad \frac{p_o}{\sqrt{RT_o}}\sqrt{\gamma}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} A_t$$

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

$$\dot{m}_{store,p} + \dot{m}_{store,V} = \dot{m}_b - \dot{m}_{exit}$$

Internal Ballistics (con't)

- Solve for rate of pressure change

$$\boxed{\frac{V_o}{RT_o}\frac{dp_o}{dt}=rA_b\left(\rho_s-\rho_o\right)-p_oA_t\underbrace{\sqrt{\frac{\gamma}{RT_o}\left(\frac{2}{\gamma+1}\right)^{\gamma+1/\gamma-1}}}_{=1/c^*}} \quad \textbf{(IV.28)}$$

- For steady burning

$$\frac{dp_o}{dt}\equiv 0 \quad \Rightarrow \boxed{p_o=r\frac{A_b}{A_t}\left(\rho_s-\rho_o\right)c^*} \quad \textbf{(IV.29)}$$

  - using standard burning rate law

$$p_o=ap_o^n\frac{A_b}{A_t}\left(\rho_s-\rho_o\right)c^* \quad \Rightarrow \boxed{p_o=\left[aK\left(\rho_s-\rho_o\right)c^*\right]^{1/1-n}} \quad \textbf{(IV.30)}$$

~ρ_s in many cases

$$A_b/A_t\equiv K$$

For steady burning (if a , n , T_o, γ, and A_t constant) then A_b must be constant

$$p_o\sim K^{1/1-n}$$

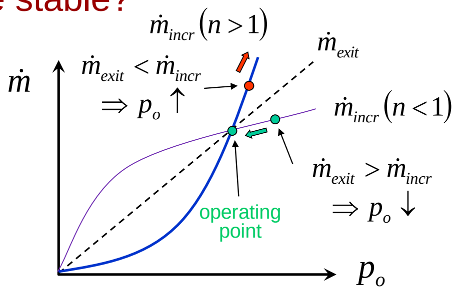
Motor Stability

- Recall mass conservation (for fixed T_o)

$$\dot{m}_{store,p}=\dot{m}_b-\dot{m}_{store,V}-\dot{m}_{exit} \qquad \dot{m}_{exit}=c^*p_oA_t\propto p_o$$

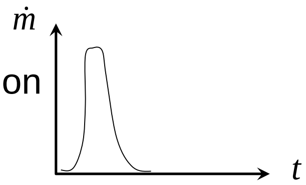
$$=\dot{m}_{incr}-\dot{m}_{exit} \qquad \dot{m}_{incr}=A_b\left(\rho_s-\rho_o\right)r\propto p_o^n$$

- For stable operation (p_o= const), need $\dot{m}_{store,p}$= 0
- So when are we 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 too high p_o
  - possibility of erratic, unpredictable burning
  - e.g., $p_o > 5000$ psi)

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 $\tau = p_o A_t c_\tau$
  - 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

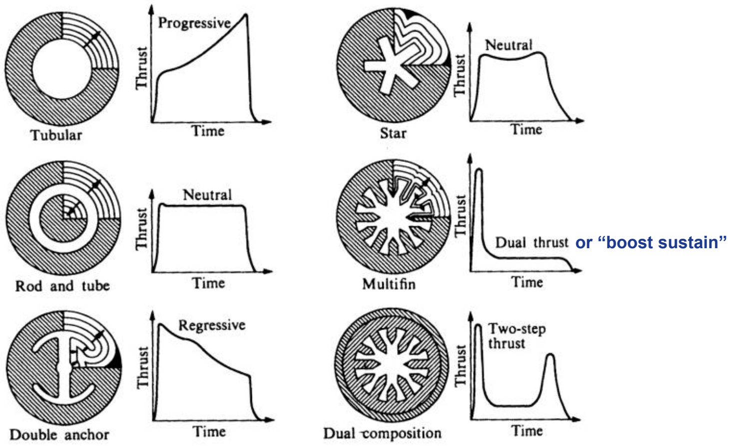


FIGURE 12.17 Internal-burning charge designs with their thrust-time programs. (Courtesy Shafer [18].)

From Hill and Peterson

More Solid Motor Grain Geometries

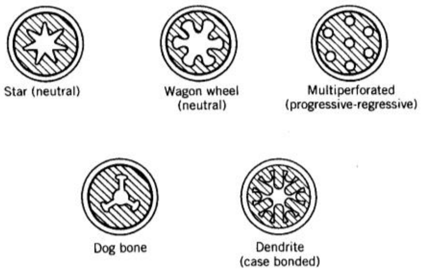
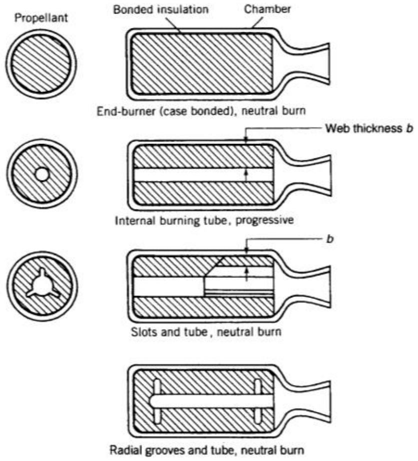
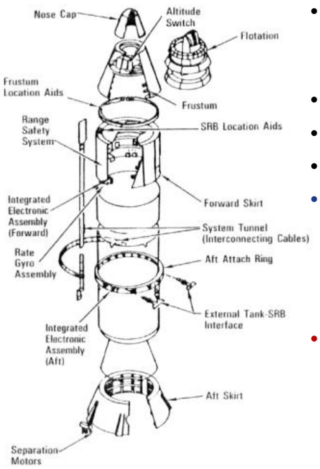


FIGURE 11–16. Simplified diagrams of several grain configu



From Sutton

SSRB (Space Shuttle Rocket Booster)



Solid Rocket Booster—Exploded View

- Largest SRM flown and first designed for reuse
  - diameter = 12.17 ft, length = 149.16 ft
- Sea Level Thrust: 3,300,000 lb
- Weight: 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%,
    Fe_2O_3 (catalyst): 0.4%,
    HTPB (binder): 12.04%
    epoxy (curing agent): 1.96%
- Four segments
  - 11 point star (neutral) in forward segment
  - double truncated cone (regressive) in 3 aft segments

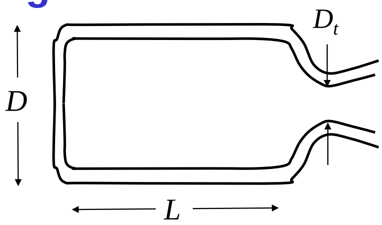
http://spaceflightnow.com/2015/03/11/worlds-largest-solid-rocket-motor-fired-in-utah/

Rocket Propulsion

Solid Rocket Motors

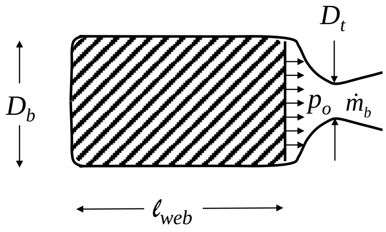
Design Issues and Example

SRM Design



- **Typical Requirements**
  - thrust, $\tau(t)$
  - burn time, Δt_b or total impulse, I_{tot}
- **Design Variables**
  - propellant composition ($\Rightarrow c^*, a, n$)
  - grain design
  - motor geometry: D, L
  - nozzle geometry: ε, D_t
- **Unsteady variables**
  - $p_o(t), \dot{m}(t), \ldots$
- **Other constraints/issues**
  - high volume loading fraction ($V_{propellant}/V_{chamber}$)
  - low residual propellant mass
  - structural integrity
  - limit erosive burning
  - limit max operating press.

Design of an End-Burning Motor



- Start with end burning motor
  - easiest to analyze
  - constant thrust
  - used in some small motors and gas generators
- **Requirements**
  - Δt_b=100 s, τ_{vac}=500 kN (10^5 lb_f)
- **Constraints**
  - p_o=4 MPa (assume uniform)
  - nozzle: c_τ=1.85 (ε~30-50)
  - propellant: c^*=1500 m/s, γ=1.2, MW=24, ρ_s=1800 kg/m^3,
    r=0.40 [p_o(MPa)]$^{0.3}$ cm/s
- **Design Variables**
  - $\boldsymbol{D_t, D_b, \ell_{web}}$ (assume axisymmetric-cylindrical geometry)

End-Burning Motor Example

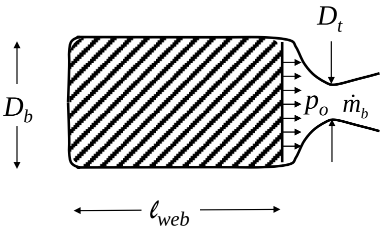
- Nozzle throat size, $\boldsymbol{D_t}$

from (IV.12)

$$A_t = \frac{\tau}{p_o c_\tau}$$

$$= \frac{5\times10^5\,N}{\left(4\times10^6\,N/m^2\right)1.85}$$

$$= 0.0676 m^2$$



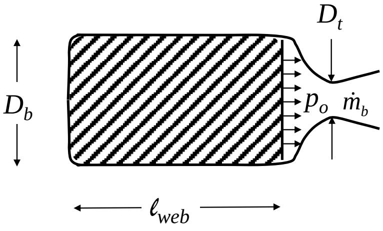
$$A_t = \pi D_t^2/4 \quad \boxed{\Rightarrow D_t = 29cm(\sim 1ft)}$$

End-Burning Motor Example

- Motor length, $\boldsymbol{\ell_{web}}$

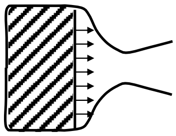
$$r = \frac{dx}{dt} \quad \text{steady burning}$$

$$= \frac{\ell_{web}}{t_b}$$



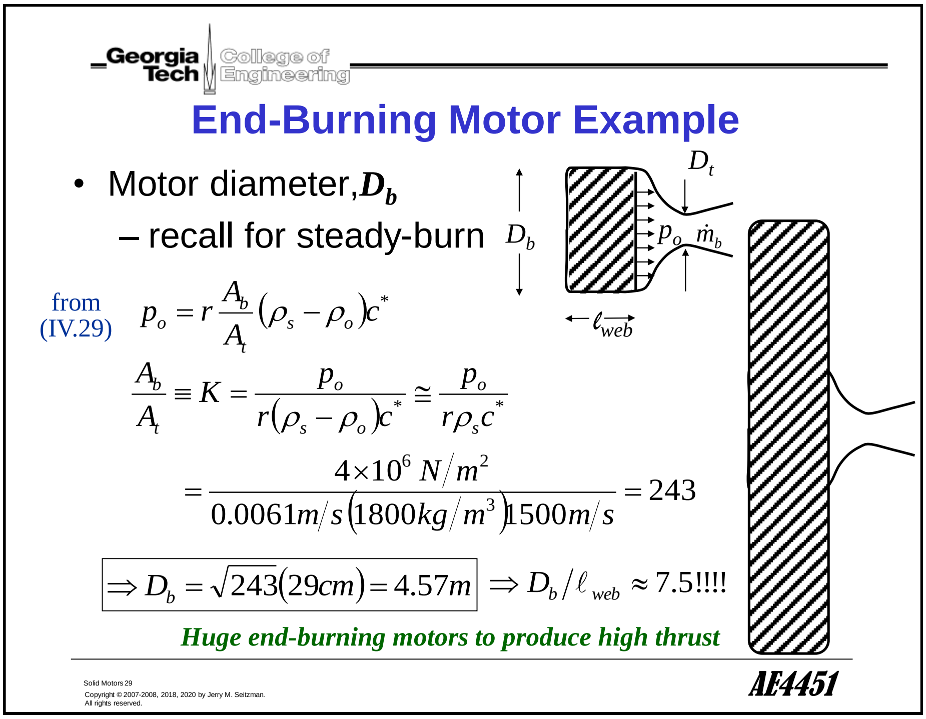
$$\ell_{web} = rt_b = 0.4(4)^{0.3}\,cm/s\,(100s)$$

$$= 0.61\,cm/s\,(100\,s)$$



$$\boxed{\ell_{web} = 61cm} \qquad \Rightarrow \ell_{web}/D_t \approx 2$$

$$D_t = 29cm$$



End-Burning Motor Example

- Motor diameter, D_b
  - recall for steady-burn

from (IV.29)

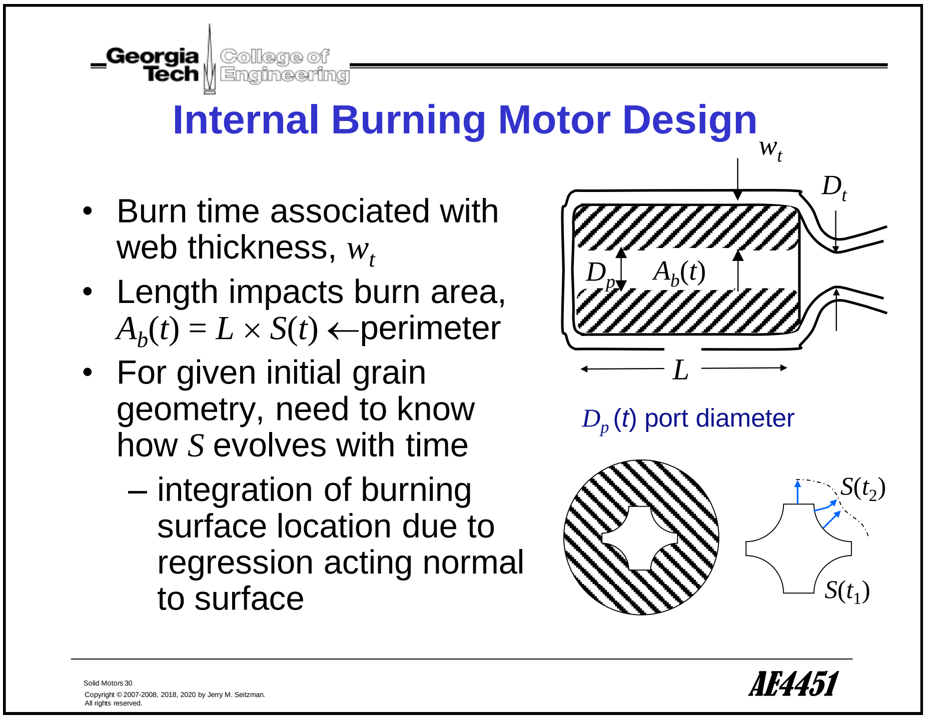
$$p_o = r\frac{A_b}{A_t}(\rho_s-\rho_o)c^*$$

$$\frac{A_b}{A_t} \equiv K = \frac{p_o}{r(\rho_s-\rho_o)c^*} \cong \frac{p_o}{r\rho_s c^*}$$

$$= \frac{4\times10^6\, N/m^2}{0.0061 m/s\,(1800 kg/m^3)\,1500 m/s} = 243$$

$$\boxed{\Rightarrow D_b = \sqrt{243}(29cm) = 4.57m} \Rightarrow D_b/\ell_{web} \approx 7.5!!!!$$

Huge end-burning motors to produce high thrust



Internal Burning Motor Design

- Burn time associated with web thickness, w_t
- Length impacts burn area, $A_b(t) = L \times S(t)$ ←perimeter
- For given initial grain geometry, need to know how S evolves with time
  - integration of burning surface location due to regression acting normal to surface

$D_p\,(t)$ port diameter