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This is the executive summary report for the Propulsion 2000 study.

The results of the study are described in detail in the final report P2000-RIBRE-TN-0003.

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Überarbeitung Revision	**Datum** Date	**Betroffener Abschnitt/Paragraph/Seite** Affected Section/Paragraph/Page	**Änderungsgrund/Kurze Änderungsbeschreibung** Reason for Change/Brief Description of Change
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Executive Summary -- Propulsion 2000

Within the last few decades a few propulsion concepts established themselves as common on the market, while other, primarily electrical concepts were under long development and test phases, but until very recently saw only a limited use. As new ideas and new technologies emerged in the last years, and as the concerns about both the environment and the handling and ground use of the usually toxic propellants in use on current launchers and spacecraft increase, the evaluation of alternative propulsion concepts for future satellite missions may indicate potential improvements with respect to either performance (i.e. an increase in delivered payload mass) or handling (non-toxic substances, reduced preparation time, etc.).

American agencies and the US industry are actively evaluating and testing new monopropellants, propellant combinations for bipropellant engines, electric propulsion and several other advanced propulsion concepts. These activities are accompanied by fundamental research both supporting the near-term technologies and looking at very advanced breakthrough propulsion physics. Even though Europe contributes considerably to space science by numerous co-operative missions and missions of its own, and builds an important fraction of and launches about half of the World’s commercial satellites, a comparable effort with respect to advanced propulsion concepts is lacking. In order to identify advanced propulsion options and to assess their applicability to space missions in the next 20 years, the current study, called “Propulsion 2000” was conducted. The objective was to identify – from the European point of view – the most promising propulsion concepts and technologies of the foreseeable future.

The Phase 1 of the Propulsion 2000 Study described in this report was carried out in a team of European companies comprising Astrium GmbH (the former DaimlerChrysler Aerospace) as prime contractor with its subcontractors Alenia Spazio in Torino, Astrium Ltd. in Stevenage, and EADS Launch Vehicles in Les Mureaux. An internal “subcontract” was given to Astrium GmbH in Ottobrunn for a work package dealing with liquid launcher propulsion. Also, the work of Alenia Spazio was supported by LABEN/PROEL, contributing to electric propulsion. The industrial group composition and the distribution of the major activities are shown in Figure 1.

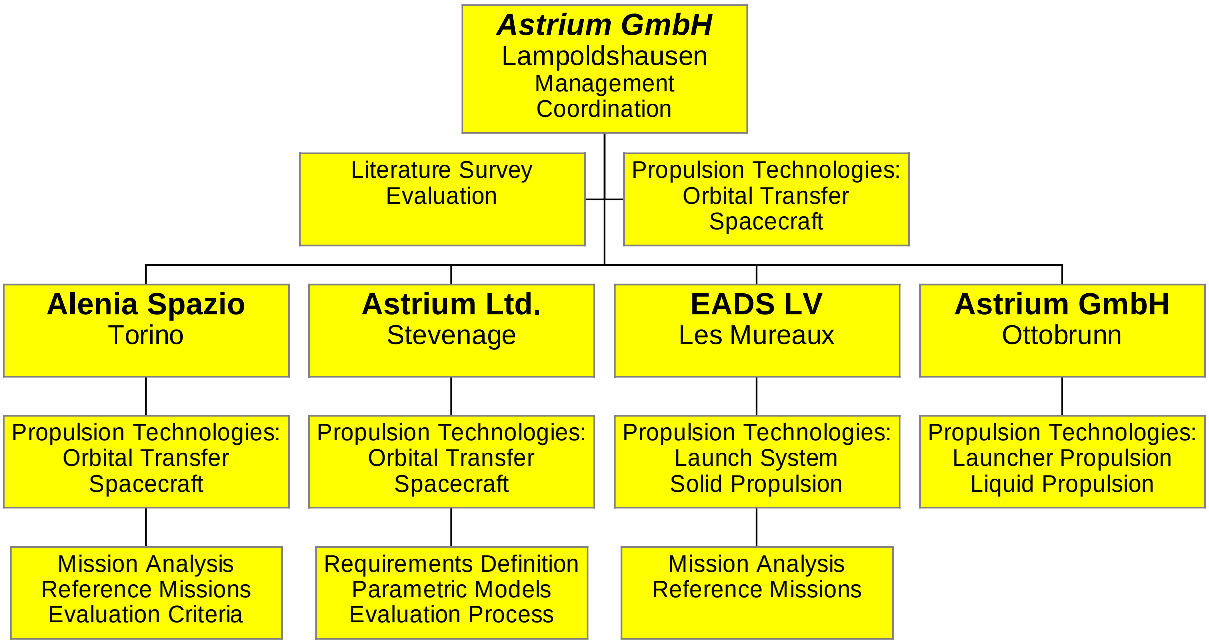


Figure 1: Industrial Group Composition and Major Work Shares

The objectives of the current study were as follows:

- Identification of Advanced Propulsion Concepts
- Identification of Space Missions for the next 10 - 20 years and
- Classification of these Missions into Categories
- Derivation of Basic Mission Requirements (Propulsive and Other)
- Evaluation of Mission Requirements and Propulsion Capabilities
- Selection of the most Promising Advanced Propulsion Concepts
- Identify Targets of Further (Detailed) Study, and finally to
- **Propose a European Space Propulsion Roadmap**

The following assumptions, constraints and exclusions were made for the frame of the study:

- **Exclusive European Point of View:**
  - Technology Availability / Technology Readiness
  - Needs and Requirements
- Summary of Advanced Propulsion Technologies for
  - Spacecraft Propulsion (Attitude and Limited Orbit Control)
  - In-Space Transfer (Upper Stages, wide Ranges of Orbit Control, etc.)
  - Launcher Propulsion
- Analysis of Transfer to GEO for Communications Satellites
  - Launch to and Transfer from Various Initial Orbits
- Trade-offs only for In-Space Propulsion for
  - Orbit Transfer
  - Spacecraft Propulsion (On-Station/Cruise Phase)
- No Trade-off for Launcher and Launcher Propulsion, only
  - Technology Trends
  - Mission Analysis for Various Initial Parking Orbits
  - Performance Data for Advanced Propellants

Based on a market analysis and, especially on the analysis of proposed missions described in detail in the full report, representative and challenging reference missions are selected for further analysis. The mission requirements are identified and translated into requirements for the propulsion systems. In parallel, promising propulsion concepts and technologies that are either readily available or could be made available within the next 10 to 20 years are selected to assess their applicability to the reference missions. In order to match the capabilities of these propulsion concepts/technologies with the propulsion system requirements identified for the reference missions, several propulsive and general parameters are considered, and special weighing factors, depending on the importance placed on each parameter by the respective reference mission are defined. A numerical value is derived that represents the match or mismatch of the propulsion system capabilities with the propulsion system requirements for each parameter. The sum of the products of the weighing factor and the matching value for each parameter yields a certain number for each propulsion system considered for the respective reference mission. Mission critical parameters, i.e. requirements that the propulsion system has to fulfil in order to achieve the mission, are also taken into account. Finally a ranking of the different propulsion concepts is established for each reference mission. Based on these individual results, the final conclusions are drawn and roadmaps for future European space propulsion are derived. The trade-off process is schematically shown below in Figure 2.

The reference missions selected within the study, and the propulsion concepts considered for the investigation are summarised in Table 1 and Table 2 below. The satellite reference missions are marked in light green, while the transfer tasks are highlighted in pink.

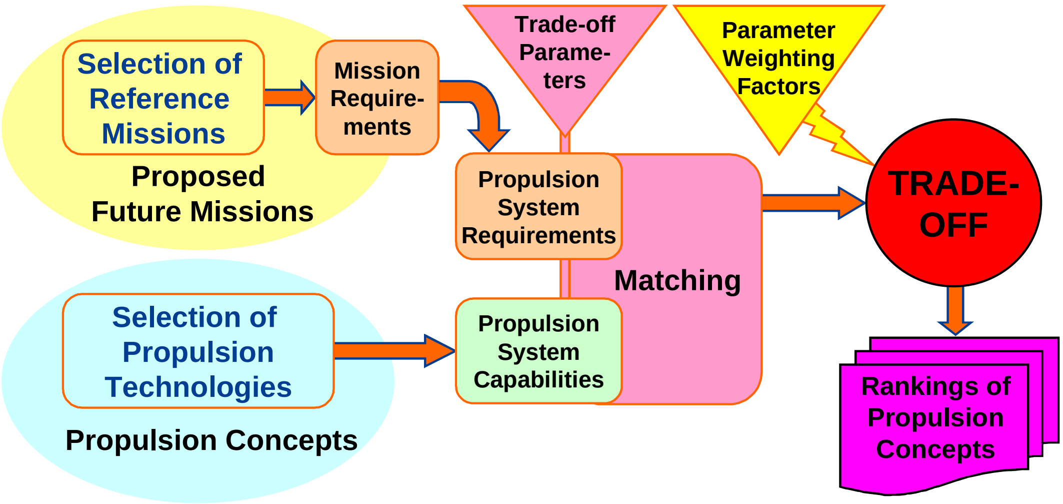


Figure 2: Schematic Representation of the Trade-off process

S/C class	Mission type
M > 3.7 tons	Communications Satellites in GEO
	GEO Transfer
1 t < M < 3.7 t	Planetary Landing: Cruise / On-Station
	Planetary Landing: Descent / Ascent
	Planetary Flyby: Cruise / On-Station
	Planetary Exploration: Transfer
0.5 t < M < 1 t	Constellation Satellites
0.5 t < M < 1 t	Remote Sensing in LEO
0.1t < M < 0.5t	High-Precision Scientific Observatories in HEO
0.001t<M<0.1t	Micro/Nano Satellites in LEO

Table 1: Reference Missions

Propulsion Technology		Average Density [kg/m^3]	Availability for Satellite / Transfer	Technology Readiness Level
Cold Gas	N_2 Cold Gas System	DoA	SoA	9
Monopropellant	N_2H_4 Monopropellant System	1000	SoA	10
	H_2O_2 Monopropellant System	1360	Near Term	4
	HAN-Based Mono-propellant System	1400	Mid Term	2
	TEGDN/AP/Al Monopropellants	1640	Mid Term	2
Bi-propellant	Cryogenic (LH_2/LOx) $	320	SoA	10
	LOx/Methane $	860	Mid Term	3
	LOx/Kerosene $	1030	Near Term	6
	Storable (H_2O_2 / Kerosene)	1320	Mid Term	4
	Storable (MMH / NTO)	1200	SoA	10
	Dual Mode Engine (N_2H_4 / NTO)	1200	Near Term	6
	Electrolysis (GH_2/GOx): Cold Gas or Combustion	1000	Mid to Long Term	3
Electric Propulsion	Ion Engine		Near Term	8
	Hall Thruster		Near Term	7
	FEEP		Near Term	7 - 8
	Arcjet		Near Term	7
Solids and Hybrids	Conventional HTPB Propellant $	1750	SoA	10
	Advanced Propellant $	1600	Mid to Long Term	2
	Hybrid (LOx/HTPB)	1050	Mid Term	2
	Hybrid (H_2O_2/PE)	1315	Mid Term	3
Other	Solar Thermal	70 ?	Long Term	2
	Nuclear Thermal $	70 ?	Long Term, if at all	1
	Tethers	N/A	Mid Term	5

$: Only to be used for Launch Vehicle or Upper Stage / Orbit Transfer Propulsion

Table 2: Propulsion Concepts

Special propulsion solutions, such as micro-propulsion (phase-change thruster, etc.), solar sailing etc, or very advanced propulsion concepts beyond a realisation potential until about 2015 to 2020 are not considered. These are special applications for a limited number of missions with certain special requirements, which are barely reflected by the set of evaluation parameters used here. Micro-propulsion is still in its infancy, and has application potential to small micro- and nano-satellites.

The results of the matching and weighing of propulsion system requirements for the selected reference missions and propulsion system capabilities results in the major conclusions and recommendations summarised thereafter.

In-Space Propulsion

The propulsion concepts found most promising for future in-space mission applications (orbit transfer, stationkeeping, attitude and orbit control, etc.) can be summarised as follows:

- Conventional hydrazine monopropellant and storable bipropellant systems
- Advanced monopropellants
    - demonstrate that they fulfil their promised performances of $I_{sp} > 270$ s
    - additional studies/demonstrators to reduce/eliminate the technical unknowns
    - a research program should be initiated focussing on non-toxic propellants, which would be safer, better to handle and easily storable on ground
    - better performances by enhancement of the complete propulsion system together with the thruster (common goal: performances similar to bipropellant systems); therefore monopropellant systems might eventually be used as primary propulsion on spacecraft, leading to safer, more reliable and potentially cheaper systems
- Electric Propulsion
    - ion engines
    - single stage and double stage hall effect thrusters
    - arcjets (to a certain extent)
    - adapt existing technologies to the widest range of potential future necessities (i.e. thrust modulation, noise, power consumption, cycle-life, lifetime, etc)
- Micropropulsion for fine-pointing and nano-satellites
    - micro/nano technologies in general are considered of a great interest for the near and far future. They will apply to the micro and nano satellites envisaged for both telecommunications constellations and scientific programs
    - activities should emphasise both the components and the manufacturing processes
    - FEEP / micro-FEEP:
        - enhance applicability of Indium thrusters (safer, lighter, easier to handle and install on board)
    - cold gas microthrusters (MEMS): activities are at a very early stage both in Europe and in the USA
    - microthrusters (ITOC, Phase Change thrusters, e.g. subliming solid micro-thruster, etc.)
    - dedicated study required to identify the most promising concepts
    - **NOTE:**
        - in the framework of the micro-FEEP Europe is leader all over the world
        - cold gas micro-thrusters and phase change micro-thrusters are also under development in USA (approximately same early level for the cold gas)
        - Therefore, once the technology will reach a greater maturity, European companies could provide a wider range of products, putting Europe in a better position for the global competition
- Electrolysis of water
    - only preliminary judgement based on rough estimates for performance data
    - promising concept with many technological and operational unknowns
    - feasibility has to be demonstrated in a detailed study, including a verification of basic assumptions
    - questions of hydrogen pressurisation and storage, reliable re-ignition for a very high number of pulses etc. remain open

- Solar Thermal Propulsion
  - promising concept with technological unknowns for transfer missions
  - technical/operational feasibility remain to be demonstrated in a detailed study
  - major issues: unfolding of mirrors, materials, hydrogen storage, size, etc.
  - Near term technology:
    - Not in the State of the Art: Existing materials + RAC with a minimum of development can be envisaged only for a demonstrator
  - Medium term technology:
    - Classical missions (including LEO-GEO on a heavy launcher) possible after a reasonable effort
    - Continuous mode transfer appears as a much simpler solution than intermittent mode
  - Long-term technology
    - Fresnel lens, boron thermal energy storage material would afford efficient thermal energy storage material for trip time ~1 month
- Hybrid Propulsion utilising LOx/HTPB
  - application only to transfer missions shortly after launch
  - potential use for upper stage (or transfer stage) or launcher propulsion

The trade-off and evaluation presented in the current study excluded special applications for a limited range of certain missions. The lack of inclusion for the detailed evaluation is primarily due to the fact that the selected evaluation parameters are barely applicable for these cases, as either the mission is very unique or the propulsion system is not of the “classical” type, which expels a reaction mass. However, an analysis of these propulsion concepts may also indicate promising results for certain mission applications. Not included in the evaluation presented in this report were:

- Solar sails for geostationary communications satellite attitude control
- Advanced (electrodynamic) tethers for orbit control and attitude control (gravity gradient)
- Very advanced tethers (“slingshot type”) for transfer missions
- Space infrastructure (ISS) missions
- Manned missions of all types

It must also be noted that the evaluation and trade-off presented in this report would give different results, if the secondary parameters, especially toxicity and ground handling grow in importance or even become mission critical parameters. In this case the results would shift towards favouring the use of

- advanced, non-toxic monopropellants
- lower performing space-storable bipropellants (e.g. H_2O_2/Kerosene)
- and electric propulsion, where applicable.

Follow-up studies are proposed to further analyse

- the true performance potential of advanced monopropellants, including e.g. the availability of a catalyst and chamber materials
- the technical and operational feasibility of Solar Thermal Propulsion, including e.g. mirror and chamber materials, mechanisms for unfolding the mirror, and long-term hydrogen storage
- the most promising concepts for microthrusters with the aim of a potential down-selection
- the feasibility of a propulsion system utilising water electrolysis for the generation of GH_2/GOx, which can then either be burnt or used as cold gas (esp. questions of propellant pressurisation and storage)

Based on the results presented above, the following key concepts and key technologies should be investigated in more detail, including the development of breadboards and demonstrators, where necessary and applicable:

Key concepts / key technologies:

General:

- Electric Propulsion
  - long life ion engines
  - high thrust ion engines
  - single and double stage hall effect thrusters
- Low cost thruster and thrust chamber design
  - new materials
  - processes
  - design simplification
- Advanced Monopropellants with Isp > 270 s
  - propellants
  - catalyst/ignition system
  - thrust chamber material
  - design of overall propulsion system
  - etc.
- Advanced Bi-Propellants, e.g. GH_2/GOx, LOx/Hc
  - propellants
  - injection
  - combustion
  - cooling
  - integrated propulsion systems
- Solar Thermal Propulsion
  - mirror materials
  - unfolding of mirrors (inflatable materials or deployment mechanisms, ...)
  - chamber materials
  - long-term hydrogen storage
  - integrated systems for transfer missions
  - operational aspects

Specific:

- Micro-Propulsion
  - ITOC
  - MEMS
  - FEEP
  - integrated propulsion system
- Solar Sail Propulsion
  - materials
  - inflatable materials or deployment mechanisms
- Tethers
  - protection from micrometeorites and space debris
  - tension control mechanisms
  - tether dynamics
  - power-thrust generation and plasma effects for electrodynamic tethers
- ISRU Technologies
  - extraction of oxygen and propellants
  - storage and pressurisation of propellants
  - engine technology (e.g. LOx/CH_4)

Launcher and Launcher Propulsion

As launcher and launcher propulsion were not part of the matching of propulsion capabilities with mission requirements and subsequent evaluation and trade-off analysis, the conclusions are based on a synthesis of the launcher technology section and the market survey.

It is recognised that the main competitor of Ariane-5 will be Boeing both with its EELV and with its Sea Launch. The major trends from the market analysis are that the size and mass of geostationary communications satellites continue to grow. A temporary drop in launch mass may be possible due to advanced injection and transfer strategies, e.g. injection into MEO and transfer to GEO with electric propulsion. However, at the same time the mass for those satellites that are based on older bus designs or continue to rely on conventional chemical propulsion remains at a high level or continues to grow further. Therefore a launch provider has to be able to cover a range of injected masses to a variety of orbits. Most of the necessary injection strategies require multiple ignitions of the upper stage of the launch vehicle. While the number of geostationary satellite launches remains roughly constant, the LEO market currently provides for a limited number of launches, but may explode again, if new satellite constellations are to be realised. The resulting launcher requirements for the near future can thus be summarised as follows:

- Increased launch mass for conventional geostationary communications satellites
    - The launch mass will continue to increase for satellites based on conventional chemical propulsion
    - Heavy lift capability (ESC-B) required to ensure cost-effective double launches
- Reduced launch mass for advanced geostationary communications satellites
    - The launch mass could be considerably reduced, if electric propulsion is heavily employed on the satellite, e.g.:
        - full electric propulsion system to cover complete mission range of GEO comsats
        - hybrid system with chemical propulsion thrusters for orbit control and electric propulsion for transfer and attitude control
    - Launch to non-GTO initial orbit requires a re-ignitable upper stage
- Unpredictable LEO Market Situation
    - Limited number of launches assured
    - Potential explosion in number of launches due to future satellite constellations
    - Europe is not very present on the LEO market:
        - dedicated Ariane 5 is too heavy and too expensive for single launch
        - difficulties in finding satellite partners for a shared launch
        - constellation launches may require a re-ignitable upper stage
- Research of Cost-Effectiveness
    - Launcher architecture with a reduced number of stages
    - Commonality between stages or engines of a family
    - Propellant density increase
    - Low cost technologies (materials, manufacturing, launch preparation)
    - Operational aspects
        - non-toxic propellants
        - optimised launch preparations (rapid turnaround times for next launch)
        - re-ignitable upper stages

Therefore, in order to cope with the future market needs,

three basic requirements can be identified:

➨ **1. Re-Ignitable Upper Stage**

➨ **2. Low Cost Intermediate Launcher**

➨ **3. Cost-Effectiveness**

Follow-up studies are proposed to further analyse

- alternative concepts for improved Ariane 5 rocket boosters, taking into account propellant combinations, performance, operations, ecological impact and cost
- Ariane 5 optimised upper stage concepts in view of mission and payload versatility, together with
- new transfer orbits and satellite transfer propulsion to fit the market demands
- the benefit of the preferred concepts and technologies for a future RLV application.

Based on the results presented above, the following key concepts and key technologies should be investigated in more detail, including the development of breadboards and demonstrators, where necessary and applicable:

Key concepts / key technologies:

ELV:

- ➩ LOx / hydrocarbon technologies
    - ➨ propellants
    - ➨ injection
    - ➨ combustion
    - ➨ cooling
- ➩ Low cost thrust chamber and turbo pump design
    - ➨ new materials
    - ➨ processes
    - ➨ design simplification
- ➩ Performance increasing technologies
    - ➨ nozzle extension
    - ➨ self-adapting nozzles
    - ➨ etc.

RLV:

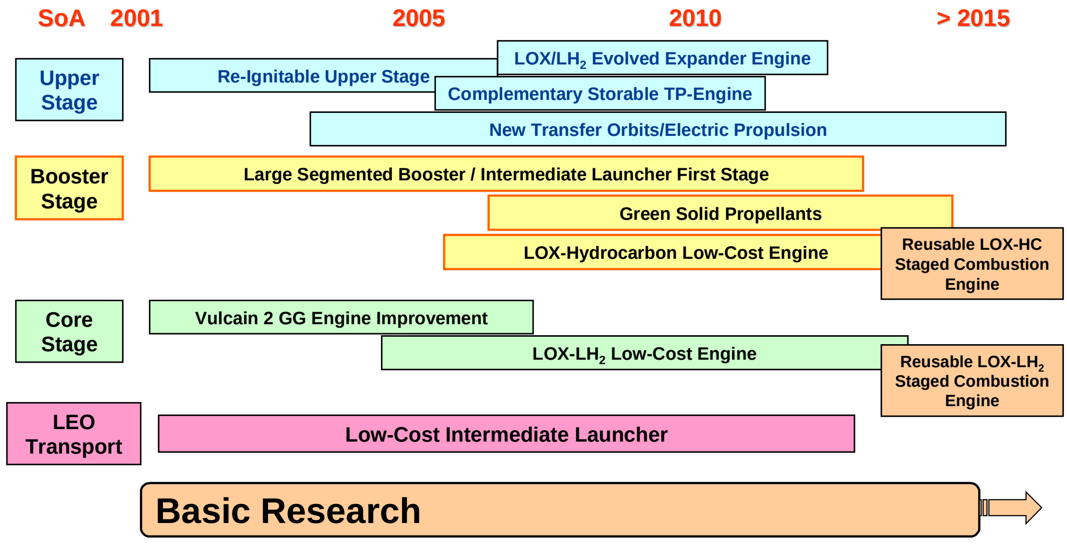
- ➩ Lifetime enhancement for thrust chamber and turbo pumps
    - ➨ thermal barrier coatings
    - ➨ elastic CC structures
    - ➨ etc.
- ➩ Health monitoring and low maintenance design
- ➩ High performance staged combustion technology

This application-related work should be further supported by basic research and technology development, reaching from advanced propulsion of the near future to very far term concepts, including what is generally termed as breakthrough physics.

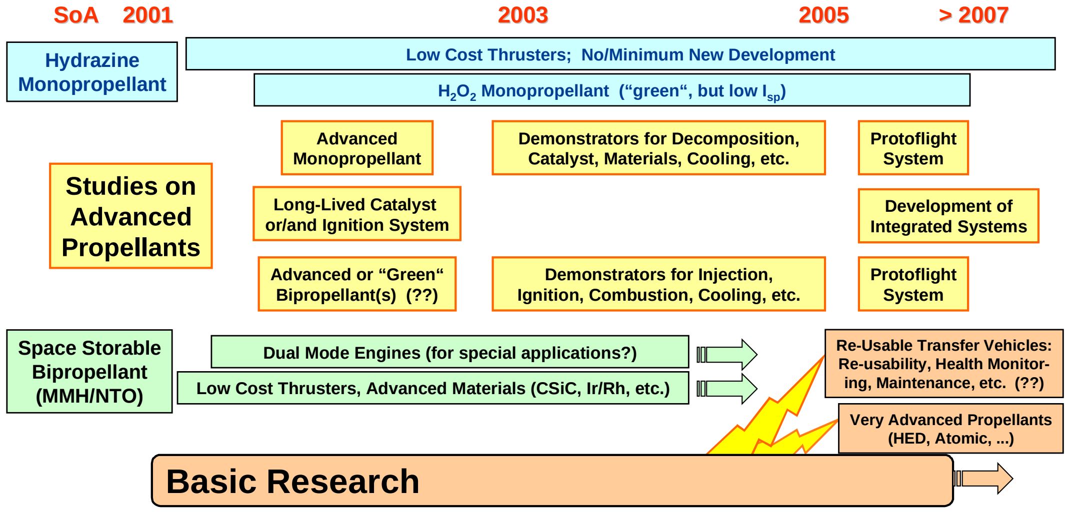
Roadmaps

From these conclusions the general roadmaps for Europe’s future in propulsion can be derived:

General Launcher (Liquid) Propulsion Roadmap:



Chemical Transfer and In-Space Propulsion Roadmap



SoA 2001 2003 2005 > 2007

Hydrazine Monopropellant
- Low Cost Thrusters; No/Minimum New Development
- H_2O_2 Monopropellant ("green", but low I_{sp})

Studies on Advanced Propellants
- Advanced Monopropellant → Demonstrators for Decomposition, Catalyst, Materials, Cooling, etc. → Protoflight System
- Long-Lived Catalyst or/and Ignition System → Development of Integrated Systems
- Advanced or "Green" Bipropellant(s) (??) → Demonstrators for Injection, Ignition, Combustion, Cooling, etc. → Protoflight System

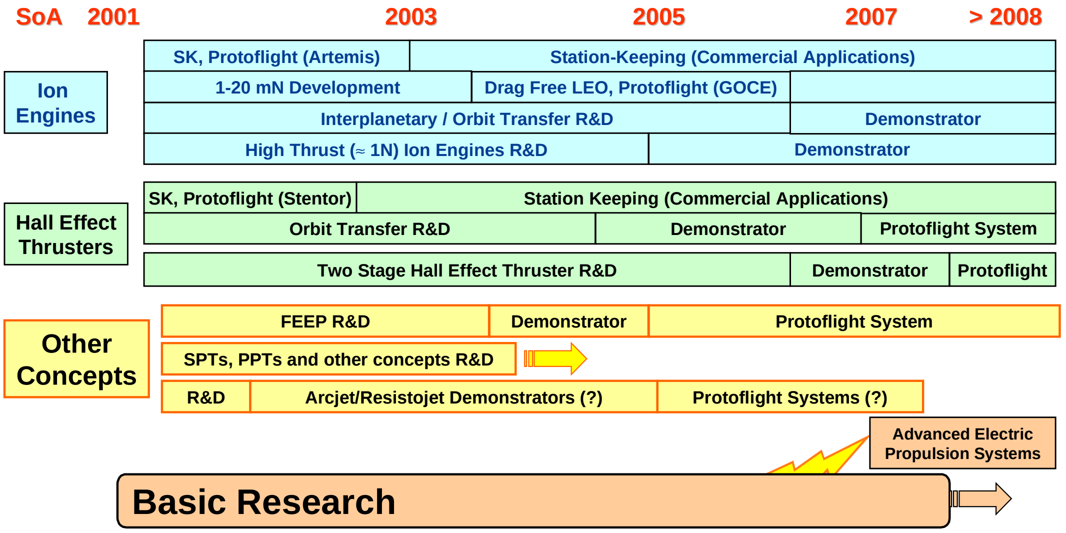
Space Storable Bipropellant (MMH/NTO)
- Dual Mode Engines (for special applications?)
- Low Cost Thrusters, Advanced Materials (CSiC, Ir/Rh, etc.)

Re-Usable Transfer Vehicles: Re-usability, Health Monitoring, Maintenance, etc. (??)

Very Advanced Propellants (HED, Atomic, ...)

Basic Research

Electrical Transfer and In-Space Propulsion Roadmap



SoA 2001 2003 2005 2007 > 2008

Ion Engines
- SK, Protoflight (Artemis) | Station-Keeping (Commercial Applications)
- 1-20 mN Development | Drag Free LEO, Protoflight (GOCE)
- Interplanetary / Orbit Transfer R&D | Demonstrator
- High Thrust (≈ 1N) Ion Engines R&D | Demonstrator

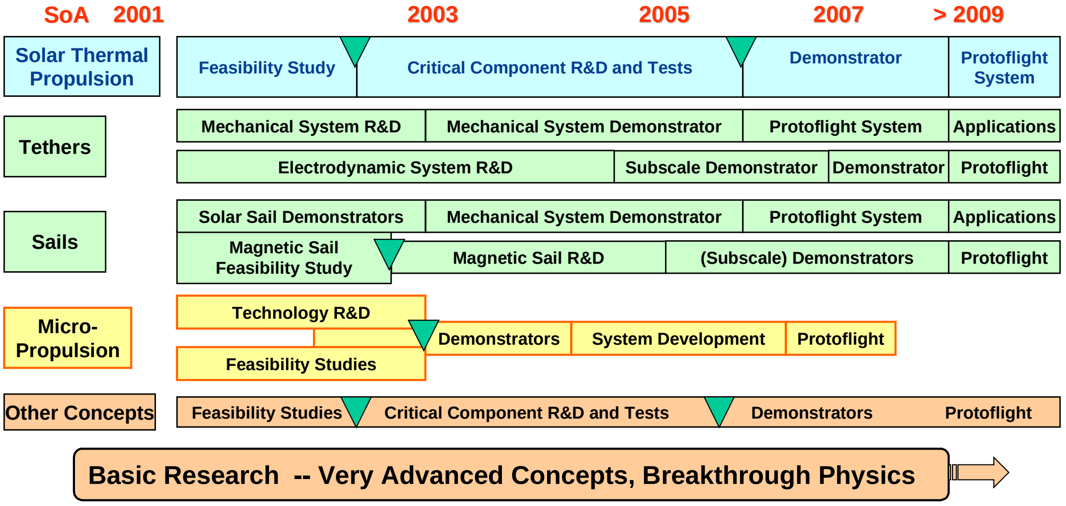
Hall Effect Thrusters
- SK, Protoflight (Stentor) | Station Keeping (Commercial Applications)
- Orbit Transfer R&D | Demonstrator | Protoflight System
- Two Stage Hall Effect Thruster R&D | Demonstrator | Protoflight

Other Concepts
- FEEP R&D | Demonstrator | Protoflight System
- SPTs, PPTs and other concepts R&D
- R&D | Arcjet/Resistojet Demonstrators (?) | Protoflight Systems (?)

Advanced Electric Propulsion Systems

Basic Research

Advanced Transfer and In-Space Propulsion Roadmap



SoA 2001 2003 2005 2007 > 2009

Solar Thermal Propulsion
- Feasibility Study | Critical Component R&D and Tests | Demonstrator | Protoflight System

Tethers
- Mechanical System R&D | Mechanical System Demonstrator | Protoflight System | Applications
- Electrodynamic System R&D | Subscale Demonstrator | Demonstrator | Protoflight

Sails
- Solar Sail Demonstrators | Mechanical System Demonstrator | Protoflight System | Applications
- Magnetic Sail Feasibility Study | Magnetic Sail R&D | (Subscale) Demonstrators | Protoflight

Micro-Propulsion
- Technology R&D
- Feasibility Studies
- Demonstrators | System Development | Protoflight

Other Concepts
- Feasibility Studies | Critical Component R&D and Tests | Demonstrators | Protoflight

Basic Research -- Very Advanced Concepts, Breakthrough Physics