National Aeronautics and
Space Administration

NASA Student Launch ARW Propulsion Systems

PRESNTED BY NASA Student Launch

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NASA STEM

Total Impulse

Impulse is the work done by the propellant

Typically measured in units of Newton-seconds

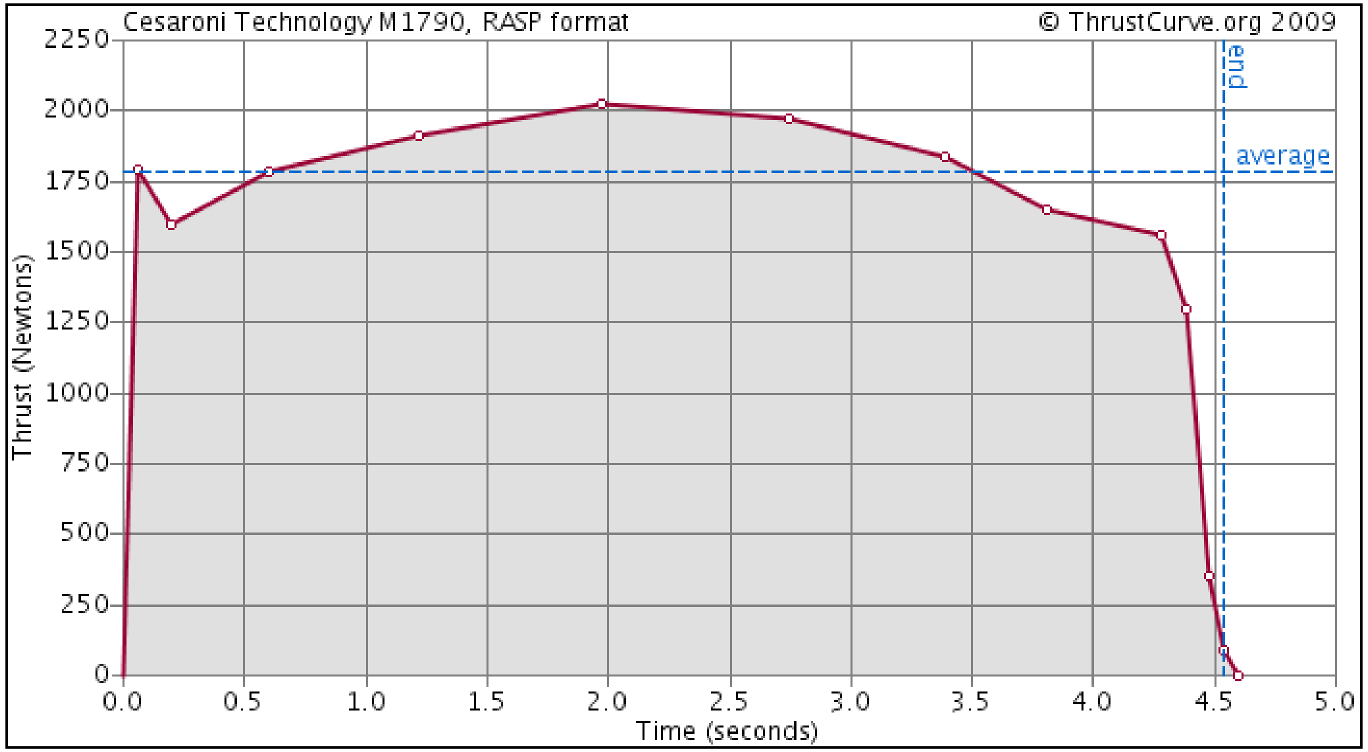
The impulse parameter is used to categorize different classes of rocket motors in hobby rocketry

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

SLI teams are limited to motors with a maximum impulse of 2,560 Ns



Thrust curves can be downloaded from Thrustcurve.org and imported into RockSim or Open Rocket.

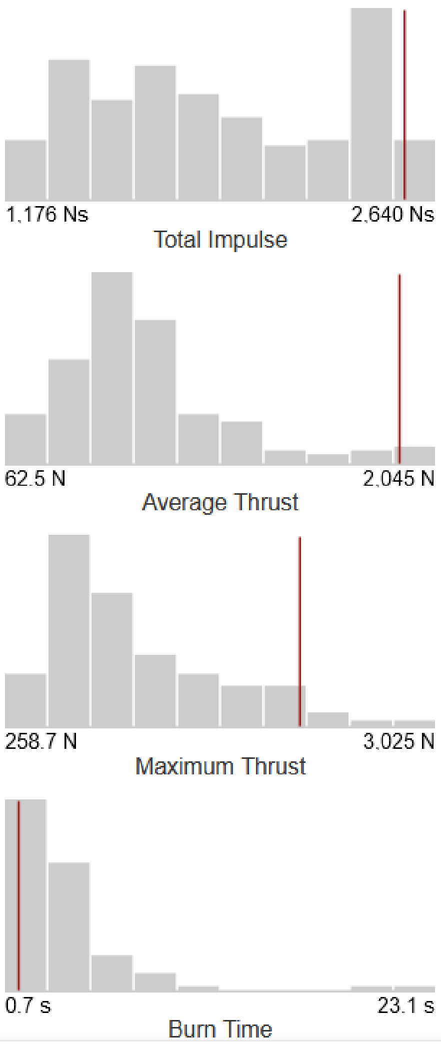
Practical Example of Impulse

- I = TΔt
- Exact Impulse is derived by integrating the Thrust Curve over the time interval of interest.
- Impulse can be estimated by $I = T_{avg} *$ burn time
- I = (1790N)*(4.5sec) = 8055 Ns (8088 Ns is advertised by vendor)

AeroTech K1999N

Manufacturer	AeroTech
Designation	K1999N
Common Name	K1999
Motor Type	reload
Delays	P
Diameter	98 mm
Length	289 mm
Total Weight	2,989 g
Prop. Weight	1,225 g
Avg. Thrust	1,887.4 N
Initial Thrust	1,920.5 N
Max. Thrust	2,159.6 N
Total Impulse	2,540.0 Ns
Burn Time	1.3 s
Motor Case	RMS-98/2560
Propellant	Warp 9
Cert. Org.	TRA
Cert. Date	April 30, 2006
Cert. Designation	K1887 (98%)
Availability	regular
HazMat Shipping	HazMat
CSFM Approved	approved

Compared with all 168 **K** motors:



Black Powder vs. Composite

Black Powder Motors

Charcoal, potassium nitrate, sulfur

Always come in paper casings

Pros

- Cheaper
- Ready to fly out of the box
- BP is very flammable, so ignition is consistent

Cons

- Lower energy density (not as much bang for your buck)
- Propellant can crack easier causing uneven pressurization leading to burst casings and/or rockets
- Limited in sizes (typically smaller motors)
- Larger motors require hazmat shipping

Composite Motors

Mixture of ingredients; fuel and oxidizer

Can be single use or reload

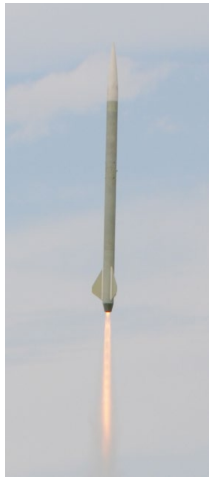
Pros

- Higher energy density
- Rubbery material so more resistant to cracking
- Available in nearly all diameters and impulse classes
- Optional flame colors

Cons

- More expensive
- Can be difficult to light

Composite Propellant

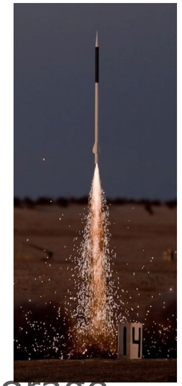



Inorganic Oxidizers

- 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

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

Definitions 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)

The SLI team maximum Impulse limit of 2,560 Ns translates to a K or lower motor.

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	

Junior L1 Rocketry Certification

The exam is twenty-five (25) questions

The exam consists of a master question bank available (with answers) for study

The exam will be distributed to NAR Sections and Certification Team members meeting the minimum requirements

The exam will be administered by Section Officers and JrHPP Certification Team members who are L1 or higher

The exam will be taken and passed prior to the certification flight

The exam may be re-taken immediately in case of a failure but may only be taken twice in a seven-day period

The exam will comply with any other details and processes as with the L2 exam

1. Launch rockets containing multiple motors with a total installed impulse of 320.01 Newton-seconds to 640 Newton-seconds, or
2. Launch rockets containing a single motor with a total installed impulse of 160.01 Newton-seconds to 640 Newton-seconds, or
3. Launch rockets that weigh more than 53 ounces (1500 grams), or
4. Launch rockets powered by motors not classified as model rocket motors per NFPA 1122, e.g.:
    - Average thrust in excess of 80.0 Newtons
    - Containing in excess of 125 grams of propellant and are limited to only H and I motors

National Association of Rocketry

Commercially Certified Motors

Student Launch requires use of commercially certified motors

Certifying Agencies:

- National Association of Rocketry (NAR)
- Tripoli Rocketry Association (TRA)
- Canadian Association of Rocketry (CAR)

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

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

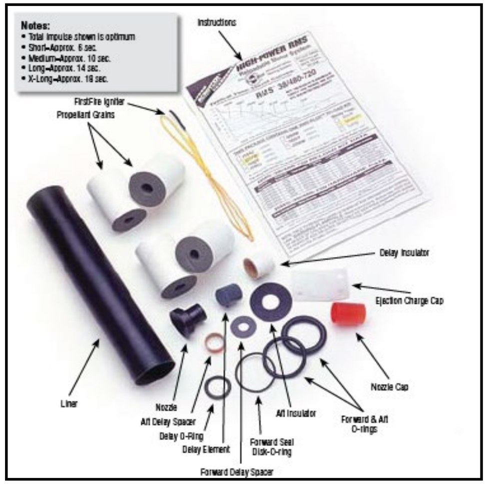
- A reusable motor case
- A reload kit

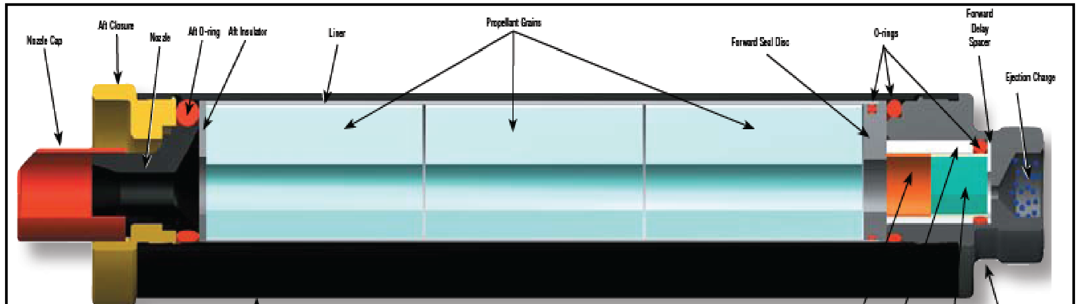
Cases have 3 standard parts:

- 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.

The motor list in RockSim is neither complete nor always up to date.

Single Use vs. Reloadable Motors

Single Use

- Cannot screw up assembly
- Cheaper initial setup, as there is no casing to purchase
- More expensive in the long-run. If you'll be launching mid-power more than 3 times, it's a better investment to get a reload system.
- No casing to replace if you lose your rocket
- Available with both black powder and composite propellants.
- Most (with a few exceptions on high power varieties) don't require age 18+
- No age requirement for low and mid power SU motors
- No control on delay times (with a few exceptions on high power varieties) -- Delays are pre-set, so you need to purchase the correct delay.
- Expensive to ship in larger diameters or lengths due to HAZMAT requirements (check motor info to see if required).

Reloadable Motors

- Cheaper propellant means lower cost-per-flight. You typically save $6-10 per flight.
- Requires casing purchase, so there is a higher initial investment. That investment is paid off by cheaper propellants.
- Larger variety of options, particularly in more powerful motors
- Assembly required, with Aerotech having more steps than Cesaroni
- Precise control over delay times (except if it's plugged).
- More difficult to find at hobby shops, often require a special order or online purchase.
- Age of 18+ verification required (due to access to propellant itself)

Aerotech vs. Cesaroni

Aerotech

Cesaroni

Aerotech

- Readily available. Typically takes less time to receive than Cesaroni motors. Lead time can be up to 6 weeks.
- All 38mm and larger motors require HAZMAT shipping
- You can use up to 3 casing spacers (one more than Cesaroni) to reduce the number of casings you need for a full arsenal.
- Getting the casing and closures can be more expensive than Cesaroni, but you have several options for forward and aft closures depending on your needs.

Cesaroni

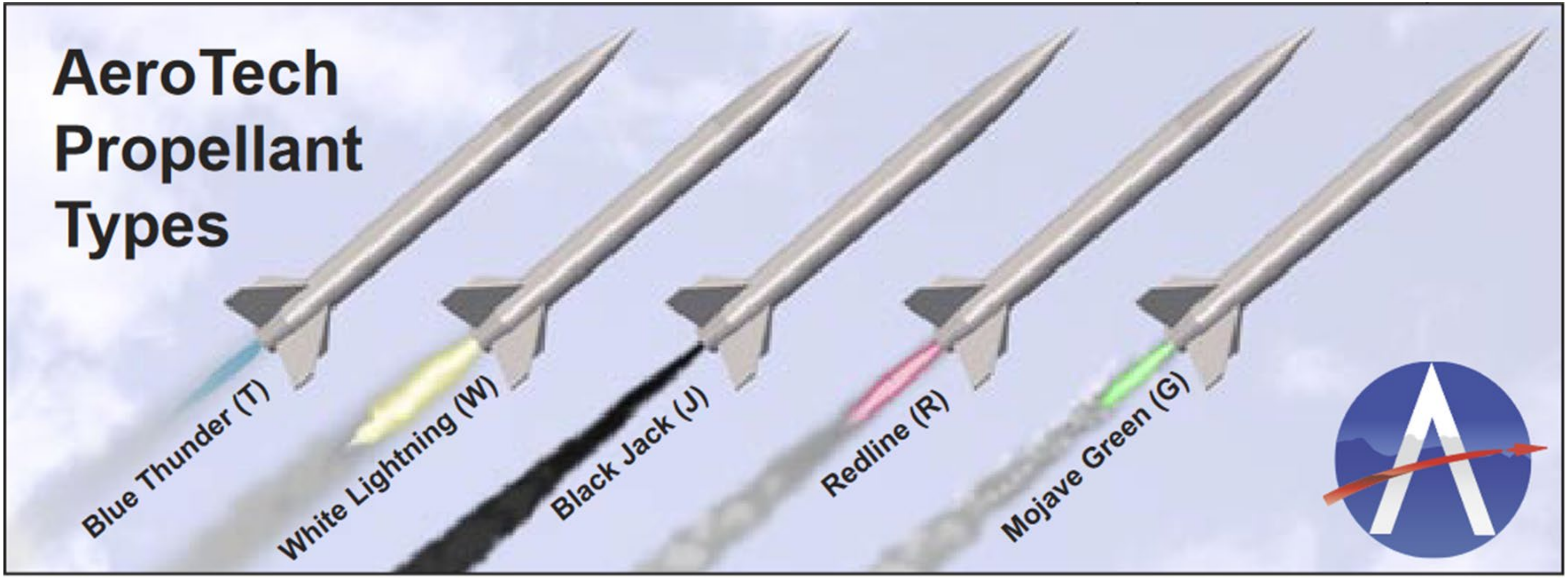
- Canadian based company so when vendors run out the lead time on restock can be very lengthy.
- Since Cesaroni propellant kits come mostly pre-assembled, you just need to adjust the delay, then slide the propellant into the Cesaroni casing.
- Since the propellant kits are contained in an enclosed plastic sheath, you just need to slide that out, take a quick paper towel wipe to the casing and you're ready to load up for your next launch.

Aerotech

- Assembly and cleaning of the motors are more time consuming. Since Aerotech motors ship piecemeal, it can help with shipping costs in some cases, but requires careful assembly before use. open-ended sheath around the propellant slugs makes residue buildup more likely.
- Aerotech offers a few high-power single-use motors. This means that there is no expensive casing to purchase and potentially lose. While they are currently only available in 38mm diameter.

Cesaroni

- All Cesaroni motors are required to ship via HAZMAT (average $50 shipping cost), so it’s best to order as many as you can at once since the fee is per shipped box, not per motor.
- There are often 7, 8, 9, or more motors that will work in each casing, depending on what you like.
- You can use up to two spacers in each casing, so you only need the 3-grain and 6-grain casings to get the most out of your Cesaroni collection.


AeroTech
Propellant
Types
Blue Thunder (T)
White Lightning (W)
Black Jack (J)
Redline (R)
Mojave Green (G)

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.

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

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 thrust 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:

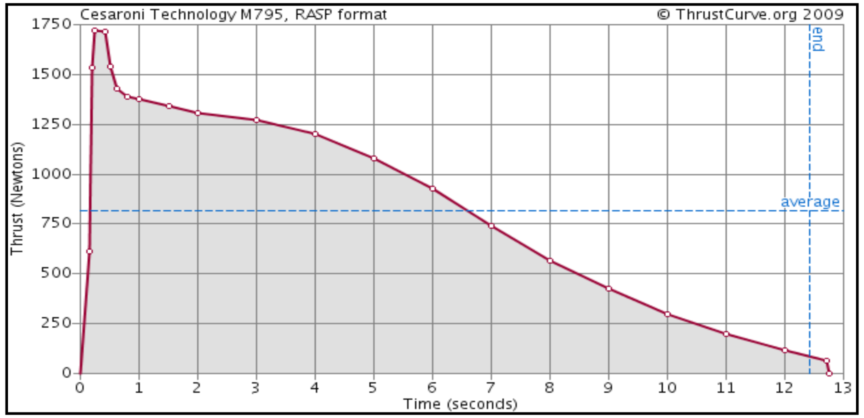
- Neutral – does not vary more than 10%
- Regressive – Decreasing thrust/surface area
- Progressive – Increasing thrust/surface area

Thrust varies directly with the surface area of propellant being combusted

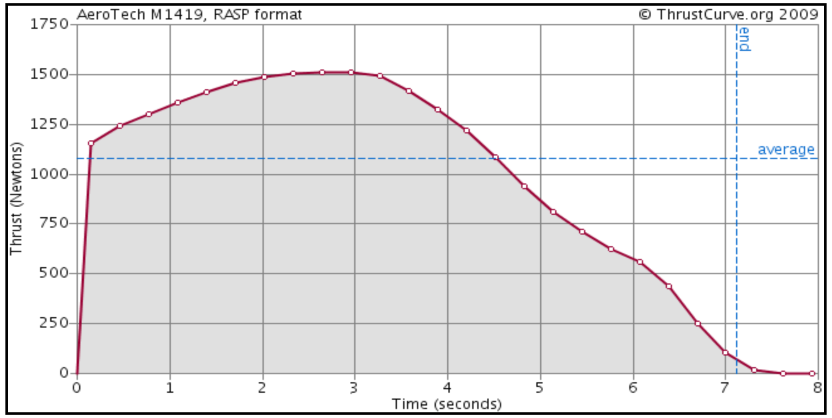
Initial Thrust is vitally important for establishing a rocket's dynamic stability

Thrust Curves

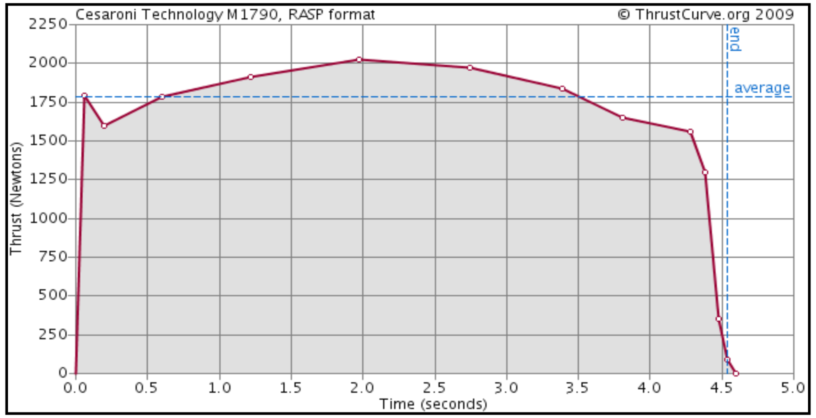
Regressive



Progressive



Neutral




AURA
Rocketry Association at Auburn University
Follow us on Instagram! @auburnrocketry
A Visit to Children's of Alabama for Brighter Futures

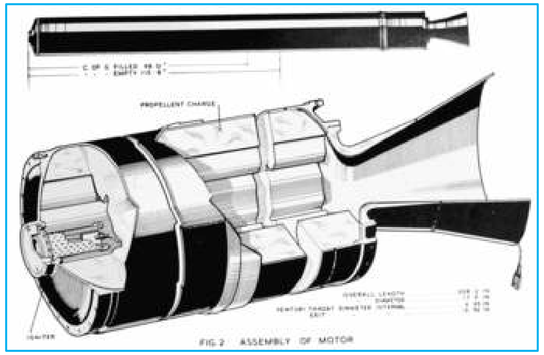
Questions?

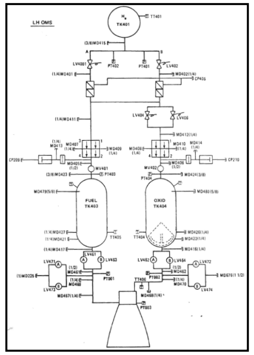
NASA

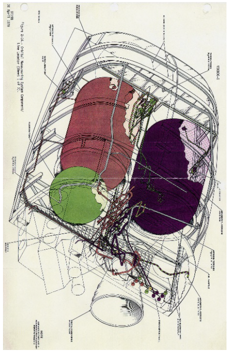
Backup Slides

(For those looking more into theory and mathematics of propulsion systems)

Solid vs. Liquid Propulsion







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

SL teams are limited to commercial solid motors

Liquid Propulsion

Fuel and oxidizer stored separately

Efficiency: 250 – 450 sec ISP

Can be restarted

Requires tanks, valves

Failures are catastrophic

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

Newton's Laws

1st Law: "Law of Inertia"

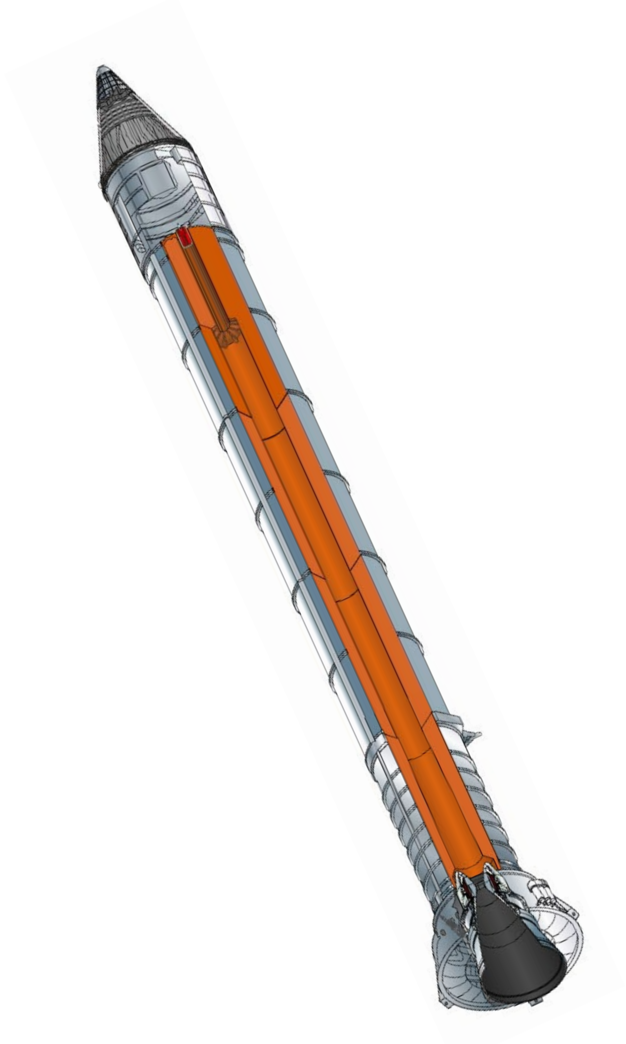
- *Objects in motion/rest will remain in that state until acted on by an outside force.*

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*



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, $\mathbf{F}_{\text{net}} = m\mathbf{a}$ □

Newton's Laws and Rocketry

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

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

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

Ideal Rocket Equation

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

$$\ln(m_f) - \ln(m_i) = \frac{-1}{v_e}\Delta\mathrm{v}$$

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

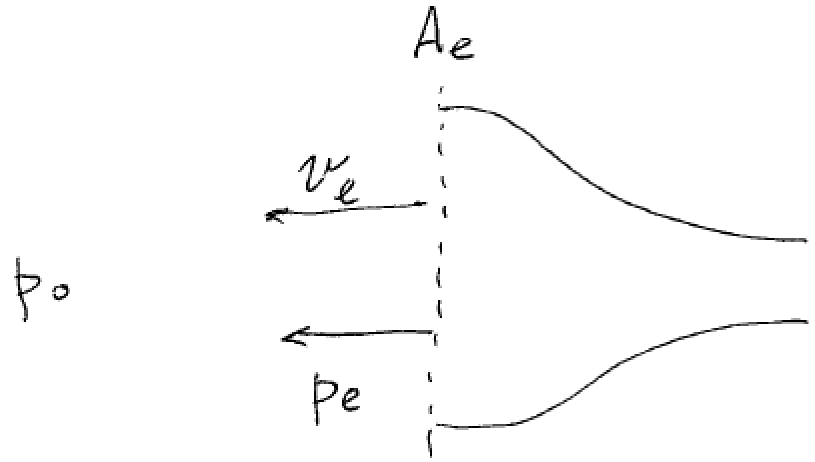
Assuming no other external forces

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

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

Rocket Thrust Equation and Specific Impulse

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



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

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

$$T = m * v_e + (p_e - p_0) * A_e$$

Assume (fully expanded flow)

$T = m * v_e$ Momentum exchange between exhaust & vehicle

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

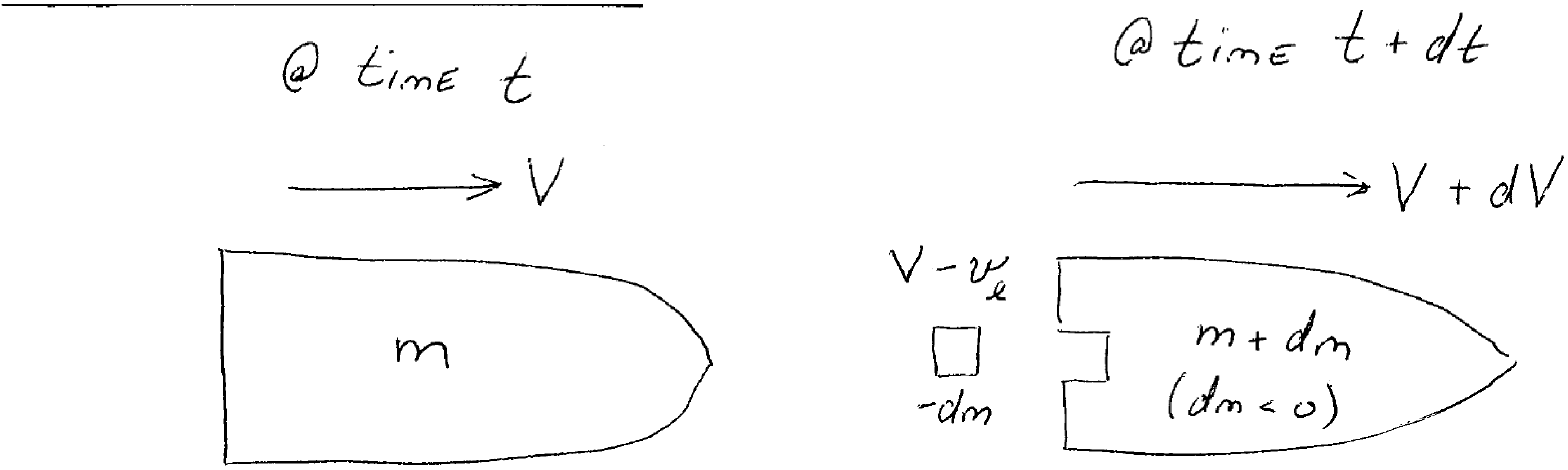
$m * v_e = m * g_0 * I_{sp}$ $v_e = g_0 * I_{sp}$

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

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

All these variables depend on the design of the nozzle

Ideal Rocket Equation



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

Mass Equations

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

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

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

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

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

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

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

Basic Flavors of Propulsion

Liquid Propellant

- Both fuel and oxidizer are separately stored liquids
- Mechanically complex, expensive, not generally used by amateurs
- Examples: LH_2/LOX, kerosene/LOX, alcohol/H_2O_2, NTO/MMH
- Applicability: Earth Surface and Outer Space

Solid Propellant

- Both fuel and oxidizer are mixed as a solid mass.
- Examples: black powder, ammonium perchlorate propellant
- Applicability: Earth Surface and Outer Space

Hybrid

- Solid fuel, liquid oxidizer
- Examples: plastic/NO_2, HTPB/O_2, HTPB/NO_2, Paraffin/O_2
- Applicability: Earth Surface and Outer Space

Basic Flavors of Propulsion

Monopropellant

- Catalyzes a propellant to generate hot, high-pressure
- Examples: hydrazine, H_2O_2
- Applicability: Outer Space mostly

Electric

Electrical ions generate thrust

Very low thrust, very high efficiency

Applicability: Outer Space only

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

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

- 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