Space Propulsion
enabling the future of
space transportation and exploration

Vigor Yang
Georgia Institute of Technology
Atlanta, Georgia, U.S.A.
von Karman Lecture in Astronautics
September 13, 2016
Saturn I SA-1
07/14-15 1965 Mariner 4 first Mars flyby
10/11 1968 Apollo 8
11/14 1969 Apollo 10
04/11 1970 Apollo 13
07/26 1971 Apollo 15
12/07 1972 Apollo 17 The last lunar landing mission
01/31 1971 Apollo 14
04/16 1972 Apollo 16
02/21 1967 Apollo 5
01/22 1968 Apollo 7
03/03 1969 Apollo 9 First manned flight of all lunar hardware in Earth Orbit
10/11 1968 Apollo 8
11/09 1967 Apollo 4
01/22 1968 Apollo 7
07/16 1969 Apollo 11 One Small Step Neil Armstrong becomes the first human to walk on the moon.
07/11 1979 Skylab Reentry
05/14 1973 Skylab Launch
04/12 1981 Space Shuttle Columbia the first flight of the Space Shuttle Program
08/30 1984 Discovery
04/24 1990 Discovery mission launches the Hubble Space Telescope
12/04 1998 First human flight to the International Space Station
07/21 2011 Nasa officially retired the Space Shuttle Program after 30 years of service
04/12 1981 Space Shuttle Columbia the first flight of the Space Shuttle Program
08/08 1985 Atlantis
11/11 1982 Challenger
05/02 1992 Endeavour’s maiden flight and the first 3-person space walk
02/01 2003 Columbia Disaster
2/12/2011 Mars: Curiosity Rover Jupiter: Juno Spacecraft
2/12/2011 Mars: Curiosity Rover
12/04 1998 First human flight to the International Space Station
07/11 1979 Skylab Reentry
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11/11 1982 Challenger
05/02 1992 Endeavour’s maiden flight and the first 3-person space walk
02/01 2003 Columbia Disaster
2/12/2011 Mars: Curiosity Rover
2016 InSight
2020s Europa Multiple-Flyby mission
2013 Mars Atmosphere and Volatile Evolution (MAVEN)
Rocket Engine Development in U.S. (1945-2012)

Solid Rocket Development

Liquid Rocket Development
Twelve SE-8 reaction control engines guided Columbia safely through reentry on her way to splashdown and the crew’s appointment with history.

One RS-18 lunar ascent module engine lifted Eagle off the lunar surface for a safe rendezvous with Columbia.

Two SE 7-1 ullage engines settled propellant after first J-2 Burn and during restart chill down prior to second J-2 Burn.

One third stage J-2 engine put Apollo 11 into Earth orbit... and then boosted Neil Armstrong, Buzz Aldrin and Michael Collins toward the moon.

Four S-II ullage engine settled Stage II propellants before Stage II ignition.

Five J-2 engines boosted Stage II with over a million pounds of thrust.

Five F-1 booster engines provided 7.5 million pounds of first stage thrust for Saturn V.

Lift-off thrust: 7.5 Mlbf. 30 B747 take-off thrust
Twelve SE-8 reaction control engines guided Columbia safely through reentry on her way to splashdown and the crew’s appointment with history.

One RS-18 lunar ascent module engine lifted Eagle off the lunar surface for a safe rendezvous with Columbia.

Two SE 7-1 ullage engines settled propellant after first J-2 Burn and during restart chill down prior to second J-2 Burn.

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Four S-II ullage engine settled Stage II propellants before Stage II ignition.

Five J-2 engines boosted Stage II with over a million pounds of thrust.

Five F-1 booster engines provided 7.6 million pounds of first stage thrust for Saturn V.

Six different engines developed: F-1, J-2, LMDE, LMAE, CSME, R4D-C (100-1.5M lbf)
Landing a Man on the Moon

Call to Action: President John F. Kennedy makes a speech before Congress on May 25, 1961, dealing with his plan “of landing a man on the Moon and returning him safely to the Earth before the end of the decade.” – July 20, 1969
Engines in Manned Flights (1960s)

Source: John F. Kennedy Space Center
Combustion Instability in F-1 Engine

Typical Pressure Oscillations Observed in Early F-1 Engines

Chamber Pressure: 5000 psi
LOX Injection Pressure: 5000 psi
Fuel Manifold Pressure: 5000 psi

resurges
Damaged Combustion Chambers
### Injector Patterns Investigated during F-1 Development

<table>
<thead>
<tr>
<th>Pattern</th>
<th>No. Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modified 5U</td>
<td>1344</td>
</tr>
<tr>
<td>5U</td>
<td>507</td>
</tr>
<tr>
<td>Radially Aligned, “Wagon Wheel”</td>
<td>75</td>
</tr>
<tr>
<td>Double Row Cluster</td>
<td>16</td>
</tr>
<tr>
<td>Single Row Fuel, Double Row LOX</td>
<td>14</td>
</tr>
<tr>
<td>H-1</td>
<td>4</td>
</tr>
<tr>
<td>Reverse 5U</td>
<td>2</td>
</tr>
<tr>
<td>Rotated Fan</td>
<td>2</td>
</tr>
<tr>
<td>Spray Nozzle</td>
<td>2</td>
</tr>
<tr>
<td>Double Row Fuel</td>
<td>2</td>
</tr>
<tr>
<td>Splash Ring</td>
<td>1</td>
</tr>
<tr>
<td>Shielded Stream</td>
<td>1</td>
</tr>
<tr>
<td>O-F-O Triplet</td>
<td>1</td>
</tr>
<tr>
<td>Coaxial</td>
<td>17</td>
</tr>
</tbody>
</table>

### Element Designation and Configuration

- **Concentric Tube**
  - GAS
  - LIQ
- **Concentric Tube with Liquid Swirl**
  - GAS
  - LIQ
  - RECESS
- **Unlike Pentad (4 on 1)**
  - LIQ
  - GAS
- **Unlike Doublet (1 on 1)**
  - LIQ
  - OX
  - FUEL
- **Unlike Triplet (2 on 1)**
  - LIQ
  - OX
  - OX
  - FUEL
- **Like Doublet (1 on 1)**
  - LIQ
  - OX
  - OX
  - FUEL
- **Showerhead**
  - LIQ
  - FUEL
- **Variable Area (Pintle)**
  - LIQ
  - OX
- **Splash Plate**
  - LIQ
  - OX
  - FUEL
water flow test of F-1 engine injection system
(5735 lbm/sec)
Baffle Patterns Investigated During Development

<table>
<thead>
<tr>
<th>Comp’ts</th>
<th>Length, in</th>
<th>No. Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>--</td>
<td>--</td>
<td>27</td>
</tr>
<tr>
<td>e</td>
<td>3</td>
<td>35</td>
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<tr>
<td>b</td>
<td>4</td>
<td>5</td>
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<tr>
<td>c</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>d</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>e</td>
<td>13a</td>
<td>383</td>
</tr>
<tr>
<td>e</td>
<td>13b</td>
<td>1</td>
</tr>
<tr>
<td>f</td>
<td>13r</td>
<td>1446</td>
</tr>
<tr>
<td>g</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>h</td>
<td>21c</td>
<td>17</td>
</tr>
<tr>
<td>i</td>
<td>25</td>
<td>48</td>
</tr>
<tr>
<td>j</td>
<td>41</td>
<td>1</td>
</tr>
<tr>
<td>k</td>
<td>53</td>
<td>1</td>
</tr>
<tr>
<td>l</td>
<td>81</td>
<td>1</td>
</tr>
</tbody>
</table>
Typical FRT/Qualification Injector Configuration (Modified 5U)
Development of Stable F-1 Engine – Project First

  207 full-scale tests with 11 injectors

  422 full-scale tests with 46 injectors

- Flight Qualification Tests (FQT), January 1965 – September 1966
  703 full-scale tests with 51 injectors

A total of 1332 engine tests and 1337 component tests with 108 injectors.
### F-1 ENGINE/J-2 ENGINE COST HISTORY

<table>
<thead>
<tr>
<th>FY 59</th>
<th>FY 60</th>
<th>FY 61</th>
<th>FY 62</th>
<th>FY 63</th>
<th>FY 64</th>
<th>FY 65</th>
<th>FY 66</th>
<th>FY 67</th>
<th>FY 68</th>
<th>FY 69</th>
<th>FY 70</th>
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</thead>
<tbody>
<tr>
<td>3.578</td>
<td>22.152</td>
<td>45.859</td>
<td>81.922</td>
<td>116.935</td>
<td>195.894</td>
<td>256.235</td>
<td>286.698</td>
<td>232.734</td>
<td>175.916</td>
<td>117.201</td>
<td>63.573</td>
</tr>
<tr>
<td>3.578</td>
<td>22.152</td>
<td>44.404</td>
<td>77.149</td>
<td>104.580</td>
<td>175.579</td>
<td>237.006</td>
<td>242.872</td>
<td>200.894</td>
<td>150.932</td>
<td>96.850</td>
<td>50.630</td>
</tr>
<tr>
<td>3.578</td>
<td>22.152</td>
<td>37.121</td>
<td>50.958</td>
<td>59.202</td>
<td>100.614</td>
<td>137.424</td>
<td>129.876</td>
<td>101.720</td>
<td>78.830</td>
<td>45.125</td>
<td>18.604</td>
</tr>
</tbody>
</table>

### Development Cost of F-1 and J-2 Engines

- **F-1:** $2.4B in 1966 or $17.85B in 2016
- **J-2:** $1.7B in 1966 or $12.64B in 2016
A large External Tank that holds fuel for the main engines. The tank is the only component of the Space Shuttle that is not reused. Approximately 8.5 minutes into the flight, with its propellant used, the tank is jettisoned.

Two Solid Rocket Boosters which provide most of the Shuttle's lift during the first two minutes of flight. Each provided a maximum 1,400,000 kg (3,100,000 lbf) thrust

The Orbiter which houses the crew.

Space Shuttle Main Engines:
Each Space Shuttle Main Engine operates at a liquid oxygen/liquid hydrogen mixture ratio of 6 to 1 to produce a sea level thrust of 179,097 kilograms (375,000 pounds) and a vacuum thrust of 213,188 kilograms (470,000 pounds).
Development Cost of SSME

$2.45B in 1980 or $7.71B in 2016
## Costs and Test Histories of Engine Development

<table>
<thead>
<tr>
<th>Engine</th>
<th>Cost of Development ($Billion *)</th>
<th>No. Tests to Single Engine Cert</th>
<th>No. of Rework Cycles</th>
<th>Avg. Cost per Rework Cycle ($M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-1</td>
<td>2.4 (17.85)</td>
<td>2040</td>
<td>203</td>
<td>9 (67)</td>
</tr>
<tr>
<td>J-2</td>
<td>1.7 (12.64)</td>
<td>1850</td>
<td>223</td>
<td>6 (45)</td>
</tr>
<tr>
<td>SSME</td>
<td>2.5 (7.71)</td>
<td>670</td>
<td>163</td>
<td>12 (37)</td>
</tr>
</tbody>
</table>

(* Cost in $1966, $1980 and $2016 through single engine certification, excluding facilities.)

The average cost per rework cycle is calculated as the total cost of the development program multiplied by the fraction of the development program number of rework cycles in the program.

Example: F-1 Cost/Rework Cycle = $2.4B × 0.75/203 = $9 M

$1.00 in 1966 and 1980 had the same buying power as $7.44 & $3.08 in 2016 respectively.

Ref: Glenn Havskjold1 (AIAA 2009-5436)
President Obama said (April 15, 2010)

“By 2025 we expect new spacecraft designed for long journeys to allow us to begin the first ever crew missions beyond the Moon into deep space,”

“So, we’ll start by sending astronauts to an asteroid for the first time in history. By the mid 2030, I believe we can send humans to orbit Mars and return then safely to earth, and a landing on Mars will follow.”
The Future of Exploration

- **Human Space Operations**
  - International Space Station
  - Commercial Partners
  - Earth

- **Human Space Exploration**
  - Lagrangian Point L2
  - Moon
  - Near-Earth Asteroid
  - Mars
  - Europa

- **Robotic Science**

**Timeline**

- **2025**
- **2035**

Distances:
- 100s of Miles
- 1,000s of Miles
- 10,000s of Miles
- 100,000s of Miles
- 1,000,000s of Miles
- 10,000,000s of Miles
- 100,000,000s of Miles
Launch Propulsion
make access to space more reliable, routine, and affordable

In-Space Propulsion
• Enhance missions by improving performance, durability, cost and manufacturing;
• Develop new capabilities.
Propulsion Issues

Launch Propulsion:
-- make access to space more reliable, routine, and affordable

solid rocket propulsion  ancillary propulsion systems
liquid rocket propulsion  unconventional systems
air breathing propulsion  balloon launch systems

In-Space Propulsion:
Enhance missions by improving performance, durability, manufacturing, and cost;
Develop new capabilities.
chemical propulsion  supporting technologies
non-chemical propulsion
Advanced propulsion technologies (TRL<3)

Ref. NASA Technology Roadmaps (July 2015)
Space Launch System (SLS) Solid Rocket Motor

**Total Weight:** 1.3 Mlb  
**Propellant Weight:** 1.1 Mlb  
**Average Thrust:** 2.8 Mlbf  
**Burn Time:** 123.4 sec

**Total Weight:** 1.6 Mlb  
**Propellant Weight:** 1.4 Mlb  
**Propellant:** polybutadiene acrylonitrile (PBAN)  
**Average Thrust:** 3.6 Mlbf  
**Burn Time:** 126 sec

**Improvement in SLS Block II**
- From PBAN to HTPB to improve performance, energy density, and system compatibility
- Increase motor dimension for higher thrust (to support payload from 70 mt to 130 mt)
- Reduce case weight and enhance reliability
SLS Solid Rocket Booster: Issues & Opportunities

DM-3 Static Test (Sep 8, 2011)

DM-2 Static Test (Aug 31, 2010); 4 °C

DM-1 Static Test (Sep 10, 2009); 32 °C

- **AP/AI/PBAN/additives**
  (70/16/12/2% by mass)
  -- Isp 242 seconds at sea level or 268 seconds in vacuum.

- **AP/AI/HTPB/additives**
  (70/16/12/2% by mass)
  -- Isp 300 seconds in vacuum

- **Toxicity**
  AP -> H₂O, HCl, O₂, HClO₄, Cl₂, ClOH, NO, NO₂, N₂O, ClO₂

- **Incomplete combustion of Al particles**

- **Composite case and health monitoring**

- **Reliably**

Background Photo : Orbital ATK / Front Photo : NASA
Liquid Propulsion
Make access to space more reliable, routine, and affordable
Power Cycles of Pump-Fed Engines

Expander Cycle
- Fuel pump
- Fuel
- Turbine
- Oxidizer
- Thrust chamber assembly

Gas Generator Cycle
- Fuel pump
- Fuel
- Turbine
- Oxidizer pump
- Gas Generator
- Oxidizer
- Thrust chamber assembly

Staged Combustion Cycle (Oxidizer-rich)
- Fuel pump
- Fuel
- Turbine
- Oxidizer pump
- Preburner
- Oxidizer
- Thrust chamber assembly
Evolution of Staged-Combustion Engines

Legend:
- Tripropellant
- LOX/LNG
- LOX/LH2
- LOX/Kerosene
- NTO/UDMH


RD-270 → RD-0120 → RD-120 → RD-170 → RD-180 → RD-191

SSME (U.S.) → LE-7 (Japan) → LE-7A (Japan)

RD-0120 TP
experimental engines
(incomplete development)

RD-253

knowledge transfer
update

NK-15 → NK-33

RD-120

update

knowledge transfer

BE-4 (U.S.)

AR1 (U.S.)

Raptor (U.S.)

under development

derivatives

RD-275

derivatives

YF-100 (China)

update
Historical Engine Development Cost Breakdown

Composite cost profile for development of innovative advanced technology products (rocket engine example) -- Glenn Havskjold (AIAA 2009-5436)
Oxidizer-Rich Staged Combustion Engine (RD-170) -- a case study --

Propellant: LOX / kerosene
Mixture Ratio: 2.63
Nozzle Ratio: 36.87
First Flight: 1985-04-13

Thrust (vac.): $4 \times 1976$ kN; Isp (vac.): 337 sec
Burning Time: 150 sec; 24.52 MPa
Dry Weight: 10,750 kg
A Defense-in-Depth Approach
-- design philosophy --
Main Combustion Chamber Injector
-- a dynamical system --

Body

Sleeve

Tangential Fuel Ports
Main Combustor Injector
-- design attributes --

Injector Inlet
Oxidizing-gas passage
Fuel Passage
Tangential Fuel Ports
Sleeve
Injector Outlet
Body
Key Dimensions of Injector
-- design of experiments --

Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th></th>
<th>Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5. Fuel Port Radius</td>
<td>11. Exit Radius (mm)</td>
<td>6. Fuel Recess from Exit</td>
<td>12. # of Tangential Fuel Ports</td>
</tr>
</tbody>
</table>

- 12 design parameters
- Full factorial rule: $10^{12}$ combinations
  (10 design options of each parameter)
- Advanced DoE (Rule of Thumb):
  $N$ (parameters) $\times$ 10 design options
  (120 design options)
Flame Stabilization in the Wake of GOX Post
-- multi-fidelity modeling, simulation & diagnostics --
Main Combustor Injector Layout
-- data analytics --

- 271 injector elements in patent 331 injector elements in actual
- four different groups of elements, each with $3 \leq \Delta m \leq 10\%$ of nominal value
- injector layout based on a definite law, with cyclic sequential helical repetition
- reduced fuel flow rate of injectors next to firewall by increasing fuel hydraulic resistance
- main injector: inner gas jet with outer fuel swirling (double tangential entries)
- baffle injector: inner gas jet with outer fuel swirling (spiral)
To substantially reduce the development cost and time as well as production cost, the real opportunities lie in the following areas:

- advanced design philosophy and methodology
- advanced manufacturing and material
- effective project management
Composite cost profile for development of innovative advanced technology products (rocket engine example) -- *Glenn Havskjold (AIAA 2009-5436)*
Launch Propulsion
make access to space more reliable, routine, and cost effective

In-Space Propulsion

• Enhance missions by improving performance, durability, cost and manufacturing;
• Develop new capabilities.
Flight Times for Mars Missions

- **Flyby**
- **Orbit**
- **Rover**
- **Lander**

<table>
<thead>
<tr>
<th>Year</th>
<th>Flight Time (Days)</th>
<th>Mission</th>
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</thead>
<tbody>
<tr>
<td>1960</td>
<td>167 days</td>
<td>MARS 1 &amp; 2 (USSR)</td>
</tr>
<tr>
<td>1970</td>
<td></td>
<td>MARS 1 &amp; 2 (USSR)</td>
</tr>
<tr>
<td>1980</td>
<td>253 days</td>
<td>Global Surveyor</td>
</tr>
<tr>
<td>1990</td>
<td></td>
<td>Opportunity</td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td>Curiosity</td>
</tr>
<tr>
<td>2010</td>
<td></td>
<td>InSight</td>
</tr>
<tr>
<td>2020</td>
<td></td>
<td>MARS Odyssey</td>
</tr>
<tr>
<td>2030</td>
<td></td>
<td>MARS Odyssey</td>
</tr>
</tbody>
</table>

**Missions:***
- **Viking 1 & 2** (NASA·JPL)
- **Pathfinder** (NASA·JPL)
- **Opportunity** (NASA·JPL)
- **Curiosity** (NASA·JPL)
- **InSight** (NASA·JPL)
Two issues of human deep-space exploration

- Excessive flight time
- Limited payload

Mars Missions
- Mariner 9 (1971) -- first spacecraft to go into Mars (167 days)
- Viking 1 (1976) – 335 days
- Viking 2 (1976) – 360 days
- Mars Reconnaissance Orbiter (2006) – 210 days
- Phoenix Lander (2008) – 295 days
- Curiosity Lander (2012) – 253 days
Launch Propulsion:
Make access to space more reliable, routine, and affordable
solid rocket propulsion    ancillary propulsion systems
liquid rocket propulsion    unconventional systems
air breathing propulsion    balloon launch systems

In-Space Propulsion:
• Enhance missions by improving performance, durability, manufacturing, and cost;
• Develop new capabilities.
chemical propulsion    supporting technologies
non-chemical propulsion
Advanced propulsion technologies (TRL<3)

Ref. NASA Technology Roadmaps (July 2015)
**The Rocket Equation**

**Velocity Increment**
\[ \Delta u = c \ln\left(\frac{m_o}{m_f}\right) = I_{sp} g_o \ln\left(\frac{m_o}{m_f}\right) \]

**Vehicle Mass Ratio, MR**
\[ MR = \frac{m_f}{m_o} = e^{-\Delta u/c} \]

---

**Vehicle Mission Velocity (km/sec)**

- **LEO**
  - soft landing, no return: 9.1
  - soft landing, return: 12.5

- **Earth to Moon**
  - soft landing, no return: 15.2
  - soft landing, return: 17.7

- **Earth to Mars**
  - soft landing, no return: 20
  - soft landing, return: 27

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*Background Photo: NASA/Bill Ingalls*
In-Space Propulsion Options

- chemical propulsion systems
  - storable (hyperlolis, metal)
  - cryogenic (LOX/H2, LOX/methane)
- non-chemical propulsion systems
  - solar electric
  - nuclear
- Advanced propulsion technologies (TRL<3)

Increase performance, lifetime, and reliability
Cryogenic Engine Tests

LOX/Hydrogen Engine Test

LOX/Methane Engine Test
High Energy Materials

- **Specific Impulse,** $I_{sp}$
  \[ I_{sp} = \frac{1}{g_0} \sqrt{\frac{2\gamma}{\gamma-1} \frac{R_uT_c}{M} \left[ 1 - \left( \frac{P_e}{P_c} \right)^{\frac{\gamma-1}{\gamma}} \right]} \]

- **Metallized propellants**
  -- e.g., aluminum particles

- **Strained molecules:** straining molecular structures
  -- e.g., benzvalene C$_6$H$_6$, cubane C$_8$H$_8$, carborane C$_2$B$_{10}$H$_{12}$.
  large carbon-to-hydrogen ratio & stronger propensity to soot formation.

- **Functionalized Molecules:** attaching energetic and/or catalytic functional groups to molecular structure.
  -- e.g., adding the azide group N$_3$ to hydrocarbons.

- **Ionic liquids:**
  -- e.g., hydroxylammonium nitrate (HAN), e.g., AF-M315E; ammonium dinitramide (ADN)
Metal as Fuel

- Metals are attractive fuel option due to their high gravimetric and volumetric energy densities.
- Aluminum is an ideal fuel candidate:
  - High volumetric and gravimetric energy densities
  - Most abundant metal in Earth’s crust and low cost
  - “Green” fuel and relative safety

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Heat of combustion kJ/g</th>
<th>Heat of combustion kJ/cm³</th>
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<tbody>
<tr>
<td>hydrogen</td>
<td>141.9</td>
<td>9.9</td>
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<tr>
<td>gasoline</td>
<td>47.0</td>
<td>35.0</td>
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<tr>
<td>diesel</td>
<td>45.0</td>
<td>37.4</td>
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<tr>
<td>Jet-A</td>
<td>43.5</td>
<td>35.2</td>
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<tr>
<td>aluminum</td>
<td>31</td>
<td>84</td>
</tr>
</tbody>
</table>
Aggregation & Agglomeration of $\mu$Al vs. $n$Al

$\mu$Al 30 $\mu$m in HTPB at 10 bar

$n$Al 0.15 $\mu$m in PPG at 10 bar
Burning Rate $r_b$ vs Pressure of nAl and Water

$r_b [\text{cm/s}] = 4.5 \times (P [\text{MPa}])^{0.47}$

ADN* CL-20*

HNF*

JA2#

HMX*

* Altwood, 1999

# Kopicz, 1997

## Electric Propulsion

<table>
<thead>
<tr>
<th>Ion thruster</th>
<th>Mangetoplasmadynamic (MPD) thruster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hall thruster</td>
<td>Pulsed inductive thruster</td>
</tr>
<tr>
<td>Arcjet thruster</td>
<td>Electrospray propulsion</td>
</tr>
<tr>
<td>Resistojet thruster</td>
<td>Wave drive thruster</td>
</tr>
<tr>
<td>Etc.</td>
<td></td>
</tr>
</tbody>
</table>
## Performance of NEXT and SOA Ion (NSTAR) Thrusters

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>NEXT</th>
<th>SOA Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thruster Power Range, Kw</td>
<td>0.5-6.9</td>
<td>0.5-2.3</td>
</tr>
<tr>
<td>Throttle Ratio</td>
<td>&gt; 12:1</td>
<td>4:1</td>
</tr>
<tr>
<td>Max. Specific Impulse, sec</td>
<td>&gt;4100</td>
<td>&gt;3100</td>
</tr>
<tr>
<td>Max. Thrust, mN</td>
<td>236</td>
<td>92</td>
</tr>
<tr>
<td>Max. Thruster Efficiency</td>
<td>&gt;70%</td>
<td>&gt;61%</td>
</tr>
<tr>
<td>Max, PPU Efficiency</td>
<td>94%</td>
<td>92%</td>
</tr>
<tr>
<td>Propellant Throughput, kg</td>
<td>&gt;530</td>
<td>157</td>
</tr>
<tr>
<td>Specific Mass, kg/kW</td>
<td>1.8</td>
<td>3.6</td>
</tr>
<tr>
<td>PPU Specific Mass, kg/kW</td>
<td>4.8</td>
<td>6.0</td>
</tr>
<tr>
<td>PMS Single-String Mass, kg</td>
<td>5.0</td>
<td>11.4</td>
</tr>
<tr>
<td>PMS Unusable Propellant Residual</td>
<td>1.00%</td>
<td>2.40%</td>
</tr>
</tbody>
</table>

**NEXT (NASA Evolutionary Xenon Thruster)**  
**NSTAR (NASA Solar Technology Application Readiness)**
Solar and Drag Sail Propulsion – Propellantless

**Solar sail:** thrust generated by reflecting light (e.g., LightSail, NEAS)

**Drag sail:** thrust generated by changing the ballistic coefficient of a spacecraft, increasing the atmospheric drag.

**photons have energy and momentum**
Sail Deployment Testing at MSFC

The Near Earth Asteroid Scout
Image/characterize a NEA during a slow flyby

Key Spacecraft & Mission Parameters
• 6U cubesat (20 cm X 10 cm X 30 cm)
• ~86 m² solar sail propulsion system
• launch on SLS (EM-1/2018)
• Up to 2.5 year mission duration
• < 1 AU maximum distance from Earth
Sail Deployment Testing at MSFC
Solar thermal propulsion (STP):  high Isp, low thrust
Nuclear thermal propulsion (NTP):  high Isp, high thrust
reactor fuel design for higher temperature,
minimum erosion, fission product release, enriched uranium,
high temperature material
Nuclear Thermal Propulsion -- Mars Piloted Stack

Design Constraints / Parameters:
- # Engines / Type: 3 / NERVA-derived
- Engine Thrust: 25 klbf (Pewee-class)
- Propellant: LH2
- Specific Impulse, Isp: 900/nom. - TBD/max sec
- Tank Material: Aluminum-Lithium
- Truss Material: Composite
- RCS Propellants: NTO / MMH
- RCS Thruster Isp: 328 sec (Fregat Isp)
- Passive TPS: 0.75” SOFI + 60 layer MLI
- Active CFM: ZBO Brayton Cryo-cooler
- I/F Structure: Stage / Truss Docking Adaptor w/ Fluid Transfer

2037 Trajectory Constraints / Parameters:
- TMI ΔV1: 1934 m/s (1813-1936)
- TMI ΔV2: 2084 m/s (1976-2172)
- MOI ΔV: 934 m/s (1029-1806)
- TEI ΔV: 1475 m/s (827-1524)
- Outbound time: 212 days (158-225)
- Stay time: 489 days (448-569)
- Return time: 220 days (195-238)
- TMI, MOI & TEI 1% ΔV Margin/FRP/other
- TMI Gravity Losses: ~377 m/s total, f(T/W0)
- MOI & TEI g-losses: Additional 1%
- Post-TMI RCS ΔVs: 182 m/s (>>7 burns)
- Tank Masses (C, I, D) Details In MEL

Description:
NTP system consists of 3 elements: 1) core propulsion stage, 2) in-line tank, and 3) integrated saddle truss and drop tank assembly that connects the propulsion stack to the crewed payload element for the Mars 2037 mission. Each element is delivered to LEO (~407 km circ) fully fueled on an SLS LV (183.77.00, 10-m O.D. / 9.1-m 25.5 m cyl. §). They are sized for an SLS capability of ~109 mt. The stage uses three 25.1 klbf engines w/ either a NERVA-derived or ceramic-metallic (CerMet) reactor core. It also includes RCS, avionics, power, long-duration CFM hardware (e.g., COLDEST design, ZBO cryo-coolers) and AR&D capability. Saddle trusses use composite material and the LH2 drop tank employs a passive TPS. I/F structure includes fluid transfer & electrical.
NCPS Mission Profile

Mars Orbit

Propulsive capture into Mars Orbit after 158-225 days

Ideal MOI ΔV = 934-1806 m/s

Ideal TMI Burns (total) ΔV = 3788-4109 m/s

Drop Tank Expended ~TMI+1 day

Integrated stack rendezvous with payload in LEO

Earth Return 195-238 days

NCPS Stack + Hab Expended (entry~1 d.)

Direct Entry Water Landing

Crew round trip: ~30-31 months

Piloted Stack Assembly 4-5 SLS Launches

Assembly: ~6-7 months

Space Launch System

Core Stage Launch @ TMI-134 days

In-Line Tank Launch @ TMI-194 days

Core, In-Line, and Drop Tank with Saddle Truss autonomously rendezvous in LEO prior to payload arrival

Payload Launch @ TMI-14 days

Ideal TEI ΔV = 827-1524 m/s

Earth Entry Velocity <13 km/sec

Not to scale
Advanced Propulsion Technologies

- Beamed Energy Propulsion
- Electric sail propulsion
- Fusion propulsion
- Antimatter propulsion
- Advanced fusion
- Breakthrough propulsion

Antimatter Propulsion Concept Vehicle
Electrodynamic Tether Propulsion
Beamed Energy Propulsion Concept Vehicle
Breakthrough Propulsion Concept Vehicle
Nuclear Thermal Propulsion Concept Vehicle
Fission Fragment Propulsion Concept Vehicle
Solar Sail
Solar Thermal Propulsion
Drag Sail Propulsion
Fusion Propulsion Concept
Launch Propulsion make access to space more reliable, routine, and cost effective

In-Space Propulsion

- Enhance missions by improving performance, durability, cost and manufacturing;
- Develop new capabilities.
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