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Talking: Beth Gilbert

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A: You are able to ask question live. You can raise your hand and I will unmute your line.

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Amy Naylor,
Instructor, Mitchell Community College

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2014 Drug Discovery Series:
"The Role of Chemistry in Clinical Trials:
The Big Expense & Lessons Learned"
Session 6

Featuring Graham Johnson, President of NuPharmAdvise LLC and Dr. Jay Sisco, Founder of JM Sisco Pharma Consulting and President of the American Association of Pharmaceutical Scientists

Thursday, July 31, 2014

"Drug Discovery Series
"The Role of Chemistry in Clinical Trials:
The Big Expense & Lessons Learned"

Graham Johnson, NuPharmAdvise LLC
Dr. Jay Sisco, JM Sisco Pharma Consulting
Dr. John Morrison, Bristol-Myers Squibb

ACS WEBINARS® Aug 7 @ 2PM ET

"How to Write Abstracts that Capture your Audience"

Featuring Celia M. Elliott, Department of Physics, University of Illinois at Urbana-Champaign

Thursday, August 7, 2014

"How to Write Abstracts that Capture Your Audience"

Celia Elliott, University of Illinois at Urbana-Champaign
Patricia Blum, University of Illinois at Urbana-Champaign

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ACS Webinars welcomes the NASA Wallops Visitor Center!

ACS WEBINARS®
July 24 @ 2PM ET

Rocket Science 101:
Engineering and
Propulsion

Featuring Larry de Quay,
Aerospace Engineer,
NASA's John C. Stennis Space Center

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ACS Chemistry for Life®

Rocket Science 101: Engineering and Propulsion

Dr. Larry de Quay
Aerospace Engineer,
NASA Stennis Space Center

Dr. David Harwell
Asst. Director of
Industry Member Programs,
The American Chemical Society

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Rocket Science 101: Engineering and Propulsion

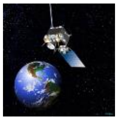
Host: Mike David, ACS
Moderator: David, Harwell, ACS
Presenter: Larry de Quay, NASA Stennis Space Center
July 24, 2014

Audience Question:

Have you ever seen a live space vehicle launch in person?

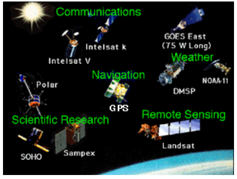
Planetary Explorers

Planetary Landers



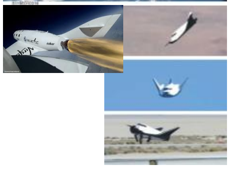
Space Telescope

Orbital Transfer Vehicle



Rocket Propulsion Applications

- Interplanetary Vehicles
- Planetary Orbiters
- Planetary Landers
- Earth Orbiting Satellites and Vehicles
- Launch Vehicles
- Ballistic Missiles
- Cruise Missiles



Rocketry History

- c. 67 AD Hero of Alexandria's "aeolipile" rotating steam jet, basic principle of reaction used in jets & rockets
- ~970 AD Chinese invention of rockets; Feng Jishen is believed by many to be the main inventor.
- 1232 Battle of Kai-fung-fu. Incendiary powder packets were tied to arrows.
- 1275 Rockets used as weapons during Invasion of Japan by Kublai Kahn.
- 1379 Battle for Isle of Chiozza. Powder rockets used to set defending tower on fire.
- 1792 Battle of Seringapatam, Indian armies under Tipu Sultan used rockets against British.
- 1805 Powder rockets with 2000 yard range demonstrated by Congreve of England.
- 1806 British use Congreve rockets in attacks against Boulogne, France.
- 1807 Copenhagen razed by 25,000 powder rockets.
- 1814 British use rockets during War of 1812 in the United States, incl. Fort McHenry in Baltimore Harbor ("rockets' red glare" in the "Star Spangled Banner").
- 1903 Tsiolkovsky published first treatise on space travel advocating liquid rockets, *"The Exploration of Cosmic Space by Means of Reaction Devices."*
- 1919 Goddard wrote *"A Method of Reaching Extreme Altitudes."*
- 1923 Oberth wrote *"The Rocket into Interplanetary Space."*
- 1926 Goddard launched a liquid rocket to an altitude of 184 ft. in 2.5 sec.
- Opel flew aircraft propelled by solid rocket propellant charges mounted on a glider.
- 1935 Rocket launched to an altitude of 7500 ft. by Goddard.
- 1937 Peenemunde Research Institute established.
- 1938 Early model of V-2 attained altitude of 40,000 ft. and range of 11 miles.
- 1942 JATOs used in World War II.
- 1947 Rocket-powered Bell X-1 completed first piloted supersonic flight in history.
- 1956 Bell X-2 reached altitude of 126,000 ft. and speed of 2150 mph.
- 1957 Sputnik launched (first man-made satellite).
- 1958 Explorer I launched (America's first satellite).
- 1961 Yuri Gagarin launched into orbit on Vostok I (first person in space).
- 1969 Neil Armstrong and Buzz Aldrin land and then walk on the moon.



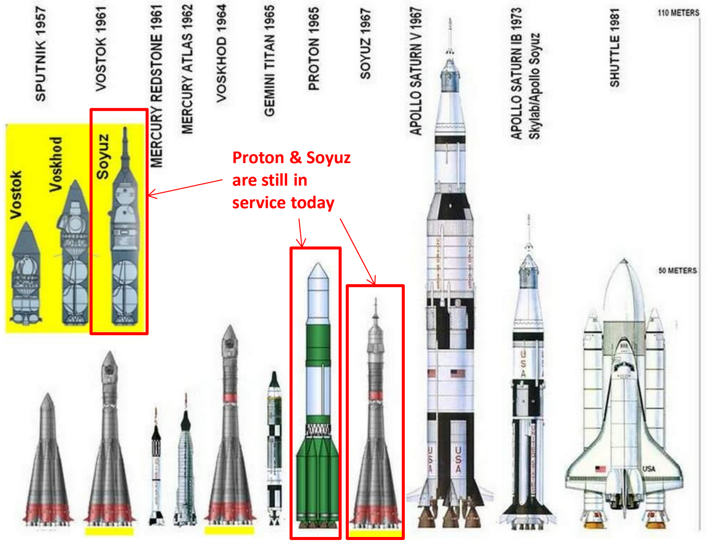





Space Launch System (SLS)
Delta 4 Heavy
Falcon Heavy
Angara 5
Atlas 5
Zenit
Ariane 5
Long March 3B
Falcon 9
Proton
H-2B
GSLV
Soyuz
Long March 4C
Long March 2C
Antares
Delta 2
Vega
Minotaur 4 & 5
Minotaur 1 & 2
Pegasus

Blue = U.S.A.
Red = Russia
Brown = Ukraine
Green = Europe
Orange = Japan
Gray = China
Purple = India

Others: South Korea (Naro 1), North Korea (Unha 3), Israel (Shavit), Iran (Safir)

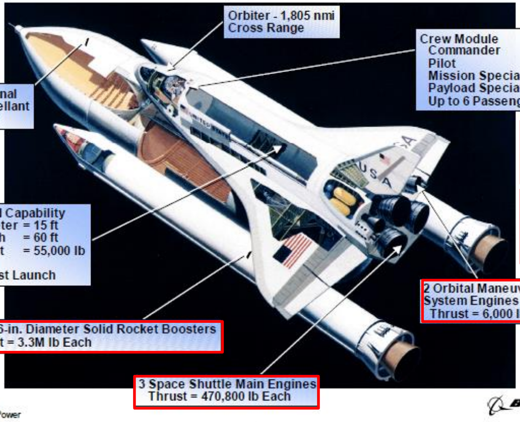


Proton & Soyuz are still in service today

Heritage Launch Vehicles

Rocket Engines on a Space Flight Vehicle; first example

Space Shuttle



Orbiter - 1,805 nmi Cross Range

Crew Module
Commander
Pilot
Mission Specialist
Payload Specialist
Up to 6 Passengers

External Propellant Tank

38 Primary Thrusters (Thrust = 870 lb Each), 14 in Orbiter Nose, 12 in Each of 2 OMS Pods

6 Vernier Thrusters (Thrust = 24 lb Each), 2 in Orbiter Nose, 2 in each of 2 OMS Pods

Payload Capability
Diameter = 15 ft
Length = 60 ft
Weight = 55,000 lb

Due East Launch

2 Orbital Maneuvering System Engines
Thrust = 6,000 lb Each

Two 146-in. Diameter Solid Rocket Boosters
Thrust = 3.3M lb Each

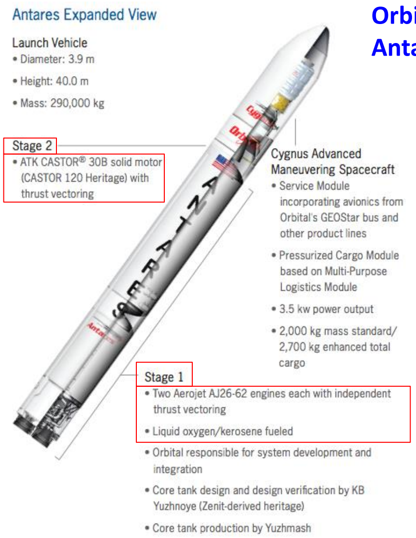
3 Space Shuttle Main Engines
Thrust = 470,800 lb Each

Rocketdyne
Propulsion & Power

BOEING

9604015c.ppt
aw/rl

Orbital Sciences Corporation Antares Launcher with Cygnus



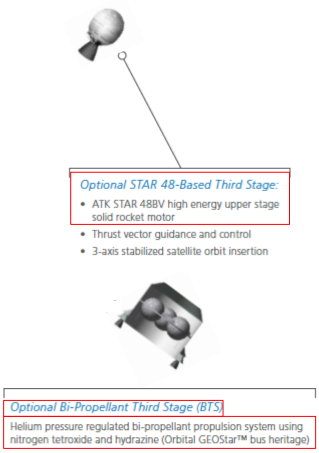
Antares Expanded View

Launch Vehicle
- Diameter: 3.9 m
- Height: 40.0 m
- Mass: 290,000 kg

Stage 2
- ATK CASTOR® 30B solid motor (CASTOR 120 Heritage) with thrust vectoring

Cygnus Advanced Maneuvering Spacecraft
- Service Module incorporating avionics from Orbital's GEOStar bus and other product lines
- Pressurized Cargo Module based on Multi-Purpose Logistics Module
- 3.5 kw power output
- 2,000 kg mass standard/ 2,700 kg enhanced total cargo

Stage 1
- Two Aerojet AJ26-62 engines each with independent thrust vectoring
- Liquid oxygen/kerosene fueled
- Orbital responsible for system development and integration
- Core tank design and design verification by KB Yuzhnoye (Zenit-derived heritage)
- Core tank production by Yuzhmash

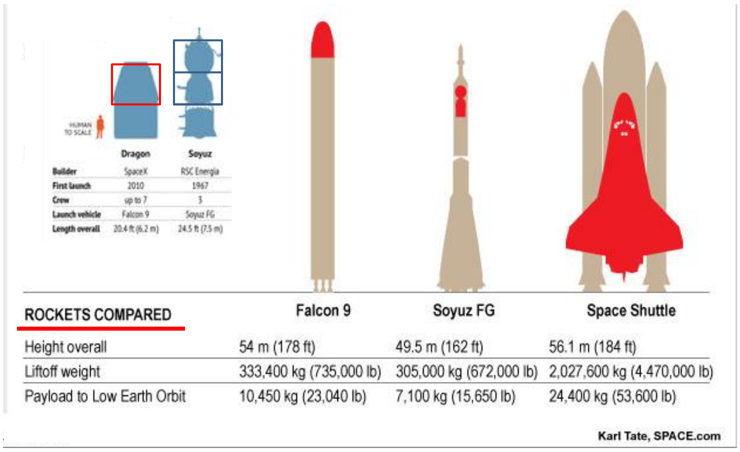


Optional STAR 48-Based Third Stage:
- ATK STAR 48BV high energy upper stage solid rocket motor
- Thrust vector guidance and control
- 3-axis stabilized satellite orbit insertion

Optional Bi-Propellant Third Stage (BTS)

Helium pressure regulated bi-propellant propulsion system using nitrogen tetroxide and hydrazine (Orbital GEOStar™ bus heritage)

Rocket Engines on a Space Flight Vehicle; second example



	Dragon	Soyuz
Builder	SpaceX	RSC Energia
First launch	2010	1967
Crew	up to 7	3
Launch vehicle	Falcon 9	Soyuz FG
Length overall	20.4 ft (6.2 m)	24.5 ft (7.5 m)

ROCKETS COMPARED	Falcon 9	Soyuz FG	Space Shuttle
Height overall	54 m (178 ft)	49.5 m (162 ft)	56.1 m (184 ft)
Liftoff weight	333,400 kg (735,000 lb)	305,000 kg (672,000 lb)	2,027,600 kg (4,470,000 lb)
Payload to Low Earth Orbit	10,450 kg (23,040 lb)	7,100 kg (15,650 lb)	24,400 kg (53,600 lb)

Karl Tate, SPACE.com

Payload Size and Weight Comparisons of Two Currently Operational Space Launch Vehicles and the Space Shuttle

Thrust

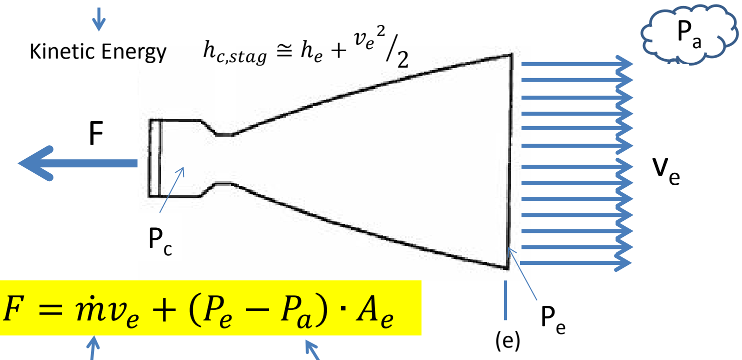
Propellant Chemical Enthalpy

↓

Heat (Increased Sensible Enthalpy)

↓

Kinetic Energy $h_{c,stag} \cong h_e + {v_e}^2/2$



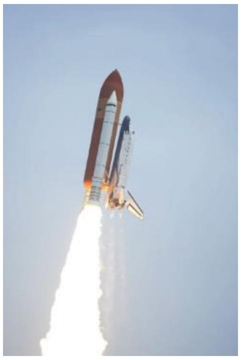
$$F = \dot{m}v_e + (P_e - P_a) \cdot A_e$$

Momentum Thrust

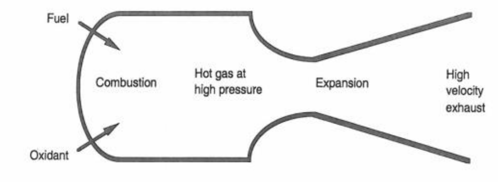
Pressure Thrust

The Different Types of Chemical Rocket Engines

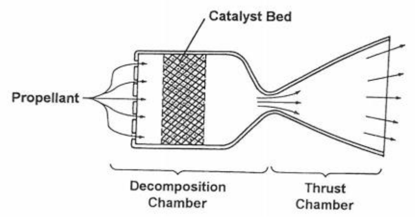
- Liquid (Propellant) Rocket Engines (LREs)
- Solid (Propellant) Rocket Engines (SREs)
- Hybrid Rocket Engines (HREs)



Liquid Rocket Engines (LREs)



Bipropellant Type LRE

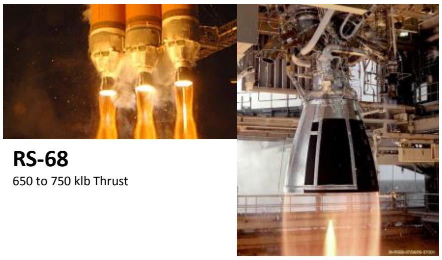


Monopropellant Type LRE

Typical Propellants for LREs (Liquid Rocket Engines):

Name	Chemical Formula	Type	Saturation Temperature at 1 Bar		
			K	$^{\circ}$R	$^{\circ}$F
Liquid Fluorine	F_2	Oxidizer	85.1	153.1	-306.6
Liquid Oxygen	O_2	Oxidizer	165.2	297.4	-162.3
Nitrous Oxide	N_2O	Oxidizer	184.7	332.4	-127.3
Hydrogen Peroxide	H_2O_2	Oxidizer or Monopropellant	424.2	763.6	303.9
Nitrogen Tetroxide (NTO)	N_2O_4	Oxidizer	294.8	530.7	71.0
Liquid Hydrogen	H_2	Fuel	20.3	36.6	-423.1
Liquid Methane	CH_4	Fuel	111.8	201.2	-258.5
RP-1	$CH_{1.953}$	Fuel	475.7	856.2	396.5
Octane	C_3H_8	Fuel	398.8	717.8	258.1
Ethanol	C_2H_5OH	Fuel	351.6	632.8	173.1
Isopropyl Alcohol (IPA)	C_3H_7OH	Fuel	355.4	639.7	180.0
Hydrazine	N_2H_4	Fuel or Monopropellant	387.0	696.7	237.0
Monomethylhydrazine (MMH)	$CH_3(NH)NH_2$	Fuel	364.3	655.7	196.0
Unsymetrical Dimethyl-hydrazine (UDMH)	$(CH_3)_2N_2H_2$	Fuel	337.1	606.8	147.1
Hydroxyl Ammonium Nitrate (HAN)	$H_4N_2O_4$	Monopropellant	>418	>752.4	>292.7
Nitromethane	CH_3NO_2	Monopropellant	373.9	673.1	213.4
Nitroglycerin	$C_3H_5N_3O_9$	Monopropellant	323.2	581.7	122.0
Tetranitromethane	CN_4O_8	Monopropellant	398.7	717.7	258.0
Ethylene Nitrate	$C_2H_4N_2O_6$	Monopropellant	N/A	N/A	N/A

Sampling of LREs

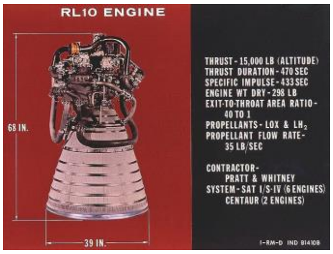


RS-68
650 to 750 klb Thrust

2.43 m = 95.7”

J-2X

Cycle	GG
Thrust, vac (klbs)	294
Isp, vac (sec)	448
Pc (psia)	1,337
MR	5.5
AR	92
Weight (lbm), max	5,450
Secondary Mode MR	4.5
Secondary Mode PC	82%
Restart	Yes
Operational Starts	8
Operational Seconds	2,600
Length (in), Max	185
Exit Dia. (in), Max	120



RL10 ENGINE

68 IN.

39 IN.

THRUST - 15,000 LB (ALTITUDE)
THRUST DURATION - 470 SEC
SPECIFIC IMPULSE - 433 SEC
ENGINE WT DRY - 298 LB
EXIT-TO-THROAT AREA RATIO - 40 TO 1
PROPELLANTS - LOX & LH_2
PROPELLANT FLOW RATE - 35 LB/SEC

CONTRACTOR - PRATT & WHITNEY
SYSTEM - SAT I/S-IV (6 ENGINES)
CENTAUR (2 ENGINES)

I-RM-D IND 814108

SSME (RS-25)
418 to 512 klb Thrust

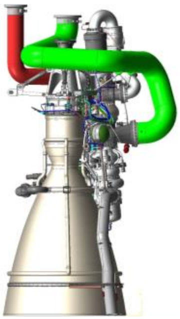
2.40 m = 94”

Merlin 1C 147 to 161 klb Thrust

1.68 m = 66”

RD-180 860.6 to 933.4 klb Thrust

AJ-26
355 to
394 klb
Thrust



2.0 m = 79”

Solid Rocket Engines (SREs)

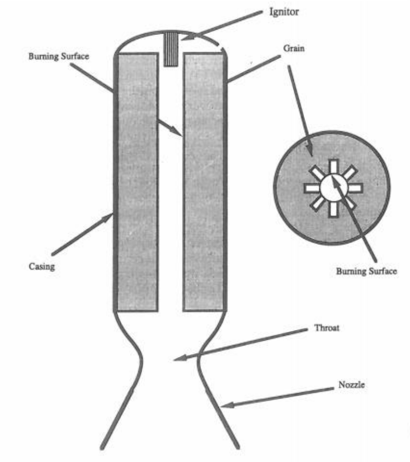
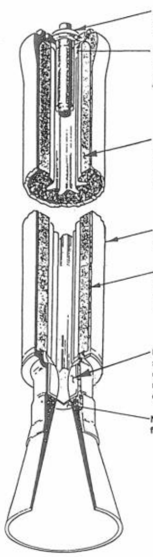


Figure 4.1. Schematic of a solid-fuelled rocket motor.



IGNITER - The function of the igniter is to raise the grain surface temperature to the ignition point and to increase chamber pressure to self sustaining levels.

INSULATION - Most solid rocket motors have areas of exposed case which require insulation to protect the case from combustion gas. The insulated areas are typically at the ends of the grain.

GRAIN - The solid propellant, regardless of configuration, is called a grain when installed in a motor. The central opening in the grain is called the port. A typical grain consists of a rubber-like binder, aluminum powder, ammonium perchlorate and additives.

CASE - The case is the pressure shell. Titanium, mild steel and Kevlar are used.

LINER - Liner is used at the propellant-case joint. The purpose of the liner is to inhibit grain burning and insulate the case when the flame front arrives. The liner is usually propellant binder.

NOZZLE -The nozzle provides the converging- diverging section which accelerates the exhaust gas. The design challenge in the nozzle is the high temperatures which are reached. The usual construction is graphite epoxy or carbon-carbon with a carbon throat.

NOZZLE CLOSURE - The nozzle closure protects the grain from exposure to hard vacuum.

Both solid fuel and oxidizer plus binders and other additives are contained in the "grain"

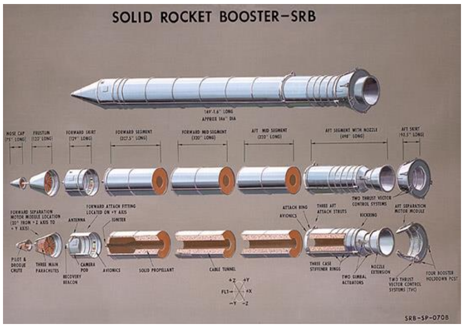
Typical Fuels, Oxidizers, Binders, and Other Additives in SRE Propellant Grains

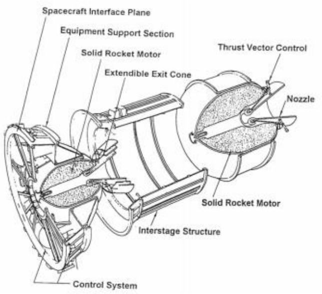
Name	Abbrev. Name or Acronym	Chemical Formula	Type
Aluminum (fine powder)	Al	Al	Fuel
Zirconium (powder)	Zr	Zr	
Ammonium Perchlorate	AP	NH_4ClO_4	Oxidizer
Ammonium Nitrate	AN	NH_4NO_3	
Ammonium Dinitamine	AND	$NH_3(NH)(NO_2)_2$	
Potassium Perchlorate	KP	$KClO_4$	
Potassium Nitrate	KN	KNO_3	Oxidizer, Visible Flame Suppresant
Potassium Sulphate	KS	K2SO4	Visible Flame Suppresant
Cyclotetramethylene-tetrantromine	HMX	$C_4H_8N_8O_8$	Solid Explosive Crystal/ Filler
Cyclotetramethylene-trinitromine	RDX	$C_3H_6N_6O_6$	
Nitroguanadine	NQ	$CH_4N_4O_2$	
Hydroxyl-terminated Polybutadiene	HTPB	$C_{654}H_{988}N_8O_{20}$ $C_{656}H_{978}N_5O_{13}$ $C_{73}H_{110}O_6$ $C_{67}H_6N_4O$ $C_{73}H_{103}O$	Fuel, Binder *(polybutadiene type)*
Carboxyl-terminated Polybutadiene	CTPB	$C_{72}H_{108}O$ $C_{73}H_{105}O$	
Polybutadiene acrylonitrile acrylic acid	PBAN	$C_{671}H_{999}N_{19}O_{16}$	
Polybutadiene acrylic acid	PBAA	$C_{70}H_{104}O_4$	
Polyethylene Glycol	PEG	$C_{2n}H_{4n+2}O_{n+1}$	Fuel, Binder *(polyether or polyester type)*
Polycaprolactone polyol	PCP	$C_{564}H_{999}O_{217}$	
Polyglycol adipate	PGA	$C_{10}H_{16}O_5$	
Polypropylene glycol	PPG	$C_{52}H_{108}O_{17}$	
Polyurethane polyester or polyether	PU	$C_{536}H_{987}N_{12}O_{140}$	
Methyl Aziridinyl Phosphine Oxide	MAPO	$C_9H_{18}N_3OP$	Curing Agent or Crosslinker *(reacts with polymer binder)*
Isophorone diisocyanate	IPDI	$C_{11}H_{18}N_2O_2$	
Toluene -2,4-diisocyanate	TDI	$C_9H_6N_2O_2$	
Hexamethylene diisocyanate	HMDI	$C_8H_{12}N_2O_2$	
Dimeryl diisocyanate	DDI	$C_{10}H_{12}N_4O_3$	
Trimethylol propane	TMP	$C_6H_{14}O_3$	

16% and 18% in grain respectively for Space Shuttle and Ariane 5 Solid Rocket Motors

69.6% and 68% in grain respectively for Space Shuttle and Ariane 5 Solid Rocket Motors

~14% in grain for Space Shuttle and Ariane 5 Solid Rocket Motors





IUS (Inertial Upper Stage), 2-Stage Solid Rocket Motor Unit, Stage 1: 42 klb Thrust; Stage 2: 17 to 24 klb Thrust

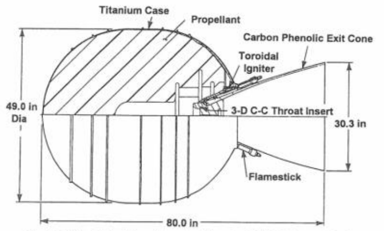
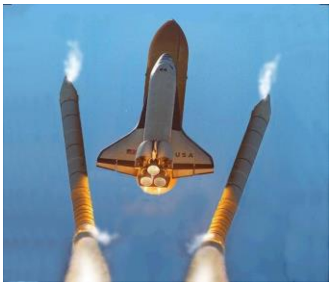
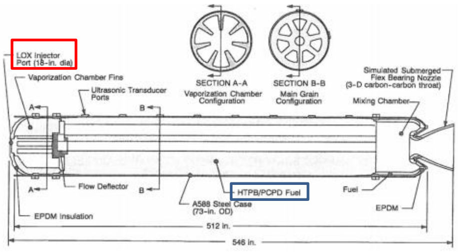


Fig. 6.19 Star 48B solid rocket motor (Courtesy Thiokol Corporation.)

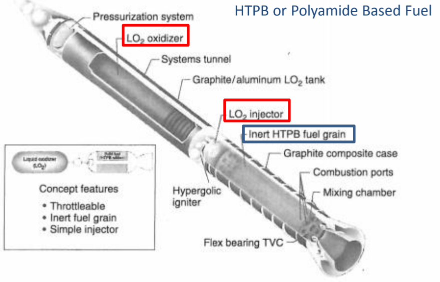
15 klb Thrust





Hybrid Rocket Engines (HREs)

Nitrous Oxide (N_2O) Oxidizer
HTPB or Polyamide Based Fuel



Comparison of the Types of Chemical Rocket Engines

Type	Advantages	Disadvantages
LREs	Throttle-able	More Complex
	Can test prior to use/launch	Lower Propellant Mass Fraction
	Higher I_{SP} (Specific Impulse)	Leaking & Boiloff Issues
	Can be multiple use (booster, sustainer, orbital adjustments)	More preparation time before use/launch
	Can be shut off any time after start	Complex pumps often required
SREs	Simple operation	Can only have pre-set throttle vs. time
	High propellant mass fraction (boosters)	Cannot be shut off once started
	Easily scalable to higher thrust levels/classes	Fuel and oxidizer (all propellants) in combustion chamber
	Ready and useable at moment's notice	I_{SP} (Specific Impulse) lower than LREs
	Efficient packaging	Difficult to test; Cannot test same engine prior to its use/launch
HREs	Throttle-able	Fuel surface non-uniform regression and erosion issues
	Simpler operation than LREs	I_{SP} (Specific Impulse) lower than LREs
	Can be shut off any time after start	Cannot test same engine prior to its use/launch
		Limited operational and proven experience

$$F = \dot{m}v_e + (P_e - P_a) \cdot A_e$$

Thrust Equation from Slide 10

Specific Impulse, **the <u>most important engine performance measurement</u>**

$$I_{SP} = \frac{F}{\dot{m}} = v_e + (P_e - P_a) \cdot \frac{A_e}{\dot{m}}$$

Why?

$$\boxed{\Delta v = g_o I_{SP} \ln\left|\frac{m_o}{m_f}\right| - \Delta v_{losses}}$$

<u>Tsiolkovsky's (the general) rocket equation (for a single stage rocket)</u>

Where:

$\boxed{\Delta v \equiv Change\ in\ velocity\ of\ rocket}$

$g_o \equiv Acceleration\ due\ to\ Earth\ gravity,$
$unit\ conversion\ reference$

$m_o \equiv Initial\ mass\ of\ the\ rocket$
$m_f \equiv Final\ mass\ of\ the\ rocket$

$\Delta v_{losses} \equiv Velocity\ losses\ due\ to\ gravity, aerodynamic\ drag,$
$steering, and\ earth's\ (planet's)\ rotation$

Higher I_{SP} results in higher Δv, higher payload mass, lower initial propellant mass, or combinations of these

Audience Question:

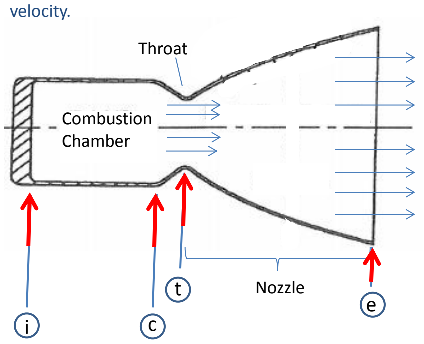
What is the change in velocity, Δv, needed to get from the Earth's surface to the ISS (International Space Station); which is in LEO (Low Earth Orbit) between 330 and 435 km (205 and 270 miles) above the surface?

- 1,220 km/hr (760 mph)
- 4,830 km/hr (3,000 mph)
- 19,950 km/hr (12,400 mph)
- 28,160 km/hr (17,500 mph)
- 40,230 km/hr (25,000 mph)

Assume that the Earth is not rotating at time of launch
(this does make a difference)

Determining **I_{SP} (Specific Impulse) and thrust** of a rocket engine or designing a rocket engine to have the desired or maximum practicable I_{SP} and thrust requires use of **thermochemistry and thermodynamics**.

1. **Station 'i:'** Mass flow rate of propellants into the combustion chamber at (injector) are set.
2. **Station 'c:'** Thermochemistry is used to determine temperature of combustion product gas mixture and mole (or mass) fractions of constituent gases in this gas mixture.
3. **Station 'c' to Station 't' (throat):** Thermodynamics is used to determine change in gas properties and velocity.
   - if gas velocity at station 't' is not sonic, combustion chamber pressure (or throat diameter) is changed and step 2. is repeated (iterative process).
4. **Station 't' to Station 'e:'** Thermodynamics is used to determine change in gas properties and velocity.



5. **Station 'e:'** Velocity and pressure of the gas mixture are used to calculate **thrust and I_{SP}**.

Note: For steps 3. and 4., Thermochemistry is also used to determine change in mole fractions of constituent gases for "Shifting Equilibrium" analysis; overestimates I_{SP} by ~1 to 4%

"Frozen Equilibrium" analysis; no change in const. gas mole fractions between Stations 'c' and 'e'; underestimates I_{SP} by ~1 to 4%

I_{SP} and Other Performance Data, Existing & Operational LREs

Engine	Propellants	O/F MR	Thrust, vacuum		Thrust, sea level		I_{SP}, vac.	I_{SP}, s.l.
			(kN)	(klb$_f$)	(kN)	(klb$_f$)	(sec)	(sec)
Vulcain (HM60)	LOX/LH$_2$	6.20	1075	241	815	183	431	310
SSME (RS-25)	LOX/LH$_2$	6.03	2285	513	1825	410	455	363
HM7 B	LOX/LH$_2$	5.14	62	14	N/A	N/A	445	N/A
RL-10	LOX/LH$_2$	5.00	68	15	N/A	N/A	410	N/A
J-2	LOX/LH$_2$	5.50	1052	236	N/A	N/A	425	N/A
F-1	LOX/RP-1	2.27	7893	1772	6880	1544	304	265
RS-27	LOX/RP-1	2.25	1043	234	934	210	295	264
XLR-105-5	LOX/RP-1		370	83	250	56	309	215
11D58	LOX/Kerosene		850	191	N/A	N/A	348	N/A
RD 170	LOX/Kerosene	2.63	8060	1809	7425	1667	337	309
RD 180	LOX/Kerosene	2.72	4150	932	3830	860	338	311
AJ-26	LOX/RP-1	2.74	1755	394	1581	355	332	299
Merlin 1C	LOX/RP-1	~2.5 - 2.8	480	108	420	94	305	275
Merlin 1C Vac.	LOX/RP-1	~2.5 - 2.8	411	92	N/A	N/A	342	N/A
Viking 5C	N_2O_4/UDMH	1.70	725	163	678	152	278	248
RD 253	N_2O_4/UDMH		1670	375	1410	317	316	267
Aestus	N_2O_4/MMH	2.05	29	7	N/A	N/A	324	N/A

I_{SP} and Other Performance Data, Existing and Operational SREs

Engine	Propellants and their Mass Fractions	Thrust, vacuum		Thrust, sea level		I_{SP}, vac.	I_{SP}, s.l.
		(kN)	(klb$_f$)	(kN)	(klb$_f$)	(sec)	(sec)
Space Shuttle SRM	AP 69.6%, Al 16%, PBAN 14%, FeO 0.4%	15012	3370	14700	3300	268	~226
Ariane 5 MPS	AP 68%, Al 18%, PBAN 14%	6470	1452	6470	1452	275	~245
AJ-60A	(Nominally Same as Space Shuttle SRM)	1270	285	1270	285	275	~245
IUS, Stage 1, Orbus 21	(Nominally Same as Orbus 6)	185	42	N/A	N/A	296	N/A
IUS, Stage 2, Orbus 6E	(Nominally Same as Orbus 6)	75.3 to 79.3	16.9 to 17.8	N/A	N/A	289-304	N/A
Star 48B	AP 71%, Al 16%, HTPB 11%	68.6 to 78.0	15.4 to 17.5	N/A	N/A	292	N/A
Star 27	AP 72%, Al 16%, HTPB & Other Binders, Additives 12%	23.2 to 28.5	5.2 to 6.4	N/A	N/A	291	N/A
Orbus 6	AP 68%, Al 18%, HTPB & Other Binders, Additives 14%	75.7 to 106.0	17.0 to 23.8	N/A	N/A	290	N/A

Audience Question:

LREs that use hydrogen and oxygen propellants have the highest I_{SP}. However, there are various reasons that designers often select SREs, HREs, or LREs with different propellants for particular flight vehicles or stages thereof. **Which of the following is false** and would therefore **not** be a reason that a designer might design or select a rocket engine that uses a fuel propellant other than hydrogen?

- Liquid hydrogen density is much less than the density of other propellants
- Hydrogen molecules are smaller than those of other propellants
- Saturation temperature of hydrogen is below -400 ^oF
- Hydrogen is a toxic substance
- Hydrogen is colorless and odorless

Rocket Engine Design Issues and Challenges:

- Combustion Processes
  - Propellant Atomization, Vaporization and Mixing; Injector Design and Performance; is Essential
  - Prevention of Ignition Quenching (mainly during start transients)
  - Combustion Stability (Prevent coupling between chamber pressure and propellant flow rates)
  - Pogo, coupling between vehicle acceleration and propellant flows
  - Hot streaking, Local Over-temperature Zones across Injector Face and near Combustion Chamber walls; LREs
  - Uniform Propellant Regression, HREs and SREs

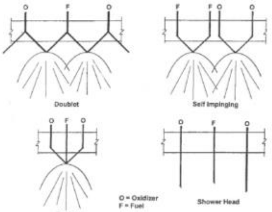
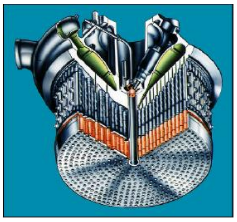


Fig. 5.2 Injector configurations in use.



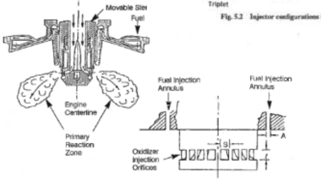


Fig. 4-59 Pintle injector.

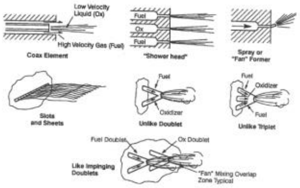
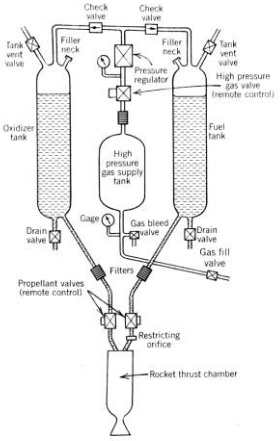


Fig. 4-57 Typical injector element types.

Rocket Engine Design Issues and Challenges:

- Source (s) of Pressure to Inject Propellant(s) into Combustion Chamber for LREs and HREs
  - **Pressurized propellant tanks** on vehicle
    - Relatively simple operation and high reliability; one or two propellant valves to each engine
    - But, usually not possible or practical for large high-thrust rocket engines or vehicles with high propellant mass fraction at launch or initial engine start (typical initial mass fractions over 85%)
    - Limited to smaller vehicles or thruster engines used for maneuvering and attitude control



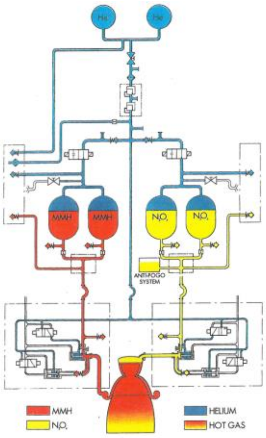
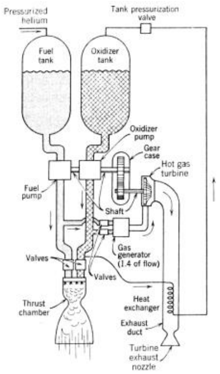
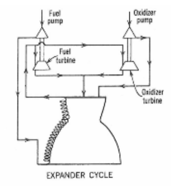


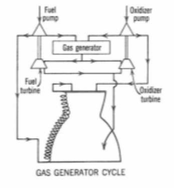
Figure 3.5. The Ariane 5 Aestus engine.

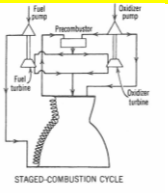
Rocket Engine Design Issues and Challenges:

- Source (s) of Pressure to Inject Propellant(s) into Combustion Chamber for LREs and HREs (Continued)
  - **Pump Fed Rocket Engines** (lower pressures in vehicle propellant tanks , lighter weight tanks & vehicle)
    - But the price is more complexity and a host of other design issues to address
    - High flow rate and rotational speed (10,000 to 45,000 rpm) pumps needed
    - Gas turbines used to drive pumps (turbopumps); very high power density
    - Additional combustion or high heat flux (H-X) devices for gases to drive these turbines
    - Turbine blades , discs, blisks; high thermal and dynamic stresses
      - Hot streaking issues are amplified (across full injector face, not just along walls)
      - Active cooling passages inside blades and/or ceramic or MMC coating of blades necessary (very complex and costly fabrication processes)
    - Hazards of oxygen-rich preburner or gas generator combustion devices that are now often used with RP-1 and other hydrocarbon fueled LREs
    - Highly complex operation
      - Interaction between multiple control valves, esp. during throttling, start and shut-down transients
      - Propellant and hot gas flow rates and O/F mixture ratios during throttling and transient need to stay within operating limits of turbines, combustion and H-X devices



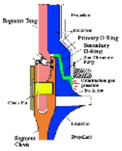






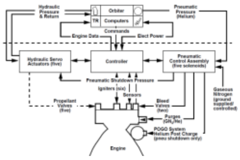
Rocket Engine Design Issues and Challenges (Continued):

- **Material Properties and Limitations**
  - Combustion chamber gas temperatures above melting point of wall materials or are where material strength is reduced significantly; need for fuel rich or all fuel flow along walls
  - Containment of pressures vs. wall thicknesses; Weight constraints
  - Differential thermal expansion and rates of thermal expansion between mating parts; often with close fit tolerances
  - Thermal ratcheting, changes engine performance and also related to fit tolerances
  - Active cooling required for LREs
    - Propellant(s) used as coolant for Combustion Chamber, Throat, and Nozzle walls
    - Also serves to pre-heat propellant(s) prior to injection into Combustion Chamber
    - Flowing coolant is barrier between inner walls in contact with hot gases and outer walls that contain pressure (reduces amount of differential pressure acting on inner walls)
    - Film cooling, using fuel propellant, along chamber, throat, and nozzle walls also used
      - Results in some energy losses
  - Solid propellant itself and stagnant gas regions used to provide thermal barriers between hot gases and pressure containment casings for SREs and HREs
  - High temperature materials used as barriers between hot gases and pressure containing parts of throats and nozzles for SREs and HREs; Carbon-Carbon, Phenolics, Graphite
  - Ablative material used for nozzle cooling; some LREs, SREs, and HREs
  - Mechanical joint sealing of hot gases; metal seals vs. non-metallic seals
  - Dynamic shaft seals of turbopumps; high pump speeds, keep propellants on pump-side isolated from hot gases on turbine side (pump fed LREs and HREs)
  - Throat and nozzle wall stress induced corrosion; OH, H, O, plus for SREs Cl, HCl, other acids
  - Throat and Nozzle erosion; high gas velocities; mainly with SREs as they have solid particles in hot gas mixtures
  - Propellant compatibility and hazards:
    - Flammability of Oxygen, Fluorine, and other oxidizers (metals and other materials of rocket engine are all potential fuels)
    - Hydrogen embrittlement of metals; mainly at high temperatures or pressures



Rocket Engine Design Issues and Challenges (Continued):

- Material Properties and Limitations (Continued)
  - Propellant compatibility and hazards (Continued):
    - Cryogenic propellants; incl. handling, storage
      - They vaporize at room pressure & temperature
      - Reduced material toughness (ductility) at low temperatures
      - Differential thermal expansions and rates thereof at low temperatures
      - Low temperature seals; sealing materials less pliable, more brittle
      - Need for helium purges and pressurants for LH propellant systems or where vehicle weight constraints dictate (does not liquify or freeze at LH temperatures, inert gas having the lowest mass density)
      - More prone to leak, esp. hydrogen and helium (smallest of molecules)
    - Coking (carbon buildup) on H-X walls with RP-1 and other hydrocarbon fuels
      - A solution to this is use of oxidizer-rich combustion devices (mentioned on prior slides)
    - Thermal runaway hazards of monopropellants
    - Highly toxic propellants; MMH, UDMH, N_2O_4, H_2O_2, others
    - SRE Propellant Storage and Handling, High Hazards; Static electricity and unwanted heat sources
- **Throttling**
  - Often needed for controlling vehicle flight trajectory velocity vs. time or position profile
    - Optimum use of propellant as rocket travels through atmosphere and gains altitude
    - Prevent exceeding 'g' (acceleration) limits of vehicle structure (as its mass decreases)
  - Complex for LREs, esp. those that are pump fed (as described on prior sheets)
  - SREs can only throttle to preset profile; cannot adjust during operation
  - SREs cannot be shut down once started



Rocket Engine Design Issues and Challenges (Continued):

- **Thrust Vector Control (TVC)**
  - Needed for Steering Rocket, Controlling its flight trajectory
  - Three methods generally used currently; (Engine) "Gimbal," "Flexible Laminated (Nozzle) Bearing," and "Gimbaled Auxiliary Thrust Chambers"
  - Two others used in early designs; "Jet Vanes" and "Jet Tabs"
  - One other method, "Side Injection," proposed and experimented with, but not yet employed
  - Each has advantages and disadvantages

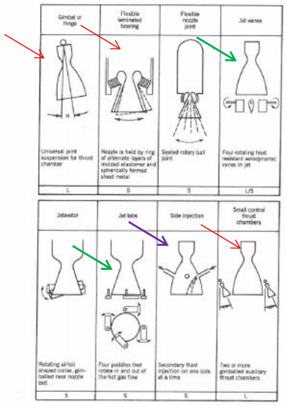


FIGURE 16–3. Simple schematic diagrams of eight different TVC mechanisms. Actuators and structural details are not shown. The letter L means it is used with liquid propellant rocket engines and S means it is used with solid propellant motors.

Thrust Vector Control; Schematic Diagrams

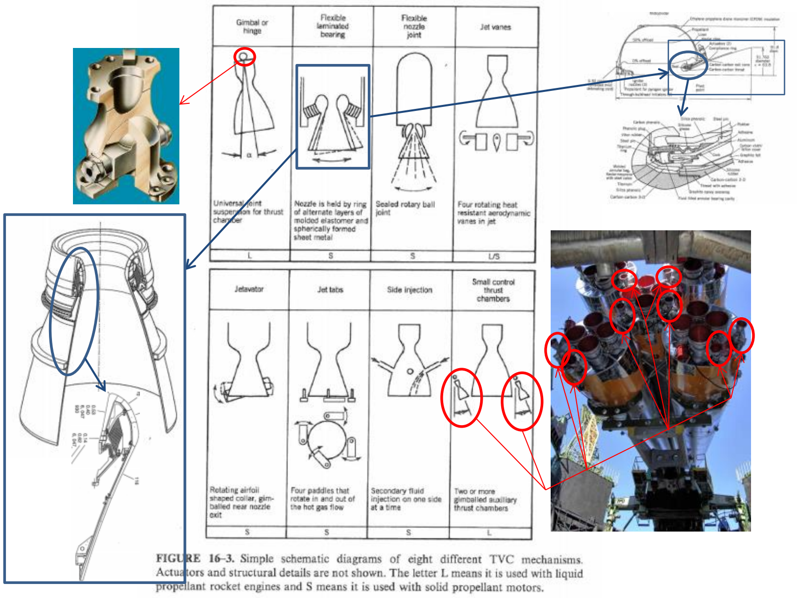


FIGURE 16–3. Simple schematic diagrams of eight different TVC mechanisms. Actuators and structural details are not shown. The letter L means it is used with liquid propellant rocket engines and S means it is used with solid propellant motors.

Summary:

- Chemical rocket engines used in many applications that are part of everyday life;
  Spacecraft and satellites for research, exploration, weather & earth monitoring, communications; Also used for weapons delivery systems, entertainment
- Three types of chemical rocket engines; LREs, SREs, HREs
- The importance of I_{SP}, specific impulse (the most important performance measure)
  - Thrust is important, but it's not the only thing
- Thermochemistry is essential for rocket engine design and analysis
- Thermodynamics is also needed for design and analysis of rocket engines;
  Downstream from the combustion/exothermic reaction process
- There are a many other design challenges and details that go into rocket engine design; "Yes, it really is "Rocket Science."

References:

“Space Transportation System Training Data: Space Shuttle Main Engine Orientation” Boeing BC98-04, June 1998

Brown, C. D. (1996). “Space Propulsion,” AIAA Education Series, ed. Przemieniecki, J. S., American Institute of Aeronautics and Astronautics, Washington, DC.

Hill, P. G. & Peterson, C. R. (1992). Mechanics and Thermodynamics of Propulsion, 2nd Edition, Addison-Wesley Publishing Company, Inc., Reading, MA.

Huzel, D. K. & Huang, D. H. (1992). “Modern Engineering for Design of Liquid-Propellant Rocket Engines,” Progress in Astronautics and Aeronautics, Volume 147, ed. Seebass, A. R., American Institute of Aeronautics and Astronautics, Washington, DC.

National Aeronautics and Space Administration Press Kit/October 2012, SpaceX CRS-1 Mission, First Cargo Resupply Services Mission Press Kit

NIST Standard Reference Database 23, Reference Fluid Thermodynamic and Transport Properties Database (REFPROP), Version 9.1

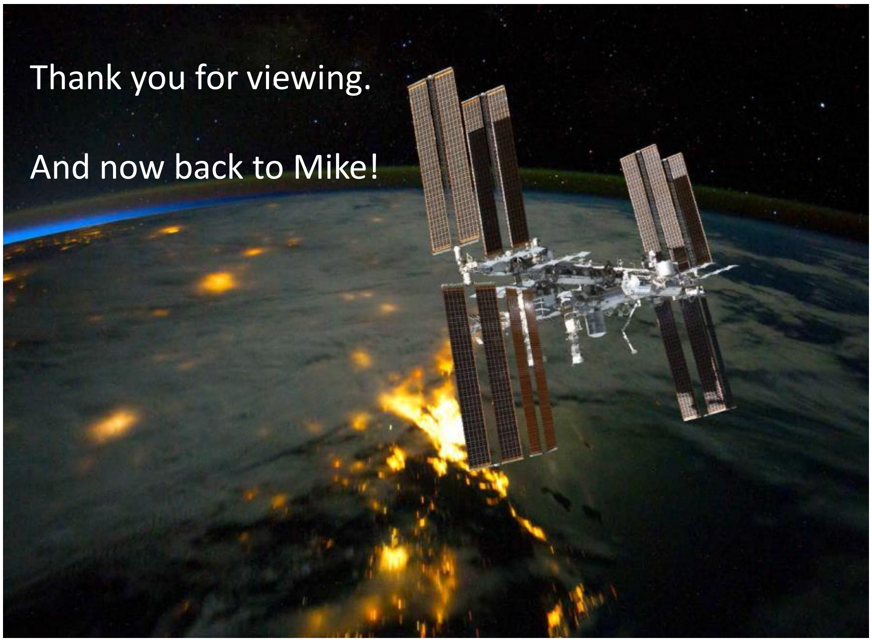
Orbital Sciences Corporation Brochure, “Antares Medium-Class Launch Vehicle,” ©2013 Orbital Sciences Corporation D12_00084

Orbital Sciences Corporation Brochure, “Antares Medium-Class Launch Vehicle Fact Sheet,” ©2014 Orbital Sciences Corporation FS007_06_2429

SpaceX and MDA ™ Press Kit/September 2013, CASSIOPE (and Upgraded Falcon 9) Mission Demonstration Press Kit

Sutton, G. P. & Biblarz, O. (2001). Rocket Propulsion Elements; An Introduction to the Engineering of Rockets, 7th Edition, John Wiley & Sons, New York, NY.

Turner, M. J. L. (2000). Rocket and Spacecraft Propulsion, Springer-Praxis Publishing Ltd, Chichester, UK.



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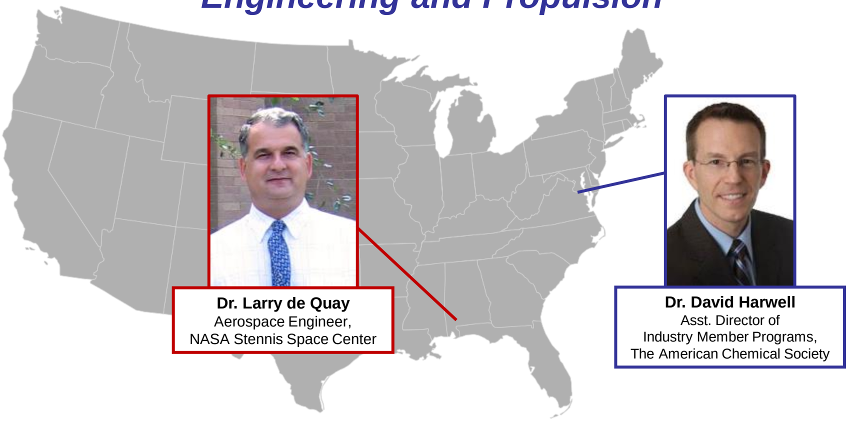

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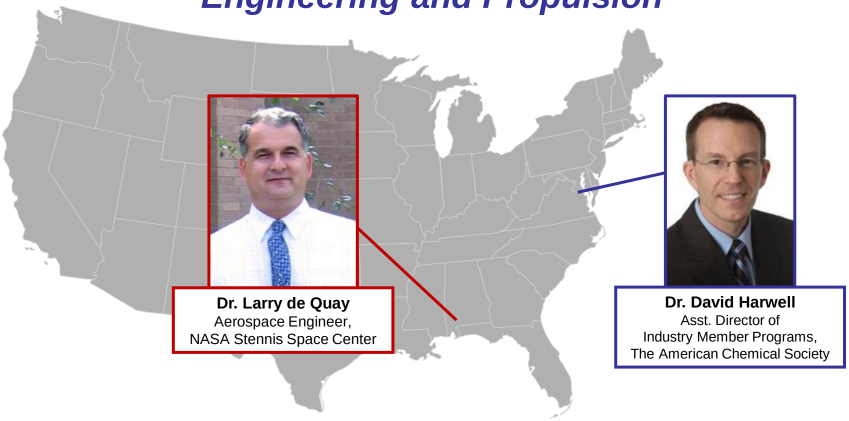

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