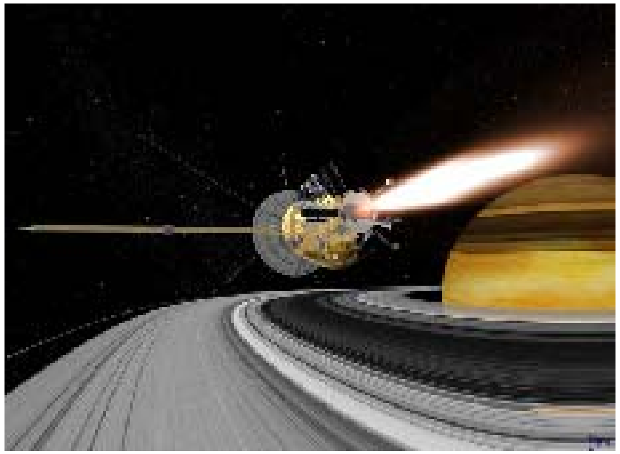
Chapter 1: Introduction to Spacecraft Propulsion

Peter Erichsen, September 2006

S.1 Spacecraft Propulsion Systems

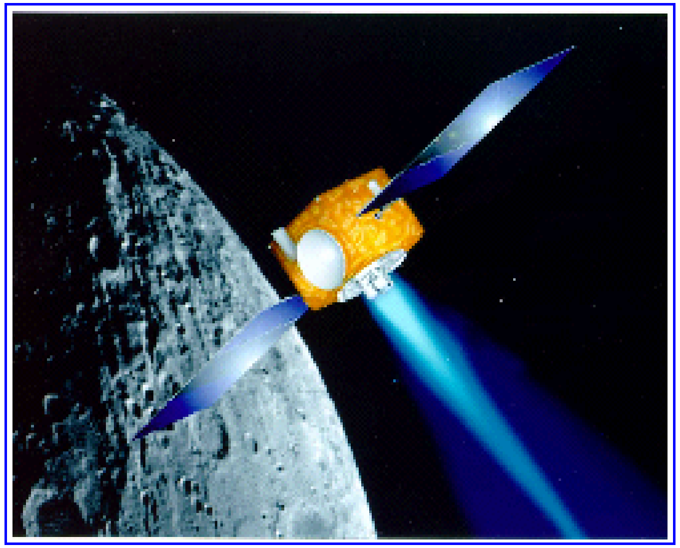
- Spacecraft propulsion is based on jet propulsion as used by rocket motors. The principle of rocket propulsion was known as far back as 360B.C. In the 13th century solid rocket-powered arrows were used by the Chinese military.
- The Second World War and the cold war advanced rocket missile development in modern time. Later, space opened up to exploration and commercial exploitation by satellites and robot spacecraft.
- This lecture will introduce the basic aspects of rocket propulsion, with focus on analysis and performance of spacecraft propulsion systems.
- Key features and performance characteristics of existing and planned (near future) propulsion systems for use on spacecraft are summarized.



S.2 Educational Objectives

In this chapter you will learn about:

- **Different applications of propulsion**
- **Typical space propulsion tasks**
- **The main characteristics of spacecraft propulsion**
- **What kind of propulsion systems exist**



S.3 Need of Propulsion

Propulsion is needed to:

- **Place payloads into orbit: launch propulsion is used;**
- **Send payloads to the moon or to the planets: space propulsion is used;**
- **Position, adjust and maintain orbits of spacecrafts by orbit control: auxiliary propulsion is used;**
- **Orient spacecraft by attitude control: auxiliary propulsion also called reaction-control systems is used.**

Payloads

- The *Payload* is the revenue-producing portion of a spacecraft load, e.g., passengers and cargo such as scientific experiments, TV transmitters, earth observation equipment like photo cameras, etc.

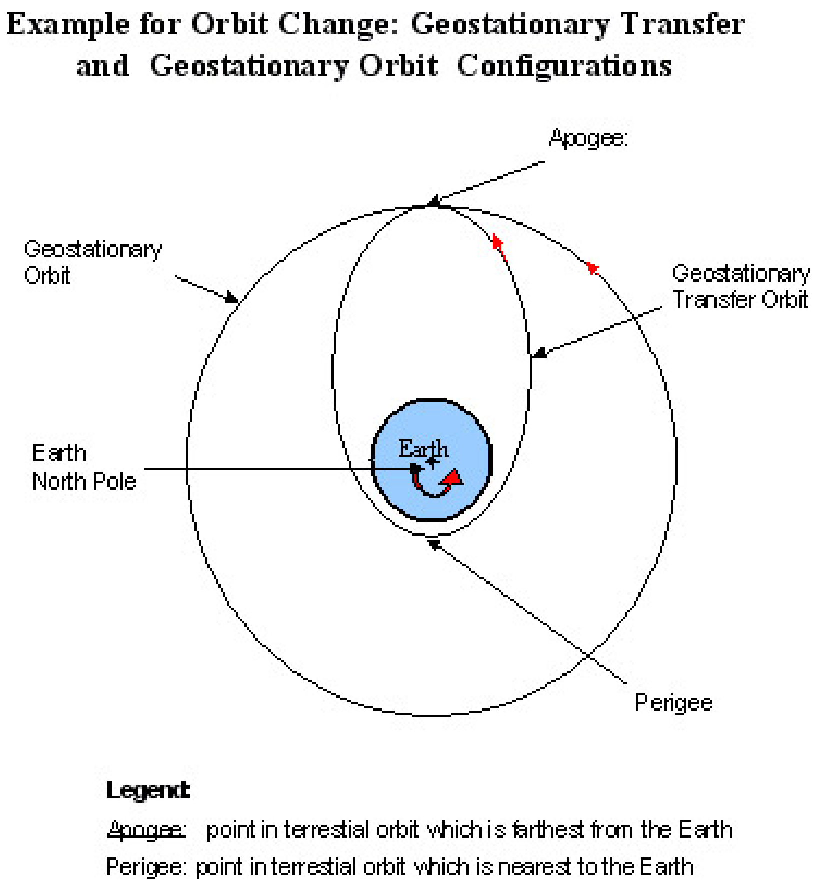
Spacecrafts

- *Spacecraft* is the collective name of devices, which are designed to be placed into space, comprising earth satellites, interplanetary and trans-solar types of space probes. Spacecraft can be manned or unmanned.

Orbit control

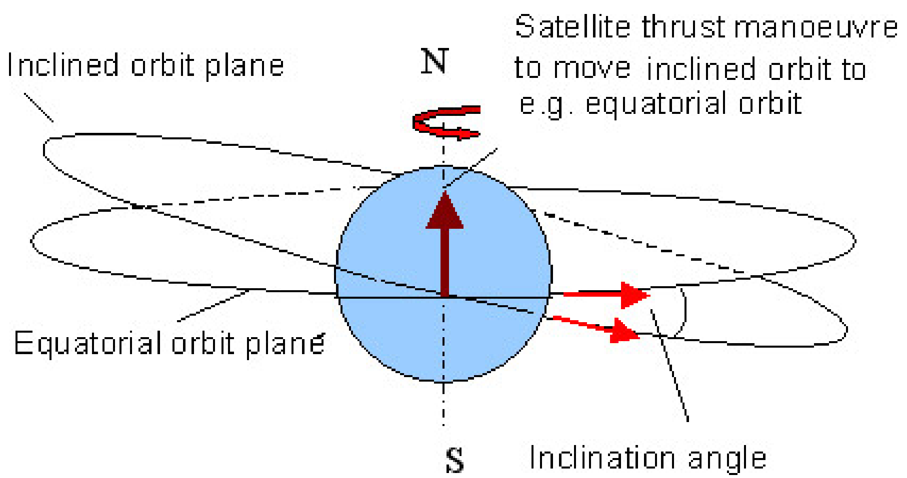
ORBIT CONTROL comprises:

- **Orbit changes:**
  - **Moving a spacecraft to a desired orbit, including plane changes, orbit injection, de-orbit, etc.**



- **Orbit Maintenance or “Station Keeping”:**
  - **Keeping a spacecraft in the desired mission orbit, i.e. compensating for effects of disturbing forces like drag, solar wind, gravitational forces, etc.**

Example for Orbit Control: Satellite Orbit Plane Correction Manoeuvre



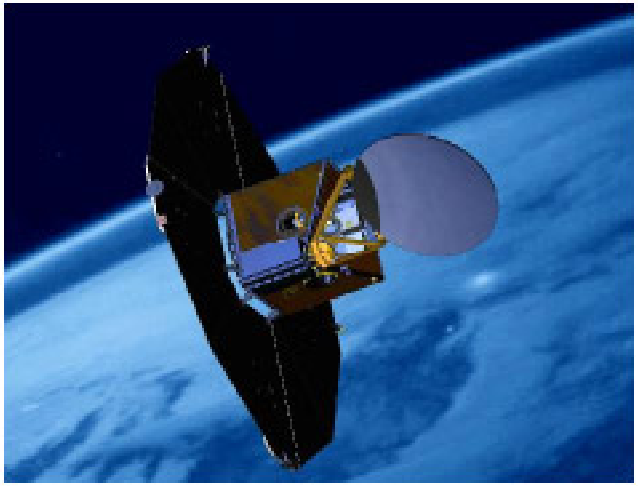
Attitude control

- **Changing the attitude, that is changing the orientation of a spacecraft to the desired direction.**
- **Keeping a spacecraft to the desired direction by compensating for disturbing torques.**

S.4 Reaction-Control System

There are the following types of reaction control systems:

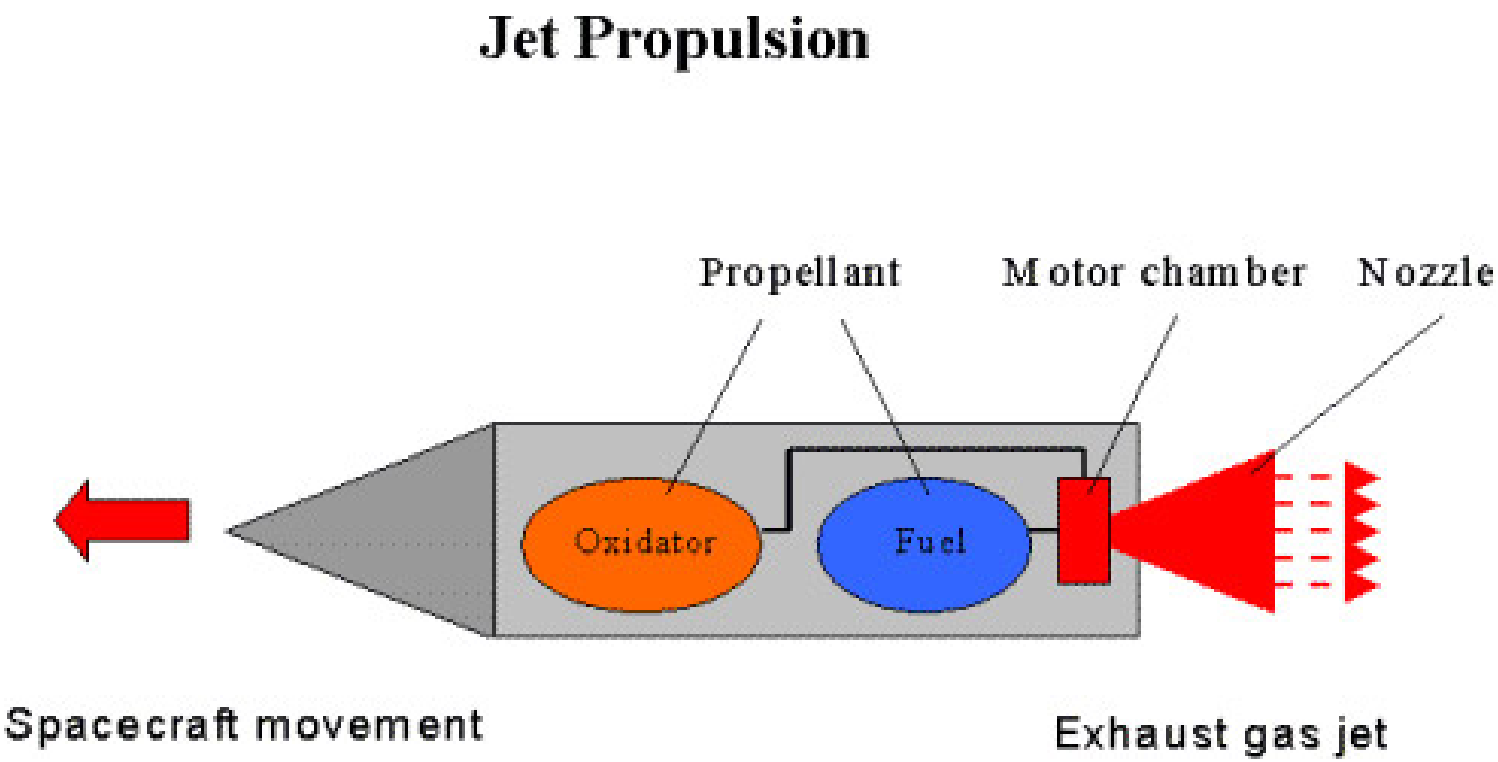
- **Reaction Jets (propulsion): which produce a control force by the expenditure of mass;**
- **Solar Sails, Magnetic Torquers (magnetic coils): which produce a control force by interaction with the environmental field;**
- **Momentum-Transfer Devices (reaction-, flywheels): which produce no net control force, but simply transfer angular momentum to or from the spacecraft.**



Odin Satellite

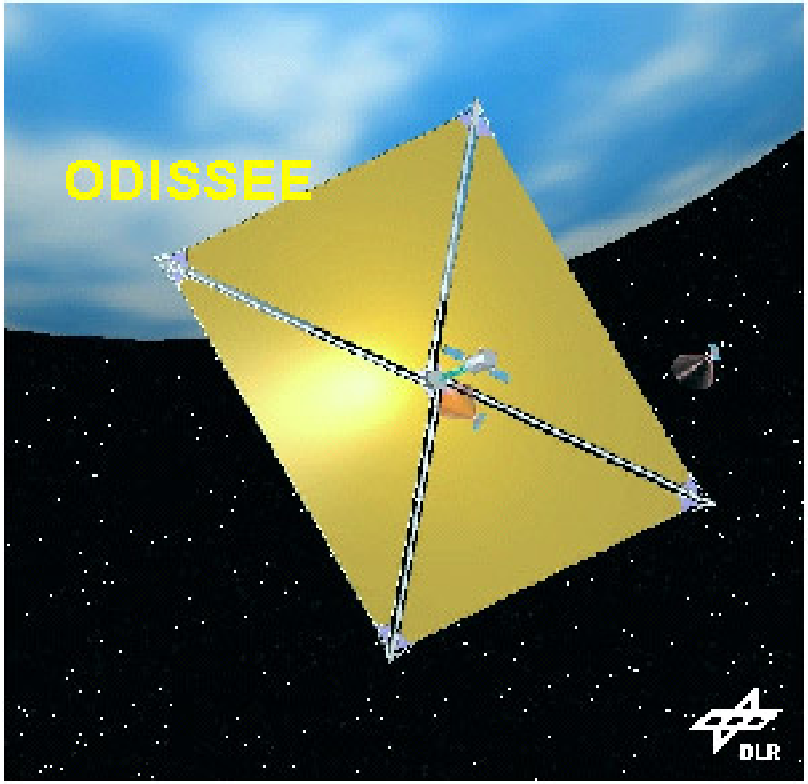
Swedish small satellite project for astronomical and atmospheric research. Launched in February 2001 on a Start-1 launch vehicle from Svobodny.

Reaction Jets



Solar Sails

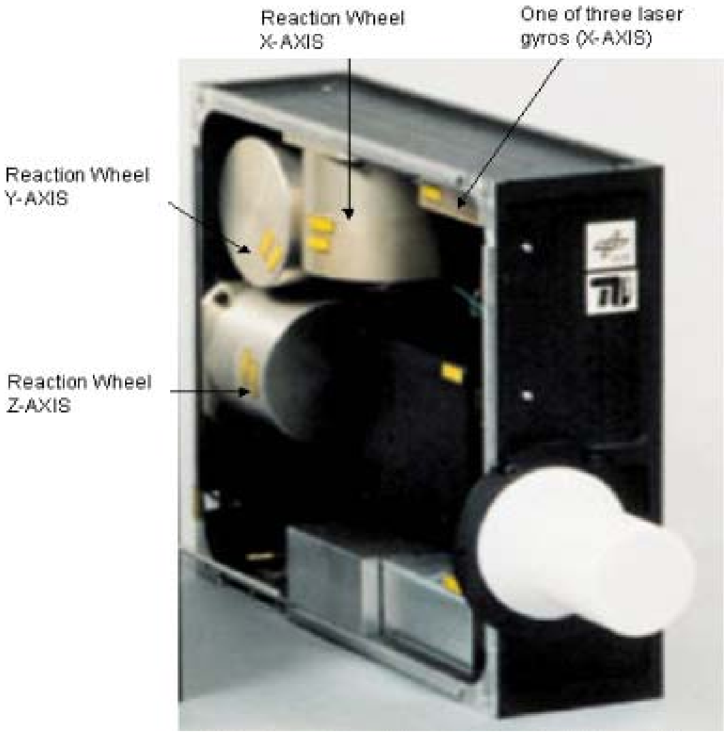
Solar Sailing Mission



Orbital **D**emonstration of an **I**nnovative, **S**olar **S**ail **D**riven **E**xpandable structure **E**xperiment (ODISSEE) was a joint technology development project in 1999 of the German Aerospace Centre (DLR) and the European Space Agency (ESA).

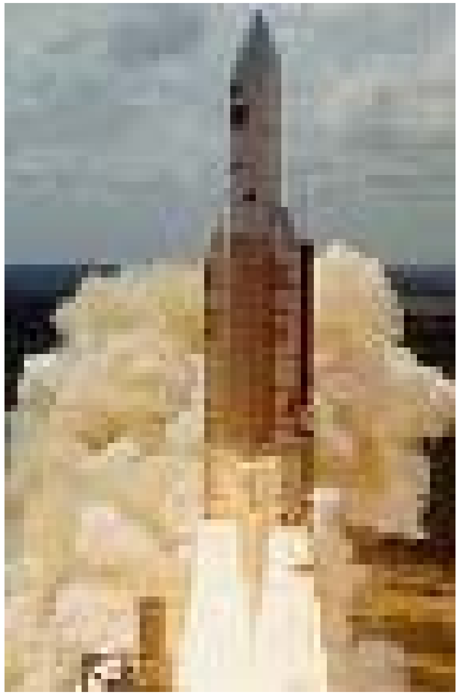
Momentum Transfer Devices of TUB-Sat

- **Part of micro-satellite "DLR-TUBSAT" with reaction Wheels (Technical University of Berlin).**
- **Reaction wheels are used for three axis stabilization and orientation of the satellite. Each reaction wheel is connected with a laser gyro in the same axis. The complete control loop electronics is integrated in the reaction wheels. Each axis gets the angle or angle velocity command from the "On Board Data Handling System" (Central Processor) but all other activities are controlled by the reaction wheel itself.**



S.5 Jet Propulsion System

- These systems are based on jet propulsion devices that produce thrust by ejecting stored matter, called the propellant.
- The main features of jet propulsion are:


Rocket launch

- Launch Propulsion for launching rockets with the following characteristics:
  - high velocity increment capability (7 - 11.5 km/s)
  - very high thrust levels (ratio thrust/launch vehicle weight: >1.3)
  - low fraction of take-off mass of launch vehicle for payload mass (1 - 5%) of the launching vehicle
  - powerful chemical rockets

Velocity increment

- **Required Velocity Change ≡ Velocity increment Δv (m/s) of launch/space maneuvers.**

  (Change in velocity imparted to the launcher/spacecraft by the propulsion system to complete space maneuvers; data listed are indicative only)

START	DESTINATION	TYPICAL ΔV REQUIREMENT m/s	REMARKS
Kourou (French Guiana)	LEO GTO	9 300 11 443	Equatorial (Δv-gain by earth rotation: 465 m/s)
Cap Canaveral (USA)	LEO GEO	9 500 13 600	Equatorial
LEO	GEO	4 260	Change of inclination: 28°, Cap Canaveral
GTO	GEO	1 500 1 800	Change of inclination: 9°, Kourou Change of inclination: 28°, Cap Canaveral
GEO →	GEO	North/South station-keeping: ≈ 50 /year East/West station-keeping: ≈ 3 –6 /year Attitude control: ≈ 3% of total propellant budget	On orbit operations (orbit maintenance requirements per year)
LEO (parking)	Earth orbit escape Lunar orbit Mars orbit	3 200 3 900 5 700	Into planetary trajectory

Legend: LEO = Low Earth Orbit (≈300 km)
GTO = Geostationary Transfer Orbit (Apogee: ≈36 000 km; Perigee: ≈200 km)
GEO = Geostationary Earth Orbit (≈36 000 km)

S.6 Spacecraft Propulsion

- **Spacecraft Propulsion is characterized in general by its complete integration within the spacecraft (e.g. satellites). Its function is to provide forces and torques in (empty) space to:**

  - **transfer the spacecraft: used for interplanetary travel**
  - **position the spacecraft: used for orbit control**
  - **orient the spacecraft: used for attitude control**

SMART-1 Spacecraft

Mission to Moon to demonstrate innovative and key technologies for scientific deep-space missions. Nov. 2003 – Sept. 2006

While jet propulsion systems for launching rockets are also called *primary propulsion systems*, spacecraft, e.g. satellites, are operated by *secondary propulsion systems*.

S.7 Characteristics of Spacecraft Propulsion Systems

In order to fulfill attitude and orbit operational requirements of spacecraft, spacecraft propulsion systems are characterized in particular by:

- **Very high velocity increment capability (many km/s)**
- **Low thrust levels (1 mN to 500 N) with low acceleration levels**
- **Continuous operation mode for orbit control**
- **Pulsed operation mode for attitude control**
- **Predictable, accurate and repeatable performance (impulse bits)**
- **Reliable, leak-free long time operation (storable propellants)**
- **Minimum and predictable thrust exhaust impingement effects**

Impulse bits

- ***Impulse bit*** **is the smallest change in momentum required to allow for e.g. fine attitude and orbit control of a spacecraft.**

Storable propellants

- **Storable Propellants are liquid (or gaseous) at ambient temperature and can be stored for long periods in sealed tanks, e.g. monopropellant hydrazine (see chapter S1B8C3).**

- **In contrast, cryogenic propellants, which are liquefied gases at low temperature, such as liquid oxygen (-147 °C) or liquid hydrogen (-253 °C) are difficult to be used for long space flight missions.**

Note: **at present only storable propellants are used for space flight missions.**

S.8 Classification of Propulsion Systems

Spacecraft propulsion can be classified according to the source of energy utilized for the ejection of propellant:

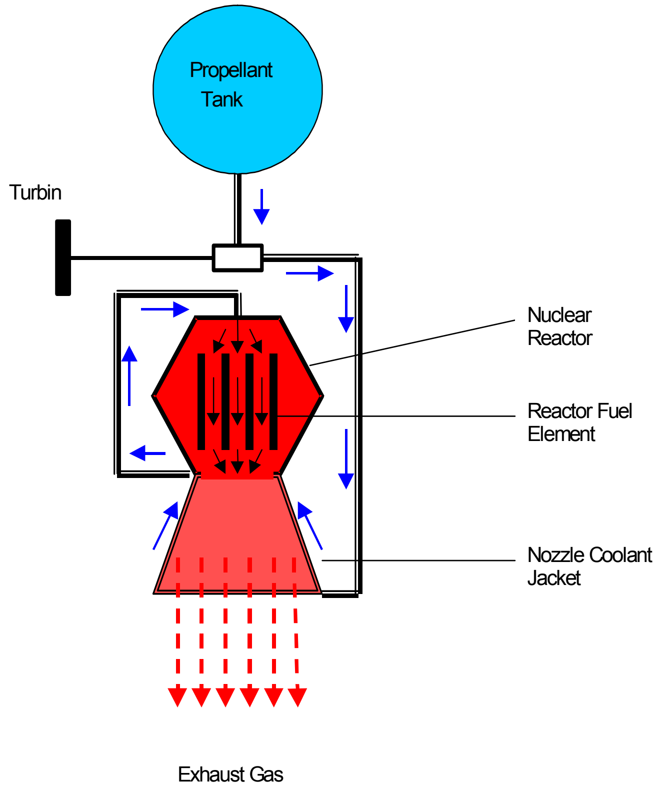
- **Chemical propulsion use heat energy produced by a chemical reaction to generate gases at high temperature and pressure in a combustion chamber. These hot gases are accelerated through a nozzle and ejected from the system at a high exit velocity to produce thrust force.**

- **Electric propulsion uses electric or electromagnetic energy to eject matter at high velocity to produce thrust force.**

- **Nuclear propulsion uses energy from a nuclear reactor to heat gases which are then accelerated through a nozzle and ejected from the system at a high exit velocity to produce thrust force.**

Nuclear propulsion

SCHEMATIC OF A THERMO-NUCLEAR ROCKET ENGINE



Note

- **While chemical and electric systems are used for the propulsion of today's spacecrafts, nuclear propulsion is still under study. Therefore, only chemical and electric propulsion will be dealt within this book.**

S.9 Summary

- **Propulsion is needed for launching of spacecrafts, for spacecraft orbit transfer as well as their orbit and attitude control.**

- **Here, only propulsion systems will be dealt with which are based on jet propulsion devices that produce thrust by ejecting stored matter, called the propellant.**

- **Differences of launch and space propulsion have been mentioned.**

- **Propulsion subsystem requirements have been listed.**

- **Jet propulsion can be classified according to the source of energy utilized for the ejection of propellant: chemical, electric and nuclear.**

Chapter 2: Basic Propulsion Equations

Peter Erichsen, September 2006

S.1 Basic Propulsion Relations

- This chapter is devoted to the basic laws governing propulsion systems. The chapter will give an overview of the set of equations used in the field of spacecraft propulsion.

- Understanding these laws is necessary in order to be able to select an appropriate propulsion system and to design its components. The basic laws include the ‘Rocket Equation’, the rocket thrust force and other propulsion performance parameters.

- In addition two types of propulsion are presented together with the appropriate set of equations characterizing the systems in question.

S.2 Educational Objectives

This chapter will cover the following topics:

- **‘Basic Rocket Equation’**
- **Determination and measure of rocket thrust force**
- **Determination of the mass of propulsion systems**
- **Key parameters which determine propulsion performance,**
- **Principles of chemical and electric propulsion systems,**
- **Chemical and electric propulsion system constraints**

S.3 Basic Equation of Thrust

- **Basic rocket propulsion equations are based on Newton Law of Motion**

- **For constant propellant exhaust velocity v_e at thruster nozzle outlet, and with thrust force F collinear to v_e, gives the**

  The Basic Equation for Force of Thrust

$$\boxed{F = \overset{\circ}{m} v_e} \quad \text{[N]}$$

- **From the Law of Conservation of Momentum follows:**

$$\Delta v \cdot m = -\Delta m \cdot v_e \quad \text{[Ns]}$$

which is the change of momentum of spacecraft. This implies the change of momentum of the expelled propellant.

Newton Law of Motion

Isaac Newton
(1643 – 1727)

$$\vec{F} = \frac{d(m\vec{v})}{dt} = m\frac{d\vec{v}}{dt} + \vec{v}\frac{dm}{dt}, \qquad \textbf{[N]}$$

- **For F=0** — **1. "Every object in a state of rest or uniform motion tends to remain in that state of rest or motion unless an external force is applied to it".**
- **For F≠0** — **2. "Force is equal to the change in momentum (mv) per change in time"**
- **For F_1=-F_2** — **3. "Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first"**

The Basic Equation for Force and Thrust

$$F = \frac{dm}{dt} v_e = \overset{\circ}{m} v_e \text{ [N], with } \frac{dm}{dt} = \overset{\circ}{m} \text{ [kg/s] for propellant mass flow rate}$$

F = Thrust force [N]

$\overset{\circ}{m}$ = Propellant mass flow rate [kg/s]

v_e = Propellant exhaust velocity at nozzle outlet (≡ thruster exhaust velocity) [m/s]

S.4 Basic Rocket Equation

- **Total Velocity Increment *Δv* of a spacecraft:**

$$\int_{v=0}^{v=\Delta v} dv = -v_e \int_{m_{S/C}}^{m_f} \frac{dm}{m}$$

→ **after integration:** $\Delta v = -v_e \ln \frac{m_f}{m_{S/C}}$ **[m/s]**

This formula can be also written in a form called 'Basic Rocket Equation'

- **'Basic Rocket Equation'**

$$\frac{m_f}{m_{S/C}} = e^{-\frac{\Delta v}{v_e}}$$

Tsiolkovsky –Equation

Tsiolkovsky

(1857 – 1935)

S.5 Total Impulse

- **From the Basic Rocket Equation follows with** $m_f = m_{S/C} - m_P$:

  Propellant Quantity required for a spacecraft velocity change Δv**:**

$$m_P = m_{S/C}\left(1 - e^{-\frac{\Delta v}{v_e}}\right) \quad \text{[kg]}$$

- **The Total Impulse delivered by a certain quantity of propellant is calculated by:**

$$I_{tot} = \int_0^{\tau} F dt = v_e \int_0^{m_p} dm = v_e m_p \quad \text{[Ns]}$$

  This equation shows again the importance of the thruster exhaust velocity. For a given mass of propellant, m_P, the thruster exhaust velocity v_e shall be high for obtaining a high (delivered) total impulse, I_{tot}.

S.6 Propulsion Performance Factors

Propulsion Performance is determined by 'Specific Impulses' which permits an objective and comparative evaluation of thrust engines and propulsion systems of different designs and with different propellants:

- **Thruster Performance Factor**

The most useful parameter for determining thrust engine (or thruster) performance is Thruster-specific Impulse:

$$I_{sp} = \frac{F}{\overset{\circ}{m}} \quad \text{[Ns/kg]}$$

The I_{sp} is defined as the impulse delivered per unit mass of propellant and which can be easily obtained by Test.

Thruster-specific Impulse

$$I_{sp} = \frac{F}{\overset{\circ}{m}} \quad \text{[Ns/kg]}$$

I_{sp} = thruster specific impulse [Ns]

F = thrust force [N]

$\overset{\circ}{m}$ = Propellant mass flow rate [kg/s]

Specific impulses are often quoted in units of seconds, corresponding to a modification of the above definition to that of the impulse delivered per unit of weight of propellant.

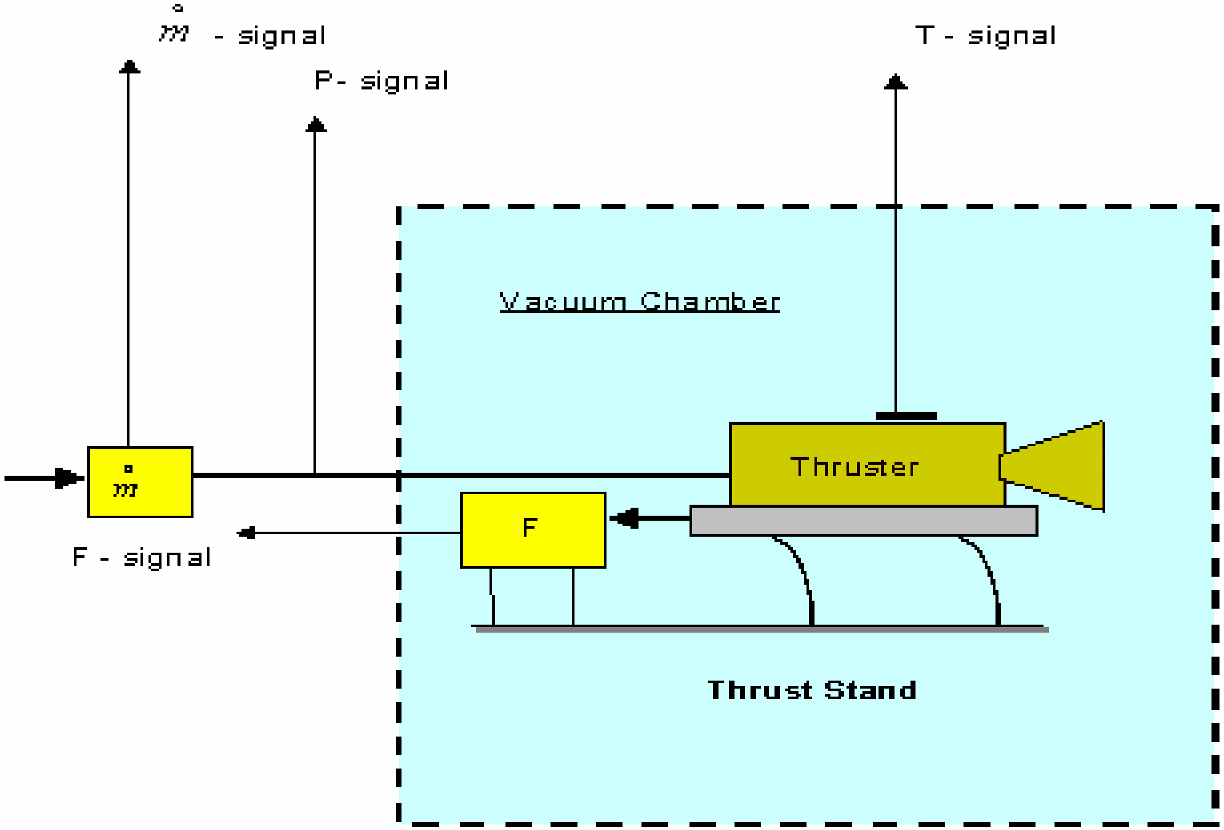
The values in seconds then follow from those in Ns/kg by division with the gravitational acceleration standard, g (=9.82 m/s^2).

$$I_{sp} = \frac{F}{\overset{\circ}{m} g_0} = \frac{F}{\overset{\circ}{w}} \quad \text{[s]}$$

with: $\overset{\circ}{m} g_0 = \overset{\circ}{w}$ [kp/s] **in propellant weight flow unit**

Test

Thrust and specific impulse can be determined by test:



Accuracy of Measurements (typical)

Pressure - P (bar)	± 0.2 %
Temperature - T (° C)	± 2 %
Propellant Mass Flow - $\dot{m}$ (g/s)	± 0.3%
Thrust - F (N)	± 0.2%
Spec. Impulse - I_{sp} (Ns/kg)	± 0.5%

S.7 Effective Exhaust Velocity

$$v_e = \frac{F}{\overset{\circ}{m}} \quad \text{[m/s]}$$

v_e = effective exhaust velocity [m/s]

F = thrust force [N]

$\overset{\circ}{m}$ = propellant mass flow rate [kg/s]

From its definition as the thrust per unit rate of mass flow of propellant, it follows that v_e is numerically the same as the I_{sp} as defined above with SI units of m/s.

<u>Note</u>: v_e is the 'effective' exhaust velocity, - although called 'thruster exhaust velocity' hereinafter-, because it is determined by test; therefore, in all propulsion related calculations with v_e, the effective exhaust velocity has to be applied, if not stated otherwise.

S.8 Propulsion System Performance

- **Propulsion System Performance Factor:**

System-specific Impulse, I_{ssp}

Another very important quantity is the System-specific Impulse, I_{ssp}, which is the total impulse, I_{tot} delivered by the system, divided by the total mass, m_{PS}, of the propulsion system, that is, all of the propulsion system and not only the propellant as for I_{sp}:

$$I_{ssp} = \frac{I_{tot}}{m_{PS}} \quad \text{[Ns/kg]}$$

I_{ssp} = system-specific impulse [Ns/kg]
I_{tot} = total impulse delivered by the propulsion system [Ns]
m_{PS} = mass of propulsion system [kg]

I_{ssp} is a very useful tool, but its practical application requires a very clear definition of what is included in "total mass of propulsion system".

Details of how the I_{ssp} is determined for each kind of propulsion system are dealt with in the 'I_{ssp} Program' in chapter 4.

The mass of propulsion systems can be determined with help of the overall 'Propulsion System Mass Fraction' $\frac{m_{PS}}{m_{S/C}}$:

$$I_{tot} = v_e m_{S/C}\left(1 - e^{-\frac{\Delta v}{v_e}}\right) \qquad \text{[Ns]}$$

$$I_{ssp} = \frac{I_{tot}}{m_{PS}} \Rightarrow I_{tot} = I_{ssp} m_{PS} \qquad \text{[Ns/kg]}$$

$$\frac{m_{PS}}{m_{S/C}} = \frac{v_e}{I_{ssp}}\left(1 - e^{-\frac{\Delta v}{v_e}}\right) = \frac{I_{sp}}{I_{ssp}}\left(1 - e^{-\frac{\Delta v}{v_e}}\right)$$

Propulsion System Mass Fraction

m_{PS} = mass of propulsion system (including propellant) [kg]
$m_{S/C}$ = total mass of spacecraft (vehicle) [kg]
I_{sp} = thruster specific impulse [Ns/kg] $\rightarrow$ v_e = thruster exhaust velocity [m/s]
I_{ssp} = system specific impulse [Ns/kg]
v_e = thruster exhaust velocity [m/s]

The first equation above is obtained from the rocket equation. The second equation is just the definition of I_{ssp}, and the final expression follows from the first two.

S.9 Type of Propulsion Systems

The basic propulsion mathematical formulas presented have to be further expanded for today's commonly used on-board spacecraft propulsion system types:

- **Chemical Propulsion Systems**

  The energy to produce thrust is stored in the propellant, which is released by chemical reactions and the propellant is then accelerated to a high velocity by expanding it in form of gas through a nozzle.

- **Electric Propulsion Systems**

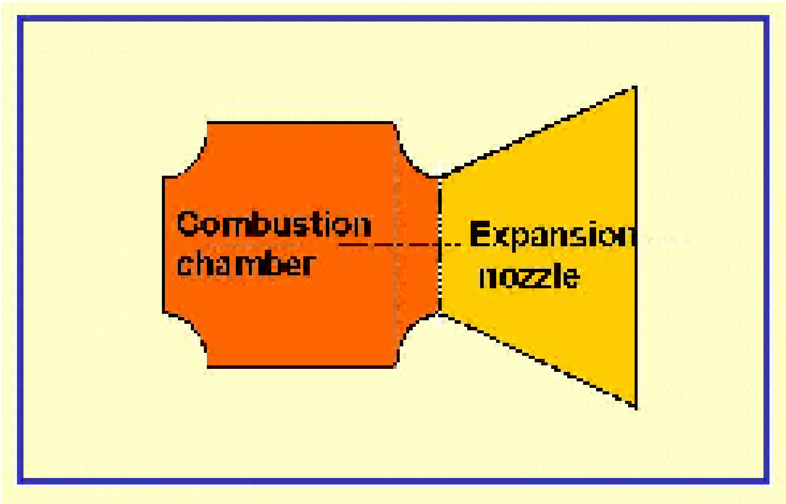
  The energy to produce thrust is not stored in the propellant but has to be supplied from outside by an extra power source, e.g. nuclear, solar radiation receivers or batteries.

  Thrust is produced by:

  - **expansion of hot gas (which is heated by electric current)**
  - **accelerating of charged particles in electric or magnetic fields to high expulsion velocities.**

S.10 Chemical Propulsion

- **Chemical Propulsion is based on the principle of converting chemical energy into kinetic energy of the exhaust gases in a nozzle of a rocket propulsion device.**
- **Typically, rockets using solid propellants are called *motors* and rockets using liquids are called *engines*. The term *thruster* is used for small thrust applications, e.g. in spacecraft auxiliary propulsion systems.**



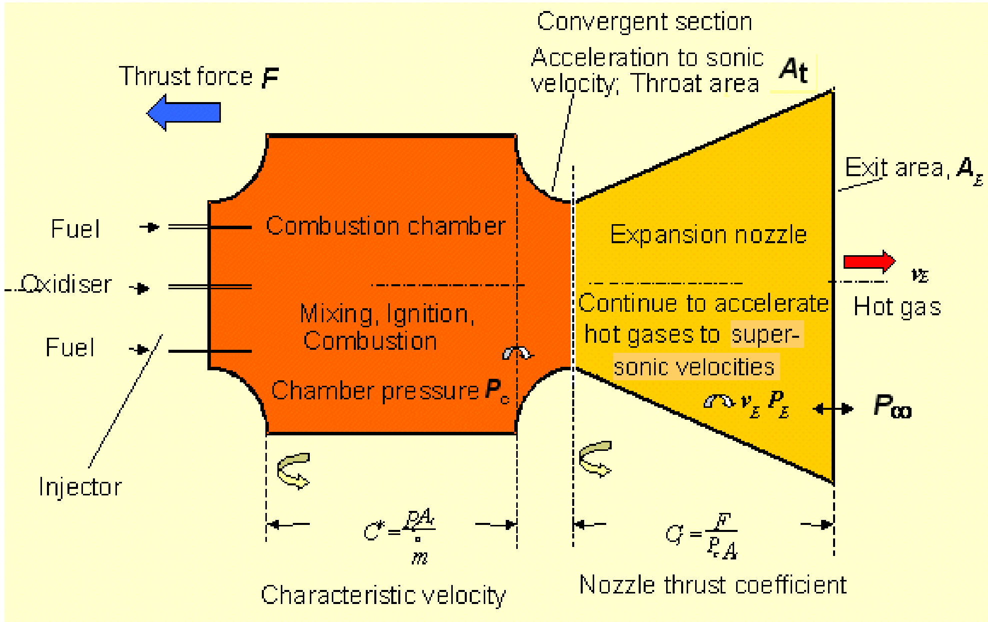
Rocket propulsion device basic parts

Rocket propulsion device basic parts

A rocket propulsion device has 3 basic parts:

- **Thrust (combustion) Chamber, where the propellant burns, producing hot gas**
- **Converging section (throat), to constrict the flow of hot gases, thus controlling chamber pressure and mass flow rate**
- **Nozzle, to accelerate the gas flow to high velocity in the desired direction**

The schematic of a rocket engine is presented below, showing the main *rocket thrust chamber performance parameters*.



Maximum Exhaust Velocity

Conservation of energy applied for gas flow in nozzles:

- **decrease of enthalpy *H* (*H*=$c_p T$) is equal to the increase of kinetic energy (½ Mv^2)**
- **applied to one mole of perfect gas → the velocity of the gas when leaving the nozzle exit (index E) is given**

$$v_E = \sqrt{\frac{2}{M}\left(H_o - H_E\right)} \quad \text{[m/s]}$$

and the theoretical maximum value for v_E is for $H_E=0$, that is all enthalpy has been used to increase the kinetic energy of the expelled gas molecules:

$$v_{E\max} = \sqrt{\frac{2}{M}\left(H_o\right)} = \sqrt{\frac{2\kappa}{\kappa - 1}\frac{RT}{M}} \quad \text{[m/s]}$$

where κ is the ratio of specific heat, *R* is the universal gas constant, *T* is the absolute temperature and *M* is the molecular mass.

Note that the exhaust velocity is a function of mainly temperature *T* and molar mass *M*

$$v_E \approx \sqrt{\frac{T}{M}} \quad \text{[m/s]}$$

The <u>Effective Exhaust Velocity</u> (measured) is:

$$v_e = v_E + \frac{P_E A_E}{\overset{\circ}{m}} = C^* C_F = \frac{F}{\overset{\circ}{m}} \quad \text{[m/s]}$$

Typical values of $\frac{v_e}{v_{E_{\max}}}$ **:** **0.85 – 0.95 for cold gas**

0.60 – 0.80 for hot gas

$v_e < v_{Emax}$ is due to:

- **Thermal losses in the motor**
- **Friction losses in nozzle (boundary losses due to separation of gas flow from nozzle wall)**
- **Nozzle exit pressure $P_E > P_\infty$ governed by nozzle expansion ratio (< 200)**
- **Losses due to gas condensation and gas dissociation in nozzle**

S.11 Electrical Propulsion

An Electric Propulsion system is a mass expulsion system in which electric energy is used to create or augment the kinetic energy in the expelled mass. Consequently electric power will be of main interest in the performance evaluation of such systems.

- **Kinetic Energy of Ejected Matter**

$$E_{jet} = \frac{1}{2} m_p v_e^2 \quad \text{[Ws]}$$

- **Power of the Jet**

$$P_{jet} = \frac{dE_{jet}}{dt} = \frac{1}{2} \overset{\circ}{m} v_e^2 = F \frac{v_e}{2} \quad \text{[W]}$$

- **Power Input**

$$P = \frac{P_{jet}}{\eta} = \overset{\circ}{m} \frac{v_e^2}{2\eta} = F \frac{v_e}{2\eta} \quad \text{[W]}$$

where η is the power conversion efficiency.

Kinetic energy in the expelled mass

- Electric propulsion leads to higher exhaust velocities achieved by chemical propulsion (v_e < 5000 m/s), by this saving mass of propellant.

Power Input

- Since power is the major constrain for electric thrusters on spacecraft, the following example will illustrate the impact of power on limiting of thrust levels for electric propulsion.
- The power input to a thruster system is:

$$P = F\frac{v_e}{2\eta} \ \text{[W]} \quad \Longrightarrow \quad F = P\frac{2\eta}{v_e} \ \text{[N]}$$

With the assumption:
P = 1000W power input
η = 1 (to simplify)
v_e = 30 000 m/s typically for electric thrusters

The resulting thrust will be:

$$F = 1000\frac{2}{30000}\left[\frac{W \equiv Nm/s}{m/s}\right] = 0.067[N]$$

Conclusion: Thrust levels of electric propulsion will be << thrust levels of chemical propulsion

S.12 Summary

- **Fundamentals of rocket propulsion:**
  - **Thrust force is generated by expelling mass (initially stored in the spacecraft) from the spacecraft at high velocity;**
  - **'Basic Rocket Equation' trades off exhaust velocity v_e with spacecraft mass fraction R;**
- **Propulsion performance is determined by 'Specific Impulses':**
  - **Thruster-specific impulse, I_{sp} (Ns/kg), which is numerically the same (If defined with SI units of m/s) as the effective exhaust velocity v_e (m/s), - although called 'thruster exhaust velocity' hereinafter. The exhaust velocity increases with increasing gas temperature and decreasing molar mass.**
  - **Propulsion System-specific Impulse, I_{ssp} (Ns/kg), which is the total impulse, I_{tot} (Ns) delivered by the system, divided by the system total mass, m_{PS} (kg).**
- **Mass of propulsion systems can be determined with help of the overall 'Propulsion System Mass Fraction', $m_{PS}/m_{S/C}$.**
- **Power is the major constraint for electric thrusters on spacecraft. Therefore thrust levels of electric propulsion will be << thrust levels of chemical propulsion.**

Chapter 3: Spacecraft Propulsion Systems Survey

Peter Erichsen, September 2006

S.1 Survey of Spacecraft Propulsion Systems

- In the progressing "Space Age", spacecrafts such as satellites and space probes are the key to space exploration, space science and space commerce.
- Of particular interest is spacecraft propulsion, which is necessary to maneuver or steer spacecrafts in the absence of aerodynamic forces.
- An overview of common basic spacecraft propulsion system designs is presented together with supporting tables and graphs.
- Key features and performance characteristics of existing and planned (near future) propulsion systems for use on spacecraft are summarized. This will help to understand their potential application based on basic system performance characteristics like thrust levels, thruster and system specific impulse, etc.

S.2 Educational Objectives

In this chapter you will learn:

- **Classification of propulsion systems based on type of energy source**
- **Basic configuration of propulsion systems**
- **Main performance characteristics of propulsion systems**
- **Advantages and disadvantages of propulsion systems**

S.3 Propulsion System Options

Spacecraft Propulsion System Options:

Spacecraft Propulsion Systems can be classified according to the type energy source. Both space propulsion and auxiliary propulsion are performed by the following two main on-board spacecraft propulsion system types:

- **Chemical Propulsion Systems:**

  The energy to produce thrust is stored in the propellant, which is released by chemical reactions and the propellant is then accelerated to a high velocity by expanding it in form of gas through a nozzle. Currently available chemical propulsion systems can be categorized as either: hot gas or cold gas system.

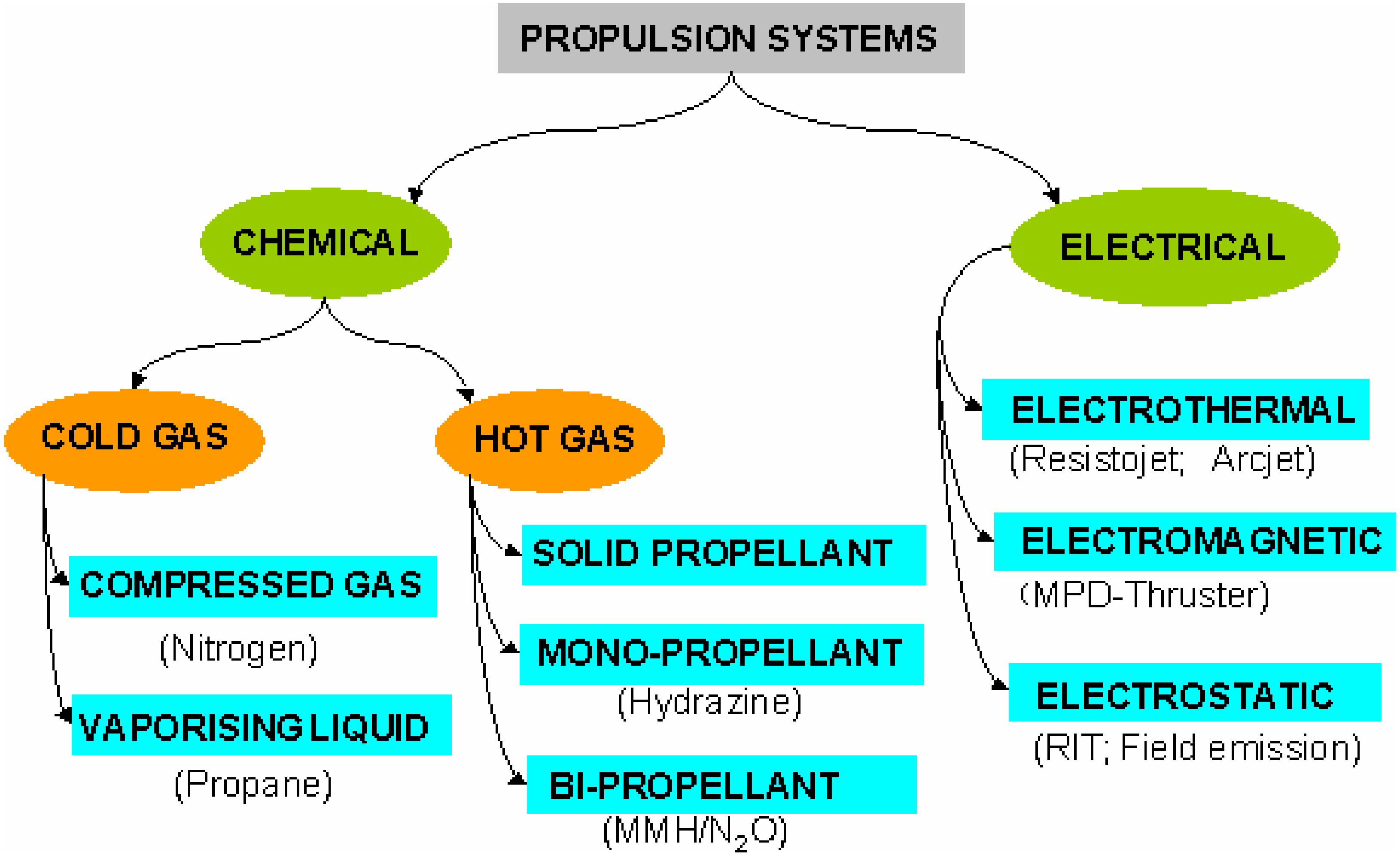
- **Electric Propulsion Systems:**

  The energy to produce thrust is not stored in the propellant but has to be supplied from outside by an extra power source, e.g. nuclear, solar radiation receivers or batteries.

  Thrust is produced by:

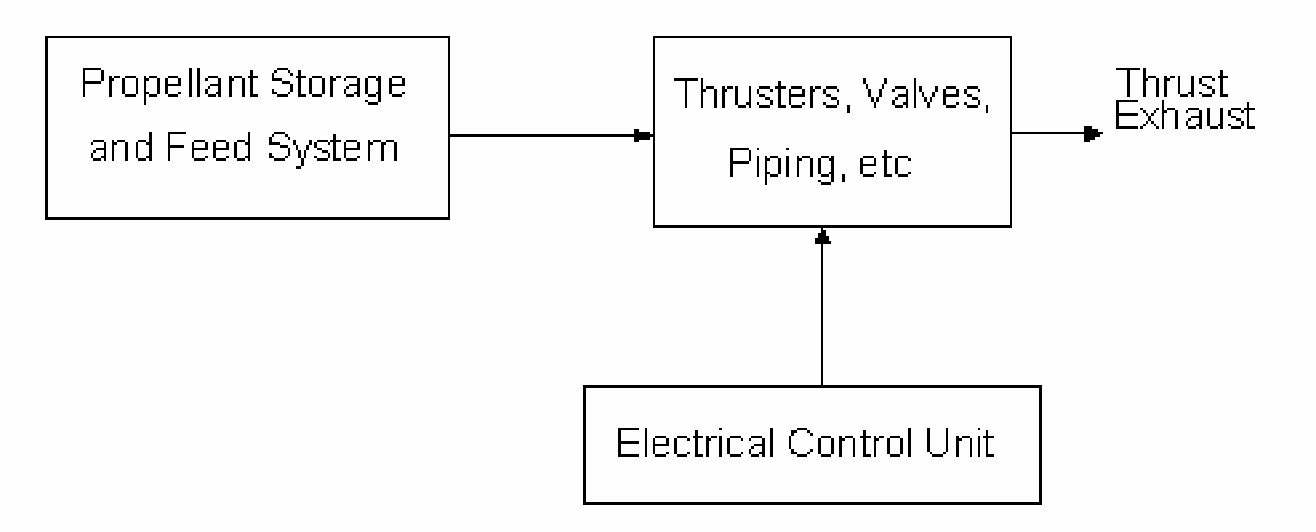
  - **Expansion of hot gas (which is heated by electric current) in a nozzle,**
  - **Accelerating of charged particles in electric or magnetic fields to high expulsion velocities.**

Classified According to the Type Energy Source



Chemical Propulsion Systems

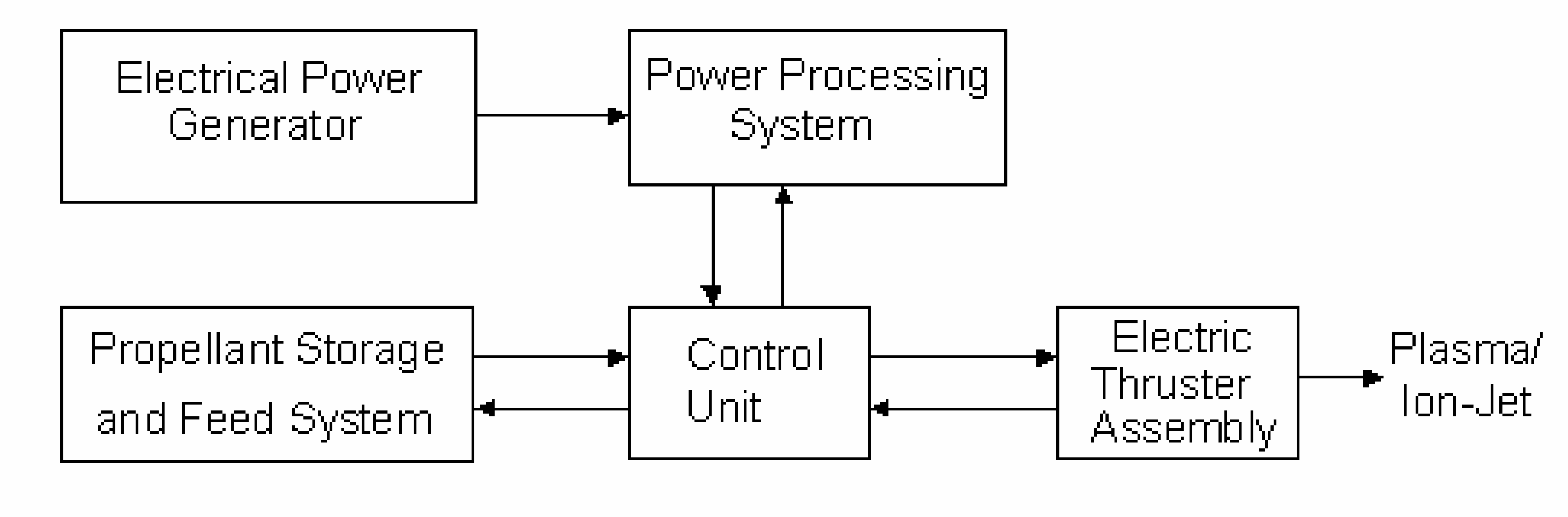
Chemical Propulsion systems comprise the following main components



- **Storage and feed system that stores and feeds the propellant to the thrusters to generate thrust**
- **Valves, piping which connects the propellant storage system with the thruster**
- **Electric control unit to operate electrically the valves and thrusters**

Electric Propulsion Systems

Electric propulsion systems comprise the following main components:



- **Storage and feed system that stores and feeds the propellant to the thrusters to generate thrust**
- **Valves, piping which connects the propellant storage system with the thruster**
- **Electric control unit to operate electrically the valves and thrusters**
- **Electric power supply and power processing system**

S.4 Cold and Hot Gas Systems

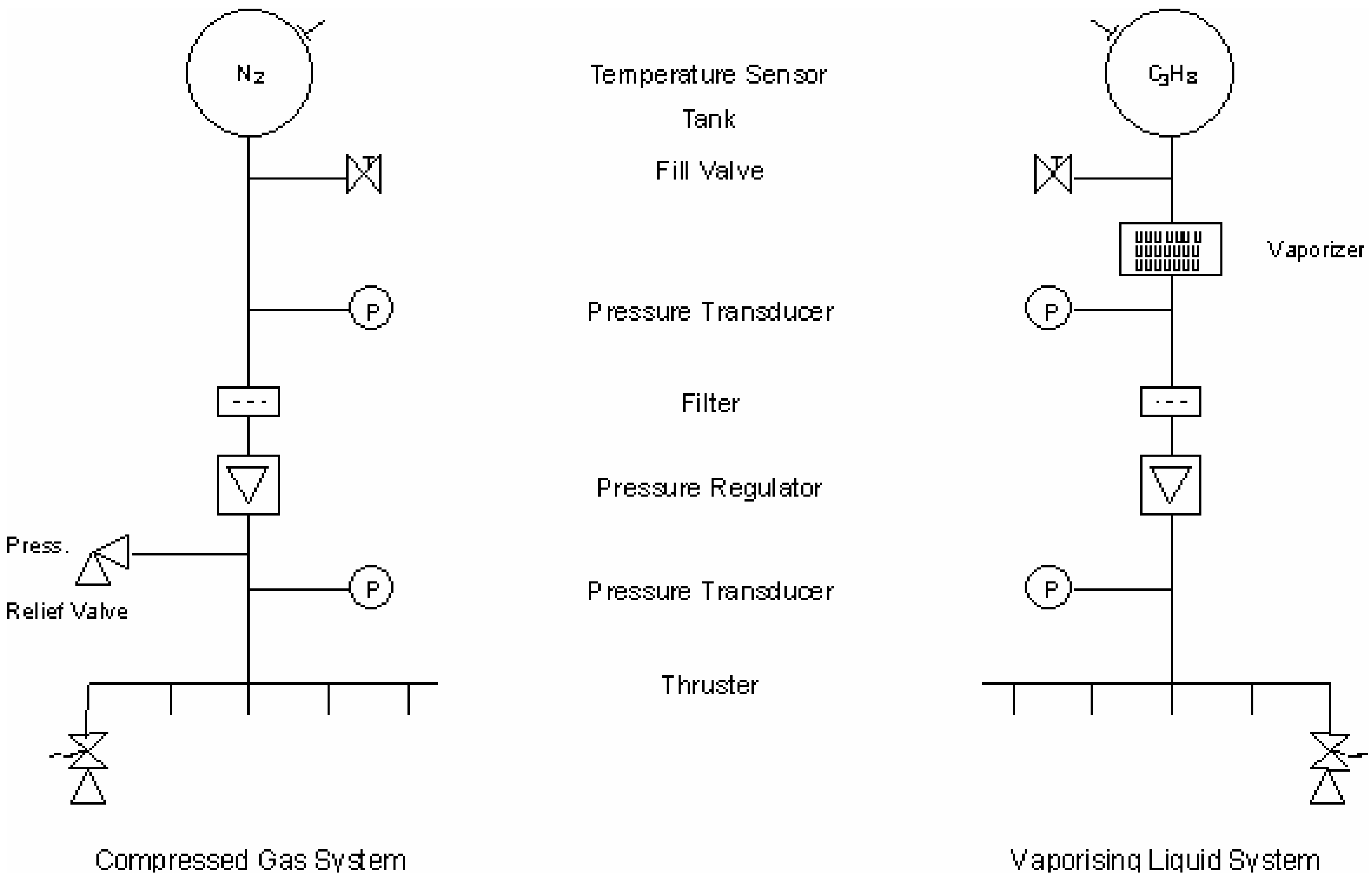
- Cold Gas Systems operate with propellants like compressed inert gas (e.g. nitrogen: N_2) or high vapor pressure hydrocarbons (e.g. propane: C_3H_8).

  - Main performance
  - Advantages
  - Disadvantages
  - Conclusion

- Hot Gas Systems are the most common type of propulsion systems for space applications. They can be divided into three basic categories defined by the physical state of the stored propellants in the propulsion system.

  In contrast to compressed gas and vaporizing liquids, liquid propellants in hot gas systems need to be pressurized in the tank to feed the thrusters with propellant. These systems are called pressure-fed systems. Note

Cold Gas Systems



Cold Gas Systems (Operate)

- **Cold gas propulsion is just controlled pressurized gas source and a nozzle. It represents the simplest form of a propulsion system.**
- **The typical system operating with cold gas consists of a propellant tank, fill valve, filter, pressure regulator, line pressure transducers and thrusters. The pressure regulator provides propellant at constant pressure as the tank pressure drops.**
- **A relief valve is incorporated downstream of the pressure regulator to prevent system rupture in the case of a regulator failure. With regard to compressed gas systems, the cold gas is stored at high pressures in a tank.**
- **The vaporizing liquid system is characterized by a liquid propellant pressurized by its own equilibrium vapor pressure and the expulsion of its vapor through a nozzle. In order to provide completely vaporized gas, a vaporized is included in liquid cold gas systems.**
- **Nitrogen, argon, krypton, Freon 14, ammonia and propane have been employed in operational spacecraft, but nitrogen has been the most common cold-gas propellant.**

Propellants

CHARACTERISTICS OF SOME CANDIDATE COLD GAS PROPELLANTS

Name	Formula	Mol. Mass M (kg/kmol)	Crit. Temp (°C)	Crit. Pressure (bar)	Compr. Factor z (200 bar, 20°C)	Exhaust Velocity v_e [1] (20°C) (m/s)	Remarks 'System-spec Impulse' I_{ssp} (Ns/kg ≡ m/s)
Compressed Gas							
Hydrogen	H_2	2	- 240	20	1.18	2668	≈ 194 [6]
Methane	CH_4	16	-83	46	0.86	1030	≈ 454 [6]
Nitrogen	N_2	28	-147	33	1.13	706	≈ 378 [6]
Argon	A	39.9	-122	49	1.02	490	≈ 319 [6]
Freon 14	CF_4	88	-45	41	0.68 [2]	441	[2] at 110 bar, 20°C; ≈ 377
Xenon	Xe	131.3	+17	58	0.3 [3]	275	[3] at 75 bar, 25°C; ≈ 262
Vaporising Liquids		Density ρ $(kg/m^3)10^3$			Max. Oper. Press. P_{op} (30°C) (bar)		
Ammonia	NH_3	0.62	+ 132	119	12	950	≈ 700 [7]
Propane	C_3H_8	0.53	+ 97	42	11	608 [4]	[4] X-4, UK-5 S/C; ≈ 486 [7]
Carbon dioxide	CO_2	0.8	+ 31	73	71	598 [5]	≈ 340 [7]

1) Holcomb, L.B.; Satellite auxiliary-propulsion selection techniques. JPL Technical Report 32-1505, 1970

5) Sackheim, R.L. et.al.; The Next Generation of Spacecraft Propulsion Systems, 15th Joint Propulsion Conference June 1979

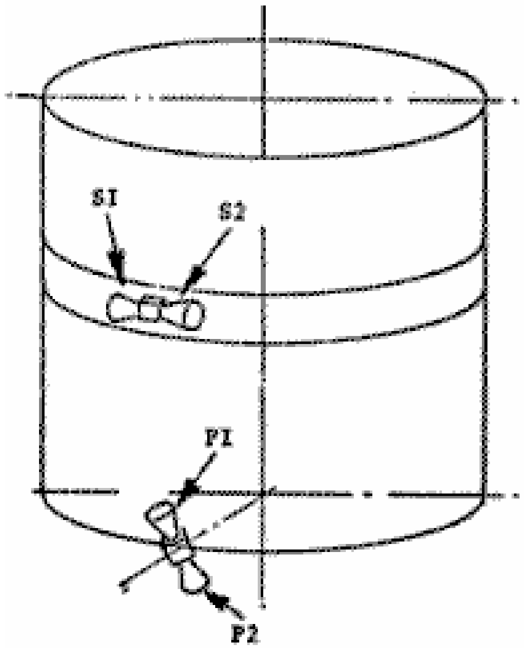
6) for gas storage tanks made of fibre composite material

7) for gas storage tank made of aluminium with heat exchanger

Typical System

COS-B, spin-stabilised scientific satellite 1975 - 1981

Example of a typical cold gas propulsion system; propellant gaseous nitrogen. Mass of propulsion system, m_{PS} = 24 kg



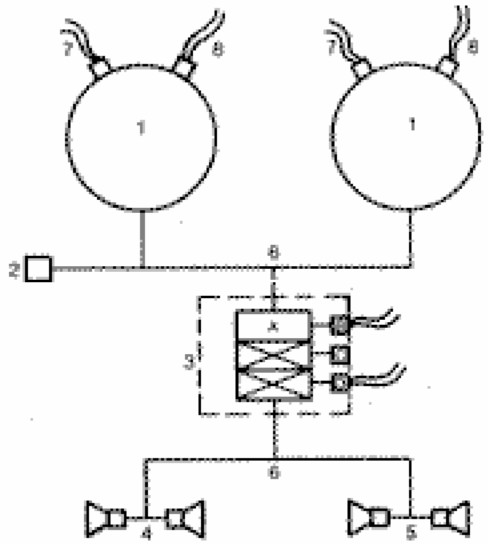
Legend

S1 = SPIN UP THRUSTER 'A'

S2 = SPIN DOWN THRUSTER 'B'

P1 = PRECESS UP THRUSTER 'A'

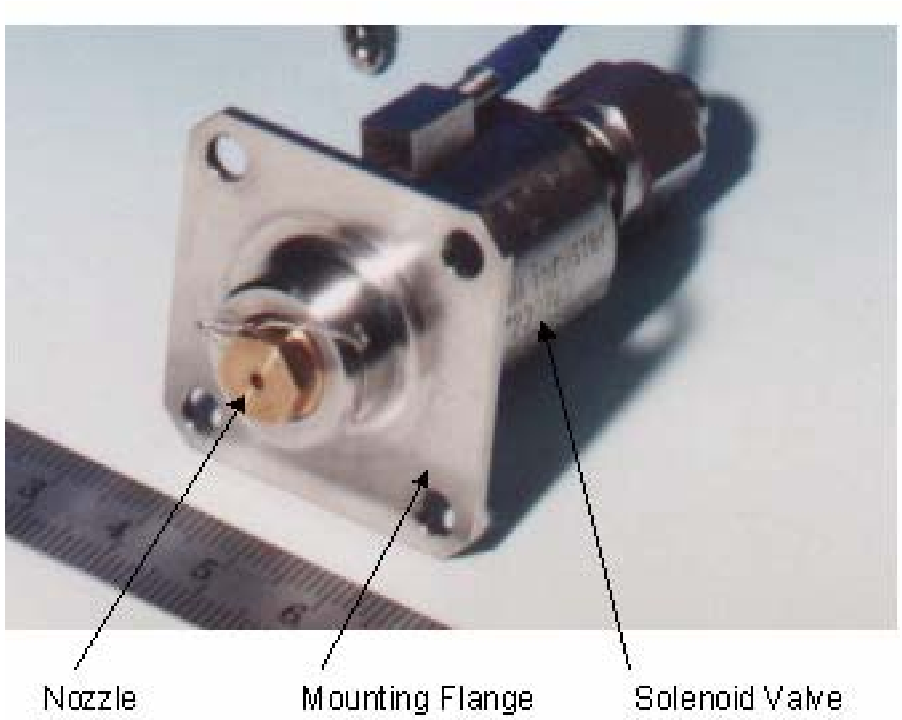
P2 = PRECESS DOWN THRUSTER 'B'



Legend

1. TANK
2. FILL VALVE ASSEMBLY
3. PRESSURE REGULATOR ASSEMBLY
   A. REGULATOR
   B. HIGH PRESSURE TRANSDUCER
   C. LOW PRESSURE TRANSDUCER
   D. RELIEF VALVE
4. SPIN THRUSTER ASSEMBLY
5. PRECESSION THRUSTER ASSEMBLY
6. PLUMBING
7. TANK TEMPERATURE TRANSDUCERS (FLIGHT)
8. TANK TEMPERATURE TRANSDUCERS (GROUND)

Thrusters



Astrium

Cold Gas Thruster

F= 20 mN

(0.0045 N ÷ 4.5 N available)

Flown on:

- Eureca
- Hipparcos
- Astro Spaces

Cold Gas Thruster (Astrium)

Simple design:

- Solenoid Valve
- Nozzle

Simple functioning:

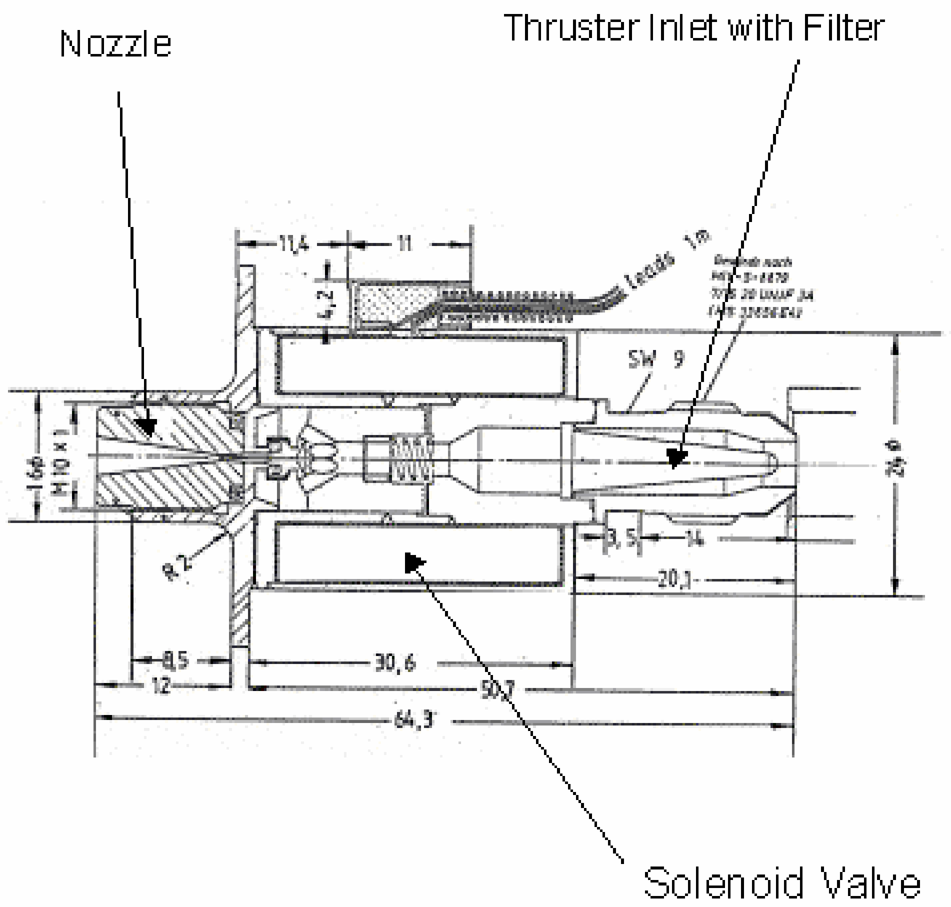
- electrical activation of solenoid valve releases gas flow

Thrust level:

- determined by gas inlet pressure
- nozzle throat diameter

Minimum impulse bit:

- determined by thrust level
- minimum on-time of solenoid valve



Main performance of Cold Gas Systems

- **Thrust level: 0.0045 ÷ 10 N**
- **Impulse bit: ≥ 10^{-5} Ns (with thruster minimum on-time of 5 ms)**

- **Note from the propellant table:**
  - **Thruster-spec. Impulse: 275 ÷ 2668 Ns/kg [≡ v_e (m/s)]**
  - **System-spec. Impulse: 200 ÷ 700 Ns/kg**

- **Although hydrogen gas provides the highest *Thruster-spec. Impulse*, it offers the lowest *System spec. Impulse* because of the low gas density with resulting high mass of propellant storage system (tank + gas).**
- **In contrary, systems operating with vapor pressure hydrocarbons (e.g. propane: C_3H_8) have higher *System-spec. Impulses* because of the high gas density (stored as a liquid). However, because of simplicity, nitrogen has been the most common cold-gas propellant.**

Advantages

- Simplicity and reliability
- Lowest cost propulsion system
- Very low thrust (≥ 0.0045 N) and impulse bit (≥ 10^{-5} N) capability
- Low contamination of exhaust gases (plume) on spacecraft outer surface

Disadvantages

- Low I_{sp} (≤ 950 Ns/kg) ≡ low I_{ssp} (≤ 700 Ns/kg) with resulting high system mass

Conclusion

- Although of moderate impulse capability, cold gas systems, in particular systems operating with compressed cold gas, are still of interest in view of their simplicity, high reliability and repeatability of impulse bit.
- Therefore, cold gas has many applications where simplicity is more important than high performance.
- For increasing absolute levels of thrust and impulse requirements for spacecraft propulsion (e.g. attitude and orbit control), cold gas systems are inadequate and more energetic propellants generating hot gas for mass expulsion are required.

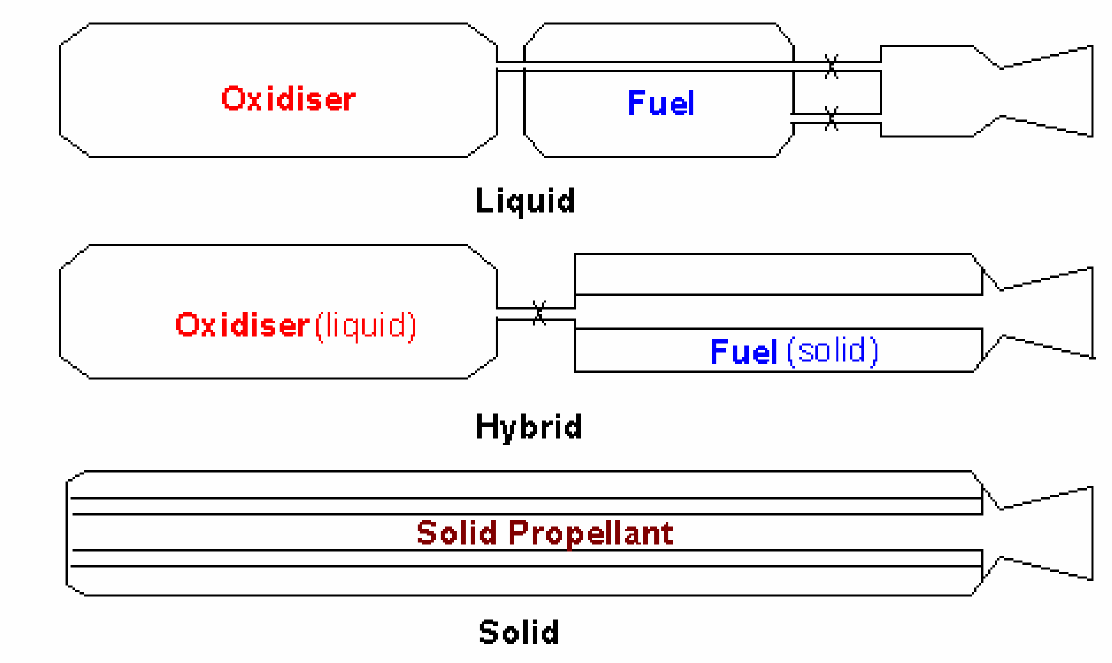
S.5 Categories of Hot Gas Systems

REMEMBER!

- **In order to obtain higher I_{ssp}, in the first instance higher v_e is needed. This can be achieved by increasing the temperature of the exhaust gases to be expanded in the thruster nozzle.**

Hot Gas Systems

- **Hot gas systems are the most common type of propulsion system used for space applications.**



Liquid Propellants

Characteristics of Liquid (storable) Propellants for Spacecraft Applications

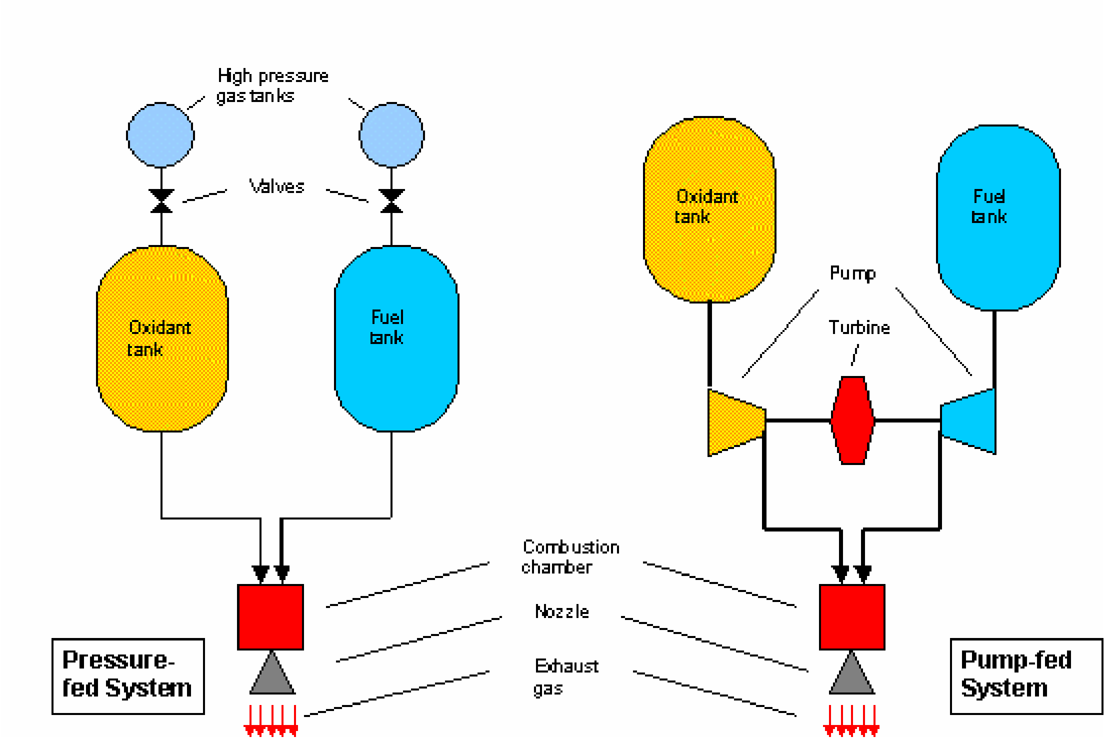
Propellant	Chemical Formula	Melting Point (°C)	Normal Boiling Point (°C)	Density of Liquid, ρ $(kg/m^3)x10^3$	Heat of Combustion (kcal/mol)	Remarks
FUELS						Performance with NTO*)
Hydrazine	N_2H_4	1.53	114.2	1.0037	148.6	(v_e = 2300 m/s : Monoprop.) v_e = 2855m/s $\bar{\rho} = 1.21 \cdot 10^3$ kg/m³ r = 1.3
Monometyl-hydrazine (MMH)	$CH_3N_2H_3$	- 52.37	87.65	0.8702	311.7	v_e = 3200 m/s $\bar{\rho} = 1.15 \cdot 10^3$ kg/m³ r = 1.64
1.1 Dymethyl Hydrazine (UDMH)	$(CH_3)_2N_2H_2$	- 57.21	62.32	0.7861	437.7	v_e = 2806 m/s $\bar{\rho} = 1.17 \cdot 10^3$ kg/m³ r = 2.65
Aerozine (AZ50)	50% UDMH 50% Hydrazine	- 5.6	70.0	0.8987	312	v_e = 2825 m/s $\bar{\rho} = 1.21 \cdot 10^3$ kg/m³ r = 2.15
OXIDIZERS						
Nitrogen Tetroxide (NTO)	N_2O_4	- 11.2	21.2	1.433		
MON I		- 12.6				
MON II		- 15				

Ref.: U.S.A.F. Propellant Handbook, 1970

*) A. Dadieu, R. Damm, E.W. Schmidt, DFVLR, "Raketentreibstoffe", Springer-Verlag, Wien, 1968

Pressure-Fed Systems

SCHEMATIC OF PRESSURE-FED AND PUMP-FED PROPULSION SYSTEM



Note

- **Note that due to long space flight mission duration, only pressure-fed systems are used because of their inherent simplicity compared with pump-fed systems, which are used commonly for launch propulsion.**
- **In addition, for long space flight missions, only *storable propellants*, which can be stored for long periods in sealed tanks, are used.**

S.6 Liquid Propellant Systems

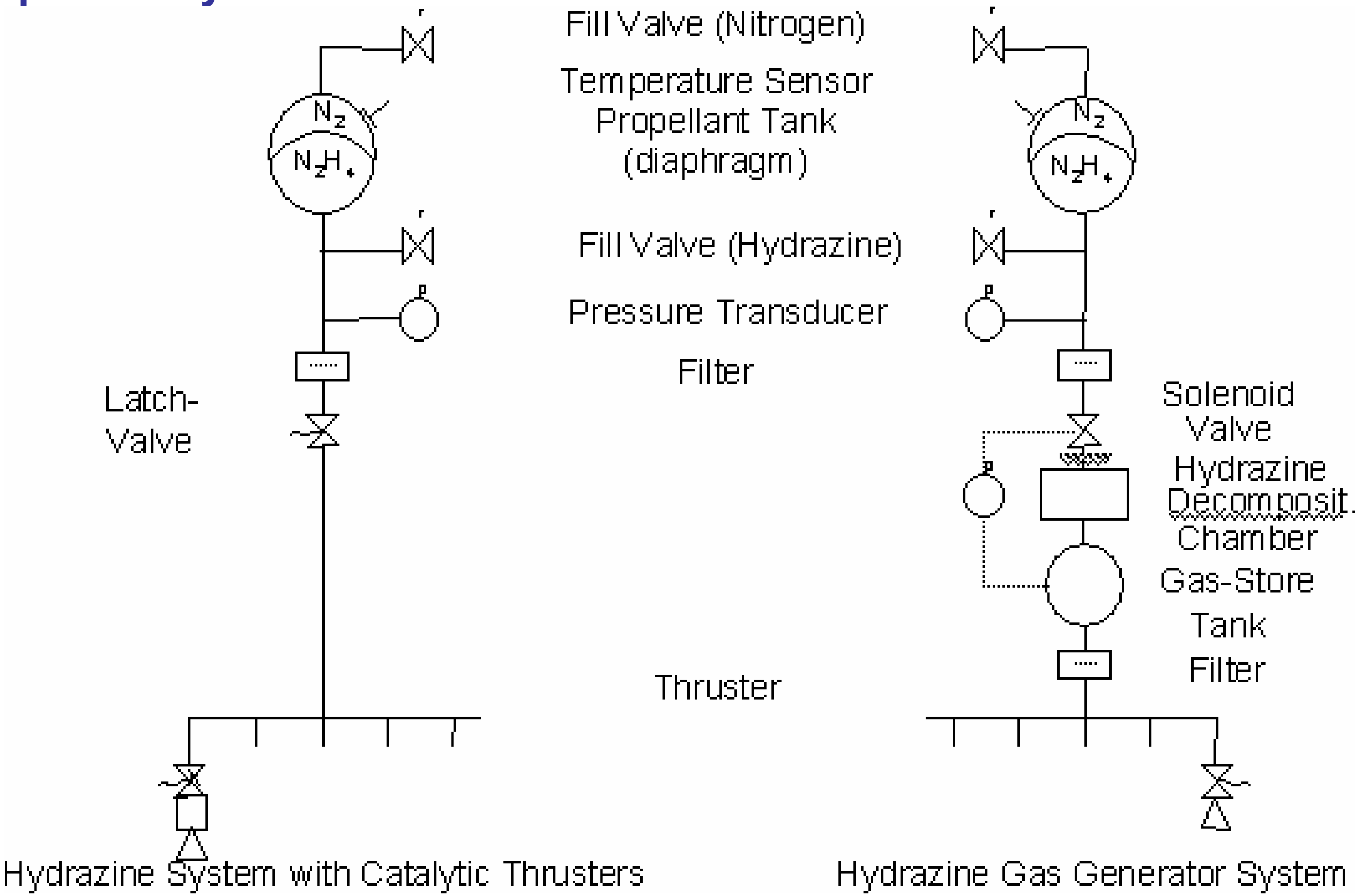
- Monopropellant systems operate with a single (Mono) propellant to produce thrust. The most commonly used monopropellant is anhydrous hydrazine (N_2H_4).
  - Main performance
  - Advantages
  - Disadvantages

- Bipropellant systems operate by the combustion of two (Bi) propellants, a fuel (e.g. MMH) and an oxidizer (e.g. N_2O_4), to produce thrust.

  Bipropellant systems are used e.g. for telecommunication satellites which operate in Geostationary Orbits.

  Here, propulsion systems are needed for spacecraft injection from the orbit delivered by the launcher into circular orbit, and during station phase for orbit (north/south & east/west) and attitude control. Therefore, these propulsion systems are also called Unified Propulsion Systems (UPS).

Monopropellant Systems



Monopropellant Systems (Operate)

- **The hydrazine propellant is decomposed in a thruster by a catalyst and the resulting hot gas is expelled through a nozzle, thus generating thrust force on the spacecraft.**
- **A typical monopropellant system uses nitrogen or helium gas to expel the propellant from a diaphragm tank into the chamber catalyst beds of the thrusters. Since the pressuring gas is stored (at a pre-selected but relatively low pressure, e.g. 22 bar) in the propellant tank, the propellant pressure varies with propellant usage.**
- **A typical selection of the ullage volume of 25% filled with pressuring gas (thus containing 75% propellant) will results in a propellant feed pressure decay, and thus in a thrust decay of 4:1.**
- **This mode of operation is also referred to as the *blow-down mode*, in contrast to the *pressure constant mode*, which requires the storage of a high-pressure gas in a tank external to the propellant tank (see bipropellant systems).**
- **In a hydrazine gas generator system, the hydrazine decomposition gases are exhausted into a gas storage tank for later gas expulsion.**
- **The catalytic thruster and gas generator systems have identical propellant feed systems consisting typically of propellant tank(s) with a diaphragm expulsion device(s), propellant and gas fill valves, eventually latch valves (start valves), line pressure transducers and filters.**

Thruster

Astrium **Catalytic**

Monopropellant Hydrazine Thruster Nominal Thrust: F=1N

For the attitude and orbit control of the Globalstar-Systems (> 64 satellites each with 5 thrusters) this 1N thruster was developed by Astrium.

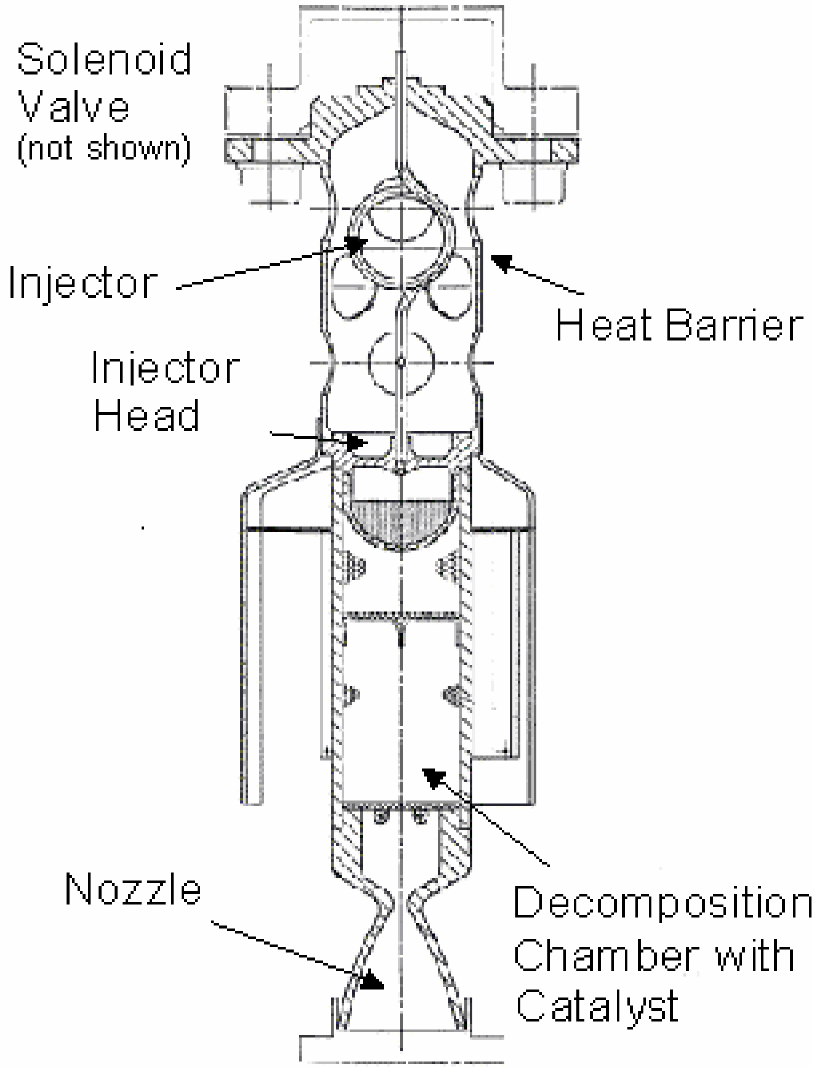
Catalytic Monopropellant Hydrazine Thruster (Astrium)

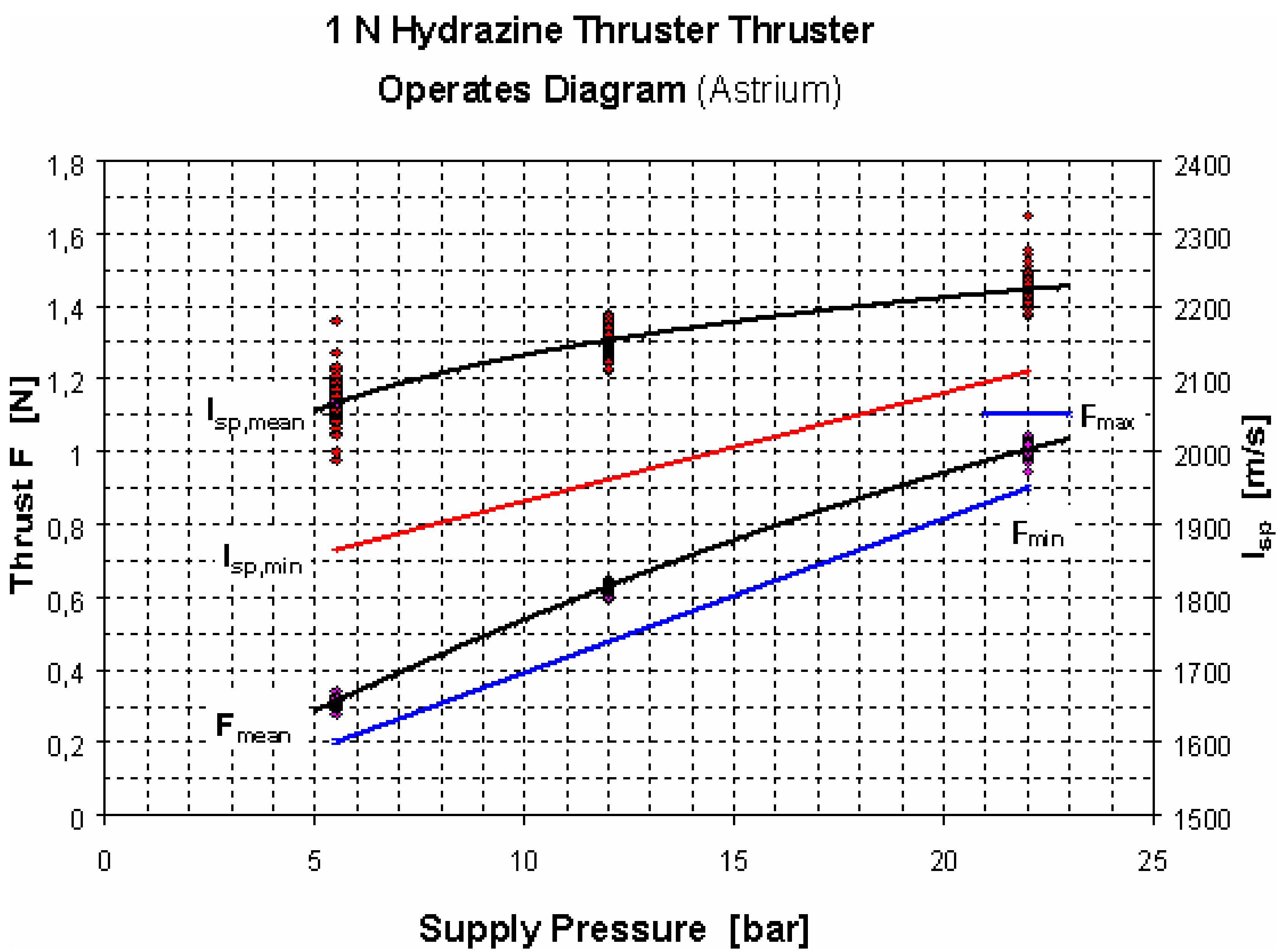
Design:
- Solenoid Valve (Flow Control Valve; FCV)
- Heat Barrier
- Injector Head
- Decomposition Chamber with Catalyst
- Nozzle

Function:
- opening of FCV
- injection of hydrazine
- exothermal decomposition of hydrazine
- exhaust of gas through the nozzle

Thrust level:
- determined by hydrazine inlet pressure
- nozzle throat diameter

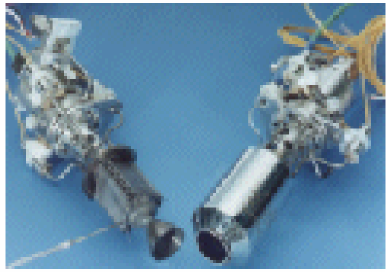
Minimum impulse bit:
- determined by thrust level
- minimum on-time of solenoid valve



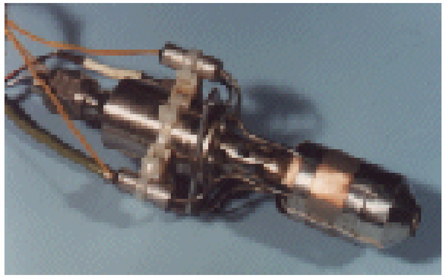

1 N Hydrazine Thruster Thruster
Operates Diagram (Astrium)
Thrust F [N]
I_{sp} [m/s]
Supply Pressure [bar]
$I_{sp,mean}$
$I_{sp,min}$
F_{mean}
F_{max}
F_{min}
1,8
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
0
5
10
15
20
25

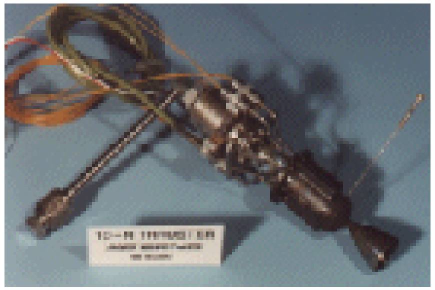
Astrium
Hydrazine Thrusters


0,5 N ECS/MCS


5,0 N Hipparcos

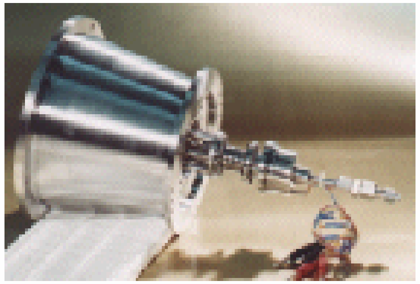

1,0 N Globalstar


2,0 N Telecom, Skynet 4t


10 N Meteosat, SAX


20 N XMM, Integral


450 N Ariane 5 SCA


450 N ARD

Typical Monopropellant System

SMART-1 Hydrazine Propulsion System

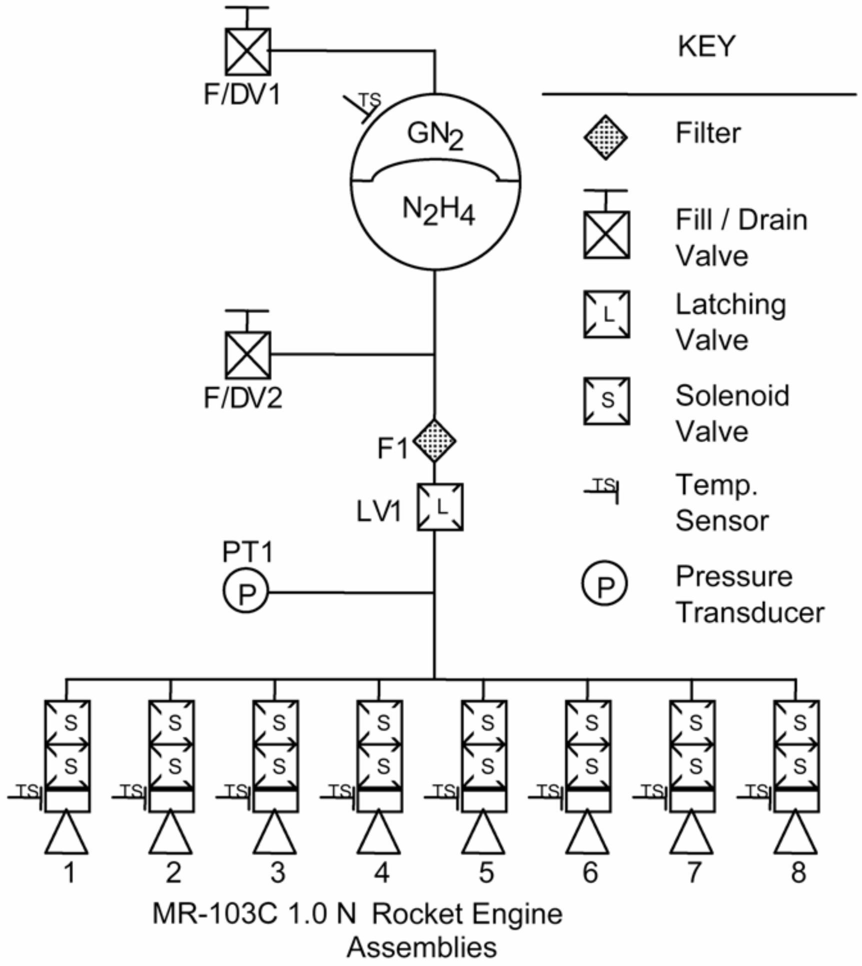
SMART-1 is an ESA moon mission. The 367 kg probe was launched piggyback on Ariane 5 in November 2003. Prime contractor is the Swedish Space Corporation (SSC).

- Mass of propulsion system, m_{PS} = 16 kg

- Mass of satellite, $m_{S/C}$ = 280 kg

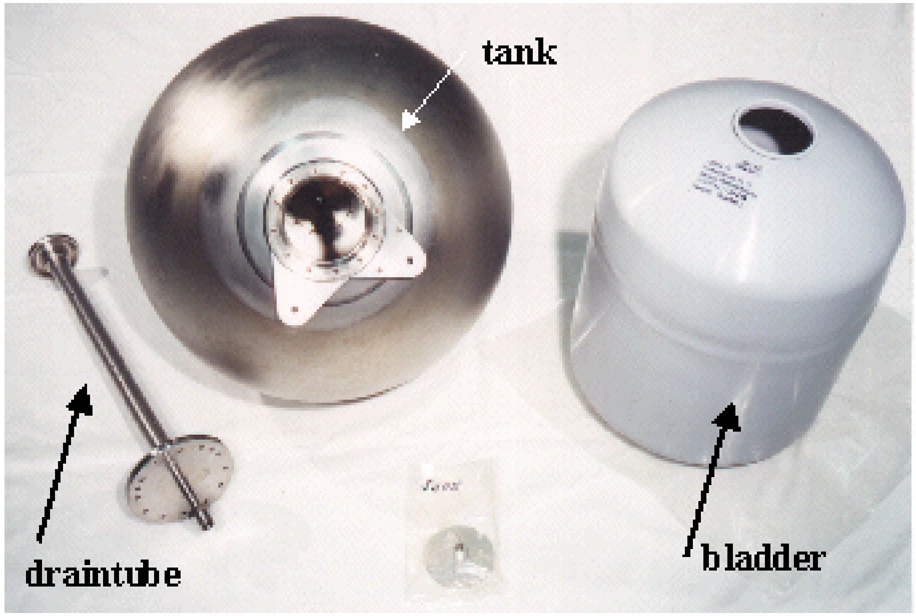
The propulsion system comprises the following components:

- Eight 1 N hydrazine thrusters
- A 15 Litre tank, filled with ~4 kg Hydrazine and pressurised to 25 bar with GN_2
- Operating in blow-down mode
- Duty cycles below 1 % at 20 ms on-times
- System supplied by Primex Aerospace Company
- System assembled and tested by SSC



Diaphragm Tank

Propellant Tanks
(Diaphragm- or Bladder Tank)



Ariane 5 SCA Tank (Astrium)

Main Performance of Monopropellant Systems

- **Thrust level: 0.5 ÷ 22N for satellites, up to 450 N for e.g. Ariane third stage auxiliary propulsion**
- **Impulse bit: ≥ 10^{-2} Ns (with thruster minimum on-time of 20 ms)**
- **Thruster-spec. Impulse: ≤ 2300 Ns/kg [≡v_e (m/s)] for continuous mode operation**
- **Thruster-spec. Impulse: ≈ 1900 ÷ 2200 Ns/kg for pulse mode operation**
- **System-spec. Impulse: ≤ 1860 Ns/kg**

Advantages

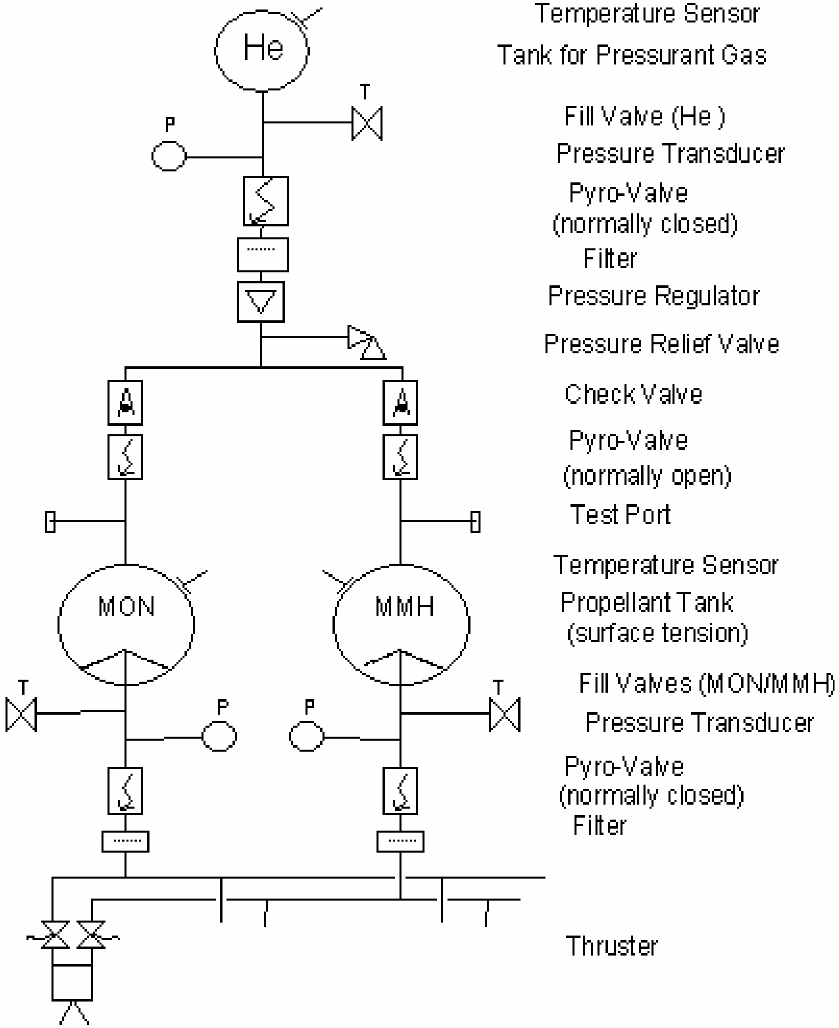
- Simplicity and reliability (monopropellant)
- Lowest cost propulsion system (other than cold gas)
- Space storable for long periods (> 12 years demonstrated)
- Low thrust capability
- Moderate thrust levels available (≤ 400 N)

Disadvantages

- Moderate I_{sp} (≤ 2300 Ns/kg) with moderate I_{ssp} (< 1900 Ns/kg) resulting in medium/high system mass
- Limited life of catalyst
- Satellite outer surface contamination (NH_3) moderate

Bipropellant/Dual-Mode Systems

Bipropellant Systems



Bipropellant Systems (Operate)

- Bipropellant systems are characterized by the combustion of two (Bi) propellants, a fuel (e.g. MMH) and an oxidizer (e.g. N_2O_4) to produce thrust. The propellants are injected separately into the bipropellant thruster combustion chamber where they react spontaneously (hypergolic propellant) to perform high-temperature, low molecular weight combustion products, which are the expelled through a nozzle.

- The system basically consists of a pressurizing-gas system, propellant tanks (with surface tension propellant management devices), propellant lines and thrusters. Unlike hydrazine thrusters, bipropellant thrusters accept only a limited range of propellant inlet pressure variation of ≤ 2. Therefore, the high-pressure gas, generally nitrogen or helium is regulated to the desired tank pressure, e.g. 17 bar. This mode of operation is also referred to as the pressure constant mode.

- The system contains check valves upstream of the propellant tanks to prevent possible back-flow, mixing, and combustion of the propellant vapors in the common pressuring gas line. Relieve valves are incorporated in the system upstream of the propellant tanks to prevent system rupture in the event of a pressure regulator failure. Filters are provided in the propellant lines directly upstream of the thruster valves to prevent clogging of the injector or damage of the valve seat by entrained foreign material. Finally, the system contains pyro- or latch valves, line pressure transducers, fill and drain valves and various test ports for system check out.

Bipropellant thruster

Design:

- Solenoid Valve (Flow Control Valve; FCV)
- trimming→ΔP
- Injector Head
- Combustion Chamber
- Nozzle

Function:

- opening of FCV
- injection of oxidiser and fuel
- hypergolic reaction
- exhaust of gas through the nozzle

Thrust level:

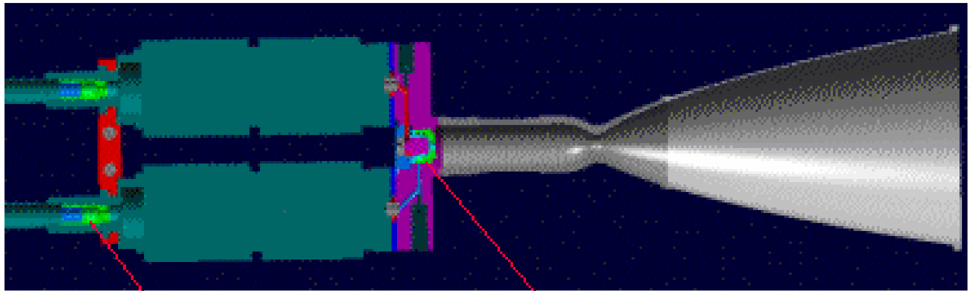
- determined by propellant inlet pressure
- nozzle throat diameter

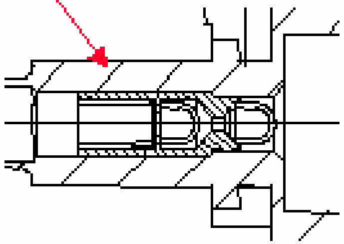
Minimum impulse bit:

- determined by thrust level
- minimum on-time of solenoid valve

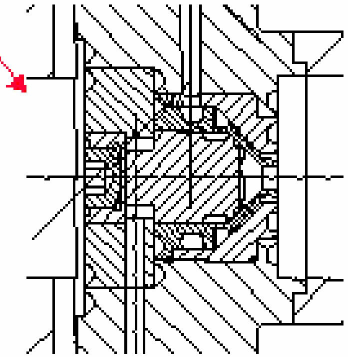
BIPROPELLANT THRUSTERS (Astrium)

22 N Bipropellant Thruster





Variable Trim Orifice



Double-Whirled Injection System

Realised thrust level for bipropellant thrusters: from 4 to 400 N

10 N Bipropellant Propellant Thruster (Astrium)

Design:

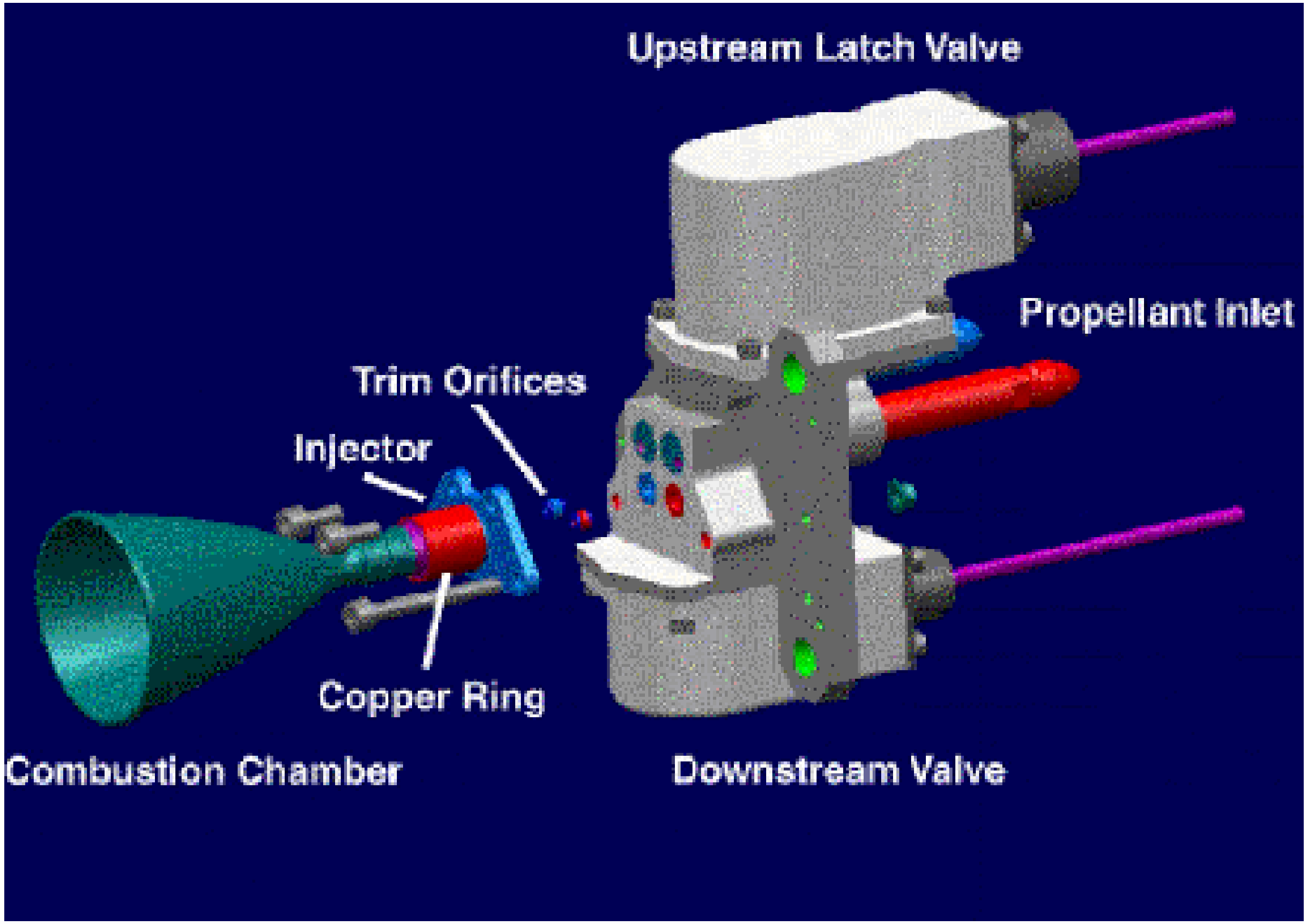
Combustion chamber and nozzle made of platinum alloy

Injector:

Double whirled injection

Flow Control Valve:

Double-seat-torque motor valve (Moog)

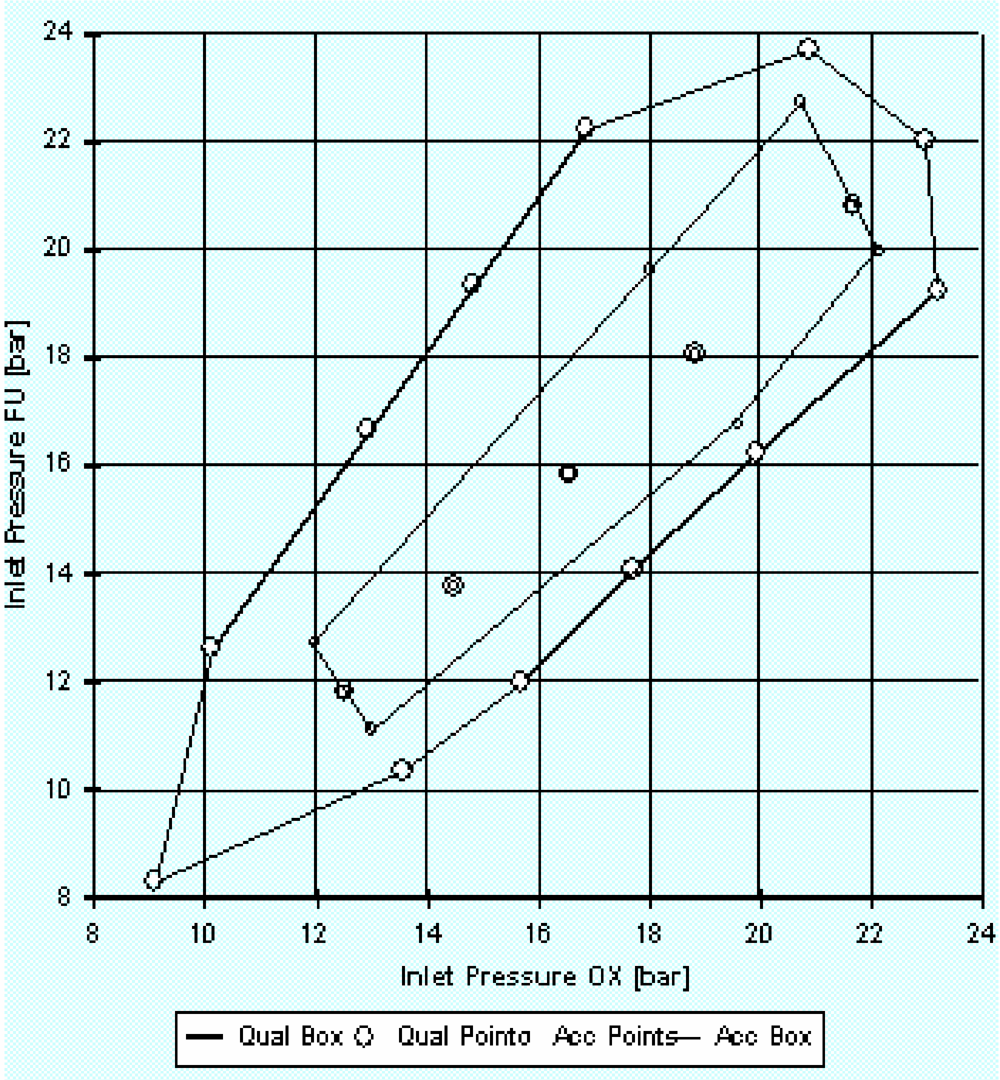


10 N Bipropellant Propellant Thruster (Astrium)

Typical **Operation Diagram** of thruster inlet pressures for fuel (MMH) and oxidiser (MON)

Inner area: Operation Box

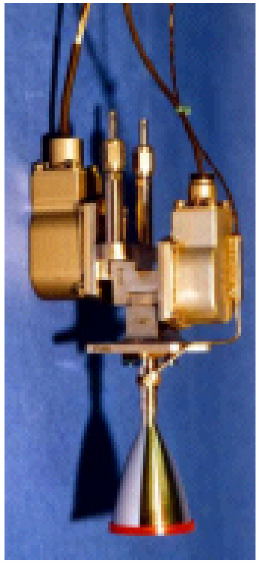
Outer area: Qualification Box



Astrium

BIPROPELLANT THRUSTERS

1st Generation
Regeneration
cooled



<u>10 N</u> 1st and 2nd Generation over 1000 produced in series production Production Rate 1998 : >150 Thrusters

<u>400 N</u>
1st and 2nd Generation over 100 produced => Series production
For each satellite more Impulse delivered in space than guaranteed

1st Generation
regeneration cooled

Astrium 400N Bipropellant Engines

1. Generation regenerative cooled,
Area Ratio: 150
Isp: 308 - 310 sec

2. Generation radiation cooled, Platinum
Area Ratio: 220
Isp: 317 - 319 sec

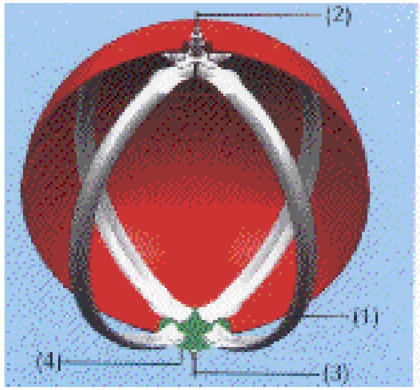
2b. Generation radiation cooled, Platinum
Area Ratio: 300
Isp: 318 - 322 sec

3. Generation radiation cooled, CMC
Area Ratio: 30 0
Isp: > 324 sec

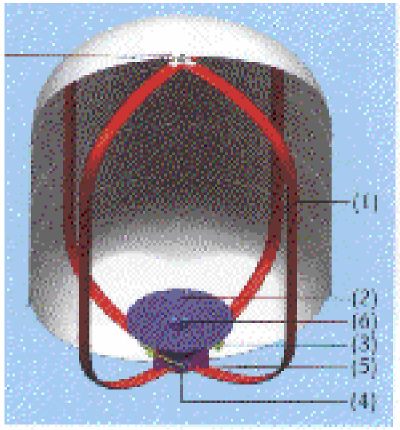
Propellant Tanks

Propellant Tanks

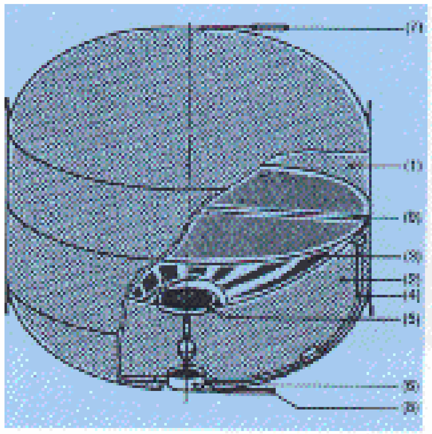
(with surface tension propellant management devices)



(1) Prop. Aquisition Vanes
(2) Gas Port
(3) Propellant Port
(4) Sump Plate



(1) Prop. Aquisition Vanes
(2) Prop. Refillable Reservoir
(3) Upper Screen
(4) Lower Screen
(5) Propellant Port
(6) Venting Tube
(7) Gas Port



(1) Upper Hemisphere
(2) Lower Hemisphere
(3) Intermediate Bottom
(4) Draining Device
(5) Screen in Intermediate Bottom
(6) Screen in Sump Adapter
(7) Gas Port
(8) Propellant Port
(9) Venting Device

Propellant tanks

(with surface tension propellant management devices)

TV-SAT OST 01/X (Astrium)

Artemis OST 22/X (Astrium)

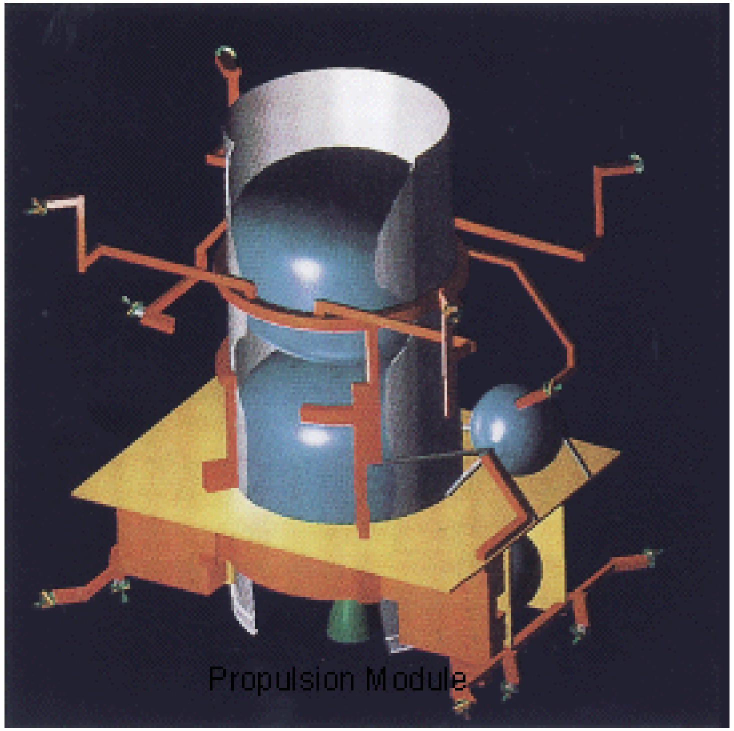
Unified Propulsion Systems

Sirius 2 Telecommunication Satellite: *Unified Propulsion System*

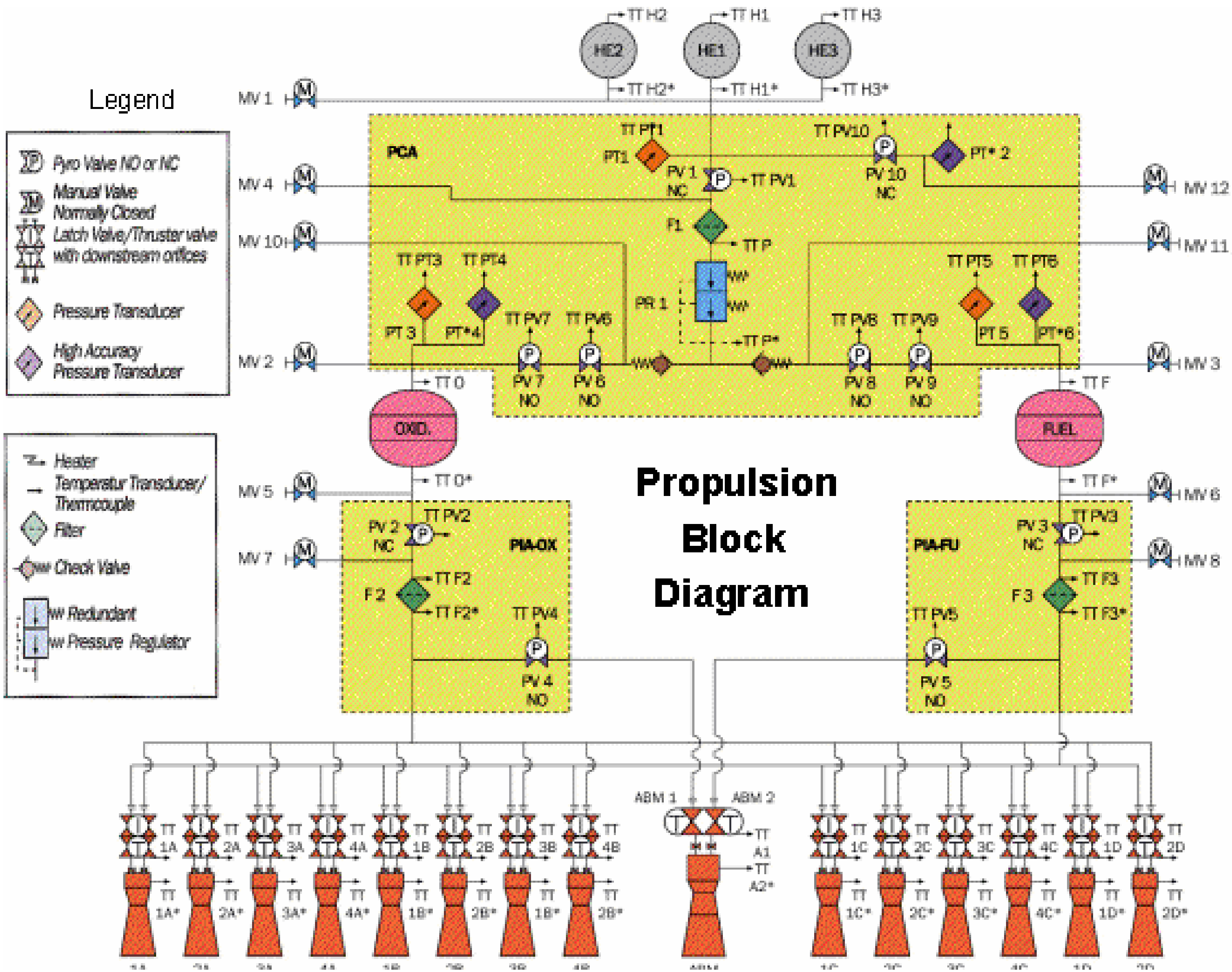
The Unified Propulsion System is based on a bipropellant system used during orbit transfer (spacecraft injection from the orbit delivered by the launcher into the circular, geostanitionary orbit), and during station phase for orbit and attitude control.

The system is composed essentially of:

- one 400 N apogee boost motor for orbit transfer manoeuvres,
- 14 x 10 N thrusters for orbit and attitude control
- 2 propellant tanks of 862 litr.
- 3 helium pressurant tanks of 49 ltr.
- a set of pyro- valves and latch valves
- 1 serial redundant pressure regulator
- 1 electronic internally redundant unit (UPS-E) which centralises all electric functions



Propulsion Module


Legend
Pyro Valve NO or NC
Manual Valve Normally Closed
Latch Valve/Thruster valve with downstream orifices
Pressure Transducer
High Accuracy Pressure Transducer
Heater
Temperatur Transducer/ Thermocouple
Filter
Check Valve
Redundant Pressure Regulator
Propulsion Block Diagram
HE2
HE1
HE3
TT H2
TT H1
TT H3
TT H2*
TT H1*
TT H3*
MV 1
MV 2
MV 3
MV 4
MV 5
MV 6
MV 7
MV 8
MV 10
MV 11
MV 12
PCA
PIA-OX
PIA-FU
OXD.
FUEL
PV 1 NC
PV 2 NC
PV 3 NC
PV 4 NO
PV 5 NO
PV 6 NO
PV 7 NO
PV 8 NO
PV 9 NO
PV 10 NC
PR 1
F1
F 2
F 3
ABM 1
ABM 2

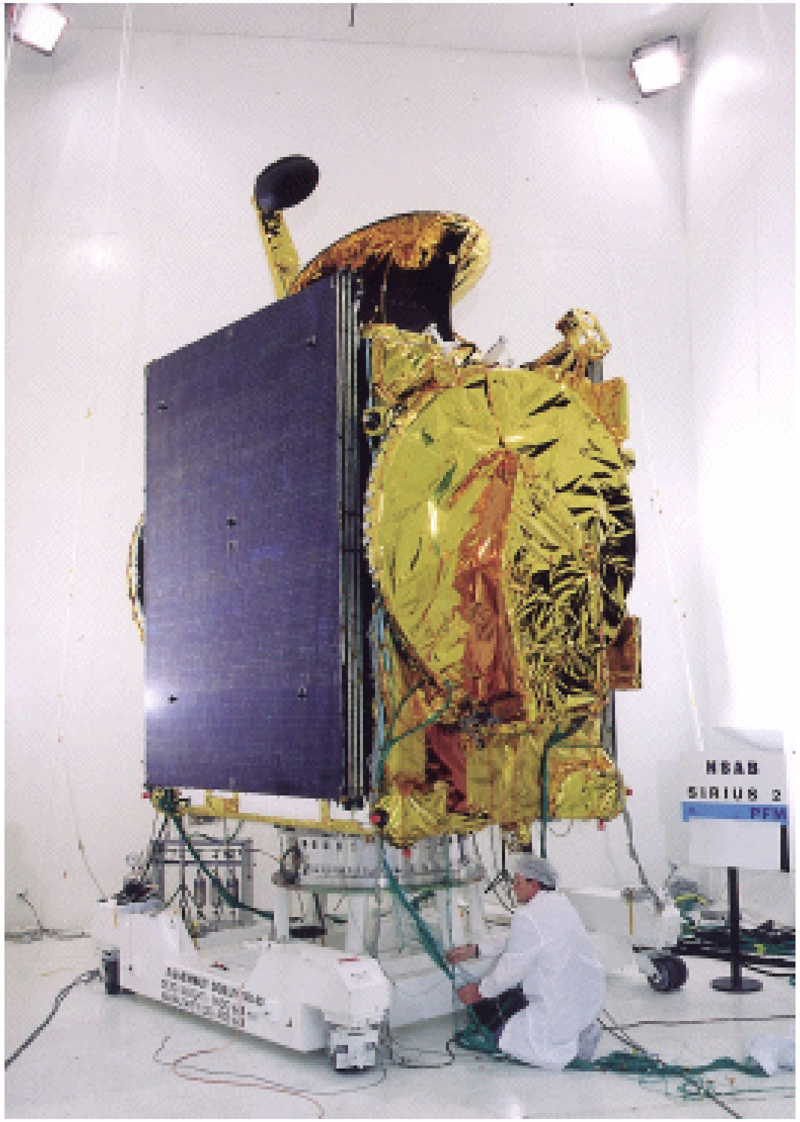
SIRIUS 2 is part of the Nordic satellite system with special focus on the digital future. It was launched in November 1998 and is placed in a geostationary orbit at 5^0 East.

SIRIUS 2 is equipped with 32 transponders. It has two main beams, each with 13 transponders, for transmission of TV programmes directly to home receivers. One beam is aimed at the Nordic region and the other at southern and central Europe.

In addition, SIRIUS 2 is equipped with six transponders specially designed for digital transmission of TV, video, sound and data.

Satellite Characteristics:

- Central body dimensions: 1.8x2.3x2.86 m
- Solar array wingspan: 26.3 m
- Maximum dry mass: 1245 kg
- Maximum propellant capacity: 1900 kg
- Designed, operational lifetime: 12 years



Propulsion Module

Main Performance of Bipropellant Systems

- **Thrust level: 4 ÷ 500N for satellites, up to 45 000 N for general spacecraft application**
- **Impulse bit: ≥ 10^{-2} Ns (with thruster minimum on-time of 20 ms)**
- **Thruster-spec. Impulse: ≤ 2850 Ns/kg for *F* ≤ 25N (for steady state operation)**
  ≤ 3110 Ns/kg for *F* ≤ 400N
- **Thruster-spec. Impulse: ≥ 1000 Ns/kg (for pulse mode operation)**
- **System-spec. Impulse: ≤ 2800 Ns/kg**

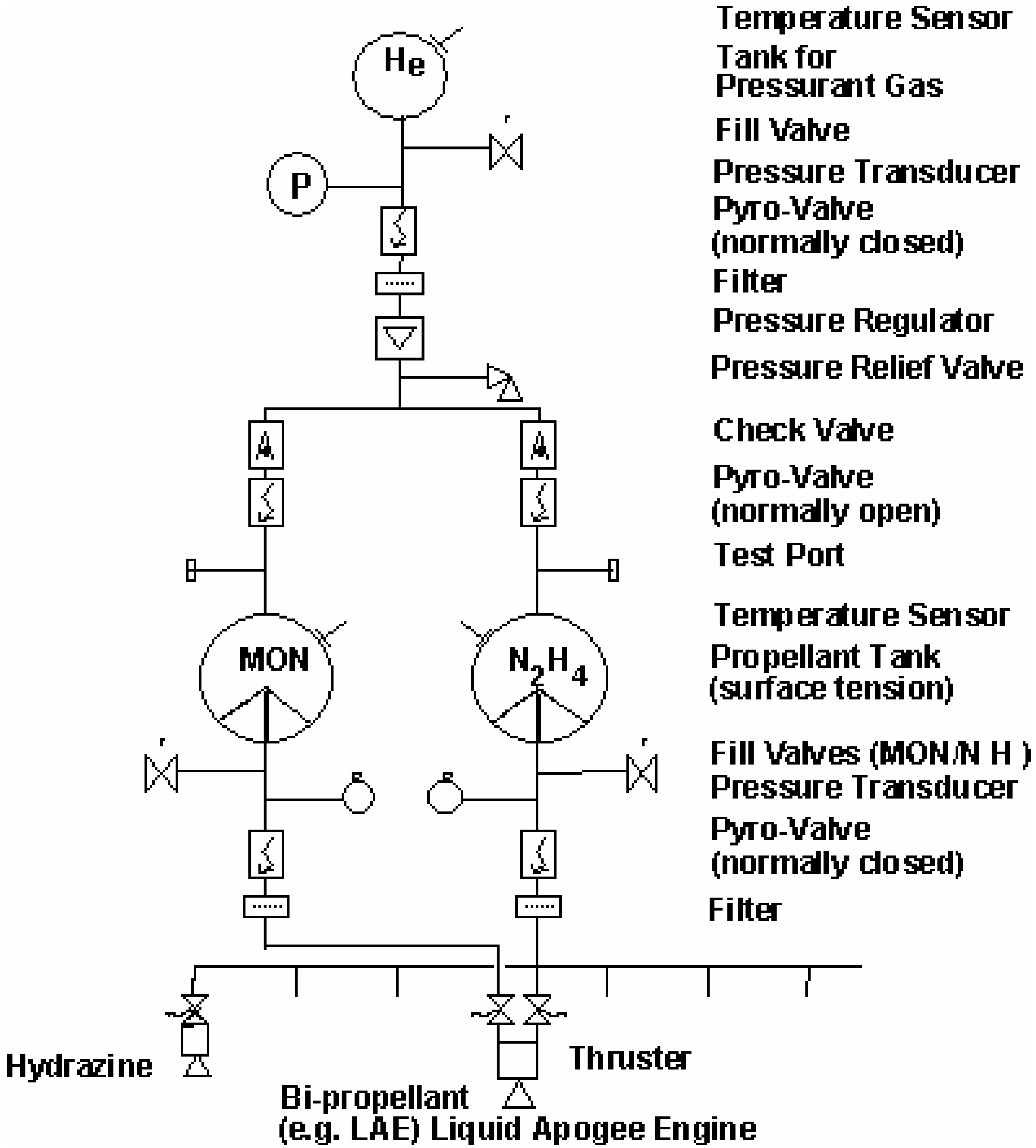
Advantages

- **Higher Thruster-spec. Impulse, I_{sp} (≤ 3110 Ns/kg)**
- **Higher System-spec. Impulse I_{ssp} (≤ 2800 Ns/kg) resulting in low system mass**
- **High thrust capability, up to 45 000 N**

Disadvantages

- **Bipropellant system complexity with added valves, regulators, etc.**
- **Higher cost in comparison to monopropellant hydrazine systems.**

Dual-Mode Systems



- Dual-Mode systems use hydrazine (N_2H_4) both as fuel for a bipropellant (N_2H_4/N_2O_4) Liquid Apogee Engine (LAE) and as monopropellant for on-orbit Attitude and Orbit Control Systems (AOCS) from a common fuel tank.

  The propulsion system layout is shown in the popup with the propellant feed system design similar to that of the bipropellant system, as described earlier.

Advantages

- Higher Thruster-spec. Impulse, I_{sp} (≤ 3110 Ns/kg) for orbit maneuvers
- Common fuel tank for attitude/orbit control and orbit
- Can use higher performance station keeping thruster, e.g. Power Augmented Catalytic Thruster (PACT) at I_{sp} = 3000 Ns/kg versus I_{sp} = 2900 Ns/kg for F = 10 – 22 N (bipropellant thrusters) if required.

Disadvantages

- Dual-Mode system complexity with added valves, regulators, etc.
- Higher cost in comparison to monopropellant hydrazine systems.

Future Developments in Liquid Propellant Technology

Need:

- **Environmentally friendly, safer propellants.**

  - **Current spacecraft and satellite users and manufacturers are looking for more environmentally friendly, safe propellants. These can reduce cost by eliminating the need for *self-contained atmospheric protective ensemble* (SCAPE) suits that are needed for toxic propellants.**

  - **Moreover, extensive and prohibitive propellant safety precautions, and isolation of the space vehicle from parallel activities during propellant loading operations can be minimized or eliminated. If used on these satellites, the costs for operating the vehicles will be lowered, in some cases dramatically.**

<u>Under Development</u>:

- **A new family of environmentally friendly monopropellants has been identified as an alternative to hydrazine. These new propellants are based on blends of e.g. hydroxyl ammonium nitrate (HAN), ammonium dinitramide (AND), hydrazinium nitroformate (HNF), nitrous oxide (N_2O), and hydrogen peroxide (H_2O_2)**

- **When compared to hydrazine, e.g. HAN blends have a range of specific impulse (I_{sp}) which can exceed that of hydrazine. Testing of HAN based propellants has begun to show promise and could soon be adopted for on-board propulsion systems of LEO satellites and constellations.**

<u>Advantages</u>:

- **Safer propellants (also called '*green*' or '*reduced hazard 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.**

S.7 Solid Propellant Motor

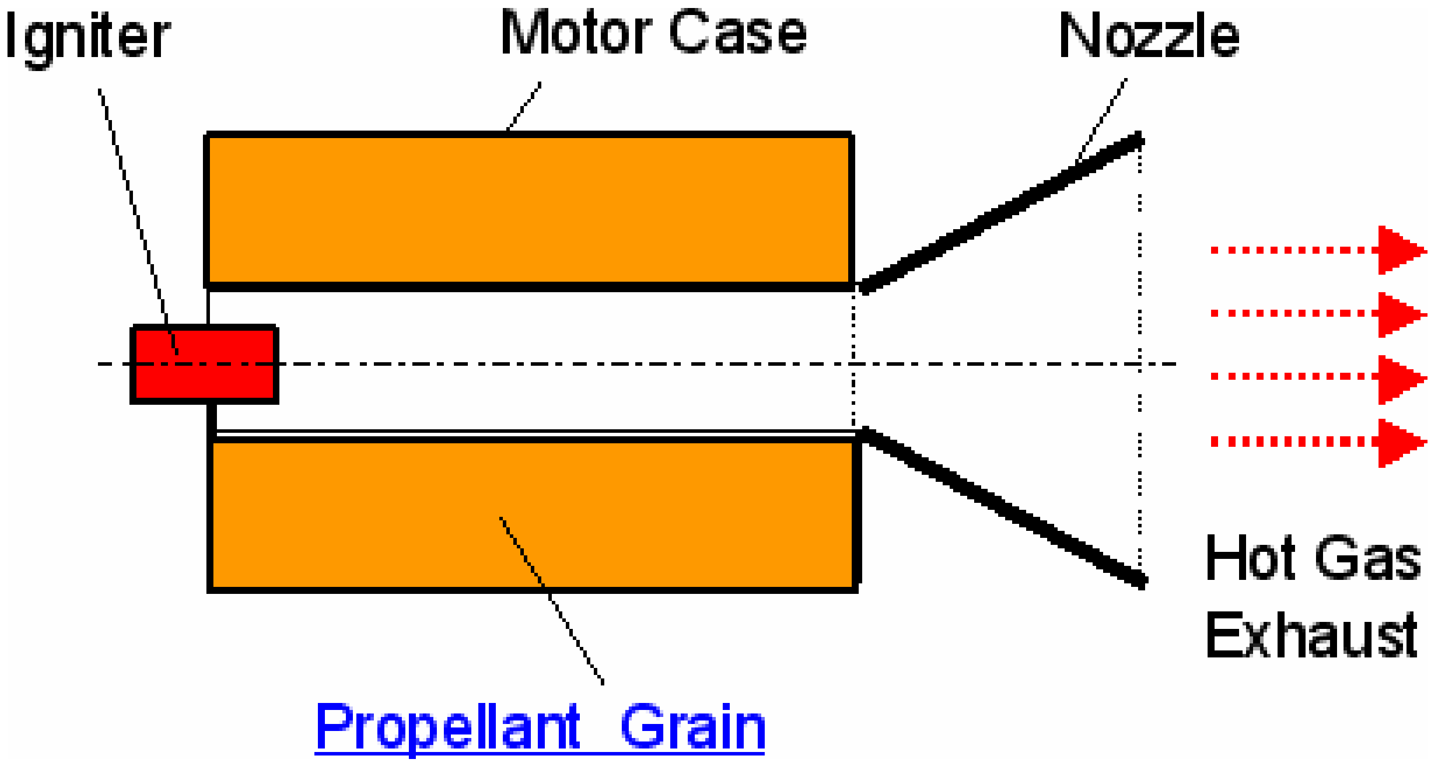
- **The solid propellant motor consists of a motor case, containing a propellant grain, a nozzle and an igniter. The main characteristics and performance are as follows:**

  - **Main performance**
  - **Advantages**
  - **Disadvantages**

In general, solid propulsion motors can only deliver their total impulse potential in one firing, because off-modulation is not possible. Therefore the usage of solid propulsion is restricted to:

- **Orbit change (e.g. apogee or perigee maneuver)**
- **Impart acceleration (e.g. liquid reorientation maneuvers, separation maneuvers)**

Solid Propellant Motor



Propellant Grain

- There are two principal types of propellants:
  - *Homogeneous propellants*, which are composed of fuels that contain enough chemically bonded oxygen to sustain the propellant burning process,
  - *Composite propellants*, which are composed of organic fuel binders and oxidizers.

- Most common is the use of *composite propellants*, usually based on solid aluminium powder held in e.g. a hydroxyl terminated polybutadiene (HTPB) synthetic rubber binder and stable solid oxidizer (ammonium perchlorate or nitro-cellulose, -double based). The propellant is premixed and batch loaded into lightweight simple motors.

- Typical solid propellant mixtures are listed below:

Double-based Propellant (fuel and oxidant chemically mixed)		Composite Propellant (fuel and oxidant mechanically mixed)	
	%		%
Nitrocellose	51.4	Ammonium perchlorate (NH_4ClO_4)	62.0
Nitroglycerine	42.9	Binding material (fuel also)	21.9
Additives	5.7	Aluminium powder (fuel)	15.0
		Additives	1.1
Total	100		100

Ref: L.J. Carter, SPACEFLIGHT, Vol. 36, June 1994

Main Performance of Solid Propellant Motors

- **Thrust level: 50 N (for e.g. spin-up/down of small satellites) ≤ 50 000 N typical for satellite orbit transfer applications; up to 5 ·10^6 N for launcher/spacecraft application.**
- **Delivered impulse: ~10 Ns (*F* =50 N, e.g. spin-up/down of small satellites) ≤ 10^7 Ns for satellite orbit transfer applications**
- **Motor-spec. Impulse: ~ 2400 Ns/kg for *F* ≤ 50 N; ≤ 3000 Ns/kg for *F* ≤ 50 000 N**
- **System-spec. Impulse: 2300 ÷ 2700 Ns/kg (~120 Ns/kg for *F* ≤ 50 N)**

Advantages

- **Relatively simple operation**
- **Very high mass fraction, excellent bulk density and packaging characteristics**
- **Good long-term storage characteristics**

Disadvantages

- **Not readily tested and checked-out prior to flight**
- **Very difficult to stop and restart, throttle, pulse, etc. (hybrid)**
- **Limited I_{sp} performance (2400 – 3000 Ns/kg)**
- **Limited redundancy with associated reliability and safety issues**

S.8 Electric Propulsion

- **In order to increase propulsion system impulse performances for e.g. interplanetary missions, exhaust velocity has to be increased beyond the 5000 m/s, which is best available from chemical rockets.**

  This can be achieved by Electric Propulsion Systems that rely on externally provided electric power to accelerate the propellant to produce useful thrust in three ways:

  - **Electrothermal systems (resistojet and arc-jets)**

    Expansion of hot gas (which is heated by electric current) in a nozzle.

  - **Electromagnetic systems (magnetoplasmadynamic (MPD))**

    Accelerating of plasma by interaction of electric and magnetic fields to high expulsion velocities.

  - **Electrostatic systems (ion engines: Kaufman, radio-frequency, field emission, stationary plasma)**

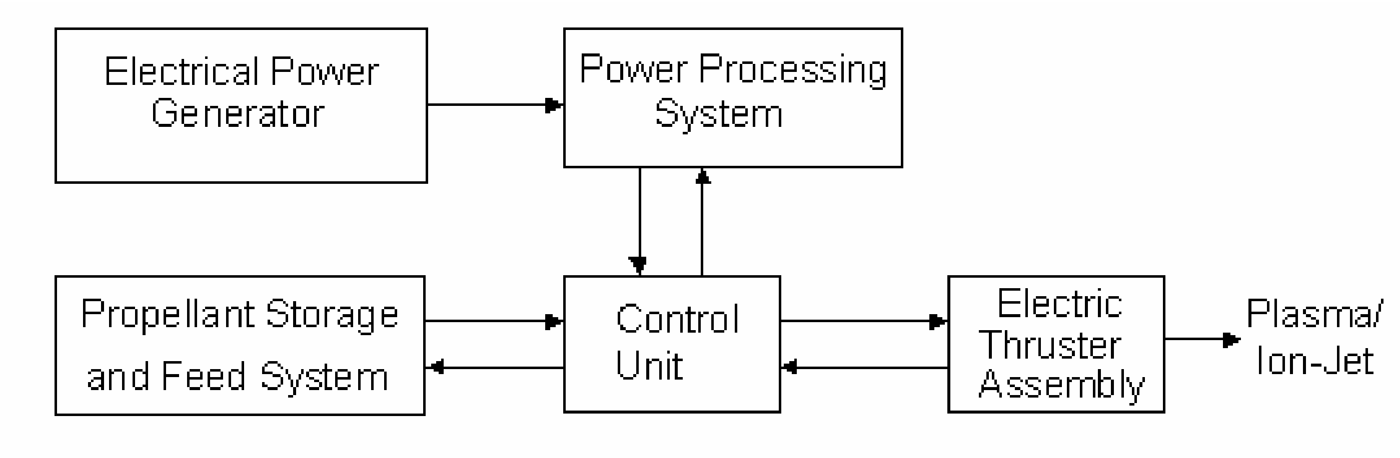
    Accelerating of charged particles in electric fields to high expulsion velocities.

- **Survey of electrical thruster with their potential application.**

- **Important comparison between electrical (ion) and chemical (bipropellant) propulsion. Note the ratios of thruster specific impulse, thrust level and power requirements.**

Electric Propulsion Systems

Electric propulsion systems comprise the following main components:



- **Storage and feed system that stores and feeds the propellant to the thrusters to generate thrust**
- **Valves, piping which connects the propellant storage system with the thruster**
- **Electric control unit to operate electrically the valves and thrusters**
- **Electric power supply and power processing system**

- **Electric Power Generator**

  Energy can be obtained from either sunlight or from a nuclear reactor. In the case of solar electric propulsion, solar photons are converted into electricity by solar cells.

In nuclear electric propulsion, thermal energy from the nuclear reactor is converted into electricity by either a static or dynamic thermal-to-electric power conversion system.

Static systems (e.g. thermoelectric generators) have the advantage of no moving parts for high reliability, but they have low efficiencies while dynamic systems have moving parts (e.g. turbines, generators, etc.) and they have higher efficiencies.

- Power Processing System

  Power processing systems are required to convert the voltage from the electric power generator to the form required by the electric thruster.

  For example, a solar electric power generator produces low-voltage DC (typically ~100 V); this would need to be converted (via transformers, etc.) to kilovolt levels for use in an ion thruster. The power processing system is often referred to as the power processing unit (PPU).

- Propellant Storage and Feed System

  In general, liquid or gaseous propellants are stored in tanks and fed to the thruster assembly as in chemical propulsion.

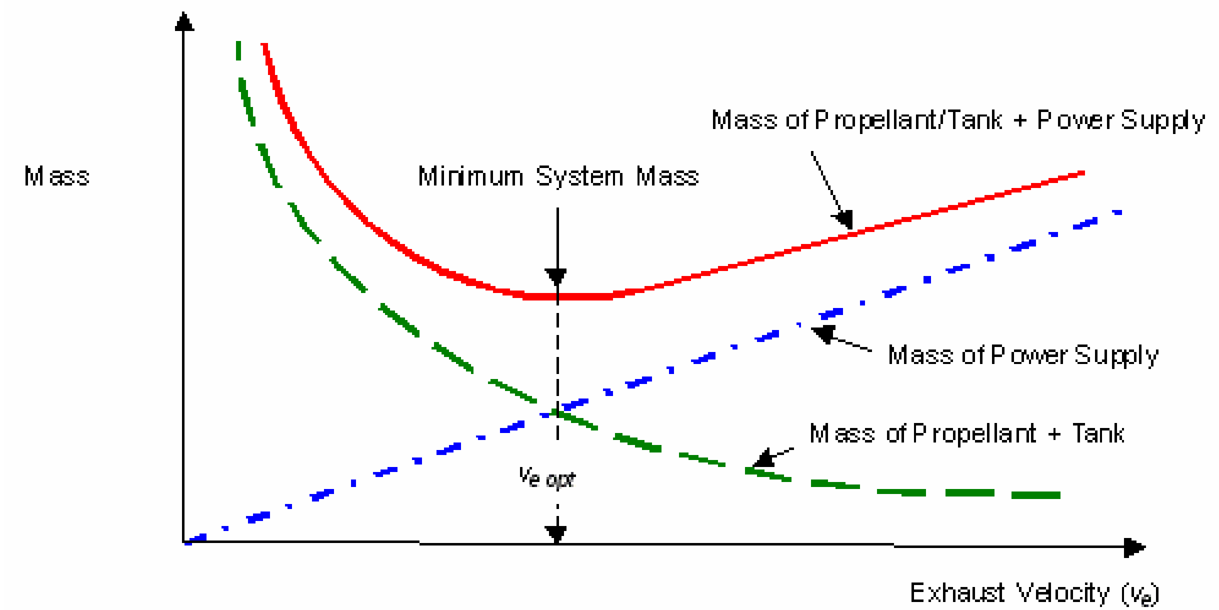
- Electric Thruster Assembly to generate thrust.

- Valves and piping which connect the propellant storage and feed system with the thruster assembly.

- Electric Control Unit to operate electrically valves and thrusters

<u>Note</u>:

For electric propulsion high impulse performance is not dictated by maximum exhaust velocity, like for chemical propulsion, but rather by optimum values of thruster exhaust velocity, $v_{e\ opt}$, that can be elucidated schematically by the following figure:



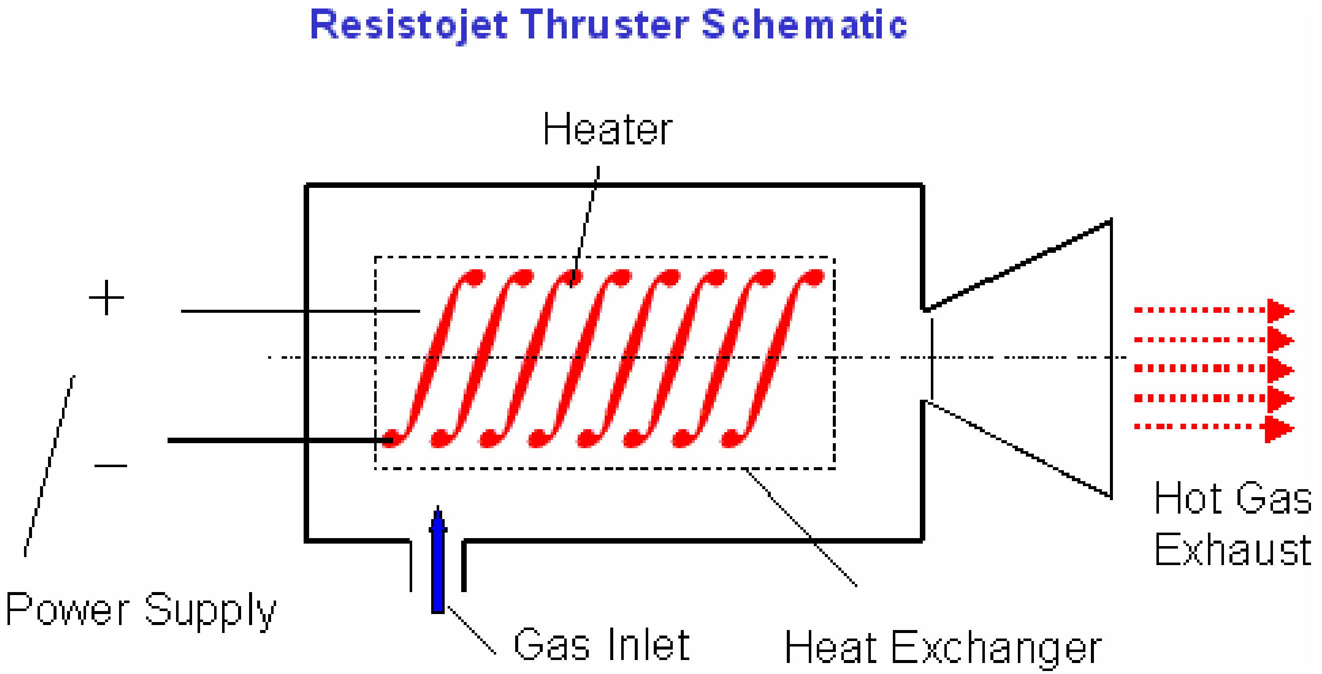
Term of Optimal Exhaust Velocity

With increasing exhaust velocity, v_e, the combined mass of propellant and tank is decreasing while the mass of the power supply is increasing. The point of intersection of the two curves determines the minimum of the system mass by $v_{e\ opt}$ resulting in a maximum value of I_{ssp}.

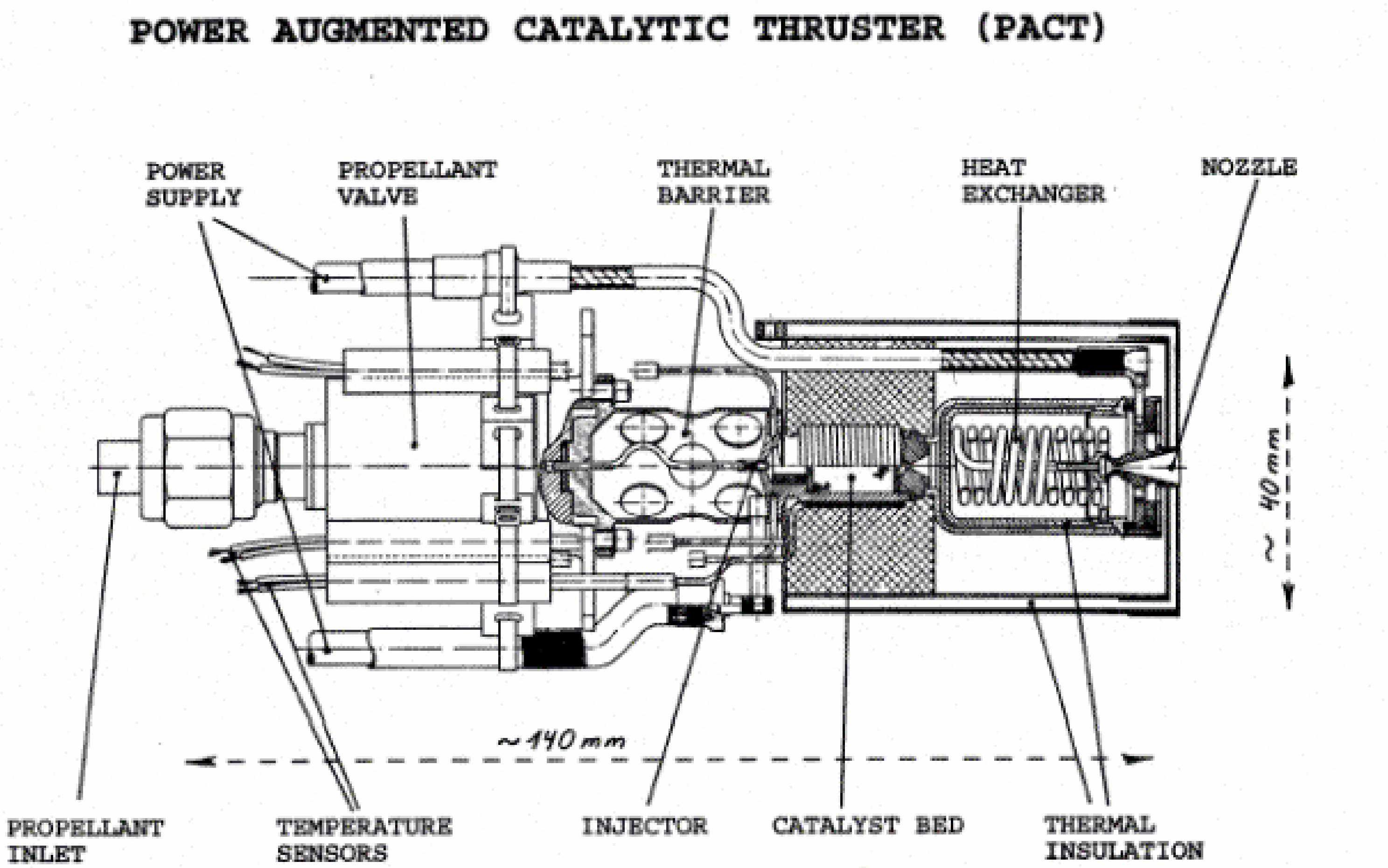
Electrothermal Systems

- Electrothermal Systems, where the propellant (gas) is heated by passing over an electric heated solid surface (resistojet) or by passing it through an arc discharge (arcjet).

- The heated gas is then accelerated by a gas-dynamic expansion in a nozzle. Typical applications of this principle are the monopropellant hydrazine operated Power Augmented Catalytic Thruster (*PACT*) and Hydrazine-Arcjet.



Power Augmented Catalytic Thruster

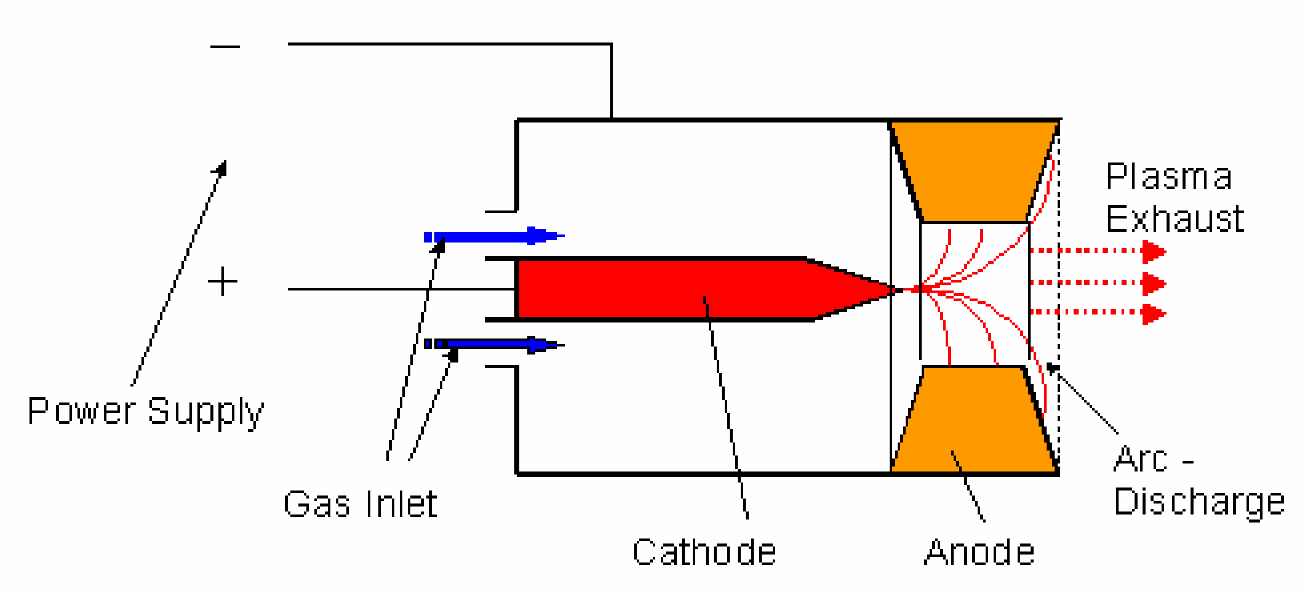


Astrium: Prototype

(Dasa sales catalogue)

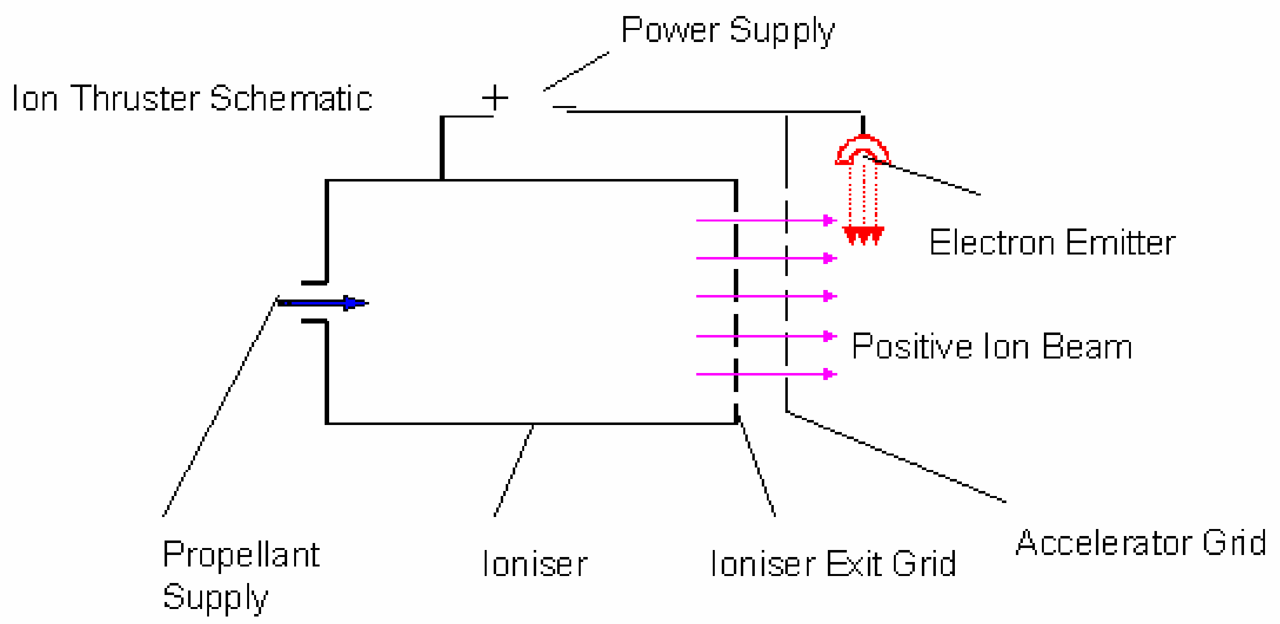
Electromagnetic Systems

- **Electromagnetic Systems, where a gas is heated in an arc discharge to such a high temperature, that it is converted to neutral plasma (plasma thruster).**
- **The plasma is then expelled at high velocity by the interaction of the discharge current with the magnetic field (Lorentz force). A typical application of this principle is the Magneto-Plasma-Dynamic (MPD) type of thruster.**

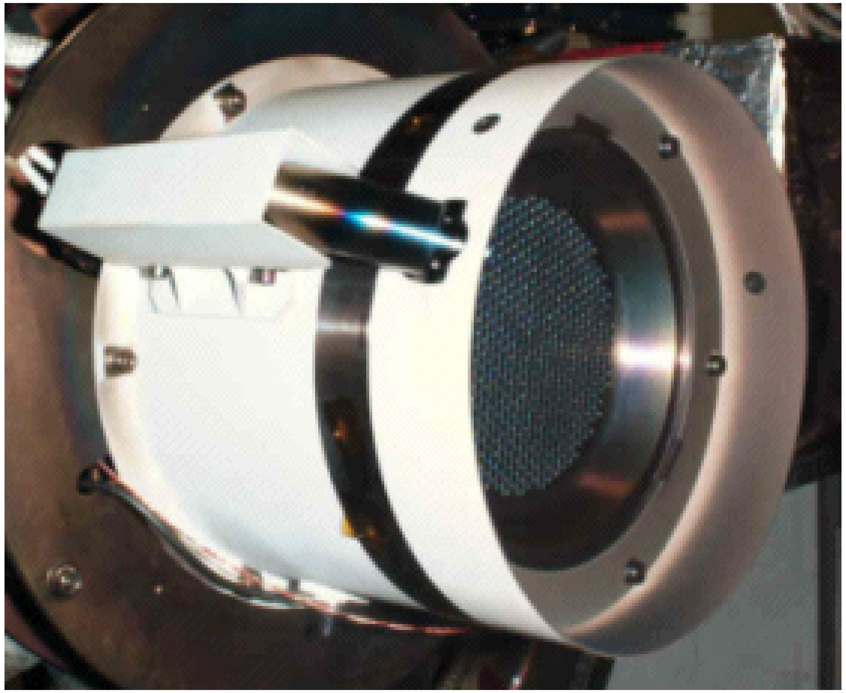


Electrostatic Systems

- **Electrostatic Systems, where usually a high molecular propellant, such as Xenon gas, is ionized (ion thruster) by e.g. electron bombardment (Kaufman), in a high frequency electromagnetic field (*radio-frequency*) or by extracting ions from the surface of a liquid metal (cesium) under the effect of a strong electrostatic field (field emission).**
- **The ions are then accelerated to high velocity (30 to 60 km/s) by a strong electric field. Electrons are injected into the ion beam from an electron emitter in order to keep it electrically neutral, thus preventing an electric charge build-up of the spacecraft.**
- **In addition to the above described category of ion thrusters, the Stationary Plasma Thruster (SPT) which belongs to the category of 'Hall-effect Thrusters', uses an applied magnetic field to control electrons in a quasi-neutral plasma discharge.**



RIT10-Thruster (ARTEMIS - 15 mN, RIT10-EVO 1 to 40 mN)



Astrium RIT-10 Thruster in the test chamber of the University of Gießen/Germany

Task:

Performing of N/S station keeping

Manufacturers:

RIT: Astrium GmbH Space Infrastructure
NTR: Laben-Proel

Design Data

Thrust level:	1 to 40 mN
Specific impulse:	3400 s
Operating temperature:	-50 to 150 °C
Beam Divergence: (full angle at 95%)	25°

No thermal conductance to S/C required

Mass:	2.5 kg

Survey of Electrical Thrusters (Examples of typical performance values)

(Data listed are indicative only)

Type of Propulsion System	Thrust (N)	Power Consumption (W)	Exhaust Velocity (m/s)	Propellant (formula)	Potential Application
Resistojet	0.2	345	1 500	NH_3;CH_4	Orbit-Control (Biowast)
Hydrazine-Resistojet (PACT)	0.3	300	3 000	N_2H_4	Orbit-Control (N/S)
Arc-Jet (Hydrazine)	0.2	1 800	5 000	N_2H_4	Orbit-Control (N/S)
MPD (Teflon)	0.015	600	30 000	Teflon	Orbit-Control (N/S)
RIT10 (Ion.-Engine)	0.01	390	30 700	Xe	Orbit-Control (N/S)
RIT35 (Ion.-Engine)	0.271	7 540	31 400	Hg; Xe	Interplanetary Missions
UK-10 (Kaufman)	0.011	600	≥30 000	Xe	Orbit-Control (N/S)
UK-25 (Kaufman)	0.196	6 000	≥30 000	Xe	Interplanetary Missions
SPT100 (Ion.-Engine)	0.08	1 350	16 000	Xe	Orbit-Control (N/S)
Hughes 8 cm (Kaufman)	$4.5 \cdot 10^{-3}$	175	25 500	Hg	Orbit-Control
Field-Emission	$\approx 10^{-5}$ - $2 \cdot 10^{-3}$	≈ 60 - 300	≈ 60 000 – 100 000	Cs	Orbit and Attitude Control
					NB: (N/S) ≡ North/South station keeping for Geostionary Orbits

Comparison

THRUSTER COMPARISON: Typical Electrical vs. Chemical Figures

(Data listed are indicative only)

Type of Thruster	Spec. Impulse (Ns/Kg)	Thrust F (N)	DC Power Required (W)
Electrical (Ion thruster)	≈ 30 000	10^{-3} – 0.2	400 – 800
Chemical (Bi-Propellant)	≈ 3 000	5 – 500	4 – 8 (short term)
Order of magnitude of the ratio ION/Chemical	10^{1}	10^{-4}	10^{2}

S.9 Summary

- Main characteristics of candidate spacecraft propulsion systems;
- Classification of propulsion systems listed based on type of energy source;
- Basic configurations of propulsion systems explained;
- Main performance characteristics of propulsion systems listed;
- Advantages and disadvantages of propulsion systems discussed;
- Still to be done: Propulsion system performances to be evaluated with regard to mission impulse and velocity-increment requirements in order to enable you to select and size propulsion systems. This will be done in the next chapter.

Main Characteristics

- **The table below summarizes the main characteristics of some candidate spacecraft propulsion systems** (data listed are indicative only)**:**

Type of Propulsion System	Thrust level [N]	Exhaust Velocity [m/s]	Advantages	Disadvantages
Cold Gas (N2)	0.0045 - 10	700	**Extremely simple, reliable, very low cost**	**Very low performance, highest mass of all systems**
Monopropellant (Hydrazine)	0.5	2 200 – 2 300	**Simple, reliable, relatively low cost**	**Low performance, higher mass than bipropellant**
Bi-Propellant (MMH/MON)	4 – 500	2 850 – 3 110	**High performance**	**More complicated system than monopropellant**
Solid Propellant	50 – 50 000	2 400 – 3 000	**Simple, reliable, low cost**	**Limited performance, higher thrust**
PACT, Hydrazine (Power Augmented Catalytic Thruster)	0.1 – 0.5	3 000	**High performance, low power, simple feed system**	**More complicated interfaces, more power than chemical thrusters, low thrust**
ARC-JET (Hydrazine)	0.2	5 000	**High performance, simple feed system**	**High power, complicated interfaces (specially thermal)**
Stationary Plasma SPT 100 (Ion Engine)	0.08	16 000	**High performance**	**High power, low thrust, complicated**
Kaufman, UK-10 (Ion-Engine)	0.011	30 000	**Very high performance**	**Very high power, low thrust, complicated**
Radio-frequency RIT 10 (Ion-Engine)	0.01	31 400	**Very high performance**	**Very high power, low thrust, complicated**
Field-Emission	$10^{-5} – 2 \cdot 10^{-3}$	60 000 -100 000	**Extreme high performance**	**Very high power, very low thrust**

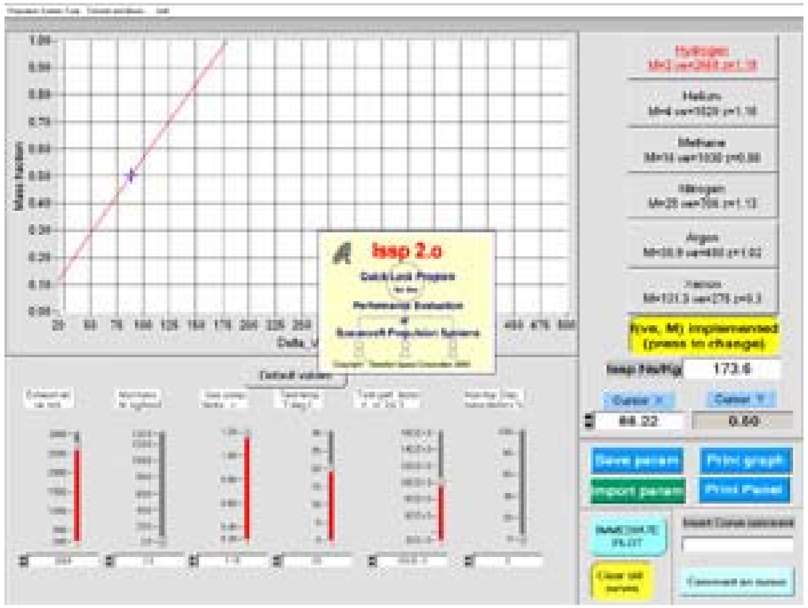
Chapter 4: Spacecraft Propulsion System Selection

Peter Erichsen, September 2006

S.1 Introduction

- The selection of the best propulsion system for a given spacecraft missions is a complex process. Selection criteria employed in the design trades include performance, cost, availability, etc.
- The selection process involves a variety of propulsion options, such as systems operated with cold gas, liquid monopropellant and bipropellant, or some form of electric propulsion.
- The evolution of future spacecraft systems will be mainly determined by a reduction of space mission costs and extend exploration of the solar system up to interstellar missions.

- A software program can be used, which is based on the evaluation of system-specific impulses, Issp, and determination of the overall propulsion system mass fraction, $m_{PS}/m_{S/C}$.
- The Issp-program can be downloaded from the Swedish Space Corporation (SSC) website http:www.ssc.se/ssd



Issp Program

S.2 Educational Objectives

From this chapter the student will learn:

- **Propulsion system selection criteria**
- **Primary selection criteria based on propulsion system performances:**
  - **System-specific Impulse, Issp**
  - **overall propulsion system mass fraction**
- **The 'Issp software program' for propulsion system performance simulation**
- **An outline of the potential evolution of future advanced spacecraft propulsion systems**

S.3 Propulsion System Selection

- **In the selection process, the most fundamental criterion for the propulsion system to be selected is its achievement of the mission impulse and velocity increment Δv requirements. Therefore, an important consideration for the selection of a suitable propulsion system is the trade-off between its velocity increment capability and propulsion system mass.**

- **The mass of propulsion systems can be determined with help of the overall Propulsion System Mass Fraction (see Chapter 2)**

- **The Curves of $m_{PS}/m_{S/C}$, plotted as a function of Δv for different actual spacecraft propulsion system designs with typical values of I_{sp} (v_e) and I_{ssp}, give the first and most important indication for the selection of propulsion systems.**

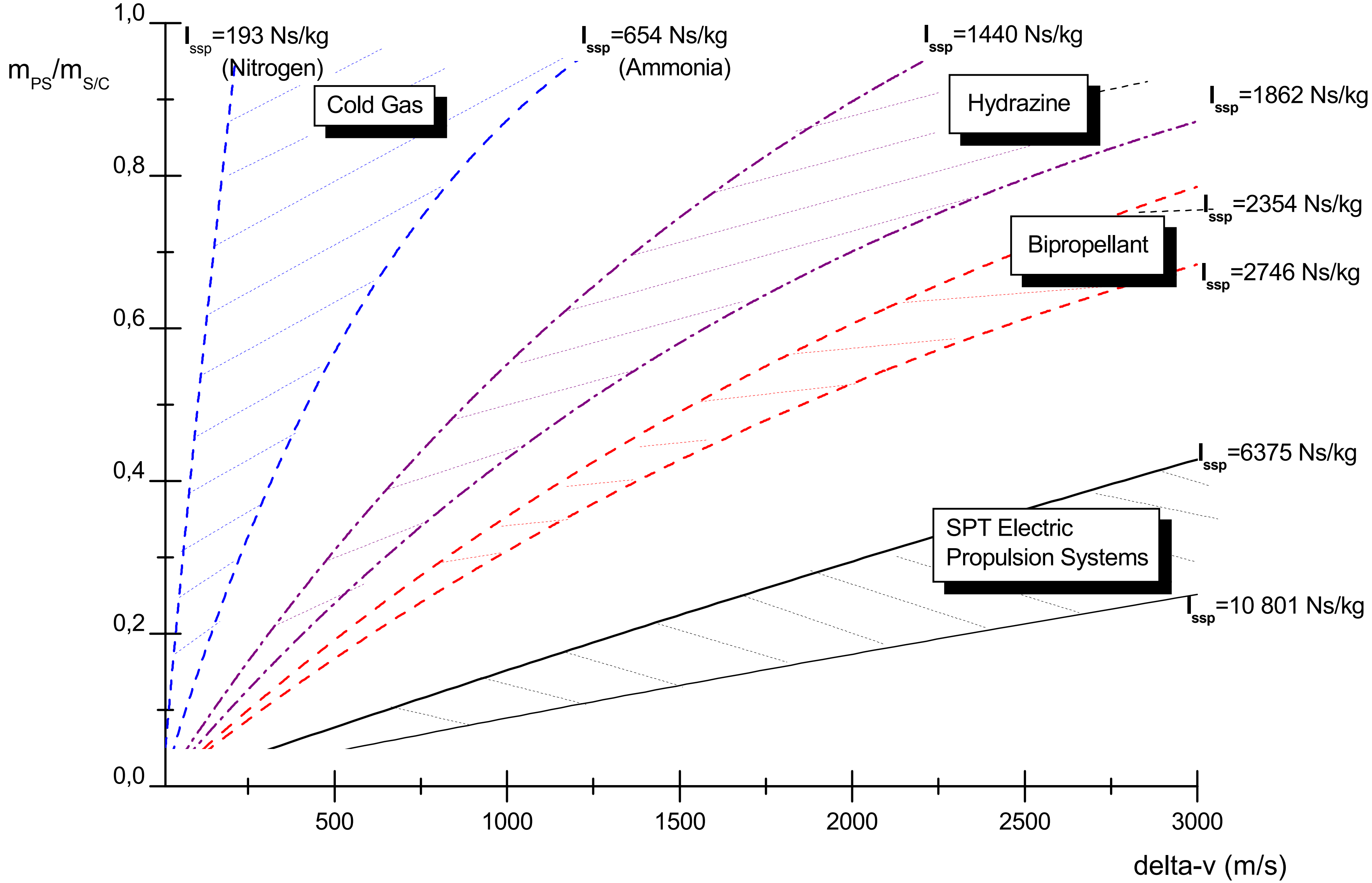
- **For a more detailed performance evaluation, the software program "Issp" can be used. It is based on the evaluation of the 'System-specific Impulse', I_{ssp}. It can be downloaded from Swedish Space Corporation Web Site.**

- **When suitable spacecraft auxiliary propulsion systems are selected, a refinement of the selection is carried out. This process takes into consideration additional parameters such as cost, complexity, operability and reliability of the system (more selection criteria).**

- **This table summarizes advantages and disadvantages as well as the basic characteristics of different propulsion systems.**

The curves

Δv-Performance Range of Built Spacecraft Propulsion System Concepts (Examples)



Important indication

If we assume $m_{PS}/m_{S/C}$< 0.30, we can read directly from the curves of $m_{PS}/m_{S/C}$:

- **For low Δv<150 m/s, compressed cold gas and vaporizing liquid propulsion systems seem to be the best choice, because they meet the requirement and have the lowest cost;**

- **For 150<Δv<650 m/s, monopropellant hydrazine fed propulsion systems are the best choice, because of their inherent simplicity (reliability) and potential low cost, while still meeting the requirement;**

- **For high Δv>650 m/s, bipropellant systems, monopropellant hydrazine fed resistojet systems (power-augmented thrusters, arcjets), and electrostatic (electromagnetic) systems will satisfy the Δv requirements best.**

Table of Candidate Spacecraft Propulsion System Characteristics

- **The table below summarizes the main characteristics of some candidate spacecraft propulsion systems** (data listed are indicative only)**:**

Type of Propulsion System	Thrust level [N]	Exhaust Velocity [m/s]	Advantages	Disadvantages
Cold Gas (N2)	0.0045 - 10	700	**Extremely simple, reliable, very low cost**	**Very low performance, highest mass of all systems**
Monopropellant (Hydrazine)	0.5	2 200 – 2 300	**Simple, reliable, relatively low cost**	**Low performance, higher mass than bipropellant**
Bi-Propellant (MMH/MON)	4 – 500	2 850 – 3 110	**High performance**	**More complicated system than monopropellant**
Solid Propellant	50 – 50 000	2 400 – 3 000	**Simple, reliable, low cost**	**Limited performance, higher thrust**
PACT, Hydrazine (Power Augmented Catalytic Thruster)	0.1 – 0.5	3 000	**High performance, low power, simple feed system**	**More complicated interfaces, more power than chemical thrusters, low thrust**
ARC-JET (Hydrazine)	0.2	5 000	**High performance, simple feed system**	**High power, complicated interfaces (specially thermal)**
Stationary Plasma SPT 100 (Ion Engine)	0.08	16 000	**High performance**	**High power, low thrust, complicated**
Kaufman, UK-10 (Ion-Engine)	0.011	30 000	**Very high performance**	**Very high power, low thrust, complicated**
Radio-frequency RIT 10 (Ion-Engine)	0.01	31 400	**Very high performance**	**Very high power, low thrust, complicated**
Field-Emission	$10^{-5} – 2 \cdot 10^{-3}$	60 000 -100 000	**Extreme high performance**	**Very high power, very low thrust**

S.4 Outline of Advanced Spacecraft Propulsion Systems

- So far, chemical propulsion has given access to space and has even taken spacecraft through the solar system. Electric propulsion, still under development, offers a further vast increase in propulsion system mass efficiency.

- The prevailing goal of advanced propulsion is to enable cost efficient space missions and extended exploration of the solar system up to interstellar missions.

- In a first instance, advanced propulsion systems can be derived from existing systems, by increasing the performance of chemical and electric propulsion with regard to their mission impulse and velocity-increment capabilities.

- New approaches are studied or under development, like:
  - Solar- thermal rockets using solar energy to heat a propellant via a concentrator to high temperature
  - Nuclear-thermal rockets using the heat produced by a nuclear reaction to produce high-temperature propellant
  - Beamed-momentum propulsion, such as Solar Sails
  - Exotic propulsion methods, such as Photon - and Antimatter Propulsion

Advanced space propulsion

- **In order to achieve efficient mission costs, an important application of advanced space propulsion is to reduce cost by:**
  - **reduction of the total mass that must be launched from Earth,**
  - **reduction of propulsion system mass fraction, allowing for higher payload mass,**
  - **increase of mission impulse performance, allowing for satellite extended orbit maintenance and attitude control.**

- **A second goal of advanced space propulsion is to perform extended (manned) exploration of the solar system and previously 'impossible' missions, like interstellar travel.**

- **Consequently, the evolution of advanced spacecraft propulsion systems will mainly focus on increased performance, that is high values of 'System-spec. Impulse', I_{ssp}.**

- **Potential improvements of propulsion performances will however require a careful analysis of development and manufacturing cost as well as complexity, operability and reliability of propulsion systems. This will have to be balanced against potential gain in propulsion performance and propulsion system weight with resulting improvement of I_{ssp}.**

Exploration of the Solar System

Velocity Change Budget (Δv) for some Interplanetary Hohmann Transf Orbits

(Data listed are indicative only)

Destination	Typical Δv values [km/s]
Mercury	17.1
Venus	5.2
Mars	5.4
Jupiter	14.4
Saturn	15.7
Uranus	15.9
Neptune	15.7

Ref.: Propulsion 2000 Program, Phase I – Final Report, FiatAvio, Rome (Italy), November 2000

Potential increase in performance of existing space propulsion systems – Chemical Propulsion

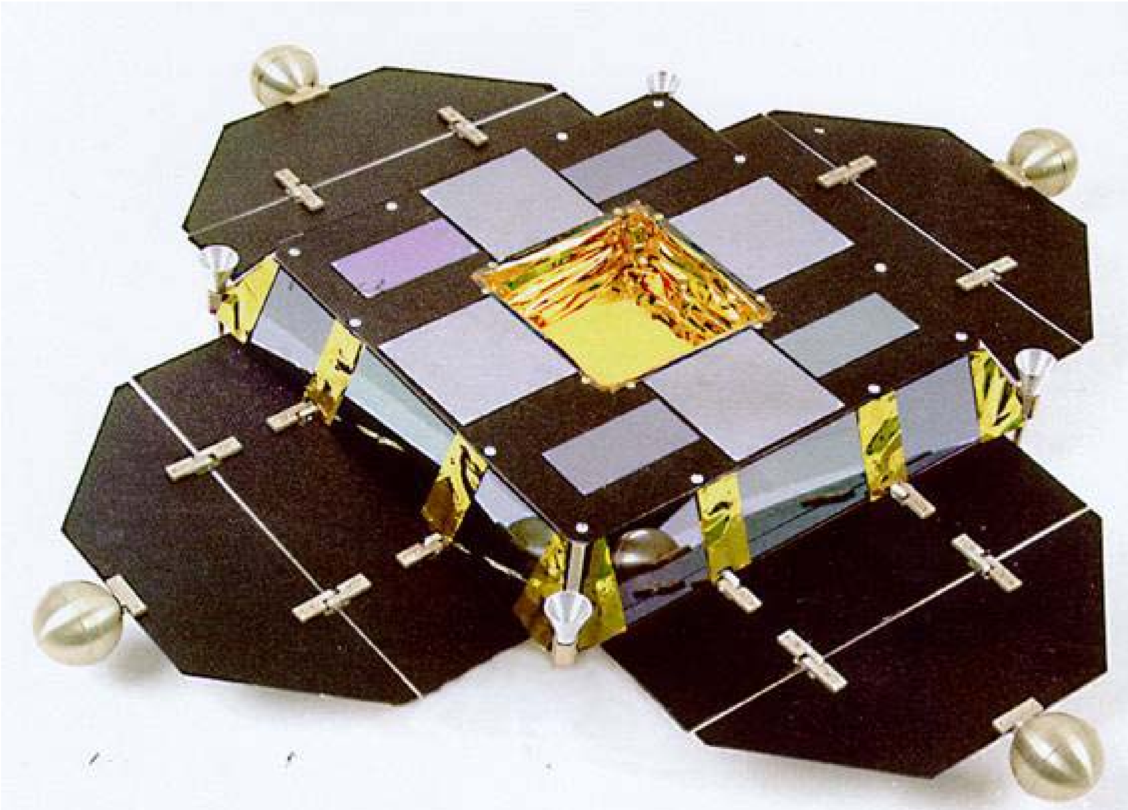
- **For chemical propulsion high performance, i.e. high values of "System-specific Impulse', I_{ssp} resulting in low values of 'propulsion system mass fraction', is primarily dictated by maximum values of 'Thruster-specific Impulse', I_{sp} (v_e); for details see Issp-Program. The performance of state-of the-art spacecraft engines operating with cold and hot gas, however, can be considered near to the theoretical limit for actual space storable propellant combinations.**

- **The emerging class of micro-and nanospacecraft require miniaturisation of the propulsion system with help of 'Microelectromechanical System' (MEMS) technology for acceptable values of I_{ssp}, in order to achieve a low 'non-impulse system mass factor' x.**

- **With increasing interest in environmental and safety issues, non-toxic monopropellant systems are under development, as already presented in Chapter 3.**

- **Consequently, actual designs of chemical spacecraft propulsion systems are well developed, but are being complemented by non-toxic monopropellant systems. The emerging class of micro-and nanospacecraft requires 'Microelectromechanical System' (MEMS) technology for miniaturisation of the propulsion system.**

- **For micro- and nanospacecraft with low Δv requirements and low thrust levels, e.g. a cold/hot gas system based on 'Microelectomechanical System' (MEMS) technology is under development at the 'Ångström Space Technology Centre' Uppsala University/Sweden.**



Nano-Satellite with Micro Propulsion Cold/Hot Gas Thrusters for High Precision Drag-free / Attitude Control

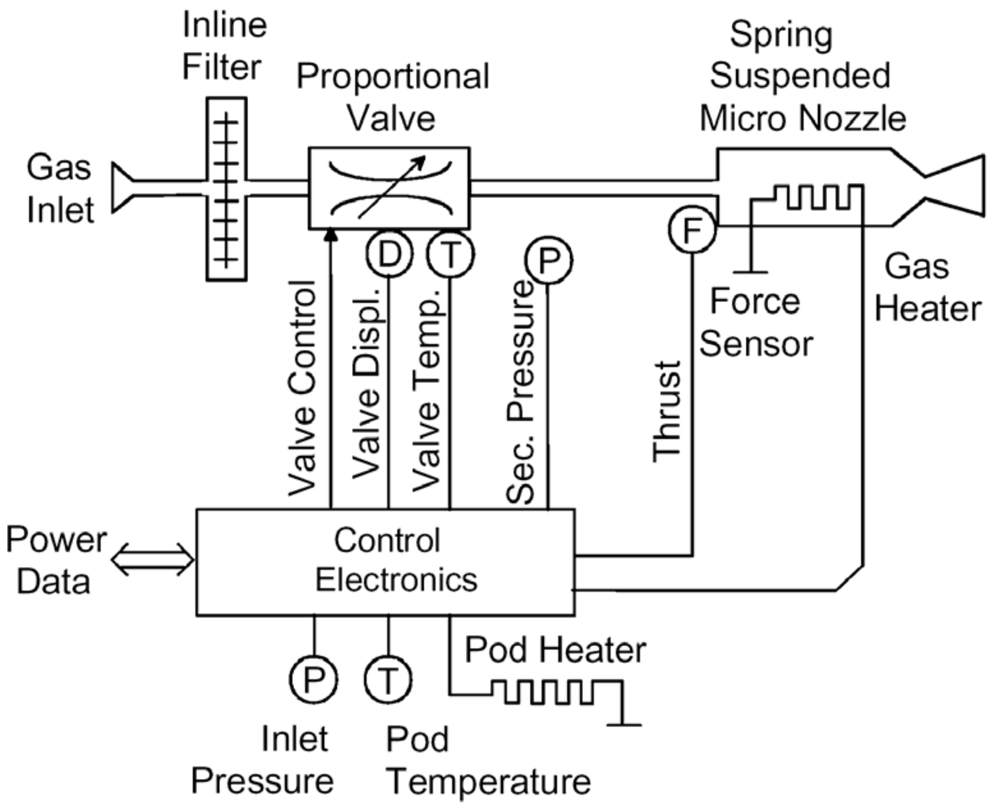
(Courtesy of 'Ångström Space Technology Centre′)

Micropropulsion System

The system consists of a number of thruster pods, each containing four proportional thrusters. The thruster pods have a spherical shape with 42.5-mm in diameter and accommodate four independent nozzles.

The micro propulsion system may be also used for larger spacecrafts, which need high resolution of stabilization and attitude control.

Micropropulsion System



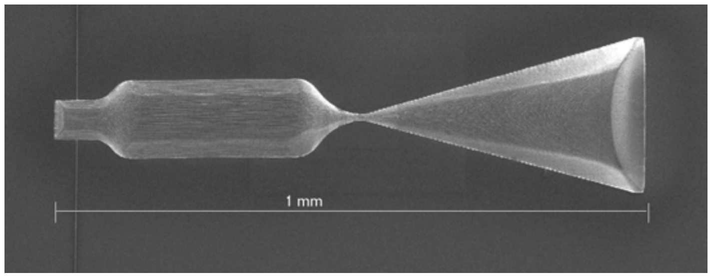
Micro Thruster Block Diagram

(Courtesy 'Ångström Space Technology Centre′)

Cold/hot gas micropropulsion system

The technical data of the Cold/hot gas micropropulsion system are summarized shortly in the following:

- Thruster pod dimension: diameter 42.5 mm
- Overall length 54,5 mm
- Weight: below 60 gram
- Expected specific impulse: 120 s (with Nitrogen and internal heater at the nozzle outlet)
- Max thrust: 0.5-10 mN (dependent on design)
- Subsystems included: 3D-particle filter, electronic control, gas handling

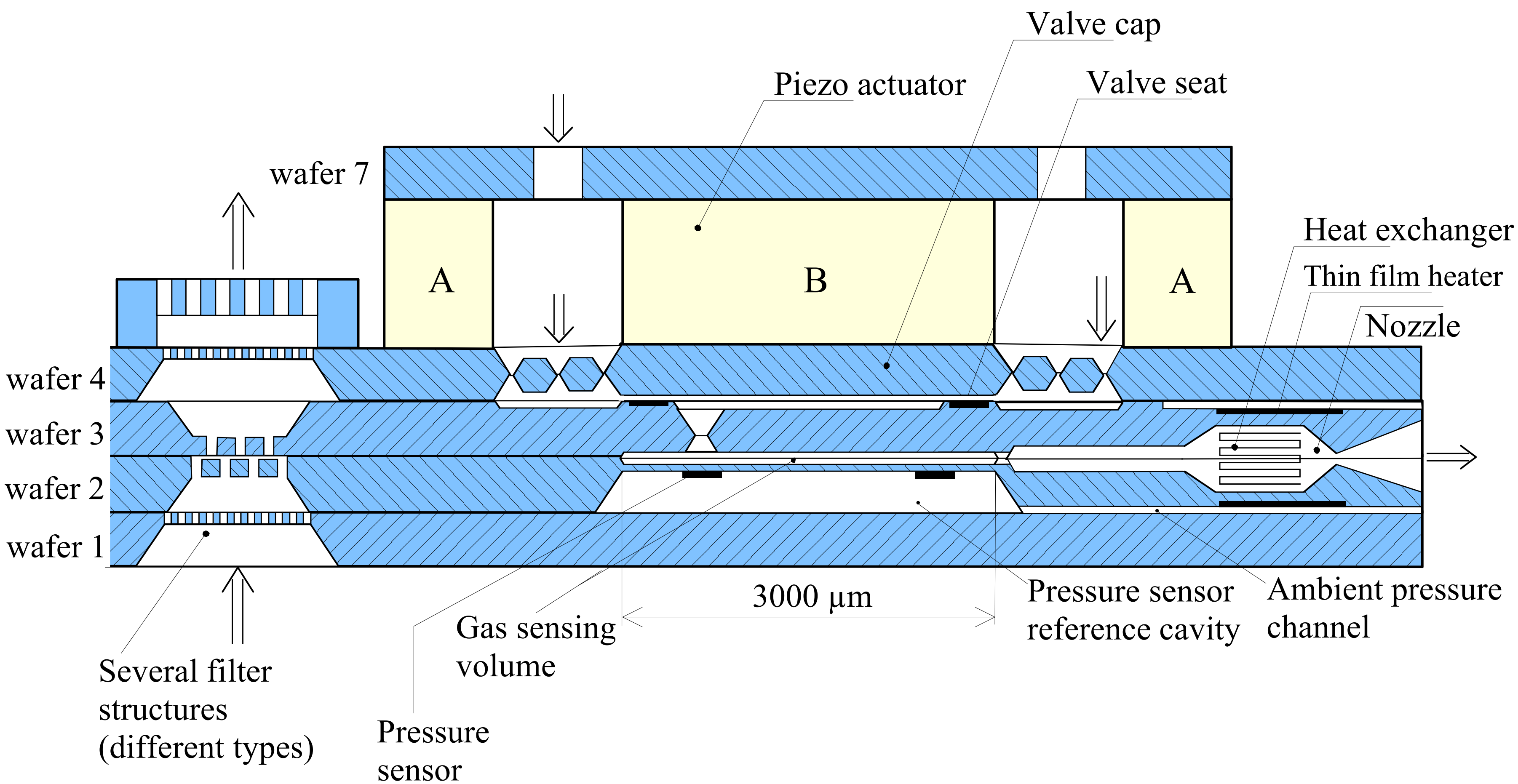


Nozzle

Ref.: H. Nguyen et. al. ”Micropropulsion Systems Research and Manufacture in Sweden”, Proceedings 4th Round Table conference May 2002, Nordwijk/Netherlands

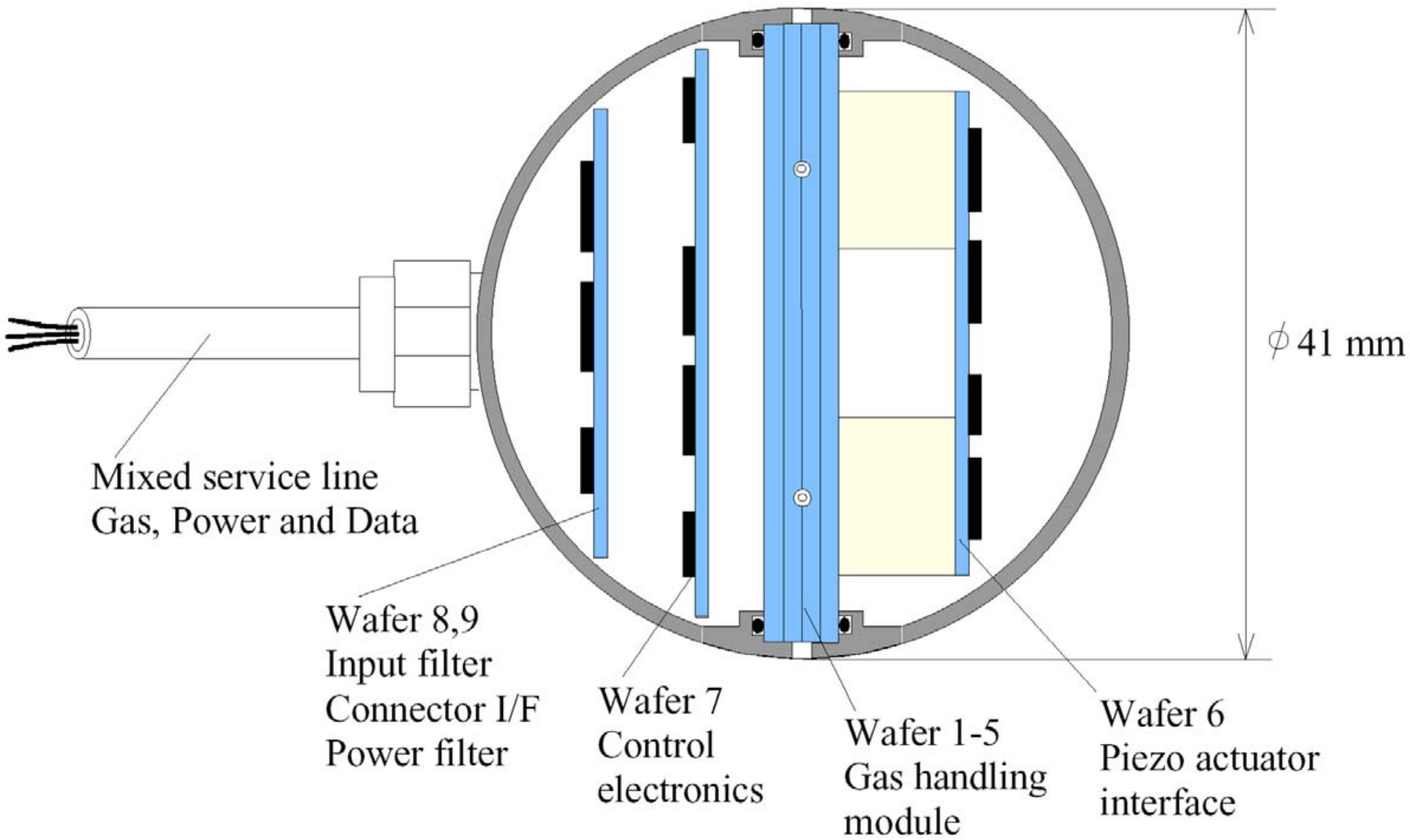
Gas Module Design

(Courtesy by 'Ångström Space Technology Centre')



Complete Thruster Module

(Courtesy by 'Ångström Space Technology Centre')



Potential increase in performance of existing space propulsion systems – Electric Propulsion

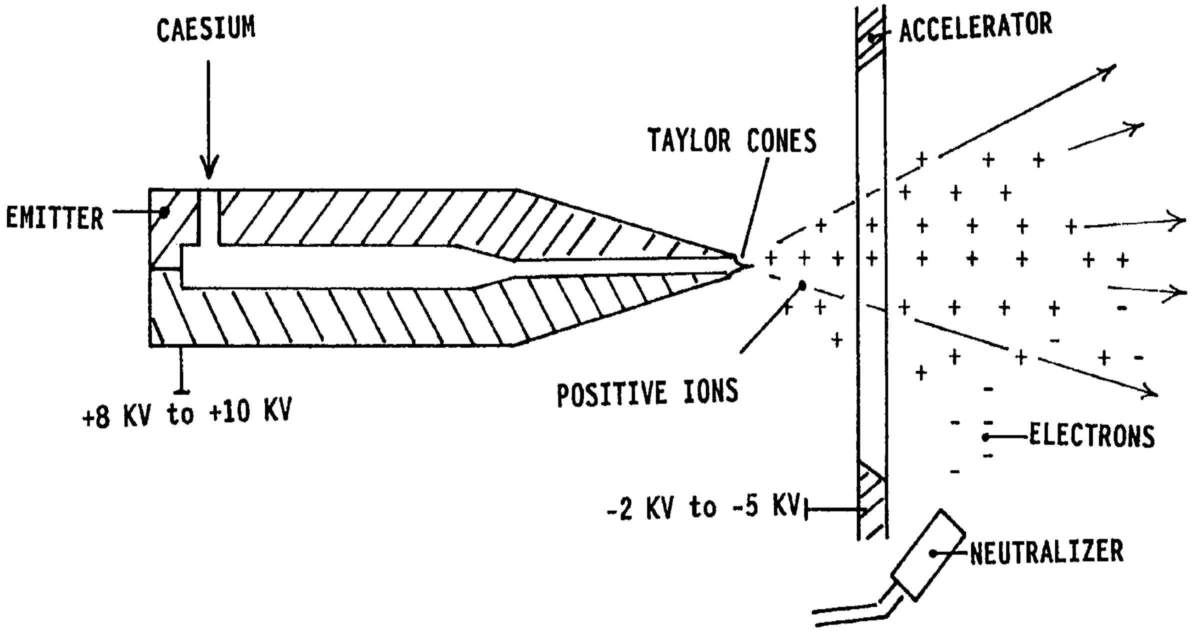
- **Most promising for further increase of propulsive performance capabilities is the use of electric propulsion. This technology, although still under development, has proven to achieve thruster exhaust velocities v_e an order of magnitude higher than the best performing chemical thrust engines.**

- **Although electric propulsion leads to substantial propellant mass savings compared with chemical propulsion, considerable power consumption will require increased mass of power supply systems. Therefore, for electric propulsion, the determination of the system-specific impulse, I_{ssp}, requires also the consideration of contained mass of the power supply/power processing systems and thruster, m_{El}. Here high performance is not dictated by maximum but rather by optimum values of thruster exhaust velocity, $v_{e\text{-}opt}$.**

- **For electric propulsion, high values of I_{ssp} will be achieved mainly for high values of $v_{e\text{-}opt}$. which requires particularly high values of overall specific power γ, overall power conversion efficiency η and thrust operation time τ.**

- **From parametric investigations it is obvious, that for deep space missions mainly power supply systems with high specific power γ need to be further developed to achieve high values of I_{ssp}. For high optimum thruster exhaust velocity, $v_{e\text{-}opt}$, e.g. Field Emission Electric Propulsion (FEEP) will have to be used.**

Field Emission Electric Propulsion (FEEP) Thruster



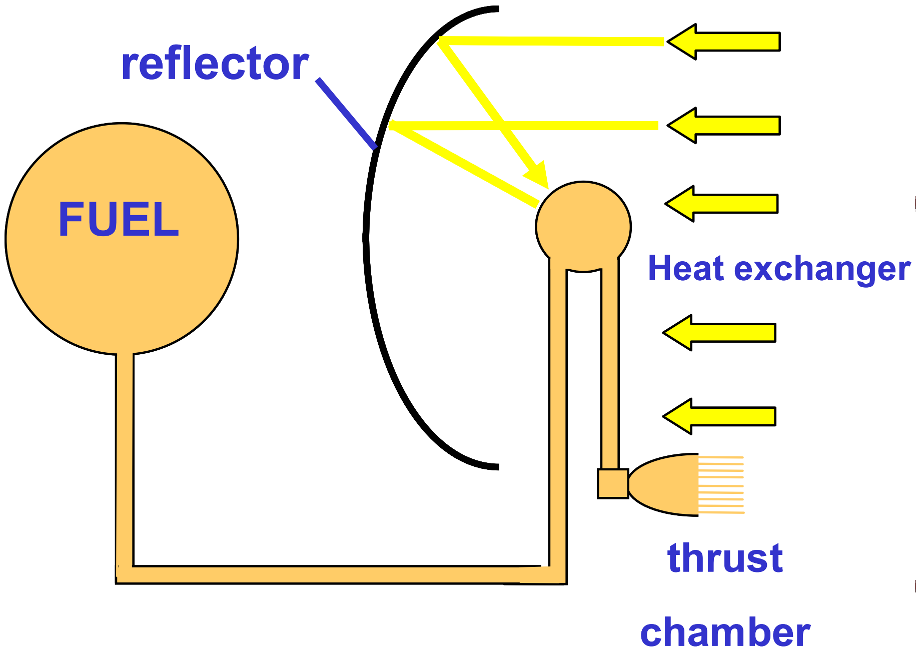
- Very High Isp

  ≈ 6000 to 10000 s.

- F = 10 μN to 2 mN
- Cesium, Rubidium, Indium.
- Efficiency = 98%
  - (Ion~30%; PPT~17
- Self contained propellant reservoir.
- No moving parts.

New Approaches in Advanced Propulsion: Solar-Thermal Rockets

Schematic of Solar-Thermal Propulsion



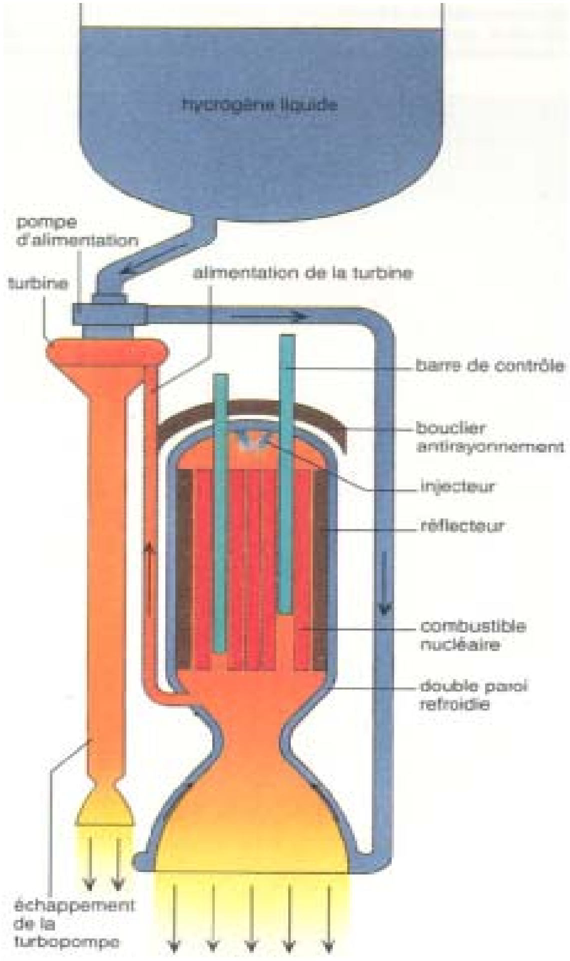
Possible application for future orbit transfer vehicles

(Courtesy of SNECMA)

- Concept: Solar energy is concentrated on a heat exchanger by using mirrors or lenses.
- E.g. liquid hydrogen propellant is passed through a heat exchanger, reaching very high temperatures up to 2500 K, before expanding through a nozzle.
- By this, solar-thermal rockets make use of the limitless power of the sun to produce relatively high thrust, F, with high exhaust velocities, v_e:
  - F = 5 to 10 N continuous for 70 kW (solar power)
  - $v_e \approx 8000$ m/s
- Basic engineering problems limit thrust levels due to limit in heat transfer from heat exchanger to propellant.
- In addition, the deployment and steering of large mirrors to collect and focus the solar energy presents an operational challenge.
- Status: Several concepts for solar-thermal propulsion systems have been proposed, however, so far none have been tested.

New Approaches in Advanced Propulsion: Nuclear Rockets

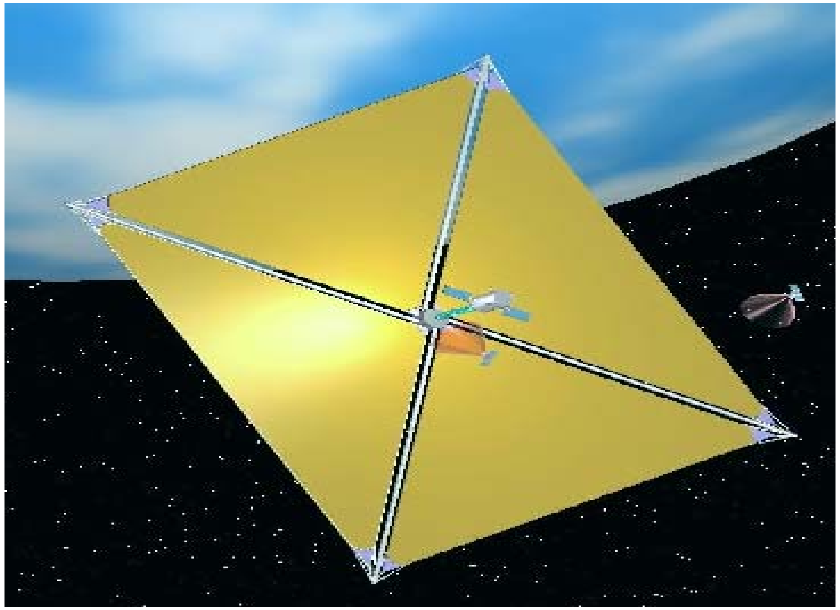
Nuclear-Thermal Propulsion



(Courtesy of SNECMA)

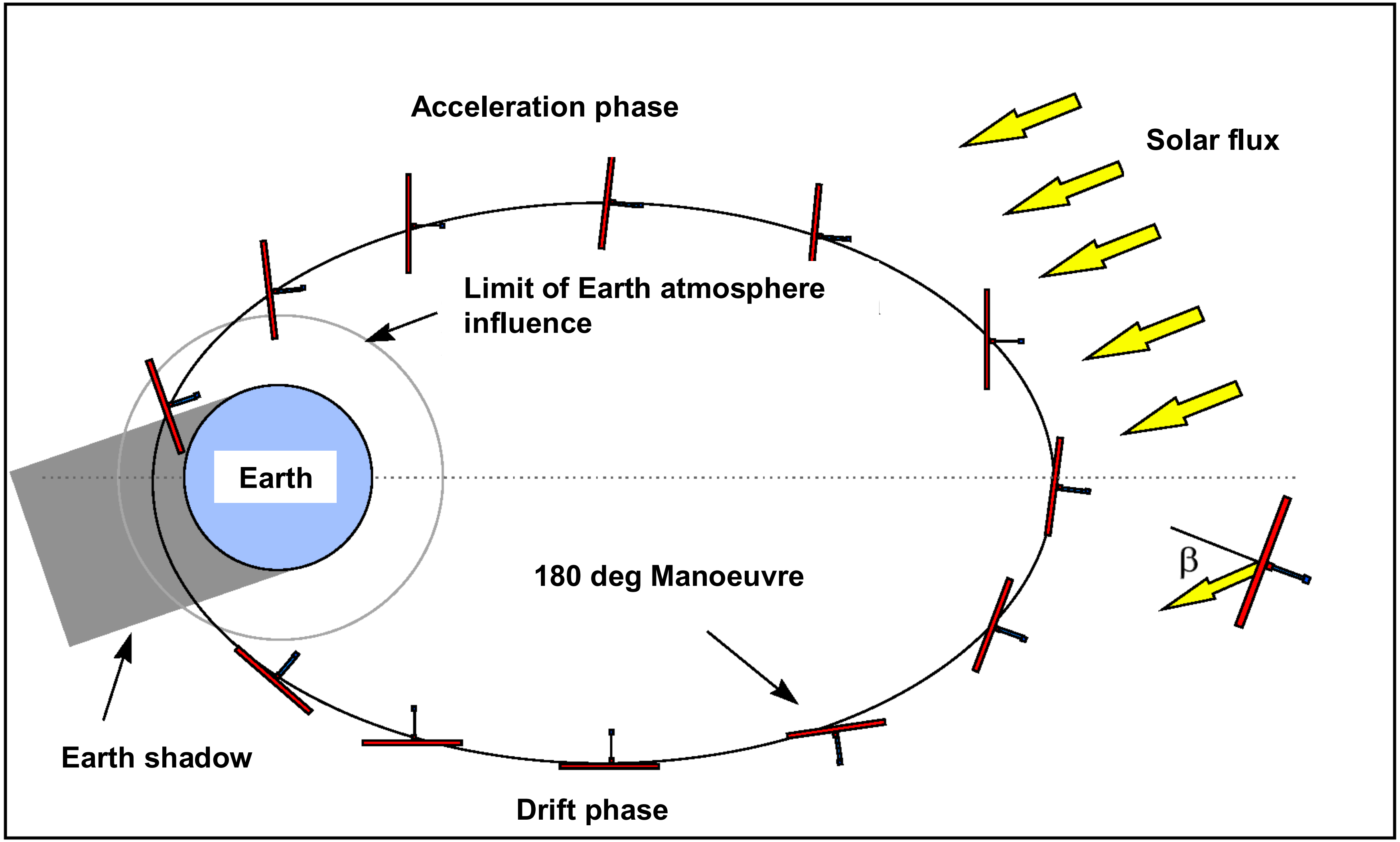
- **Concept: There are two main different categories of nuclear technology for space power and propulsion:**
  - **radioisotope thermoelectric generators (RTG) and close-cycle (e.g. Sterling technology) for nuclear electric power, NEP, to power electric propulsion**
  - **open-cycle nuclear thermal reactors, NTR, which heat e.g. liquid hydrogen propellant directly to produce rocket thrust**
- **NEP: Flight heritage of RTG's with power level $<$ 10 kWe while future NEP's aim at 10 kWe to MWe's for electric propulsion: v_e = 20 000 m/s to 100 000 m/s (FEEP)**
- **NTR: liquid hydrogen propellant absorbs heat from the core of a fission reactor, before expanding through a nozzle: v_e = 8000 m/s to 9000 m/s, F = 20kN to 70 kN**
- **Extensive research performed into nuclear-thermal rockets in U.S. in 1960 as part of the NERVA program.**
- **Status: Environmental and political concern about save ground test and launch of fueled reactor has reduced research in NEP and NTR technology.**

New Approaches in Advanced Propulsion: Solar Sailing



- Concept: Solar sails accelerate under the pressure from solar radiation, caused by a momentum transfer from reflected solar photons, thus requiring no propellant. This force is proportional to the sail area and can be directed by tilting the sail with respect to the incoming solar flux.
- Because no propellant is used, the solar sail has an infinite specific impulse ($I_{sp} = \infty$), however, the thrust to weight ratio is very low, 10^{-4} to 10^{-5} for 9 N/km^2 solar pressure at 1 AU.
- Typical applications:
    - interplanetary cargo missions
    - interstellar travel
- Status: All attempts to unfold solar sail in space have so far failed.

Schematic of Solar Sail Position during one Earth Orbit



Exotic Propulsion Methods: Antimatter and Photon Propulsion

"I have learned to use the word 'impossible' with the greatest caution."

Wernher von Braun

- **Exotic Propulsion Systems are those "far out" ideas still under study. They will be required for the ultimate dream of space exploration to travel to other star systems, as depicted in TV shows like 'Star trek'. Two examples of such exotic propulsion systems are outlined below.**
- **Antimatter Propulsion: Matter- antimatter annihilation offers the highest possible physical energy density of any known reaction substance. Since matter and antimatter annihilate each other completely, it is an incredibly compact way of storing energy. E.g. a round trip to Mars with a 100-ton payload might require only 30 gram of antimatter. However, sufficient production and storage of antimatter (with potential complex and high storage system mass) is still very much in the future.**
- **Photon Propulsion: The generation of usable thrust by ejection of photons is still very hypothetic. The generation of photons by e.g. laser technology and their subsequent decay in space, involves the mass-energy transfer expressed by Einstein's equation, $E = mc^2$. Consequently, very large quantities of energy will be required even for nominal levels of thrust. Possibly, matter-antimatter annihi-lation can be harnessed for photon propulsion in the future.**

S.5 Summary

- **Selection process involves a variety of propulsion options, such as systems operated with cold gas, liquid monopropellant and bipropellant, or some form of electric propulsion.**

- **Primarily, propulsion systems have to meet mission impulse and velocity increment Δv requirements. Therefore, the evaluation of propulsion system performances is a primary task in the selection process.**

- **The 'System specific Impulse', I_{ssp}, allows a more accurate determination of the propulsive performance of spacecraft propulsion systems than the commonly used 'Thruster-specific Impulse', I_{sp}, which only includes the propellant mass. To achieve low system mass, high values for I_{ssp} are desired.**

- **The prevailing goal of advanced propulsion is to enable cost efficient space missions and extended exploration of the solar system up to interstellar missions.**

Literature

- **Wiley J. Larsson and James R. Wertz (editors), 1995;**
  ”Space Mission Analysis and Design”. Chapter 17: Spacecraft Propulsion Systems.
  Published jointly by Microcosm, Inc.; Torrance, California and Kluwer Academic Publishers Dodrecht/Boston/London.
- **Philip G. Hill and Carl R. Peterson, 1992;**
  ”Mechanics and Thermodynamics of Propulsion”. Chapters 10-12 and 14.
  Addison-Wesley Publishing Company, New York.
- **George P. Sutton and A. Wiley, 1992;**
  ”Rocket Propulsion Elements: An Introduction to the Engineering Rockets”.
  Sixth Edition, Interscience Publication, John Wiley & Sons, Singapore.
- **Robert H. Frisbee;**
  “Advanced Space Propulsion for the 21st Century”
  Journal of Propulsion and Power, Vol.19, No. 6,November-December 2003
- **Peter Erichsen, 1997;**
  ”Performance Evaluations of Spacecraft Propulsion Systems in Relation to Mission Impulse Requirements”
  Proceedings of the Second European Spacecraft Propulsion Conference, 27-29 May, 1997 (ESA SP-398, Aug. 1997)
- **Peter Erichsen, 2003**
  “Directions of Potential Increase in Impulse Performance of Spacecraft Propulsion Systems”,
  Proceedings 10-IWCP, La Specia, Italy, Sept. 2003