EVOLUTION OF

POTENTIAL FUTURE

SPACECRAFT PROPULSION SYSTEMS

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April 2005
PROPULSION SYSTEM SELECTION CONSIDERATIONS

The most fundamental criteria for the propulsion system to be selected is its achievement of the mission impulse requirements. Therefore, an important consideration for the selection of a suitable propulsion system for given mission impulse requirements is the trade-off between its velocity increment capability and propulsion system mass. In addition, an important requirement on the spacecraft designer is that the mass of the propulsion system shall not exceed a certain percentage of the overall mass of the spacecraft.

**Remember**

– Chemical rocket propulsion is limited in that power plant and propellant are one and the same.

– For separately powered propulsion power plant and accelerator can each be adapted separately (electric propulsion) thereby allowing for higher exhaust velocity.

– For electric propulsion we do not strive for maximum exhaust velocity, like for chemical propulsion, but rather for optimum exhaust velocity.

When a suitable spacecraft auxiliary propulsion system is pre-selected, however, the cost, complexity, operability and reliability of the system also play an important role.
CLASSIFICATION OF SPACECRAFT PROPULSION SYSTEMS
(According to type of energy source)

- **CHEMICAL**
  - COLD GAS
    - COMPRESSED GAS (Nitrogen)
    - VAPORISING LIQUID (Propane)
  - HOT GAS
    - SOLID PROPELLANT
    - MONO-PROPELLANT (Hydrazine)
    - BI-PROPELLANT (MMH/N₂O)

- **ELECTRICAL**
  - ELECTROTHERMAL (Resistojet; Arcjet)
  - ELECTROMAGNETIC (MPD-Thruster)
  - ELECTROSTATIC (RIT; Field emission)
## SURVEY OF CANDIDATE SPACECRAFT PROPULSION SYSTEMS

<table>
<thead>
<tr>
<th>Type</th>
<th>Thrust Level (N)</th>
<th>Thruster-Spec. Impulse (Ns/kg)</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cold Gas</strong>&lt;br&gt;(Nitrogen)</td>
<td>0.02 – 5</td>
<td>700</td>
<td>Extremely simple, reliable, very low cost</td>
<td>Very low performance, highest mass of all systems</td>
</tr>
<tr>
<td><strong>Solid Motor</strong>&lt;br&gt;(e.g. Apogee Kick Motor: MAGE 1-2)</td>
<td>28 000 – 47 000</td>
<td>2 900</td>
<td>Simple, reliable, relatively low cost</td>
<td>Limited performance, higher thrust</td>
</tr>
<tr>
<td><strong>Liquid:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mono-Propellant</td>
<td>0.5 – 22</td>
<td>2 100 – 2 300</td>
<td>Simple, reliable, low-cost</td>
<td>Low performance, higher mass than bi-propellant</td>
</tr>
<tr>
<td>Bi-Propellant</td>
<td>4 – 500</td>
<td>2 850 – 3 110</td>
<td>High performance</td>
<td>More complicated system than mono-propellant</td>
</tr>
<tr>
<td>Electothermal:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistojet, PACT&lt;br&gt;(Hydrazine)</td>
<td>0.1 – 0.5</td>
<td>3 000</td>
<td>High performance, low power, simple feed system</td>
<td>More complicated interfaces, more power than Chemical thrusters, low thrust</td>
</tr>
<tr>
<td>Arcjet&lt;br&gt;(Hydrazine)</td>
<td>0.2</td>
<td>5 000</td>
<td>High performance, simple feed system</td>
<td>High power, complicated interfaces (especially Thermal)</td>
</tr>
<tr>
<td>Electromagnetic&lt;br&gt;(pulsed plasma, Teflon)</td>
<td>0.015</td>
<td>30 000</td>
<td>High performance</td>
<td>High power, low thrust, complicated</td>
</tr>
<tr>
<td>Electrostatic&lt;br&gt;(ion)</td>
<td>0.01 – 0.2</td>
<td>≥ 30 000</td>
<td>Very high performance</td>
<td>Very high power, low thrust, complicated</td>
</tr>
</tbody>
</table>
DELTA-V PERFORMANCE RANGE OF BUILT S/C PROPULSION SYSTEM CONCEPTS (Examples)

Curves of mass fraction $m_{PS}/m_{S/C}$ are plotted as a function of $\Delta v$ performance of different actual type of propulsion systems:

- Electr. Propulsion PPS 1350 (SMART-1) $I_{sp}=10801$ Ns/kg
- Bipropellant $I_{sp}=2615$ Ns/kg
- Hydrazine $I_{sp}=1862$ Ns/kg
- Cold Gas $I_{sp}=193$ Ns/kg (Nitrogen)
- Cold Gas $I_{sp}=654$ Ns/kg (Ammonia)
- Cold Gas $I_{sp}=2746$ Ns/kg
- Cold Gas $I_{sp}=2615$ Ns/kg
- Cold Gas $I_{sp}=1862$ Ns/kg
- Cold Gas $I_{sp}=193$ Ns/kg (Nitrogen)
## Classification of Satellites

<table>
<thead>
<tr>
<th>Group name</th>
<th>Wet Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large satellite</td>
<td>&gt;1000kg</td>
</tr>
<tr>
<td>Medium sized satellite</td>
<td>500-1000kg</td>
</tr>
<tr>
<td>Mini satellite</td>
<td>100-500kg</td>
</tr>
<tr>
<td>Micro satellite</td>
<td>10-100kg</td>
</tr>
<tr>
<td>Nano satellite</td>
<td>1-10kg</td>
</tr>
<tr>
<td>Pico satellite</td>
<td>0.1-1kg</td>
</tr>
<tr>
<td>Femto satellite</td>
<td>&lt;100g</td>
</tr>
</tbody>
</table>

**Note:** In recent years a general method of classifying satellites in terms of deployed mass has been generally adopted. The boundaries of these classes are an indication of where launcher or cost tradeoffs are typically made, which is also why the mass is defined including propellant ('Wet mass').
Micro Propulsion Cold Gas Thrusters
for
High Precision Drag-free / Attitude Control

ACR Electronic AB
P.O. Box 99; 619 22 Trosa; Sweden
MICRO PROPUSSION: Thruster Block Diagram
MICRO PROPULSION: Gas Module Design

- Gas sensing volume: 3000 µm
- Pressure sensor reference cavity
- Ambient pressure channel
- Heat exchanger
- Thin film heater
- Nozzle
- Several filter structures (different types)
- Wafer 1, wafer 2, wafer 3, wafer 4, wafer 5, wafer 6, wafer 7
- Piezo actuator
- Valve seat
- Valve cap
- Pressure sensor
Micro Propulsion: Laser Induced Etched Nozzle

ACR Electronic AB
P.O. Box 99; 619 22 Trosa;
Sweden
PERFORMANCE SPECIFICATIONS

The specifications in this section are given for Nitrogen as drive gas, but any non-corrosive gas can be used in the system with slightly different performances.

- Maximum thrust: 0.1 to 10 mN
- Trust dynamic range: 1:1000
- Thrust realisation errors: < 4.2 µN noise standard deviation
- < 7 µN thrust bias
- Noise spectrum: < 1 µN/√Hz in 0.005 – 0.1 Hz range
- Unit step response: < 10 mS
- Bandwidth: > 50 Hz
- Nozzle axis dir acc: < 90° ± 0.1°
- Thrust vector dir acc: < 2° from nominal
- Gas Consumption: max 3 g/h N₂ 500 µN thrust
- Leakage Rate: 50 µg/s when activated but passive, 5 µg/s with main valve closed
- Specific impulse: Neon 600 m/s at 300 K, 1100 m/s at 800 K
  Helium 1500 m/s at 300 K, 2400 m/s at 800 K
  Nitrogen 600 m/s at 300 K, 1100 m/s at 800 K

Environmental Requirements

  -50 °C to +100 °C Non-op.
- Radiation, total dose: > 10 krad

Electrical Power Consumption

- Thruster module power consumption:
  + 100 V  max 2 mA
  + 12 V  30 mA in standby
  110 mA with all thrusters at 500°C
  150 mA with module heater on during eclipse
- Average power consumption: < 1W
- Max. power consumption:< 1.8W

Mechanical dimensions / mass

- Estimated mass: 80 – 90 g

![Figure 6 Thruster pod mechanical dimensions](image-url)
SOLID END-BURNING MOTOR

10N Pt Thruster versus 10N Regeneratively Cooled

Model-No.: S 10-13

- TRIM ORIFICE BLOCK
  - without
  - with

- BIPROP-VALVE
  - Model No. 51-131

- INJECTOR
  - unchanged

- COMBUSTION CHAMBER
  - regeneratively cooled
  - Ni-Base alloy
  - Pt alloy

- FLIGHT SENSOR
  - thermo couple

- NOZZLE EXTENSION
  - $\epsilon_{1} = 150$, $\epsilon_{2} = 90$
  - Pt alloy
  - Ni alloy

Model-No.: S 10-10

- OVERALL WEIGHT
  - 290 gr
  - 294 gr
Future Developments in Liquid Propellant Technology

Need: Environmentally friendly, safer propellant

Under Development: New propellants based on blends of Hydroxyl Ammonium Nitrate (HAN, [N$^+H_3OH]$NO$_3$) and Ammonium DiNitramide (ADN, NH$_4$N(NO$_4$)$_2$)

Advantages:

- Safer propellants (also called ‘Green Propellants’) reduce costs by:
  - eliminating the need for self-contained atmospheric protective ensemble (SCAPE) suits needed for toxic propellants,
  - no extensive and prohibitive propellant safety precautions, and isolation of the space vehicle from parallel activities during propellant loading operations.

- Technical advantages of HAN blends:
  - higher density, lower melting point, higher range of thruster specific impulse ($I_{sp}$)
Performance ADN/Glycerol/Water (LMP-101) in comparison with HAN/Glycine/Water and Hydrazine

<table>
<thead>
<tr>
<th>Propellant</th>
<th>$I_{SP}$ (Ns/kg)</th>
<th>$T_C$ (K)</th>
<th>Density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADN/Glycerol, 26 % water</td>
<td>2420</td>
<td>1970</td>
<td>1.42</td>
</tr>
<tr>
<td>HAN/Glycine, 26 % water</td>
<td>2001</td>
<td>1370</td>
<td>1.33</td>
</tr>
<tr>
<td>Hydrazine, 60 % Amm. diss.</td>
<td>2325</td>
<td>1190</td>
<td>1.0</td>
</tr>
</tbody>
</table>

N.B.: Specific Impulse at an expansion ratio of 50.

CONFIGURATION OF PROPULSION SYSTEMS FOR GEOSTATIONARY SATELLITES

<table>
<thead>
<tr>
<th>Function</th>
<th>First Generation</th>
<th>Second Generation</th>
<th>Third Generation</th>
<th>Fourth Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apogee-boost</td>
<td>Solid Propellant</td>
<td>Bi-Propellant MMH/MON</td>
<td>Bi-Propellant MMH/MON</td>
<td>Bi-Propellant MMH/ION</td>
</tr>
<tr>
<td>Attitude-Control</td>
<td>Hydrazine</td>
<td>Bi-Propellant MMH/ION</td>
<td>Hydrazine</td>
<td>Hydrazine</td>
</tr>
<tr>
<td>Orbit-Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East-West</td>
<td>Hydrazine</td>
<td></td>
<td>Hydrazine</td>
<td>Hydrazine</td>
</tr>
<tr>
<td>North-South</td>
<td>Hydrazine</td>
<td></td>
<td>Hydrazine</td>
<td>Hydrazine</td>
</tr>
</tbody>
</table>

* PAHT
** Ion-Engines
<table>
<thead>
<tr>
<th>Type of Thruster</th>
<th>Spec. Impulse (Ns/Kg)</th>
<th>Thrust F (N)</th>
<th>DC Power Required (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical (Ion thruster)</td>
<td>≥ 30 000</td>
<td>10⁻³ – 0.2</td>
<td>400 – 800</td>
</tr>
<tr>
<td>Chemical (Bi-Propellant)</td>
<td>≈ 3 000</td>
<td>5 – 500</td>
<td>4 – 8 (short term)</td>
</tr>
<tr>
<td>Order of magnitude of the ratio ION/Chemical</td>
<td>10¹</td>
<td>10⁻⁴</td>
<td>10²</td>
</tr>
</tbody>
</table>
## SURVEY OF ELECTRICAL THRUSTERS

<table>
<thead>
<tr>
<th>Type of Propulsion System</th>
<th>Thrust (N)</th>
<th>Power Consumption (W)</th>
<th>Exhaust Velocity (m/s)</th>
<th>Propellant (formula)</th>
<th>Potential Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistojet</td>
<td>0.2</td>
<td>345</td>
<td>1 500</td>
<td>NH$_3$; CH$_4$</td>
<td>Orbit-Control (Biowast)</td>
</tr>
<tr>
<td>Hydrazine-Resistojet (PACT)</td>
<td>0.3</td>
<td>300</td>
<td>3 000</td>
<td>N$_2$ H$_4$</td>
<td>Orbit-Control (N/S)</td>
</tr>
<tr>
<td>Arc-Jet (Hydrazine)</td>
<td>0.2</td>
<td>1 800</td>
<td>5 000</td>
<td>N$_2$ H$_4$</td>
<td>Orbit-Control (N/S)</td>
</tr>
<tr>
<td>MPD (Teflon)</td>
<td>0.015</td>
<td>600</td>
<td>30 000</td>
<td>Teflon</td>
<td>Orbit-Control (N/S)</td>
</tr>
<tr>
<td>RIT10 (Ion.-Engine)</td>
<td>0.01</td>
<td>390</td>
<td>30 700</td>
<td>Xe</td>
<td>Orbit-Control (N/S)</td>
</tr>
<tr>
<td>RIT35 (Ion.-Engine)</td>
<td>0.271</td>
<td>7 540</td>
<td>31 400</td>
<td>Hg; Xe</td>
<td>Interplanetary Missions</td>
</tr>
<tr>
<td>UK-10 (Kaufman)</td>
<td>0.196</td>
<td>6 000</td>
<td>≥30 000</td>
<td>Xe</td>
<td>Orbit-Control (N/S)</td>
</tr>
<tr>
<td>UK-25 (Kaufman)</td>
<td>0.08</td>
<td>1 350</td>
<td>16 000</td>
<td>Xe</td>
<td>Interplanetary Missions</td>
</tr>
<tr>
<td>SPT100 (Ion.-Engine)</td>
<td>$4.5 \times 10^{-3}$</td>
<td>175</td>
<td>25 500</td>
<td>Hg</td>
<td>Orbit-Control</td>
</tr>
<tr>
<td>Hughes 8 cm (Kaufman)</td>
<td>$10^{-3}$ - $5 \times 10^{-3}$</td>
<td>60 - 300</td>
<td>60 000</td>
<td>Cs</td>
<td>Orbit and Attitude Control</td>
</tr>
<tr>
<td>Field-Emission</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Technology-FEEP Thruster

- Very High Isp
  - 6000 to 10000 s.
- Low System mass & overall Dimension.
- Ultra fine thrust.
- High accuracy & resolution.
- Self contained propellant reservoir.
- No moving parts.
FEEP Properties

- $F = 1 \, \mu N$ to $2 \, mN$
- Max. $F/\text{em. Length} = 15$ to $30 \, \mu N/mm$
- $Isp = 6000$ to $10000$ s
- Power/thrust = $60 \, kW/N$
  - (Ion~$35\, kW/N$; SPT~$20\, kW/N$)
- Cesium, Rubidium, Indium.
- Efficiency = $98\%$ (Ion~$30$; PPT~$17$)
FEEP Components

- Thruster Assembly
  - Emitter
  - Accelerator
  - FEEP Protecting Capsule
- Neutraliser
- Heater
- Power & Control Electronics
Thruster Assembly

- 1-cm slit emitter (~75-grams)
- Propellant: 1-gram Cs
- Derived max. Thrust: 25 $\mu$N (~1.5 W)
- Neutralizer: 50 grams (~0.4 W)
- Heater: ~ 50 grams; (~0.4W)
- Capsule: ~ 50 grams
Rymdens ångmotor

- Vatten (-gas) tillförsel
- El från solpaneler
- Värmeisolering (fiberurl)
- Höje i stålplåt
- Munstycke
- Filter
- Vattenånga
- "Doppvärmare"
- Kiselkarbidgranulat

Ny teknik / Ingenier franska 27-4-01

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SOLAR THERMAL PROPULSION

Possible application for future orbit transfer vehicles

ISP : 750 s

Thrust : 5 to 10 N continuous for 70 kW (solar)
NUCLEAR PROPULSION

2 possibles technologies

• Nuclear thermal propulsion
  • Isp 800-900s
  • Thrust 20 KN - 70 KN

• Nuclear Electric propulsion
  • Isp : 2000-7000 s
  • Power 5-20 MW

Status

• Not yet available but existing technologies (USA-Russia)
• Necessary for large missions to Mars
Raketmotor på kärnkraft

Fragment-Fission-Hydrogen engine, FFH: \( v_e = 25 \ 000 \text{ m/s} \)
Solar Sailing Mission

Orbital Demonstration of an Innovative, Solar Sail Driven Expandable structure Experiment (ODISSEE) was a joint technology development project in 1999 of the German Aerospace Centre (DLR) and the European Space Agency (ESA).
SCHEMATIC OF SOLAR SAIL POSITION DURING ONE EARTH ORBIT

### FORCES OF SOLAR RADIATION PRESSURE AT DIFFERENT PLANETS

<table>
<thead>
<tr>
<th>Planet</th>
<th>Entfernung [AE]</th>
<th>ps [N/m²]</th>
<th>Verhältnis zur Erde</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merkur</td>
<td>0,387</td>
<td>6,093·10⁻⁵</td>
<td>6,677</td>
</tr>
<tr>
<td>Venus</td>
<td>0,723</td>
<td>1,746·10⁻⁵</td>
<td>1,913</td>
</tr>
<tr>
<td>Erde</td>
<td>1,000</td>
<td>9,126·10⁻⁶</td>
<td>1</td>
</tr>
<tr>
<td>Mars</td>
<td>1,524</td>
<td>3,933·10⁻⁶</td>
<td>~ 1/2,3</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5,203</td>
<td>3,614·10⁻⁷</td>
<td>~ 1/27</td>
</tr>
<tr>
<td>Saturn</td>
<td>9,539</td>
<td>1,003·10⁻⁷</td>
<td>~ 1/91</td>
</tr>
<tr>
<td>Uranus</td>
<td>19,182</td>
<td>2,482·10⁻⁸</td>
<td>~ 1/368</td>
</tr>
<tr>
<td>Neptun</td>
<td>30,058</td>
<td>1,013·10⁻⁸</td>
<td>~ 1/903</td>
</tr>
<tr>
<td>Pluto</td>
<td>39,439</td>
<td>5,868·10⁻⁹</td>
<td>~ 1/1555</td>
</tr>
</tbody>
</table>

ESTIMATION OF MASS AND SIZE OF SQUARE SOLAR SAILS (At 1 AU)