National Aeronautics and
Space Administration

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Student Launch – Propulsion Systems

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Propulsion Systems

Propulsion Theory
Rocket Propellants
Solid Rocket Motors
Definition of HPR
Motor Classifications
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Thrust to Weight
Thrust Curves



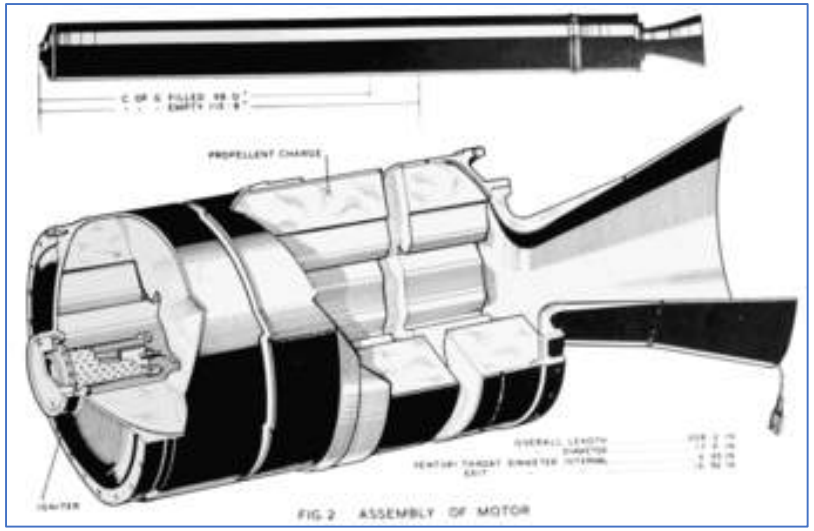


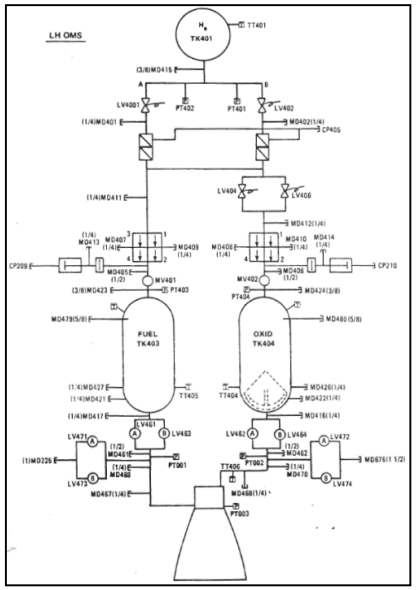


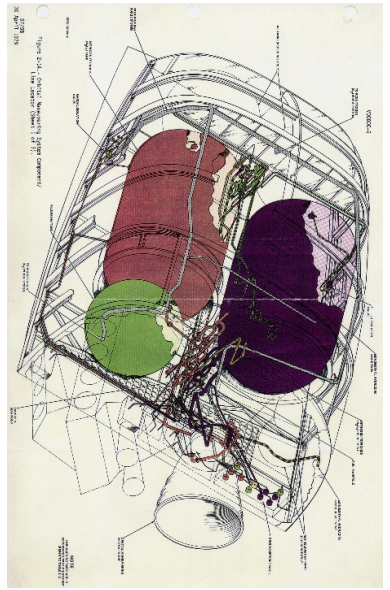
Basic Flavors of Propulsion

- Liquid Propellant
  - Both fuel and oxidizer are separately stored liquids
  - Mechanically complex, expensive, not generally used by amateurs
  - Examples: LH2/LOX, kerosene/LOX, alcohol/H2O2, NTO/MMH
  - Applicability: Earth Surface and Outer Space
- Solid Propellant
  - Both fuel and oxidizer are mixed together as a solid mass.
  - Examples: black powder, ammonium perchlorate propellant
  - Applicability: Earth Surface and Outer Space
- Hybrid
  - Solid fuel, liquid oxidizer
  - Examples: plastic/NO2, HTPB/O2, HTPB/NO2, Paraffin/O2
  - Applicability: Earth Surface and Outer Space
- Monopropellant
  - Catalyzes a propellant to generate hot, high-pressure
  - Examples: hydrazine, H2O2
  - Applicability: Outer Space mostly
- Electric
  - Electrical ions generate thrust
  - Very low thrust, very high efficiency
  - Applicability: Outer Space only

Solids vs. Liquids







Solid Propulsion

- Fuel and oxidizer are premixed
- Efficiency: 200 – 300 sec ISP
- Single use
- Compact size, moderate cost: great for throw-away stages
- Major failures are managed by minimal safe distances

Liquid Propulsion

- Fuel and oxidizer stored separately
- Efficiency: 250 – 450 sec ISP
- Restartable
- Requires tanks, valves
- Failures are REALLY catastrophic

Note: SL teams are limited to commercial solid motors.

Propulsion Theory

Propulsion Systems

- Store propellants
- Move propellants into a combustion chamber
- Burn propellants to raise their energy and pressure
- Expand the combustion gases through a converging-diverging nozzle to achieve high exit velocities



Propulsion Theory

Newton's Laws

1st Law, "Law of Inertia"

Objects in motion/rest will remain in that state until acted on by an outside force.

2nd Law, "Law of Momentum"

Resultant Force of an object is proportional to the object's change in momentum

3rd Law, "Law of Action/Reaction"

Two bodies interact with equal and opposite force

Propulsion Theory – Newton's Laws and Rocketry

$\mathbf{p} = m\mathbf{v}.$ Linear momentum = objects mass x objects velocity.

$\mathbf{F}_{\text{net}} = \frac{\Delta \mathbf{p}}{\Delta t},$ Force is equal to the change in momentum per change in time. By rearranging we get the below equation

F_{net} = net external Force
Δp = change in momentum
Δt = change in time

$\Delta \mathbf{p} = \mathbf{F}_{\text{net}} \Delta t.$ **Impulse**-momentum theorem. From the equation, we see that the impulse equals the average net external force multiplied by the time this force acts. It is equal to the change in momentum.

$\Delta \mathbf{p} = \Delta(m\mathbf{v})$ By taking the change in each side of the first equation we get this.

$\Delta(m\mathbf{v}) = m\Delta\mathbf{v}$ Assuming we have a constant mass, we can re-write our equation

$\mathbf{F}_{\text{net}} = \frac{\Delta \mathbf{p}}{\Delta t} = \frac{m\Delta \mathbf{v}}{\Delta t}$ Recall from calculus that $\frac{\Delta \mathbf{v}}{\Delta t} = \mathbf{a}$ Thus, $\mathbf{F}_{\text{net}} = m\mathbf{a}$ □

Propulsion Theory – Newton's Laws and Rocketry

Recall Newton's third law, "Two bodies react with equal and opposite force, o

$$\begin{aligned} \vec{\mathbf{F}}_{21} &= -\vec{\mathbf{F}}_{12} \\ m_1\vec{\mathbf{a}}_1 &= -m_2\vec{\mathbf{a}}_2. \end{aligned}$$

Worth noting the forces don't "cancel" because they are acting on different objects. We can take the derivative of each side and end up with

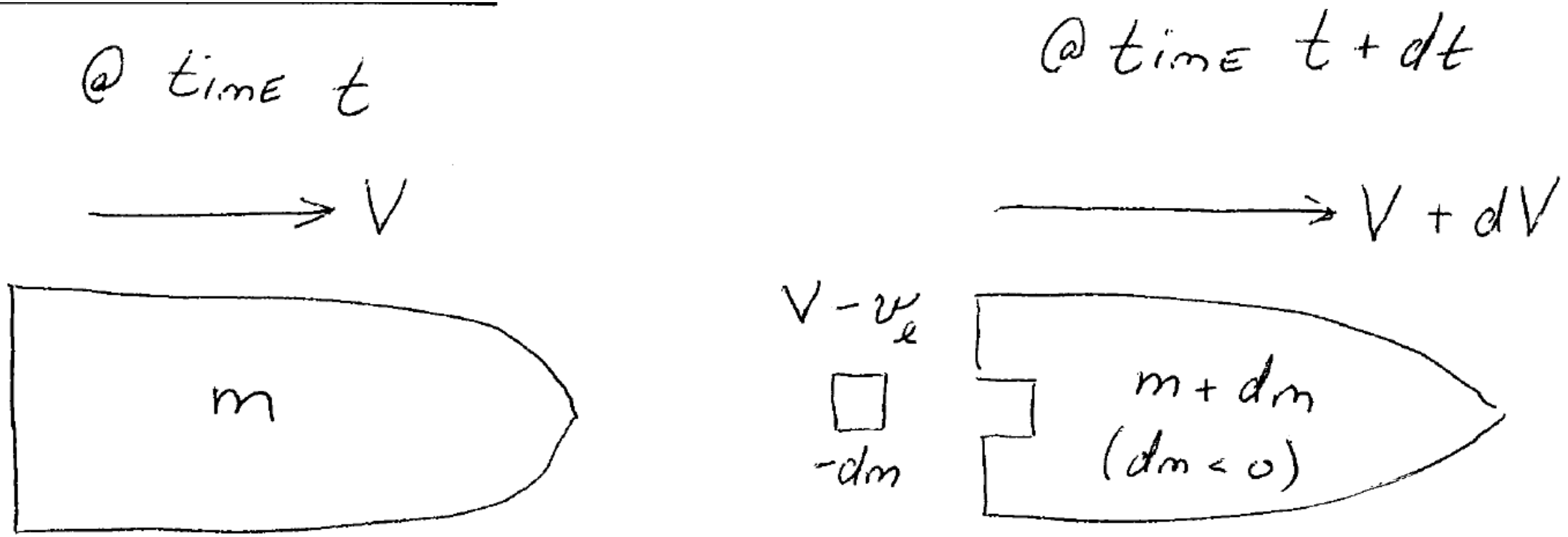
$$\frac{d}{dt}(m_1\vec{\mathbf{v}}_1) = -\frac{d}{dt}(m_2\vec{\mathbf{v}}_2)$$

By using p = m*v we replace m_1v_1 with p_1 and similar logic for p_2 we end up with

$$\frac{d}{dt}(\vec{\mathbf{p}}_1 + \vec{\mathbf{p}}_2) = 0$$

Thus, $\vec{\mathbf{p}}_1 + \vec{\mathbf{p}}_2 = \text{constant}.$

Propulsion Theory – Ideal Rocket Equation



$m*v = -(dm)(v-v_e) + (m+dm)(v+dv)$ or $m*v = -v*dm + dm*v_e + m*v + m*dv + dm*v + dm*dv$

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Propulsion Theory – Ideal Rocket Equation Continued

$m*v = -v*dm + dm*v_e + m*v + m*dv + dm*v + dm*dv$, now canceling of terms we're left with

$-v_e*dm = m*dv$ calculus allows us to separate into $\frac{1}{m}dm = -\frac{1}{v_e}dv$ and then integrate to

$$\int_{m_i}^{m_f} \frac{dm}{m} = \frac{-1}{v_e}\int_{v_i}^{v_f} dv$$ By solving this we get $$\ln(m_f) - \ln(m_i) = \frac{-1}{v_e}\Delta v$$

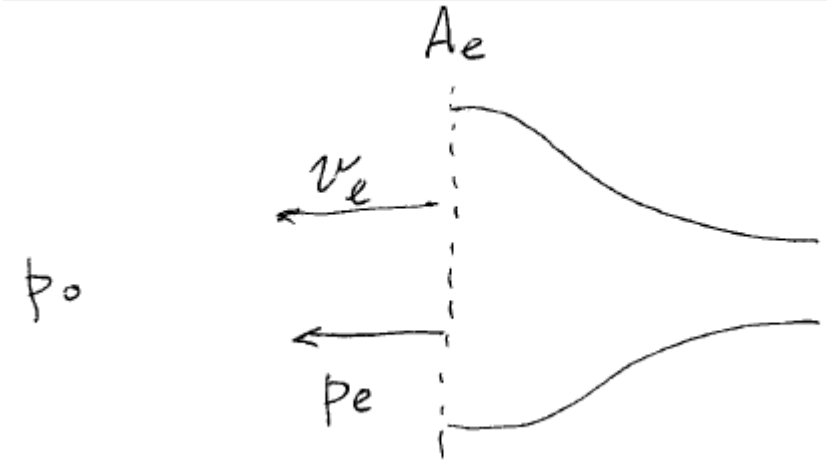
$$\Delta v_{ideal} = v_e[\ln(m_i) - \ln(m_f) = v_e * ln\left(\frac{m_i}{m_f}\right)$$ Assuming no other external forces

$$\Delta v_{actual} = \Delta v_{ideal} - \Delta v_{TVL} - \Delta v_{Drag} - \Delta v_{grav}$$

Note $\Delta v_{TVL}, \Delta v_{Drag}, \Delta v_{grav}$ are dependent on your angle of attack

Propulsion Theory – Rocket Thrust Equation and Specific Impulse

Thrust is generated by a rocket engine through the reaction of accelerating a mass of gas.



$$MR = \frac{m_i}{m_f} = e^{\Delta v / g_0 * I_{sp}}$$

$$m_f = m_i * e^{-\Delta v / g_0 * I_{sp}}$$

$$T = \dot{m} * v_e + (p_e - p_0) * A_e$$

Assume $p_e = p_0$ (fully expanded flow)

$$T = \dot{m} * v_e$$ Momentum exchange between exhaust & vehicle

Specific Impulse $I_{sp} = \frac{T}{\dot{m} * g_0}$ Or $T = \dot{m} * g_0 * I_{sp}$

$$\dot{m} * v_e = \dot{m} * g_0 * I_{sp} \qquad v_e = g_0 * I_{sp}$$

$$\Delta v_{ideal} = v_e[\ln(m_i) - \ln(m_f) = v_e * ln\left(\frac{m_i}{m_f}\right)$$

$$\Delta v_{ideal} = g_0 * I_{sp} * ln\left(\frac{m_i}{m_f}\right)$$

All of these variables depend on the design of the nozzle

Propulsion Theory – Mass equations

$$m_i = m_{inert} + m_{P/L} + m_{prop}$$

$$m_f = m_i - m_{prop}$$

$$MR = \frac{m_i}{m_f} = e^{\Delta v / g_0 * I_{sp}} = \frac{m_{inert} + m_{P/L} + m_{prop}}{m_{inert} + m_{P/L}}$$

$$f_{inert} = \frac{m_{inert}}{m_{inert} + m_{prop}}$$

$$m_{inert} = \frac{f_{inert} * m_{prop}}{1 - f_{inert}}$$

$$f_{prop} = 1 - f_{inert}$$

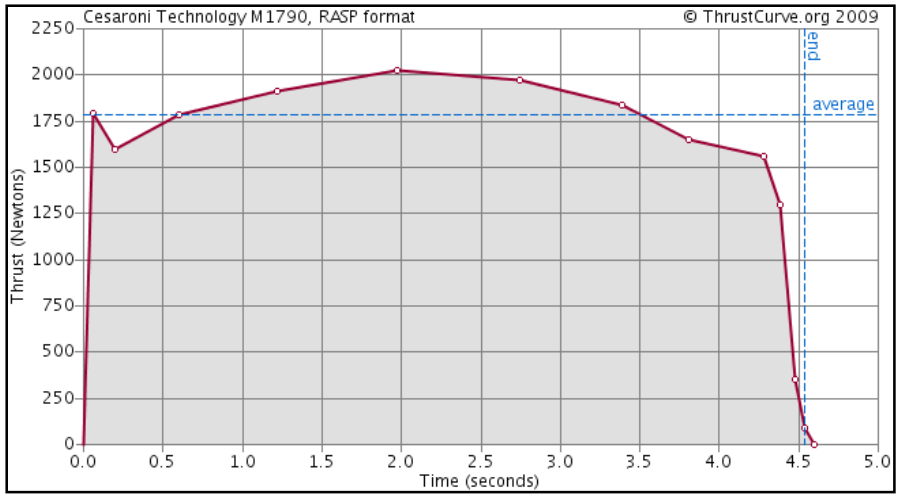
$$m_{prop} = \frac{m_{P/L}(MR - 1)(1 - f_{inert})}{1 - f_{inert} * MR}$$

Total Impulse

- Impulse is the work done by the propellant
- Typically measured in units of Newton-seconds
- The impulse parameter is used to categorize different classes of rocket motors in hobby rocketry
- Impulse can be calculated for both variable and constant thrust rocket motors

$$I = \int_0^t T dt = T_{ave} t_{burn} = \int \dot{m} V_{eq} dt = m V_{eq} \quad (Total\ Impulse\ Equation)$$

- The Thrust (T) and Total Impulse (I) equations above work for both liquid and solid rocket motor



- Practical Example of Impulse
  - I = T*Δt
  - Exact Impulse is derived by integrating the Thrust Curve over the time interval of interest.
  - Impulse can be estimated by I = T_{avg} * burntime
  - I = (1790N)*(4.5sec) = 8055 Nsec (8088 Nsec is advertised by vendor)

Note: SLI teams are limited to motors with a maximum Impulse of 2,560 N*s

Hint: Thrust curves can be downloaded from Thrustcurve.org and imported into RockSim or OpenRocket.

Specific Impulse

- Isp is a measure of efficiency for rockets, as mpg is to automobiles
- Measure of the work (thrust) per unit mass of propellant, measured in seconds
- shows the tie between engine parameters and propulsion thermodynamic parameters like exit velocity

$$\text{Isp} = \frac{F}{\dot{W}} = \frac{\text{thrust}}{\text{fuel weight flow rate}}. \qquad I_{sp} = \frac{T}{\dot{m} * g_0}$$

- The rocket weight will define the required value of thrust
- HPR solid rocket motors generally have an Isp between 170 sec and 220 sec
- It gives us an easy way to "size" an engine during preliminary analysis

Propellant Combination	Specific Impulse I_{sp}
Lox/Kerosene (RP-1, Falcon)	300s
Methane/Lox (Starship) (1/4 cost)	380s
Lox/H_2	450s
Li-F (1950's)	542s
NERVA (Nuclear Engine ended in 1970s	850s

Solid Rocket Motors

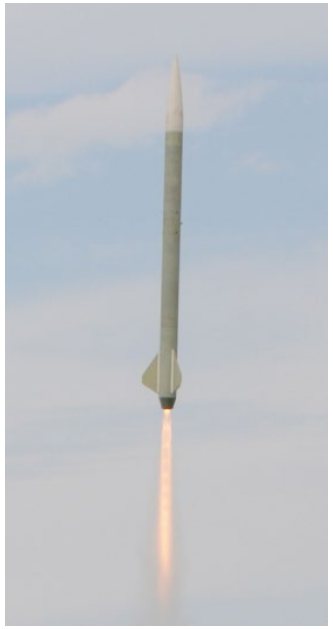
- Typical space exploration applications of SRMs include:
  - Launch vehicle booster
  - Kick stages for geosynchronous and interplanetary spacecraft
  - Breaking motors for interplanetary spacecraft
- Every solid rocket motor has:
  - Nozzle
  - Combustion chamber
  - Solid propellant
  - Igniter
- SRMs are extensively used where:
  - Total impulse requirement is known accurately in advance
  - Where no restart is required
- There are two types of solid rocket motors that you will see in sport rocketry:
  - Black powder motors
  - Composite propellant motors



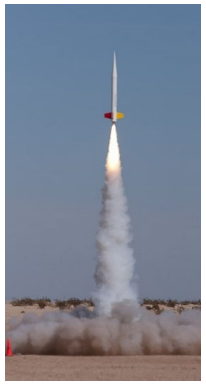
Composite Propellant

- Inorganic Oxidizers
  - Most common is Ammonium Perchlorate (AP)
  - Toxic chlorine gas in exhaust
- Fuels
  - Common metals used as fuel: powdered Aluminum, Magnesium, Barium, Strontium, Titanium
  - Causes exhaust smoke (varying colors)
- Binders
  - Serves dual purpose as fuel and binder
  - Common binders are HTPB, PBAN
- Contain small amounts of chemical additives to improve physical properties
  - Burn rate, smooth burning, casting characteristics, structural properties, absorb moisture during storage











Note: SL teams are limited to Ammonium Perchlorate (AP) motors.

Definition of HPRs

A rocket exceeds the definition of a model rocket under NFPA 1122 and becomes a high-powered rocket under NFPA 1127 if it:

- Uses a motor with more than 160 Newton-seconds of total impulse (and ‘H’ motor or larger) or motors that all together exceed 320 Newton-seconds
- Uses a motor with more than 80 Newtons average thrust (see rocket motor coding)
- Exceeds 62.5 grams of propellant
- Weighs more than 1,500 grams including motor(s)
- Includes any airframe parts of ductile metal

Rocket Motor Classifications

- HPR motors approved for sale in the United States are stamped with a two-part code that gives some basic information about the motor's power and behavior:
  - A letter specifying the impulse class ("H")
  - Number specifying the average thrust ("225")
- HPR motors cannot be purchased over the counter
- Special storage, handling, and shipping procedures are required. (overseen by Team Mentor)

Impulse Class		Category
H	160.01Ns to 320.01Ns	Level 1
I	320.01Ns to 640.00Ns	
J	640.01Ns to 1280.00Ns	Level 2
K	1280.01Ns to 2560.00Ns	
L	2560.01Ns to 5120.00Ns	
M	5120.01Ns to 10240.00Ns	Level 3
N	10240.01Ns to 20480.00Ns	
O	20480.00Ns to 40960.00Ns	

Note: The SLI team maximum Impulse limit of 2,560 N*s translates to a K or lower motor.

Commercially Certified Motors

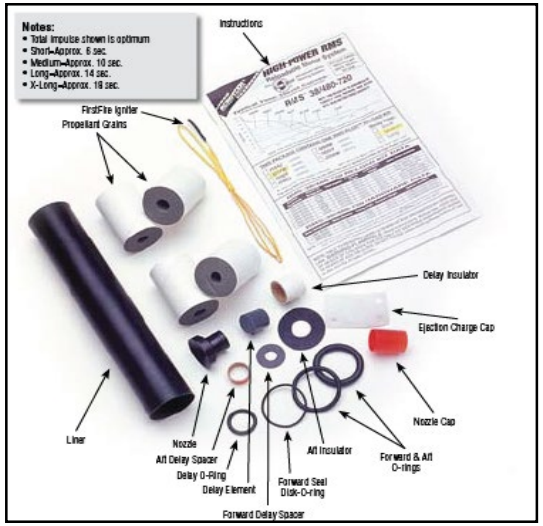
- **Student Launch requires use of commercially certified motors**
- Certifying Agencies:
  - National Association or Rocketry (NAR)
  - Tripoli Rocketry Association (TRA)
  - Canadian Association of Rocketry (CAR)

Motors are occasionally decertified – make sure you are using a recent list.

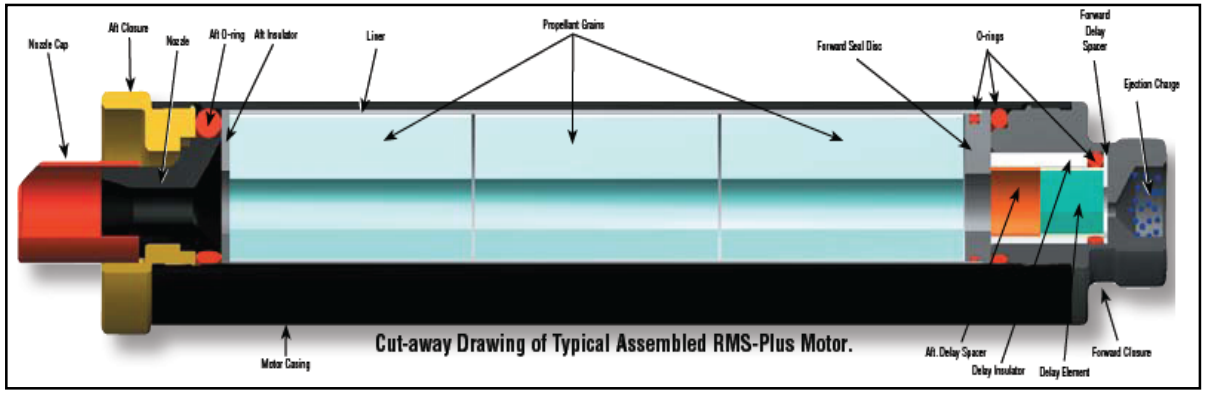
Note: TARC also requires the use of certified motors.

Commercially Certified Motors

- Some of the more popular solid rocket motor manufacturers are
  - Cesaroni Technology Inc. (CTI), Aerotech (AT)
- Wide variety in all different impulse and thrust ranges
- Reloadable solid rocket motor systems are composed
  - A reusable motor case
  - A reload kit
- Cases have 3 standard parts:
  - the case
  - forward closure
  - An aft closure
- Reloads have 4 standard parts:
  - Fuel grains
  - Nozzle
  - Liner
  - O-rings







Cut-away Drawing of Typical Assembled RMS-Plus Motor.

Hint: The motor list in RockSim is neither complete nor accurate.

Thrust To Weight

- A rocket motor must produce enough thrust to overcome the force of gravity
  - A rocket motor, at a minimum, must produce enough mechanical energy to achieve a *Thrust to Weight Ratio* of just over 1.0
  - The Space Shuttle had a thrust to weight ratio of 1.5 as it left the launch pad
    - Nearly 90% of the Space Shuttle was propellant and that ratio would quickly rise as fuel was consumed
- For model rocketry, the rule of thumb for thrust to weight is 5:1, as it helps to ensure dynamic stability as soon as rocket becomes a free-flyer
  - That means that the rocket motor must produce 5 times the force of the weight of your rocket
  - The NAR legal minimum is 3:1, however **SL requires 5:1.**

Note: SL requires a minimum thrust to weight ratio of 5:1

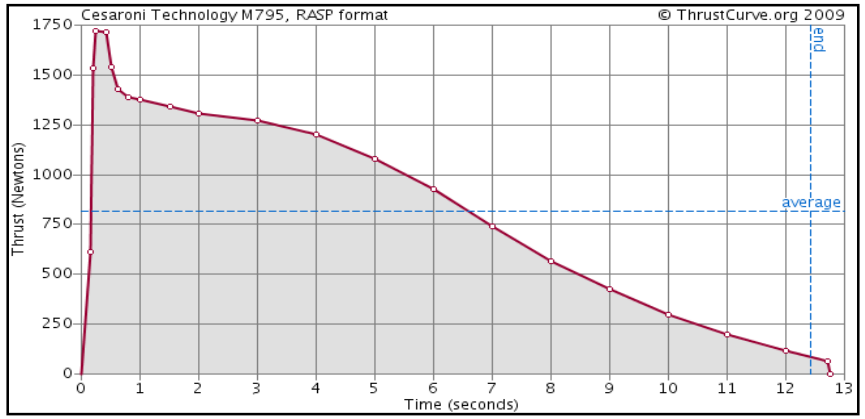
Thrust Curves

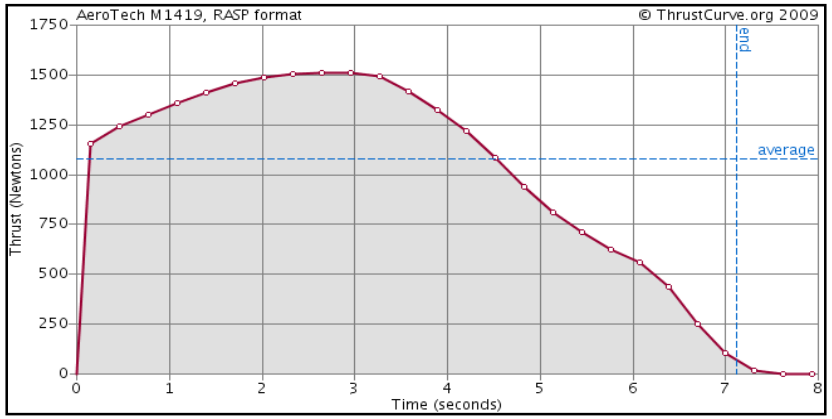
Thrust Curves:

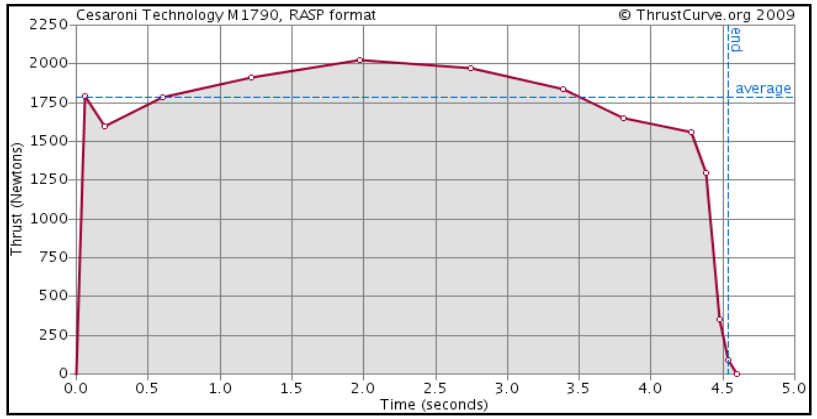
- Obtained experimentally for solid rocket motors by:
  - Placing the motor on a test stand
  - Igniting the propellant
  - Recording thrust as a function of time
- *Total Impulse* is most accurately determined by calculating the area under the curve
- *Average thrus*t is calculated as the total impulse divided by the burn time

Burn time is generally considered the time when thrust drops below 5% of the maximum thrust

- A thrust curve can show whether a motor is:
  - Neutral – does not vary more than 10%
  - Regressive – Decreasing thrust/surface area
  - Progressive – Increasing thrust/surface area
- Thrust varies directly with the surface area of propellant being combusted
- Initial Thrust is vitally important for establishing a rocket's dynamic stability







Regressive, Progressive, and Neutral burn thrust curves

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Questions?