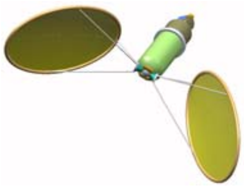
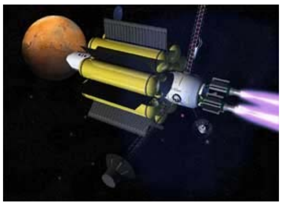


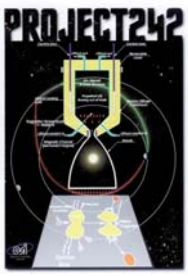


PROPULSION 2000 PROGRAM
Phase 2




- EXECUTIVE SUMMARY -



Class : 2 Category : 2

PREPARED BY:	FiatAvio, Keldysh Institute, DMA, DLR, Centrospazio, Edotek, DRG, IRS,ISP	
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ISSUED BY:	DOCUMENT CONFIGURATED	CLASSIFICATION
FIATAVIO	Yes ( ) No ( )	N/A
AUTHOR: A. Accettura	IF THE DOCUMENT IS ISSUED FOR A PROGRAM	
	Contractual	Program
Typist: A. Accettura	Yes (X) No ( )	Propulsion 2000
DISKETTE IDENTIFICATION	Contract Number	Customer
P2k-ES.doc	14024/99/NL/PA+CCN2	ESA/ESTEC

TITLE: PROPULSION 2000 PROGRAM Phase 2 – EXECUTIVE SUMMARY

Annexes: 0 Total Pages: 37

AUTHOR'S ABSTRACT: This document contains the Propulsion 2000 Phase 2 Executive Summary which is focused on Scenarios, Technologies, Development Plans and Roadmaps for the most advanced propulsion systems to be used in the 2020 timeframe scenario.
The results of the study are described in detail in the final report RAP-PRP-10000 Is.1.

DEPT.: DT/PPS/PFL NAME: A. Accettura DATE: 28.3.03

KEY WORDS

PROPULSION 2000
FUTURE CONCEPTS/SCENARIOS
KEY TECHNOLOGIES
ADVANCED PROPULSION
DEVELOPMENT PLANS
ROADMAPS

Distributed by: FIATAVIO

Internal

Dept.	Nb cop.	Date	Record
DT/PPS/PFL	1		
UBS	1		

P.M. Approval:

External

Dept.	Nb. Cop.	Date	Record
FIATAVIO	1		
ESA/ESTEC	2		

ISSUE STATUS					
Date	**Issue N.**	**Brief Description of Change**	**Mod. N.**	**ECP/PM N.**	**Config. Control Approval**
28/3/03	1	FIRST ISSUE			

Heavier-than-air flying machines are impossible.
Lord Kelvin

1. INTRODUCTION TO THE PROGRAM

General goal of PROPULSION 2000 is to generate the basis for a future European development strategy in the field of Space Propulsion. Four main scenarios have been addressed: Launch Vehicles, Orbital Transfer Vehicles, Satellites and Deep Space Missions. Phase 1 has been successfully completed on 2000.
For each of the candidate technology selected during Phase I, the scope of the second phase of Propulsion 2000 is to investigate and collect existing information from both system and technological point of views in order to propose development plans. Final scope is to prepare an output containing feasibility studies and roadmaps for each selected propulsion technology.
Perspectives of the Program can be summarized as follow:

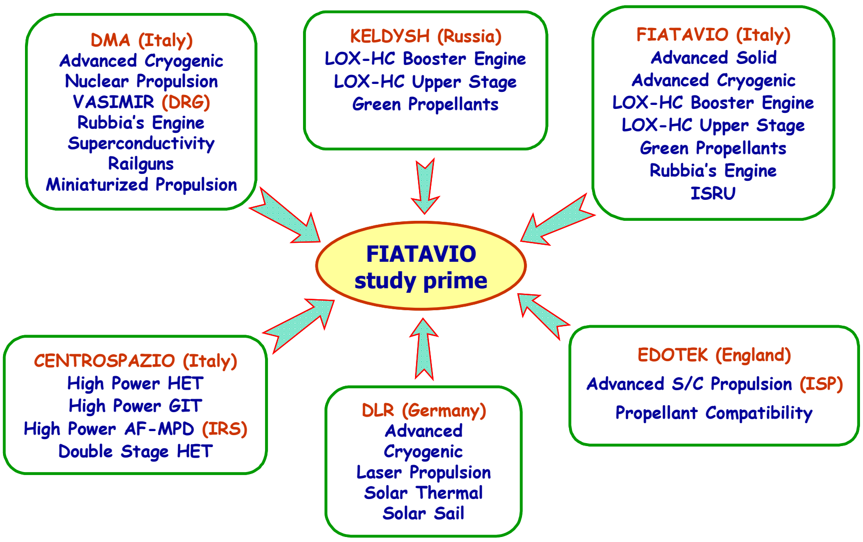
- Acquire knowledge on advanced propulsion systems in order to define mission capabilities
- Permit European technological development in the field of advanced propulsion systems
- Disclose new opportunities for both science and technologies

In ultimate analysis, advances in space propulsion systems will reduce the costs of access to space thanks to the new enabling technologies. This work represent the result achieved during one year by FiatAvio and its Partners and concluded with a Final Presentation held on ESA-ESTEC the 26th February 2003.

1.1 Work logic and industrial team

Starting from the results obtained during phase one (from both technology and system point of views) a detailed technical investigation has been performed considering three parallel areas:
- System: design and operational preliminary requirements (agreed with ESA)
- Technology: feasibility, criticalities and challenges up to 2020 horizon (at system and component levels)
- Strategy: European research/industrial capabilities and development plans & Roadmaps

Finally a Final Report has been provided and the program was concluded by a Final Presentation.
The industrial team is composed by FiatAvio (prime contractor), Keldysh Research Center from Moscow, DLR with four departments from Germany, Centrospazio and University of Rome from Italy, and Edotek from England. Twenty-one propulsion concepts have been considered with a work sharing shown hereinafter:



1.2 Objectives of the Program

Briefly we can summarize both perspectives and expectations of this phase 2 as follow:
- We would like to build-up a vision in the frame of innovative space propulsion systems
- We wants to propose development plans in the most advanced key technologies to enable future missions
- We have prepared roadmaps to address future space propulsion activities in Europe

Final goal is ambitious: to disclose new frontiers of opportunities for both science and technologies.
Just for presentation purposes we have considered four main propulsion areas (chemical, electric, nuclear and advanced). Below main results achieved for each area are shown. A complete set of information about requirements, technologies, cost and plans is enclosed in the final report (800+ pages).

2. ADVANCED CHEMICAL PROPULSION

In this section we will discuss about solid propulsion, storable propellants, cryogenic engines, green propellants and LOX-HC engines for main and upper stages.

2.1 ADVANCED SOLID MOTORS (FiatAvio)

Scenario - Solid Propellant Motors (SRMs) are the most cost-effective method to upgrade the performance of the liquid-core launch vehicles and the only cost effective method for the small satellites launch market. SRMs have been the key to success for all the U.S. and European launch systems. Other applications are foreseen as kick stages and small satellite propulsion (as low cost option). Current and future SRM technology improvements are mainly related to performance enhancement, cost reduction and clean propellants.
In this scenario efforts are directed toward simplicity, improvements of existing technologies, cost reduction, and performance increasing (including new high performance propellants) in terms of payload to orbit.

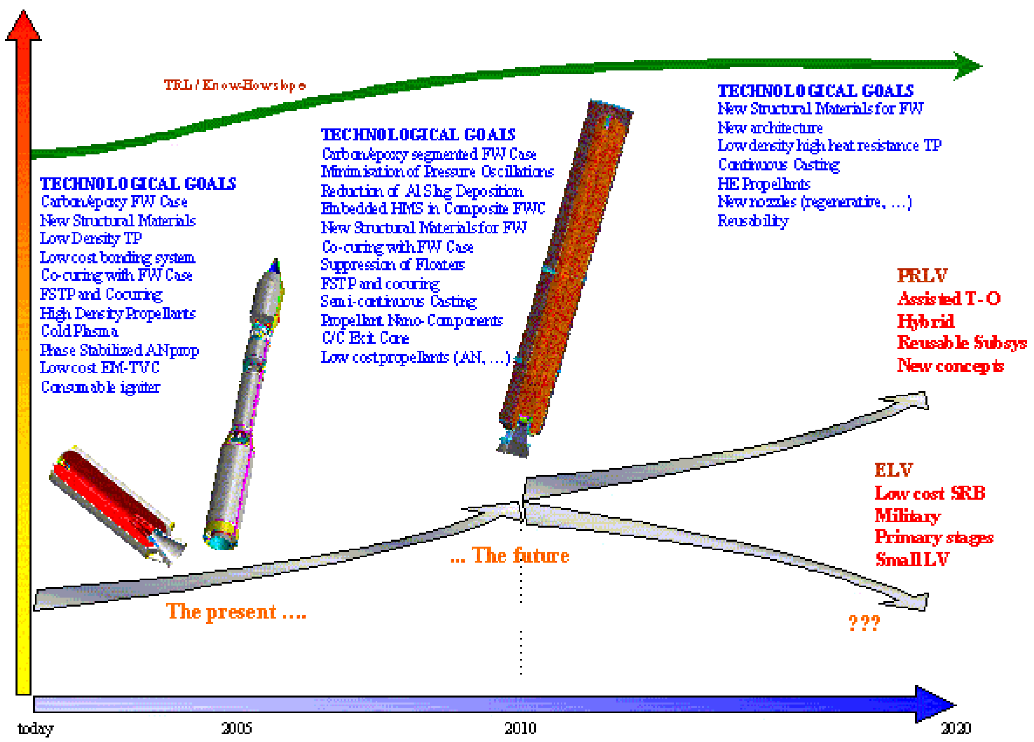
Key technologies - Main goal is to develop a new generation of large scale SRM, in order to reduce space access cost by providing a reliable high thrust source at low cost with reduced environment impacts. To reach these aims the following key technologies can be considered first priority:

- Ammonium nitrate based propellants
- Continuos Casting (reduction of costs and time cycle)
- High energy propellants (RDX, ADN, …)
- Cold Plasma
- Fiber Supported Thermal Protection and Cocuring
- Electromechanical Actuator
- Green Propellants (HNF, HMX)
- Carbon / epoxy filament wound case (including embedded HMS)

Finally we can state that in Europe there is enough experience to do everything in solid propulsion.

Development plan and estimated effort - In order to develop the above selected technologies investments for about 18 M€ are foreseen up to 2010 timeframe. Anyway we have considered key technologies up 2020.

Roadmap and vision - Below a solid rocket motor roadmap is represented up to 2020 timeframe horizon.



Suggestions and recommendations - Development of reliable SRM will reduce the cost of access to space while increasing launch capability at low cost with respect of current technologies.

2.2 ADVANCED CRYOGENIC ENGINES (FiatAvio)

Scenario - Application of cryogenic engines cover the entire launchers scenario among ELV, RLV, main stages, upper stages and OTV. Such a scenario has been investigated in terms of FiatAvio (turbopumps and cryotanks), DLR (technologies and system) and DMA (performance and system) in order to share technical activities.
Turbopumps and valves are the largest single cause in engine failure, so special attention will be given on such a concept. Areas of investigation are related to reusability, increasing performance and architecture studies.
As regard cryotanks we can say that a mass reduction for composite cryotanks respect to metallic one can be estimated in the range of 20-30%.

Key technologies - As regard turbopumps and cryotanks, we can list the following key technologies:

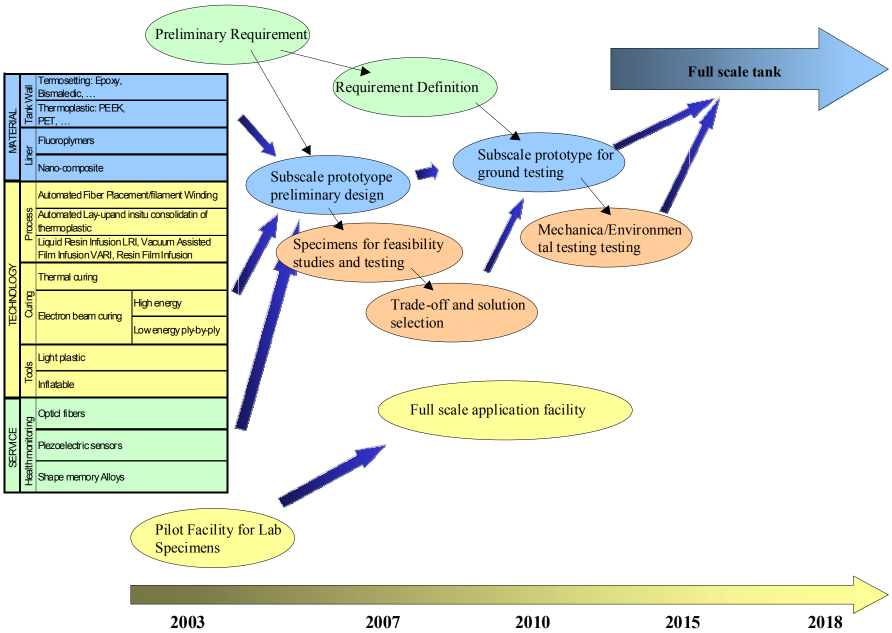
TURBOPUMPS

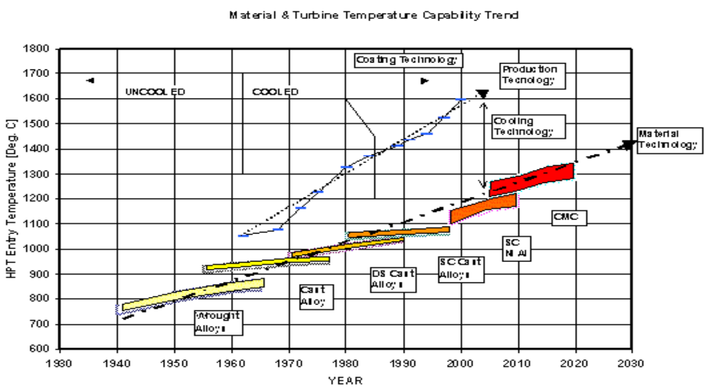
- Boost pumps
- Investigation on Materials/components for Cost reduction & improvements
- Blisk technology
- Reusability approach for turbopumps
- Advanced Bearings (Hydrostatic, Magnetic, SC, …)
- Advanced Seals
- Metallurgy processes
- Cycle life design
- High Thermal Materials
- Hydrocarbon compatibility studies
- APU for TVC

CRYOTANK

- Low temperature materials (liner and composite)
- Pressure/temperature cycle des.
- Seals & Liner porosity
- Mass optimization
- Liner compatibility with propellants
- Mechanical Interfaces design
- Reusability (10 cycles of reusable launcher mission loads)
- Inspectability (NDT) & reparability
- HMS for both

Roadmap and vision - Proposed roadmaps for both Cryotank and Material for Turbine are shown below.





2.3 ADVANCED CRYOGENIC ENGINES (DLR)

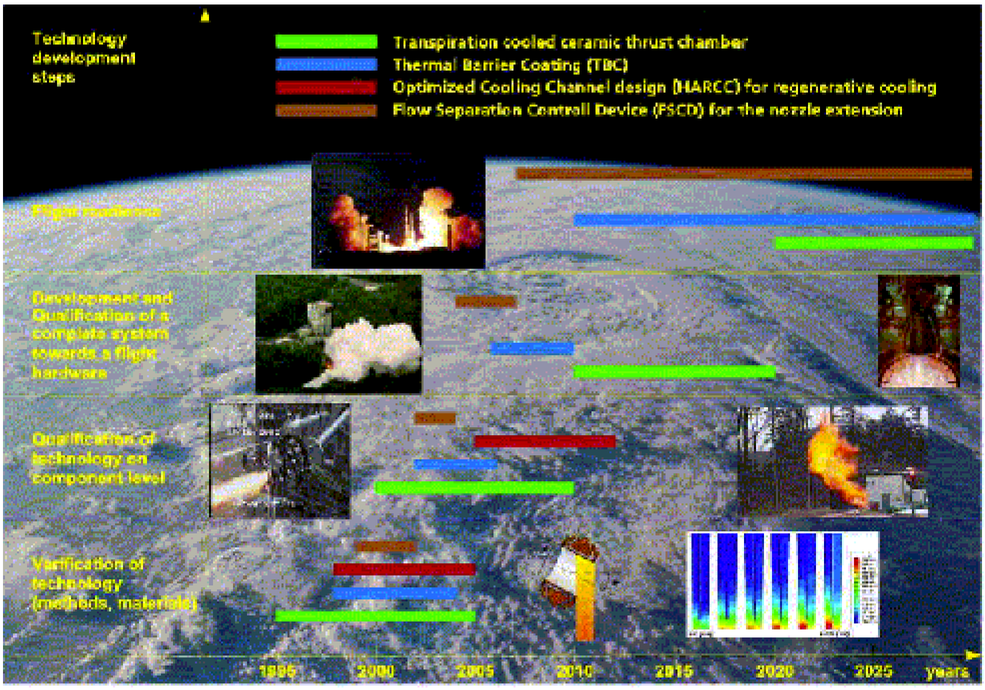
Scenario - Transportation of payload into the earth orbit with medium and heavy launchers:
- Using chemical propulsion with cryogenic liquid propellants to enhance existing rocket motors
- Cryogenic liquid propellants as i.e. LOX and LH2 provide a low molecular weight M, enabling a gain Isp
- This propulsion system bases on the trade-off between propellant mass flow and Isp to provide a comparable high thrust at low altitudes as well as at high altitudes

Key technologies - Efficient cooling methods for high pressure / high thermal load combustion chambers
- Transpiration Cooling of porous combustion chamber walls made of high temperature resistant Carbon fibre reinforced Carbon (C/C)
- Thermal Barrier Coating (TBC) with extreme thin ceramic layers (ZrO2) spread onto the hot gas side of the combustion chamber wall
- Improvement of the existing regenerative cooling technique with a better understanding and controlling of the fluid mechanics and heat transfer in cooling channels, i.e. implementing new cooling channel designs with different aspect ratios (HARCC)

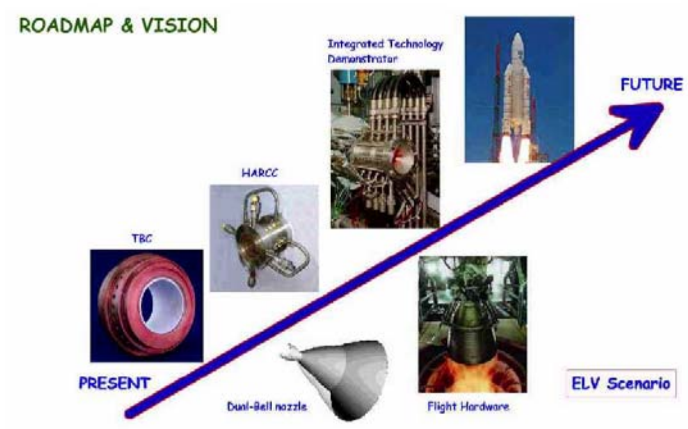
Reduction of specific impulse loss caused by flow separation during atmospheric flight: Flow Separation Control Device (FSCD), i.e. Dual Bell Nozzle.

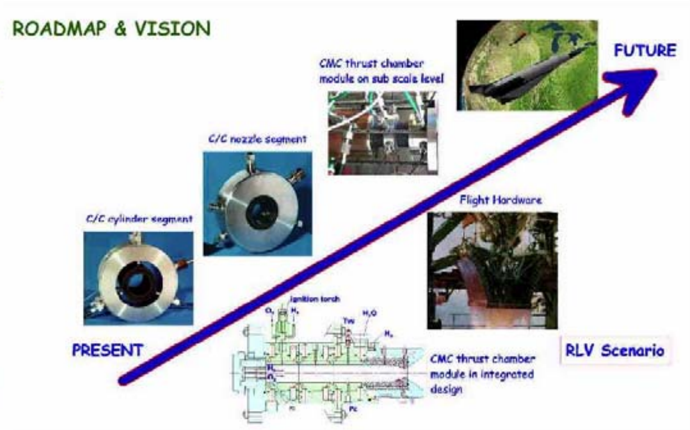
Selected Technologies	Status	expected available date	European capabilities
Transpiration Cooling employing C/C	conceptual level	2010	DLR has world wide patent on C/C material, transpiration cooling of porous combustion chamber walls of C/C is investigated solely at DLR
Thermal Barrier Coating (TBC)	improvable	2006	DLR has its own deposition technique (EB-PVD), for application of TBC in combustion chambers European competence is sufficient
FSCD (Dual-Bell Nozzle)	conceptual level	2005	Europe has a leading position in flow separation devices employing dual-bell nozzles
HARCC	available now	2003	Europe has a leading position in regenerative cooled combustion chambers

Development plan and estimated effort - The Integrated Technology Demonstrator Program (ITDP), including all selected technologies, is constituted by three phases:
- Verification of Technology (methods, materials): 7,5 M€
- Qualification of Technology on component level (sub-scale): 60,0 M€
- Development and Qualification of a complete system towards a flight hardware: 4000 M€



Roadmap and vision - Below 2 roadmaps for technologies related to both ELV and RLV are shown:





Suggestions and recommendations - Its possible benefits makes Advanced Cryogenic Propulsion (ACP) a very promising technology:

- For ELV's: Using ACP for a performance increase concerning thrust and specific impulse Isp provides a gain in payload
- For RLV's: Using the potential of ACP while remaining the engine requirements (thrust or Isp) unchanged permits to reduce loads of other engine components. This reduction of component loads obviously can be translated into an increase in component reliability and lifetime.

2.4 ADVANCED CRYOGENIC ENGINES (DMA)

Scenario - LOX-H2 engines are applied as boosters as well as upper stages worldwide:

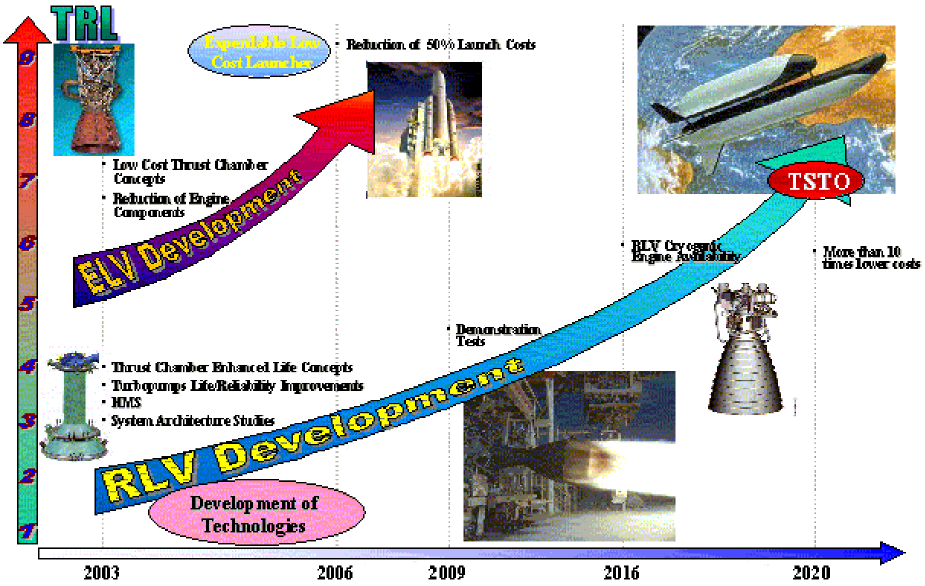
- USA have developed almost all types of engine cycles: from gas-generator to full-flow staged combustion to expander cycle
- RUSSIA is the only country with consolidated experience in oxidizer-rich technology
- EUROPE has gained high proficiency in gas-generator cycle and now in the expander cycle with the VINCI program, but has substantially no experience in high-pressure staged combustion cycles
- JAPAN cryogenic engines use both full-flow staged combustion cycle and expander cycle

Key technologies - The following technologies have been selected for future developments:

- New materials for improved performance / reliability at high temperature / pressures (Ceramic, Composites)
- High temperature and high pressure structures and advanced (cheaper) structural design
- Methods for improving chamber durability: Thermal Barrier Coatings (ceramic, metallic), transpiration cooling, high aspect ratio cooling ducts, elastic liners, low stiffness closeout and, especially, HMS
- Improving turbomachinery efficiency and reliability: advanced bearings (magnetic), advanced seals, resistance to high temperature and corrosion, boost pumps, HMS, supercavitating inducers
- Theoretical studies on: high pressure mixing and atomization processes, supercritical fluid properties, high pressure chemical kinetics, advanced nozzle concepts (dual bell, extensible, annular, plug…), high mach number boundary layer interaction (dump cooling, transpiration cooling)
- Improving manufacturing technologies to lower cost and to improve capabilities

Development plan and estimated effort - For ELV and RLV an effort of 500 M€ and 2000 M€ has been estimated respectively, while time frame is 2015 period.

Roadmap and vision - Below a roadmap for both ELV and RLV scenarios is shown.



Suggestions and recommendations - Present goals for ELV are cost reduction, simplicity and reduction in engine components. Future target is related to RLV; improved market can disclose new opportunities (i.e. space tourism). Performance at reasonable cost can only be obtained with cryogenic propulsion.
Finally reducing launch cost may improve commercial space market and vice versa.

2.5 ADVANCED LOX-HC (FiatAvio)

Scenario - Low-cost, mission flexibility, robust approach and good performance are important drivers for propulsion systems to be applied on future LVs: LOX-HC seems to match such drivers thanks to their characteristics, which can be summarized as follow:

- Low cost technology (with respect to cryogenic engines)
- Simpler ground operations ("green" properties)
- More compact vehicles (with respect to cryogenic one)
- Cooling capability (methane with respect to kerosene)
- High engine thrust-to-weight ratio (with respect to hydrogen)
- Reduced overall mass of the vehicle structure, tankage and related TPS (with respect to cryogenic one)
- Reusability issues
- Mission flexibility (application on main engines, upper stages and OTV)

Unfortunately scenario is not yet defined because of open questions like LV architecture, political issues and market evolution.

Key technologies - As regards TRL in Europe we have enough experience in liquid propulsion systems, (Vulcain and Vinci) nevertheless most of the LOX-HC technologies (see tables below) are yet to be developed.

Assembly	Critical Items
MAIN INJECTOR	- Spray, atomization & mixing strategies - High flowrate injector elements - Variable flowrate/MR elements - Flame anchoring active control - Feeding uniformity - Materials & Manufacturing - Design & testing procedures
COMBUSTION CHAMBER	- Thermal loads - Sooting (RP1) - High thermal cycle materials - Cooling strategy (*Transpiration cooling, Thermal HC cracking control, Thermal barrier coatings, High aspect ratio cooling ducts*) - Overwrapped ablative liner - Reusability issues - Potential use of methane - Combustion Instabilities control devices
GAS GENERATOR / PREBURNER	- Ox rich mode - Fuel rich mode - Soot control - Material compatibility

Assembly	Critical Items
IGNITER	- Igniter reusability
NOZZLE	- Heat Loads - Cooling (Film, Regenerative,…) - Advanced architectures (EN, DB, PN, Aerospike, …)
TURBOPUMPS	- Advanced Bearings and Seals - Metallurgy processes - Cycle life design - Investigation on Materials/components for Cost reduction/improvements - Blisk technology - Boost pumps - Reusability approach - High Thermal Materials - Implementation of self-diagnosis devices (HMS) - Hydrocarbon compatibility - APU for TVC
HMS	- Advanced sensors (high T env.) - Optical fiber technologies - Data acquisition S/W - Integration in the engine
CHALLENGES FOR LOX-HC	- new cycles - HEDM - new architectures

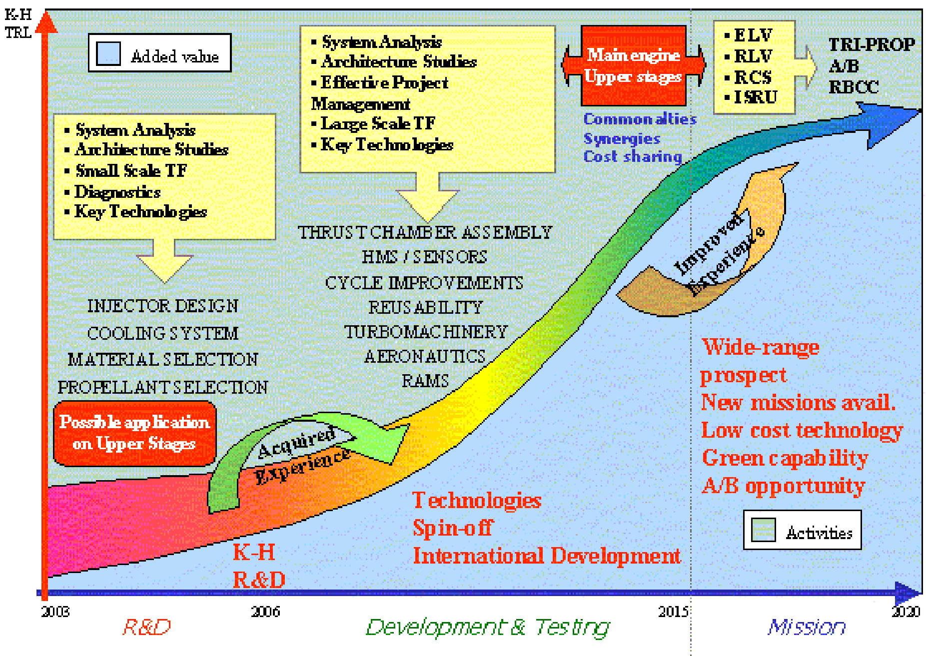
Finally it should be very clear that propulsion challenges are not only performance, but also RAMS, cost, operability, flexibility, technologies and reusability issues.

Development plan and estimated effort - Development costs are very different (ranging from 8 M$ to 900 M$ with our cost models) depending on RLV/ELV application, first/upper stage, engine cycle, ...
As regard development time, it depends on several factors, among them: existing experience, technology maturation, engine cycle and testing activities. From a general point of view we can say that:
- No significant difference in time to design and development for booster engines vs. upper stage engines
- 2-3 years typical for development of engine with Gas Generator Cycle
- 3-10 years for Staged Combustion Cycle
- High dependant on technological maturity of the engine
- In general LOX-HC appears to be shorter than LOX-LH2

Other 2 areas shall play a primary rule in LOX-HC programs: RAMS and TESTING.
Finally some questions should be solved before each development plan:
- How much we can obtain in terms of know-how acquisition?
- Can we sustain a European leadership in that field?
- Can we improve our understanding in liquid rocket engines?
- Can we acquire a technological independence from other countries?
- Last question: can we reach the development goal lowering the development cost?

All these answers have possible compromise solutions: a joint development between industrial actors, that allows from one side new development and from the other side it offers faster development and risk sharing.

Roadmap and vision - Below a roadmap for LOX-HC development path is shown.



Suggestions and recommendations - Development of LOX-HC engines could enable new perspectives for Europe, such as a low cost propulsion technology, a possible application on future RLV and a more flexible propulsion system with respect to solid and / or cryogenic. Synergies are strongly recommended in order to reduce both risk and cost.

2.6 ADVANCED LOX-HC MAIN ENGINES (Keldysh Institute)

Scenario - This scenario is related to LOX-HC liquid rocket engines (LRE) to be applied on boosters and main stages of launch vehicles. Particularly this activity is related to the Russian activities with respect to information open to public domain.

Engines developed and produced by two principal manufactures are considered:

- Glushko NPO "Energomash": developed engines (RD-105, RD-106, RD-107, RD-108, RD-111, RD-170, RD-171, RD-180, RD-191) from 1952 to present day.
- Kuznetsov Samara Research and Engineering Complex: developed engines (NK-9, K-15, NK-33) from 1962 to 1972.

The final report is focused on the following information: name, composition and brief description of engines and their main subassembly, structural and operational requirements, key problems and their solutions, LRE cycles, engine development time & cost and perspectives up 2020 year.

Key technologies - In the process of LRE development phases, scope of scientific R&D activities are directed toward:

- LRE engineering and start-up control dynamics;
- Combustion instabilities;
- Turbopumps;
- LRE regulation & control;
- Robustness;
- Methods of testing, experimental development and reliability analysis;

Also we have to consider other subjects such as choice of materials, selection of engine cycle and cooling system, gas generator / pre-burner design.

Development plan and estimated effort - Development costs have been evaluated by using a Trascost model (since information about engines cost are not available in the Russian public domain). Development plan is:

- Research work and conceptual design: 1 - 2 years
- Ground testing & development: up to 4-6 years
- Certification and flight tests: 1 - 2 years.

As example we can cite:

- RD-107, RD-108 engines and their modification were developed in 3.5 years (from 1957)
- NK-15 and NK-33 engines were developed in 6 and 5 years, respectively.
- The world's most powerful engine RD-171 (RD-170) was developed from 1976 to 1985.
- Development of the engine RD-180 (on the basis of the RD-170) was realized in 5 years.

Below main characteristics of engines developed by NPO "Energomash" and Kuznetsov SRTC are shown.

Main structured and operating characteristics of cruise engines developed by NPO "Energomash" for zero stage

Index / CHARACTERISTICS	RD-105	RD-106	RD-107	RD-108	RD-111	RD-120	RD-170	RD-171	RD-180	RD-191
Thrust ground/vacuum, kN	539/627,2	-/644,84	821/1000	745/941	1406,4/1626,8	-/833	7252/7898,8	7252/7898,8	3823,9/4149,3	1920,8/2083,5
Impulse ground /vacuum, m/s	2548/2959,6	-/3038	2520/3080	2430/3090	2695/3106,6	-/3430	3030/3302,6	3030/3302,6	3050,7/3310,4	3044,8/3302,6
Pressure in the chamber, MPa	5,88	5,88	5,85	5,1	7,85	16,2	24,5	24,5	26,0	26,2
TPU power, MW			3,82	3,82	8,46	12,9	190	190		
Operational time, s	130	330	140	310	110	360	140	140		
Mixture ratio	2,7	2,7	2,47	2,39	2,39	2,6	2,6	2,63	2,72	2,63
Engine mass, kg	782	802	1155	1250	1480	1125	9750	9500	5330	2200
Engine diameter, mm	1200	1400	2580	1950	2760	1954	4000	4150	3200	1450
ENGINE HEIGHT, MM	4500	4800	2860	2860	2340	3872	4000	3565	3580	4000
Engine cycle	Exhaust cycle					Oxidizer-rich staged combustion cycle in chamber				
Number of chambers in the engine	4	1	4+2	4+4	4	1	4	4	2	1
Years of development	1952-1954	1952-1954	1954-57 1971-75	1954-1957	1959-65	1976-85	1976-1987	1976-1985	1994-1998	
CONTROL OF FLIGHT			Control aggregates				±8°	±8°	±8°	
Engine cost (thous. USA doll.) - at the beginning of manufacturing - for assimilated series production	1510 300	1530 310	1850 370	1930 390	2210 550	1830 370	5630 1130	5550 1110	4110 2060	2590 1300

Main structured and operating characteristics of LRE
developed by Kuznetsov SRTC for zero stage

Index CHARACTERISTICS	NK-15 (11D51)	NK-33 (11D111)
Thrust on the ground/in vacuum, kN	1509,2/1542,5	1509/1636,6
Impulse on the ground/in vacuum, m/s	2910/3243,8	2910/3243,8
Pressure in chamber, MPa	14,83	14,83
TPU power, MW	33,8	33,8
Operational time, s	150	600
Mixture ratio	2,52	2,62
Engine mass, kg	1247	1222
Engine diameter, mm	1490	
Engine height, mm	3705	3705
Number of chambers in the engine	1	1
Years of development	1962-1967	1968-1972
Engine cost (thous. USA doll.) - at the beginning of manufacturing - for assimilated series production		1930 390

Roadmap and vision - The principal component for a launcher is the propulsion system (PS) with its operating cycle, its parameters and propellants. The choice of above parameters should provide minimization of cost during life cycle and the elimination of damage due to failures of engines. The accepted concept for Russian propulsion system development defines the following main requirements to LREs and next-generation PS:
- high reliability and operating safety (0,999 – 0,9995);
- ecological safety of propellants;
- minimum cost with respect to engine activity cycle (development, manufacturing and operation);
- the potentialities of redundancy of multiengine systems (a single engine failure shall not result in failure of the mission). In this connection, development of high-reliability expendable engines and redundant multiengine propulsion system with use of reusable LRE should be considered as the most important objective of engine manufacturing at present-day. From this point of view main requirements are:
  - Propulsion system reusability for first stages shall be up to 10-15, to be increased up to 50-100;
  - Propulsion system cost between-flight servicing shall not exceed 3 % the PS cost with a subsequent decreasing down to 0.5% and lower.

A possible solution on the formulated problem is the development of next-generation LRE with fuel-rich gas generator cycle (in combination with the gas generator exhaust cycle or nozzle by-pass). This is especially important for the development of new launchers to be used for delivery of crews to the International Space Station or for manned space vehicles.

2.7 ADVANCED LOX-HC UPPER STAGES (Keldysh Institute)

Scenario - This scenario is related to LOX-HC liquid rocket engines (LRE) to be applied on upper stages of launch vehicles. Particularly this activity is related to the Russian activities with respect to information that is open to public domain. Engine developed and produced by three principal manufactures are considered:
- CADB: developed engines (RD-0105, RD-0109, RD-0107, RD-0110) from 1958 up to now, and RD-0124 under development;
- Korolev Rocket-Space Corporation “Energiya”: developed engines (11D33, 11D58) since 1961;
- Kuznetsov SREC: developed engines (NK-31, NK-39) from 1962 to 1972.

The final report is focused on the following information: name, composition and brief description of engines and their main subassembly, structural and operational requirements, key problems and their solutions, LRE cycles, engine development time & cost, and perspectives up 2020 year.

Key technologies - Key technologies are the same as for main engines with additional issues such as nozzle extension, vacuum ground testing and restart capability.

Development plan and estimated effort - Development costs have been evaluated by using a Trascost model (since no information about engine cost are available in the Russian public domain). We can say that the cost of open cycle engine (RD-0110) is less more than half the cost of closed cycle engine (RD-0124).
As regard development plan we have the same phases foreseen for main engines, we have only two additional issues related to vacuum ground testing and nozzle extension testing (including verification of design margins).
As example we can cite:

- RD-0110 for the upper phases of launch vehicles “Molniya” and “Soyuz” has been developed at CADB from 1963 to 1965 based on the experience of the previous development of engines RD-0105, RD-0109 (anyway some experience was used from engine RD-0110 since 1959).
- For the engines 11D33 and 11D58M the period of time from the issue of technical assignment for engine development to the completion of certification test phase was equal to 4 and 6 years, respectively.

Below main characteristics of engines developed by CADB, RSC Energia" and Kuznetsov SRTC are shown.

Main structural and operating characteristics of upper stages’ LRE

Development firm	CADB					RSC"Energia"	
Index / Characteristics	RD-0105	RD-0107	RD-0109	RD-0110	RD-0124*	11D33	11D58M
Thrust in vacuum, kN	49.4	297.7	54.5	297.92	294	66.3	85
Impulse in vacuum, m/s	3096.8	3131.1	3170.3	3200	3520	3335	3469
Pressure in the chamber, MPa	4.59	6.8	5.1	6.8	15.7	5.4	7.8
Operational time, s	454	240	430	240	300	200	680/7
Mixture ratio						2,48	2,48
Engine mass, kg	130		121	410	460	148	310
Engine diameter, mm	1100		1100	2240	2400		1200
Engine height, mm	1620		1555	1575	1575		2300
Engine cycle	exhaust cycle				staged combustion cycle in the chamber		
Number of chambers in the engine	1	4	1	4	4	1	1
Years of development	1958-1959	1958-1960	1959-1960	1964	1994	1961-1964	1970-1975
Control of flight	Generator gas through the throttle	Rotatable nozzles	Generator gas through the throttle	Rotatable nozzles	Combustion chambers at a single plane	Rotatable nozzles	Rotatable nozzle
No-failure operation in flight tests	-	-	-	0.998	-	-	-
Engine cost (Thous. USA doll.) - at the beginning of manufacturing - for assimilated series production	600 200	1080 280	570 190	1082 216	1150 580	620 125	936 312

Main structural and operational characteristics of LRE developed by Kuznetsov SRTC

Index / Characteristics	NK-31 (11D114)	NK-39 (11D113)
Thrust on the ground/in vacuum kN	-/406.7	-/406.7
Impulse on the ground/in vacuum, m/s	-/3459.4	-/3449.6
Pressure in the chamber, MPa	9.38	9.38
Operational time, s	1200	1200
Mixture ratio	2.6	2.6
Engine mass, kg	722	584
Engine diameter, mm	1400	1300
Engine height		
Number of chambers in the engine	1	4
Engine cost (Thous. USA doll.) - at the beginning of manufacturing - for assimilated series production	1450 370	1300 260

Roadmap and vision - The nearest perspectives of upper stage LRE development is modernization of launch vehicle “Soyuz” (the third stage) by replacement of engine RD-0110 with the new engine RD-0124. In the following table it is possible to make a comparison between performance for both engines.

Main characteristics	*Engine RD-0110*	*Engine RD-0124*
Engine cycle	Open	Closed
Thrust in vacuum, kN	298	294
Specific impulse in vacuum, m/s	3154.8	3518.2
Pressure in the combustion chamber, MPa	6.8	15.53
Duration of operation, s	250	300
"Dry" weight, kg	408	460
Height, mm	1575	1575
Diameter, mm	2240	2400

RD-0124 increased performances are due to its oxygen-rich staged combustion cycle. At the same time using energetically efficient cycle will require the application of new structural materials, technological processes and exact compliance with manufacturing methods that also leads to increase the cost of engine development. The engine RD-0124 was designed in 1994-1995 under concurrent engineering methodologies and since March 1996 the engine is close to finish the development phase.
Strategically the development of new engines in the 2020 timeframe scenario should be compliant with the main requirements for LRE upper stages, which are:

- high reliability and safety of operation increased by a factor of 5-10;
- reducing approximately by half the work cost within the life of operating engine life (development, manufacturing and operation)

2.8 GREEN PROPELLANTS (FiatAvio)

Scenario - Monopropellants are toxic right now, so we have to solve the equation:

Toxicity = Storage and handling costs

This has prompted the research of possible "green monopropellants". So the trend for the future is the replacement of hydrazine by "green propellants".
We have two separated areas in this context with applications on ELV, RLV, Main stages, Upper stages, OTV:

- MONOPROPELLANTS: H_2O_2 (85 to 98 wt-%), Ternary mixtures using HAN, ADN, HNF with water
- BIPROPELLANTS: H_2O_2-Kerosene, LOX-95%Ethanol

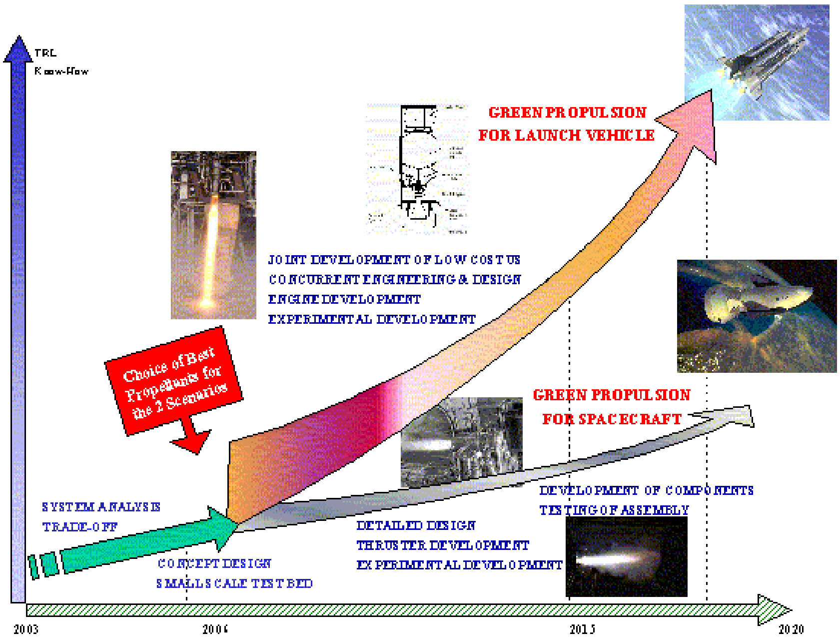
Key technologies - Main benefits and advantages of HAN are related to lower toxicity (13.6 times less than Hydrazine), higher density (1.4 times more than Hydrazine), high Isp respect Hydrazine (+ 19 s) and the elimination of SCAPE (Self-Contained Atmospheric Protective Ensemble). In Europe only LACCO (France) is working on HAN.
Due to trend of H_2O_2 to spontaneous decomposition, tests and development seems to be affected by low interest. Nevertheless due to combustion chamber temperature (lower enough to reduce thermal loads) it is recommended to perform further studies for future applications on LVs. Other advantages are: injection stability margins, simpler thermal management, low-cost tech.
Key technologies are:

- Propellant formulation and characterization
- Catalyst bed (one of the most important issue for mono-propellants)
- Propellant compatibility and management
- Manufacturing techniques & technologies

Development plan and estimated effort - H_2O_2 propellants falls in the area of liquid rocket engines (synergy is applicable). First effort: define operational and technological requirements to preliminary design stage. As regard HAN technology (which is a USAF military application) it is difficult to evaluate development cost. Anyway we suggest to investigate HAN (and similar alternatives) in order to prepare Europe for future applications. An effort of 1.5 M€ per year is considered for the first four years, with a small scale test facility (3 M€) to be used for propellant characterization and testing.

Roadmap and vision - Below a roadmap for Green Propellants is depicted.

Suggestions and recommendations - Non-Toxic OMS/RCS will provide substantial benefits to many future programs (enable future low-cost space vehicles and will reduce cost / risk). We suggest to begin with a preliminary phase in order to demonstrate feasibility of Non-Toxic OMS/RCS. Final task will be applied to be implemented on a variety of vehicles and missions, not limited to RCS/OMS (like Shuttle and RLV). Also we outline that if successfully development of HAN in US will occur, Europe should have some problems in maintain its role due to increased obsolescence of its storable propulsion systems. As result synergies at European level are strongly recommended in order to reduce risk and cost of propulsion development phases.



2.9 GREEN PROPELLANTS (Keldysh Institute)

Scenario - The term “ecologically friendly” is not strictly defined. This generally accepted notion is associated with the amount of the possible action on the "environment" such as flora, fauna, air atmosphere, water springs and human organism. From this point of view rocket propellants may be classified by ecological friendliness, because of its effects on the human and environmental objects at all stages of operating: transportation, storage, propellant loading / unloading, ground testing of LREs and their units, possible malfunctions of PSs.
Ecologically friendly propellants for LRE are the following:

- Oxidizer: liquid oxygen and hydrogen peroxide;
- Fuel: hydrocarbon fuel of oil origin, hydrogen fuel, liquefied natural gas or pure methane, as well as alcohol (methanol, ethanol, …).

Key technologies - Enabling technologies are mainly related to propellant manufacturing, management and operations. Anyway we have to take into account of propellant characteristics:

- Liquid oxygen is mostly ecologically friendly. Its minimum ecological effect is defined by the significant content of native free oxygen. Its cryogenic state may exert only restrictedly local action on environmental objects by break down of air-tightness of reservoirs and pipelines in emergencies.
- Liquid hydrogen should be also classified as an ecologically friendly propellant. Its ecological hazard is also conditioned by its low temperature, as well as by the probability of ignition in emergency spreads.
- High-concentration H2O2 used as an auxiliary propellant in LRE may exhibit chemical activity in direct contact with organic components of environment - plants, skin, mucous membranes of man and animal. Its action on air atmosphere and water springs is much lesser. However its toxicity should be take into account.
- Natural conditions of environmental objects are restored rather quickly upon the ingress of propellants listed. Hydrocarbon fuels are less toxic, and ethanol is least toxic among them. Fuels such as kerosene, methane and LNG have approximately the identical toxicity, however methane and LNG being in cryogenic state evaporate rapidly on the ingress in environmental objects and dissipate to the atmosphere. Kerosene and its pairs may be present for an extended time in ground, water and atmosphere.

It should be noted that ecological hazard of liquid propellants may occur during all the stages of operations.

Suggestions and recommendations - Based on consideration of public literature sources, the two main lines of Green Propellants LRE progress can be outlined as follow:

- LRE for expendable launchers on both modified engines and new development; the use of LOX-kerosene propellant in zero and upper stages, as well as of LOX-LH2 propellant for upper stages and boosters;
- LRE for future propulsion systems, which major requirements are related to reliability, safety and competitiveness; application of oxygen-methane propellants for reusable LREs and of oxygen-hydrogen propellant for upper stages and boosters.

2.10 ADVANCED S/C PROPULSION (Edotek)

Scenario - Many developments have been applied in the past, resulting in updated methods of propellant gauging, new tank materials, thruster, filter and valve material and design, and optimised subsystem layouts. But these developments have done little to change the overall philosophy behind these designs. Today, there is no doubt that further improvements in subsystem architecture and component design may be necessary, especially as new materials and methods have made traditional approaches invalid.
Bi-propellant systems and dual-mode systems may be improved, both in mass terms and efficiency, by incorporating a combination of new devices; by removing, or miniaturising, hardware; by reshaping to fit otherwise redundant spaces; or extending the roles of components to include dual or triple mode activities. The goal is the improvement of existing technology or the introduction of new technology while improving system performance or reducing system cost.

Key technologies - Key technologies for spacecraft propulsion are related to light-weight tanks, low-cost tanks (e.g. MAN spin-forming), low flow-rate pumps and ceramic chamber "high-performance" engines.
Pumps applied to spacecraft allow:

- Elimination several high pressure, high mass, high cost, components
- Delivery of controlled and optimised propellant supply to the thrusters (increased performance, increased payload mass, increased thruster life)

Also we outline that Europe has a significant lead in pumps (work performed at CSTM/CNES and Volvo).
Improve engine efficiency by use of ceramic combustion chambers for liquid propulsion systems:

- Higher operating temperature
- Reduction / elimination of fuel- film cooling ("wasted propellant")
- Possibly (?) reduced (energy) heat loss via radiation
- Favourable manufacturing processes; lower production costs and higher reproducibility

Development plan and estimated effort - We are focusing development activities on low flow rate pumps and ceramic rocket engines. Below there are different phases for each one.

- *LOW FLOW RATE PUMPS:*

Phase 1: Evaluate competing pump technologies (thrust levels < 20N and <400N)
Phase 2: Select most promising designs and create breadboard systems
Phase 3: Demonstrate life characteristics based on typical mission profile
Program duration is on the order of 2 years, cost is on the order of 1 M€. Critical development needs include pump seals, motor design, and spacecraft interfaces (power, telemetry, control, fluids, mechanical)

- *CERAMIC ROCKET ENGINES:*

Phase 1: Evaluate ceramic materials with environmental factors (thermal, chemical, mechanical).
Phase 2: Evaluate manufacturing and production characteristics of best identified materials from Phase 1.
Phase 3: Design and build combustion chambers using results of Phase 1 and 2. Conduct testing.
Phase 4: Demonstrate life characteristics based on typical mission profiles.
Program duration is on the order of 3 years, cost is on the order of 2.5 M€. Critical development needs include ceramic material production, chamber manufacturability, nozzle and injector interactions (thermal, mechanical), and spacecraft interfaces (thermal, mechanical)

Roadmap and vision - *For low flow rate pumps:*
Developing propellant pumps for both very low thrust and low thrust applications class will provide a moderate Isp gain (~ 1%) and significant dry mass reduction. Also Isp increase may be enhanced by the ability of new engine designs to be optimized for performance.
Use of pumps de-links the engine operating envelope from the propulsion system; engine life is increased by operating throughout the mission at, or very near, the nominal design point. Finally leap-frog US engine competition providing a significant competitive advantage to European spacecraft manufacturers.
Phase 1 and 2 can be funded immediately with moderate technical risk.
For Ceramic rocket engines:
Developing a ceramic based rocket engine in the 400-1000N class will provide a significant Isp gain (~ 5%) without the need to develop new propellant combinations.
Isp increase is sufficient to significantly impact the mission characteristics of GEO and scientific (to the point of being enabling) spacecraft without major bus modifications.

Leap-frog US low/medium thrust rocket engine competition providing a significant competitive advantage to European spacecraft manufacturers.
Phase 1 and 2 can be funded immediately with little technical risk

Suggestions and recommendations - Developing these technologies we shall improve payload mass fraction, reduce propulsion subsystem cost, leap-frog existing US capabilities.

2.11 PROPELLANTS COMPATIBILITY (Edotek)

Scenario - By necessity, all propellants are chosen for their chemical reactivity. Generally, the most reactive substances make the best propellants, but, these are also likely to react with any of the materials used to construct the propulsion system, and all related hardware (e.g. GSE).
Major problems in the past with "compatibility" issues; need to try to avoid similar problems with the Next Generation propellants.

Key technologies - Next Generation Propellants can be listed below:
(i) the nitrogen salts in aqueous solution: HAN, HNF, ADN,
(ii) "green oxidisers": HTP, O2, nitrous oxide,
(iii) "green fuel": alcohol
Major focus on "green" propellants", while objectives are the reduction of the high costs associated with toxic propellants, and to obtain improved performance (specific impulse).

- *PAST EXAMPLES:*

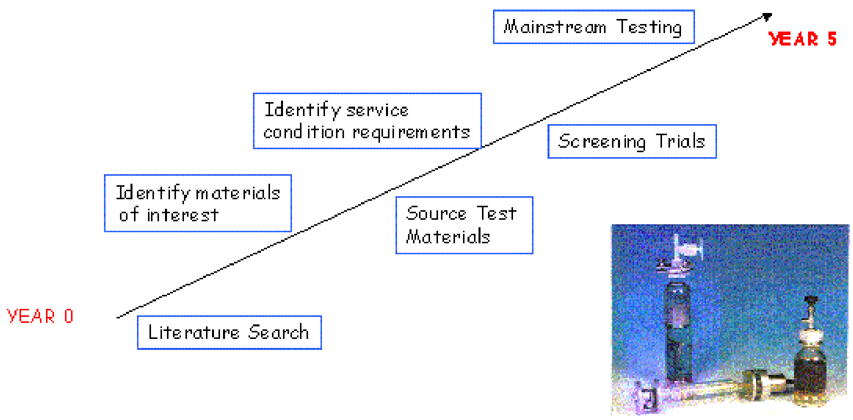
"Flow Decay" problem with steels and NTO oxidiser
Stress-Corrosion Cracking with titanium alloys and NTO oxidiser
Thruster poisoning by carbon and silica in hydrazine

- *LESSONS LEARNED:*

Previous studies of compatibility (lack of appropriate Test Methods and Conditions)
Very often it was the presence of trace impurities in propellants which caused problems

Development plan and estimated effort - Extensive data is already available for some propellants, but severely lacking for others. Where data is lacking, we need to undertake new laboratory testing , using carefully developed standard test methods / conditions. Need to establish valid technical specifications for "new" propellants, especially wrt chemical composition & impurity content. Coordination through ESTEC is recommended. Make use of lessons learned in the ESA's "NTO Chemistry Study" (from 1988 to 1994 with a budget of about 250 k€). Successfully established a comprehensive database for NTO, identified optimum conditions for use of MON1 and MON3 oxidisers.
Also provided a proven strategy and technical approach for compatibility test programs.

Roadmap and vision - General strategy is to establish a European co-ordination panel, after that to formulate e European propellant specification and finally to devise European compatibility test standard. Below there is a proposed roadmap for the development of a specific propellant.

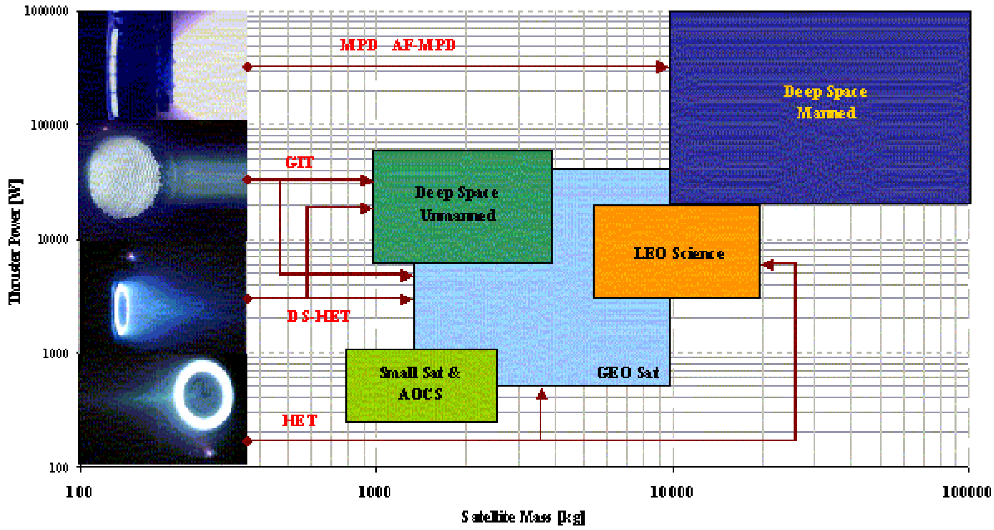


3. ADVANCED ELECTRIC PROPULSION

In this section we will discuss about high power electric thrusters, such as Hall-effect, double stage Hall-effect, gridded ion and applied-field MPD.
A very important issue about electric propulsion is the possibility to make some kind of synergies between different electric propulsion systems. Common key technologies are the following:

- Power Generation: Solar (up to 20-30 kW within the next decade), Nuclear (from 50 kW to several MW, not before 2015).
- Conditioning & Distribution: High Power PCU (Vd = 100-10000 V, I = 10 A - 10 kA), High Power FU (improvement in plasma stability and EMI reduction), High Power Harness (high insulation, low EM emission, thermal and fatigue resistance).
- High Performance Test Facility: Performance Characterisation phase, EMC/EMI compatibility test phase, Qualification phase, Low background pressure (5e-6 - 5e-5 mbar), Large cryopumping stages (PS>250000 l/s), Large chamber diameter (> 4 m).
- Cathode / Neutralizer: the problem of cathode duration could be reduced by separating ionisation and acceleration processes. Great effort is necessary for reliable, durable high-current cathode design.

A general roadmap about EP applications is shown below:



3.1 HIGH POWER HALL EFFECT THRUSTERS (Centrospazio)

Scenario - The accelerating process in a Hall Effect Thruster (HET) is based on acceleration of ions by the self-consistent electric field created in the quasi neutral plasma by the electron current flow pattern induced by the Lorentz force. Main applications are: Telecom Sat Station Keeping & AOCS, Orbit topping, End of life de-orbiting, Unmanned Interplanetary missions. As regard performance we consider the following:

- Power 10 - 50 kW
- Thrust 500 mN - 2 N
- Isp 1800 - 3000 s
- Efficiency 0.5 - 0.65
- No grids, few subparts
- Low operating voltages (<1000 V)
- High Thrust to Power ratio
- Heritage from Russian flight experience

Key technologies - A focused list of key technologies is shown hereinafter.

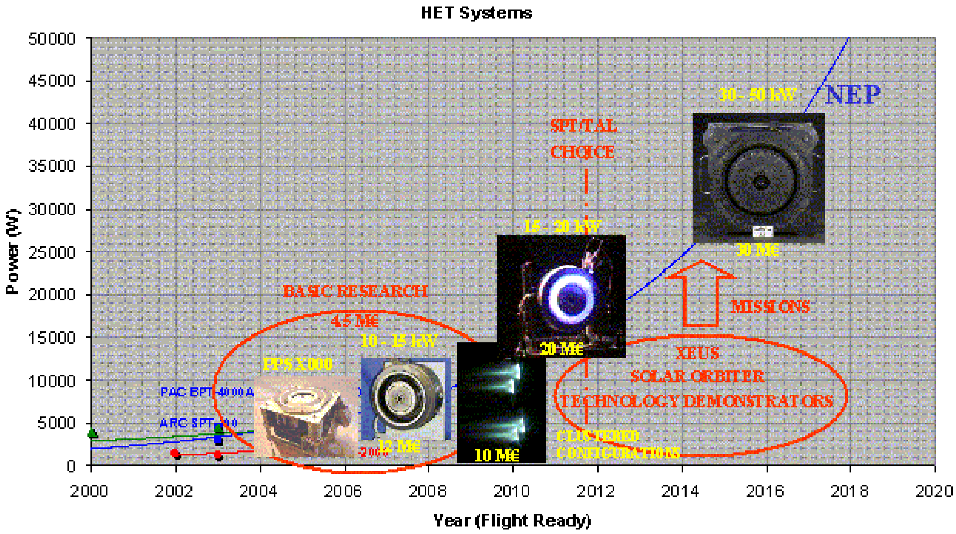
- Plasma Physics & Discharge Channel Dynamics
- Discharge Chamber Advanced Materials
- Magnetic Configuration & Materials
- High Current Cathode/Neutralizer Technology
- Electrical Subsystem (PCU, FU, harness etc.)
- Test Facilities & Diagnostic Techniques Availability
- S/C Integration (Contamination, EMI, EMC etc.)
- SPT/ TAL Comparison
- Clustered Configurations

European competence can be summarized on the following areas: Theoretical and Numerical Investigation, Thruster and Critical Subparts Design, Subparts and Subsystems Building, Testing, Performance, Characterization and Qualification. Collaborations with US and Russia are on-going but not essential.

Development plan and estimated effort - We have several areas of investigation to be considered for future development plans: Plasma Physics & Discharge Channel Dynamics, Discharge Chamber, Advanced Materials, Electrical Subsystem (PCU, FU, harness, …), Cathode Technology Development, Magnetic Configuration & Materials, and Test Facilities Availability. Each of them has been included in the following development plan:

- Design Tool Development: 1.8 M€ (2003-2005)
- Critical Hardware Items: 2.5 M€ (2003-2005)
- High Power Thruster 20-30 kW: 20 M€ (2006-2011)
- Very HP Thruster 30-50 kW: 30 M€ (2011-2016)
- Cluster: 25 M€ (2006-2012)

Roadmap and vision - Below a roadmap for HET Systems is shown.



Suggestions and recommendations - The power available on-board of the S/Cs is quickly growing and it's expected to reach about 20 kW within the next 5 years. Thus the HPHETs represent a very interesting options as primary propulsion system. Many different commercial and scientific missions have been proposed covering the range 5-50 kW and asking for HETs because of their peculiar characteristics such as reliability, thrust range, specific impulse, efficiency and throttling capability which make the HET ideal for LEO/GEO applications. Due to the large efforts spent worldwide from USA to EU and Russia, and the very promising commercial applications the development of flight qualified models of HPHET is expected within next 5-10 y.

3.2 DOUBLE STAGE HALL EFFECT THRUSTERS (Centrospazio)

Scenario - De-coupling of the typical ionisation and acceleration processes of a Single Stage HET into two stages using an additional electrode between the anode and the cathode/neutralizer. Main characteristics:

- Power: 1.5-50 kW
- Isp: 1000-4000sec
- Thrust: 100-2000 mN
- Efficiency: 35-75%

Motivations for pursue such a technology: High Flexibility for what concerns the Isp throttling (1000-4000sec) to optimize each mission's phase (e.g. orbit raising, station keeping, etc.). Main applications are related to GEO Telecom Satellite, Leo Telecom/Remote Sensing Satellite, Scientific exploration.

Key technologies - Key technologies foreseen for DS-HET are related to the following main areas:

- Thermal design: Thermal stress and cracks of the discharge chamber, Magnetic circuit saturation, Overheating and insulation loss of the coils, Heat loads towards the S/C
- Magnetic design: Choice of suitable magnetic materials (e.g. Ni-Co), Topology of the magnetic field divergence of the plume, Thermal design, Lifetime, Erosion of the discharge chamber

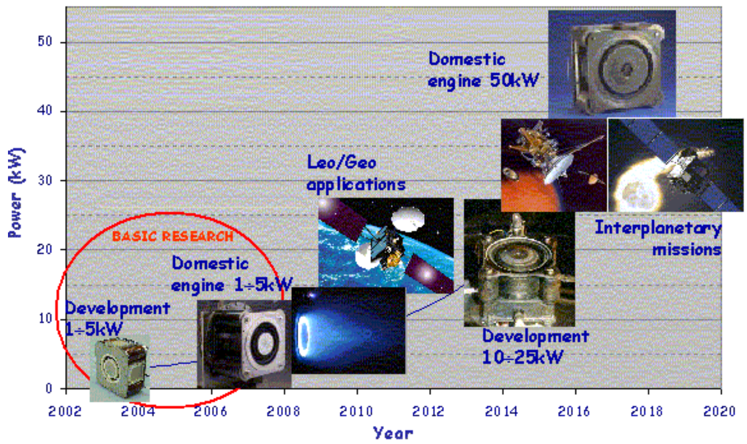
- Discharge chamber: Subjected at erosion of the walls, Fragile material, Must have high thermal conductivity, Must have high thermal emissivity, Must bear high thermal loads
- Intermediate electrode: Choice of the IE (Hollow cathode, low-work function material or second anode), Integration inside of the thruster, Optimization of the voltage
- Spacecraft-thruster interaction: Surface contamination/erosion/charging by backsputtering, EM interaction between thruster (electric circuit) or plasma beam with the S/C bus or payload electronics and telemetry or telecommunication signals

Discharge chamber seems to be not critical due to heritage of both Russia and USA (not acquired by Europe).

Development plan and estimated effort - Development plan is focused on both design and testing activities; four areas of investigation are covered: thermal design, magnetic design, discharge chamber and intermediate electrode. Efforts and timeframe are shown hereinafter.

- Design Tool Development: 1.15 M€ (2003-2020)
- Critical Hardware Item: 2.45 M€ (2003-2020)
- DS-HET at Low-Power 1-5 kW: 6.5 M€ (2003-2018)
- DS-HET at High Power 10-50 kW: 9 M€ (2006-2021)
- Micro DS-TAL: 4 M€ (2004-2020)

Roadmap and vision - Below a roadmap foreseen for DSHET is depicted.



Suggestions and recommendations - The DS-HET technology is of great interest for LEO and GEO applications and with the growing of the power on-board also for interplanetary missions. However the maturity of these thrusters is low, because, until now, large part of the efforts are directed to the Single Stage - HET. Also the qualification phase it isn't predictable before the next fifteen-twenty years.

3.3 HIGH POWER MPD THRUSTERS (Centrospazio)

Scenario - Magneto Plasma Dynamics Thrusters (MPDT's) are high thrust and power densities devices. For this characteristics together with the simple and robust design and the possibility in principle of using a large variety of propellants (pure gases or mixtures and alkali metals), MPDT's are favourably considered for exploiting important missions, as orbit raising and maneuvers of large satellites and ambitious interplanetary missions, like the manned Mars mission. Unfortunately MPDT's with or without an external magnetic field born as very high power devices with performance optimum at power levels from 100 to 1000 kW and above. The recent renewed interest in the on-board nuclear power generation has pushed ahead the research on the MPDT's technology. On the other side studies are on-going to scaling down the operating power level (few tens of kWs) of these thrusters for near-terms, near-Earth application. Typical performance are:

- Processed power: 100 kW - 10 MW
- Thrust level: 1 - 100 N
- Specific impulse: up to 5000 s
- Thrust efficiency: 45%
- Propellant: gases (Ar, He, H2, N2, N-H), alkali metals (Li)
- No neutralizer
- High power and thrust density (10^8 W/m2, 10^5 N/m2)

Key technologies - There are several key technologies associated to AF-MPDT, main areas we have considered are the following:

- Thruster technologies (efficiency concern): it is related to MHD instability (new electrodes configuration, gas type/injection mode, magnetic design, active control)
- Durable cathodes (lifetime concern)
- System level, which is related to Power bus, PCU and Propellant storage/feeding system (Li, H2)

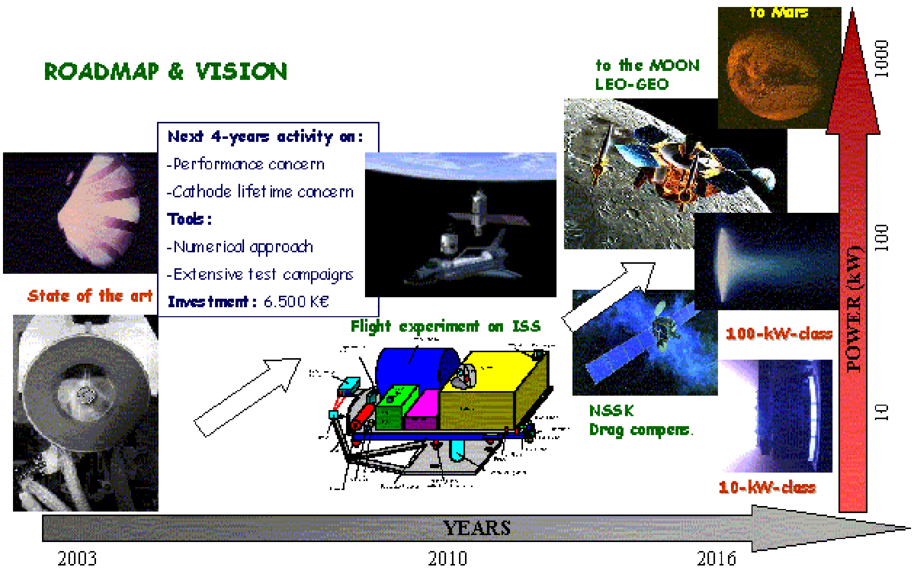
Development plan and estimated effort - For the efficiency concern the activities we have considered are: Study on plasma phenomena (models and diagnostics), Performance/scaling laws, Investigation on propellants (mixtures), Investigation on innovative designs. As regard the lifetime concern we have considered: Failure modes, Cathode operation model, High-power scaling of low-current design, Investigation on innovative designs (Multichannel hollow cathode), Short life tests.
Development plan for such an area has been proposed according to the following scheme:
- Mission studies: 0.4 M€ (2003-2007)
- Study of Performance: 3.2 M€ (2003-2007)
- Study of Lifetime cathode: 2.7 M€ (2003-2007)

Is the AF-MDP thruster worthwhile? If YES:
- High power cathodes: 1.5 M€ (2007-2009)
- 10-20 kW class thruster: 4.25 M€ (2007-2017)
- 100 kW class thruster: 6 M€ (2007-2018)

Also Magnetic circuit development and Study on clusters shall be considered for development phase.

Roadmap and vision - Below is the roadmap foreseen for HP-MPD thrusters.

Suggestions and recommendations - For some interplanetary and manned missions, MPDT's are basically the only possible option among the electric propulsion concepts, since their high thrust level allow for tolerable trip time. Also collaboration with non-European subjects (RIAME-MAI, JPL, GRC, …) should be encouraged.



3.4 HIGH POWER GRIDDED ION ENGINES (Centrospazio)

Scenario - Gridded Ion Thrusters (GIT's) have been one of the most widely studied, further developed and successfully exploited electric propulsion systems since their initial conception in the 1950s. GIT's have been seriously considered for spacecraft propulsion since the 1960s: due to their potential for providing both high exhaust velocities (>25,000 m/s) and high efficiencies (>60%), ion propulsion is well suited for primary propulsion for planetary missions requiring high ΔVs. However the market penetration of GIT's for near-Earth missions has been dramatically falling in the last few years, mainly because of the many advantages provided by the simpler Hall-Effect Thruster for this type of application. Nevertheless GIT's are still the preferred choice for deep space science missions; low-power systems (0.5-2 kW) could be used with small spacecraft to perform

deep-space exploration missions with a small launch vehicle or piggy-back launch strategies. Medium power systems (2-10kW) are applicable to rendezvous with asteroids and comets.
The propellant is ionised (by Electron Bombardment or RF excitation) and ions are accelerated by the electric field through a grid system. Typical performance are the following:

- Very high specific impulse: 3000-10000 s
- Very high thrust efficiency: >60%
- Low thrust density: 1-4 N/m2
- Low thrust power density: 10^5 W/m2
- Propellant: Xe, Kr

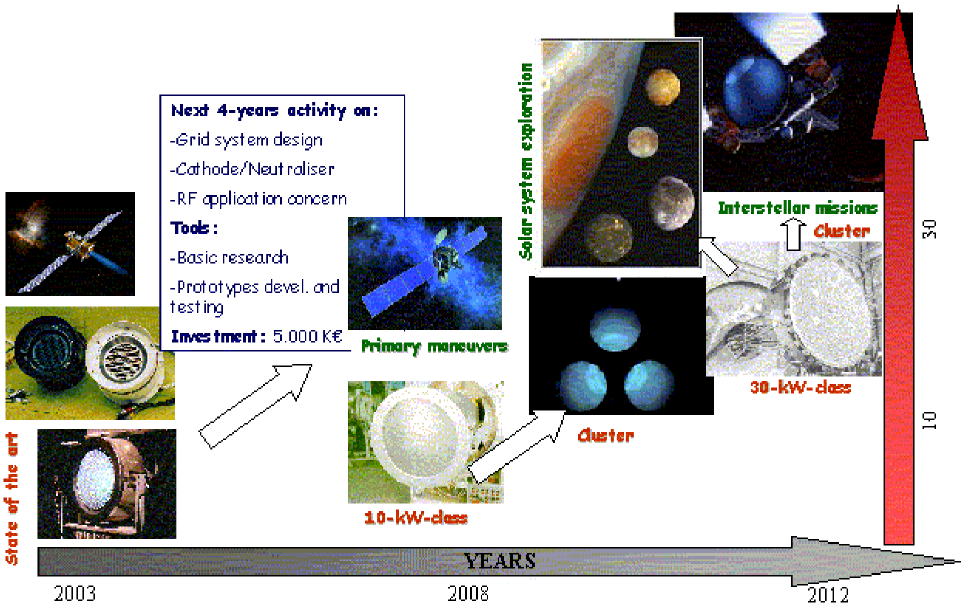
Key technologies - Selected technologies are related mainly to five areas of interest:

- Grid system materials for large diameter, thin structures (which means Strength wrt mission loads, Stiffness and Sputtering resistant) - This is the most critical key technology.
- Neutraliser design
- Durable discharge cathodes (EB)
- Ionisation chamber and screen grid (Insulating material)
- System aspects (High-voltage PCU and RF generator integration)

Development plan and estimated effort - As regard development plan a proposed list of activities and related effort is shown below:

- Mission studies: 0.3 M€ (3 years)
- Study on candidate propellants: 0.2 M€ (2y)
- Grid System: 1.6 M€ (3y)
- Critical components: 3 M€ (3y)
- Mid-power thruster 5-10 kW: 7.5 M€ (5y)
- High-power thruster 30 kW: 12 M€ (6y)
- Cluster: 5.5 M€ (3+ y)

Roadmap and vision - Below there is the proposed roadmap for the HP-GIT technologies.



Suggestions and recommendations - The proposed development plan for high and very-high power GIT's is just preliminary, but anyway it clearly indicates main topics to be investigated and developed.

4. NUCLEAR PROPULSION

In this section we will report about nuclear propulsion, such as VASIMR, NEP, NTR and Rubbia's Engine.

4.1 NUCLEAR PROPULSION (DMA)

Scenario - Nuclear Propulsion scenario is different depending from country and international rules.
- US: Nuclear System Initiative? 'Prometheus' 1 Billion $ in 2002 and "more than expected" in 2004
- Russian Federation: more than 36 power reactors (not RTG) in orbit now
- UN: Fission Materials Current Restrictions, UN Principle 3
  Reactors can ONLY use enriched 235U fuel
  Precludes 242mAm, 233U, 245Cm, 244Cm, and other fissile materials
  Recommend that reactors use materials consistent with safety, cost, & operational factors
  May be operated in LEO
- World: Coal-fired power plants release 50 T U235/y

It should be outlined that nuclear reactors are not the same as weapons.
Nuclear Propulsion has been studied since the 50s in US and USSR: NERVA and Internal/External Pulse Propulsion (Project Orion). From concept scenario point of view we have today several technologies:
- MITEE (US): based on PBR Technology, latest is electro-thermal (NETR) hybrid
- FPCR-MHD (US): Liquid/gaseous fuel UF4 (NETR), possible coupling with MPD/VASIMR
- Rubbia (EU): Fissioning Am242m Layer (NTR concept)
- Inductive Nucleothermal (Dujarric, ESA): NER, under study

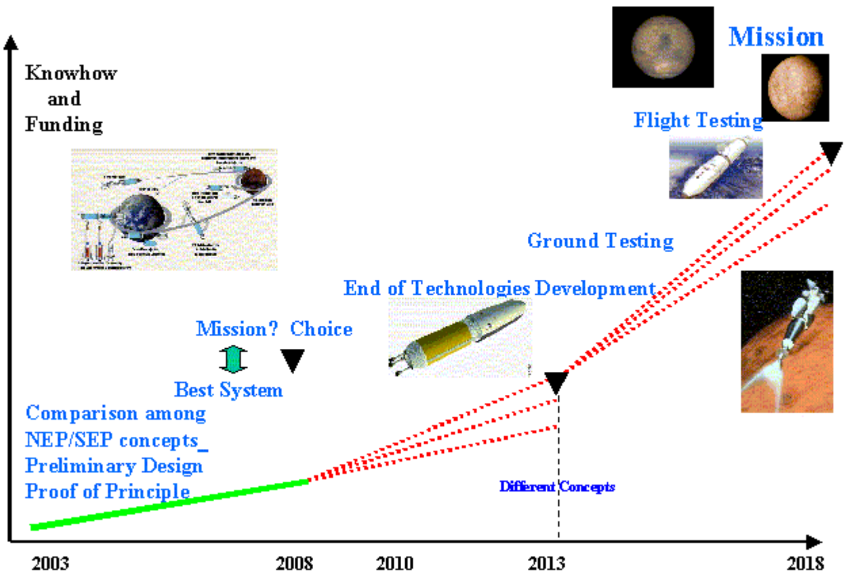
NEP or/and NETP (hybrid) concepts look most promising. For example a hybrid mode can be applied on several mission phases ('Electric' mode: high Isp, low Thrust; 'Thermal' mode: low Isp, high Thrust).

Key technologies - A list of selected enabling technologies is shown below:
- Nuclear Electric coupling:
  high power PCU
  high power generators
  compact space radiators
  compact heat exchangers
  superconductors (and cryocoolers)
- Radiative HT Knowhow
- Structural and Neutronic Materials
- Shielding and On-Board Safety
- Risk Assessment
- In Space Disposal
- Ground Testing

Europe can play a worldwide role even if most technologies have been developed in the US and presumably for military applications (anyway US TRL is higher than EU).

Development plan and estimated effort - We consider three different periods: short-, mid- and long-term.
- SHORT-TERM: This work will follow up the preliminary report prepared by DMA and will focus on analysis of NP risks (radioactive dose following a NP accident). Total budget: 230 k€ for 1.5 years.
- MID-TERM: 2003-2008 timeframe. The goal is to determine the best system relatively to each class of interplanetary mission (e.g. Mars, Asteroids) using Nuclear-Electric/ Solar-Electric comparison. 1.6 M€.
- LONG-TERM: 2008-2018 timeframe. The goal is the development of a NP system for an interplanetary mission. A rough budget estimate for a NP engine is ~800 M€ (increased by a factor 1.5-2 for hybrid).

Roadmap and vision - Below a roadmap foreseen for Nuclear Propulsion is depicted.



Suggestions and recommendations - Nuclear Propulsion Systems can enable missions (Mars, Europa) hardly practically feasible with chemical rockets. It seems to be one of the most promising propulsion concepts which will enable new space exploration phases.

4.2 VASIMR (DRG)

Scenario - The VASIMR (Variable Specific Impulse Magnetoplasma Rocket) system is a high-power density magnetoplasma rocket, which is capable of real-time exhaust modulation, varying thrust and specific impulse thanks to a constant power throttling technique (CPT).
Engineering & Physics associated to VASIMR technology are:

- High Power density magnetoplasma thruster
- Electrodeless: RF ionization & heating
- Magnetic mirror effect & magnetic nozzle
- Radiation losses: about 20%
- Real time exhaust modulation (CPT technique)
- SE or NE powered

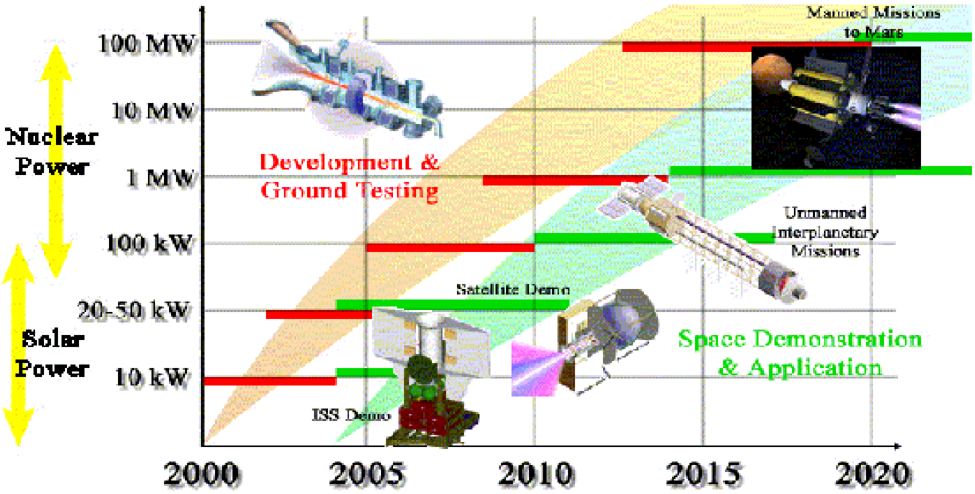
Applications Foreseen:
- On board ISS (25 kWe): attitude control, drag compensation
- Small satellite Near Earth Orbit (10-25 kWe)
- Unmanned interplanetary missions to Mars, Europa, Pluto (50-100 kWe)
- Manned missions to Mars (1-20 MWe)

Key technologies - Key Technologies (American side)
- Ionization process, ICRF heating and magnetic field design.
- Thermal management.
- Engine performance at low Isp (3000-5000 s).
- Engine scalability.
- SC magnetic coils integration.
- Manned/unmanned missions to Mars and unmanned interplanetary missions.
- Ground Testing.

European Capabilities:
- Superconductivity applied on magnetic coils to be integrated into VASIMR flight-experiment.
- Scaling laws for high-power VASIMR demonstration, including both plasma engineering and physics.
- Mission analysis for manned and unmanned space missions.
- SEP or NEP solutions (e.g. VASIMR and Rubbia's engine coupling – Hybrid NTEP

Development plan and estimated effort - Development plan from American side for the next 2 years:
Cost Estimate: ISS DEMO (24 kWe) 20 M$. As regard two years beyond cost estimate:
VASIMR SEP (50-100 kWe) 40 M$
VASIMR NEP (1-20 MWe) 300 M$
Collaboration with USA (NASA-JSC ASPL) is possible and proposed development plan for the next 3.5 years (1.7 M€) from European side is the follow:
- Superconductivity applied on VASIMR magnetic coils (Theor./Num. Analysis)
- Engine Scaling (Plasma Engineering/Physics constraints)
- Manned Mission to Mars analysis - phase A (Power budget (NEP/SEP), Mass budget, Payload definition, Subsystems design, Trajectory analysis)

Roadmap and vision - Below a proposed roadmap for the VASIMR technology is proposed.



Suggestions and recommendations - Suggested activities immediately downstream of Propulsion 2000:

- To establish EU-US collaboration on VASIMR
- To contribute to VASIMR technology qualification and development
- To focus on ESA-NASA space mission (using VASIMR as primary/secondary propulsion system) with common payload, objectives, requirements and constraints
- To create a very strong network to highlight and analyze technology-tasks, common to different EP systems, e.g., Superconductivity, Plasma/Ions flow and diagnostics, Power generation (SEP/NEP solutions), RF, Thermal design
- To set up 2-3 realistic missions (phase A level) as test bench for each EP system, allowing to create a complete case study database.
- To set-up a mission completely dedicated to EP space demonstration

4.3 RUBBIA'S ENGINE (DMA, FiatAvio)

Scenario - The new idea proposed by Carlo Rubbia is to use the high kinetic energy of fission fragments to directly heat up hydrogen gas, to obtain high exhaust velocities, hence high specific impulses. Specific impulses of 2000 to 4000 s could be obtained as compared to 450 s for chemical fuel and ~825 s for NERVA. The preferred nuclear fuel is 242mAm. A round trip to Mars would require only a few kg of 242mAm. This fuel is ideal since its neutronic cross section decreases with T: the fission process is inherently stable. Concept is under study by Italian Space Agency (ASI) sponsorship.

Key technologies - A list of enabling technologies together with associated TRL is shown hereinafter:

Key Technology	*TRL*	
	USA / Others	*Europe*
Production of Am242	7	4
Materials	5	2
Heat removal / cooling	2	1
Ground testing	2	1
Manufacturing techniques & technologies	2	1
Composite combustion chamber	5	2
Safety issues	7	4
Power conversion	2	1
Am metallurgy	4	1
Shielding instrumentation crew from engine and space radiation	8	5
On-board power conversion	5	1

A critical technology is Composite Combustion Chamber (C3); we propose to perform investigations on:

external protection of the C3, application of Am layer on the inner wall, numerical simulation of transpiration cooling process, thermal fluxes and loads estimation. Novel areas to be investigated are related to Superconductive-MPD, Data transmission, Energy accumulator, Electrolysis and On-board power.
Finally, the Rubbia's engine should be seen as a power generator in general. It could be used for Earth orbit activities also (such as ISS, Moon missions, on-orbit Spaceport, and so on). At the moment nobody has experience on Rubbia's engine; after concept validation, a consortium at European level will be recommended.

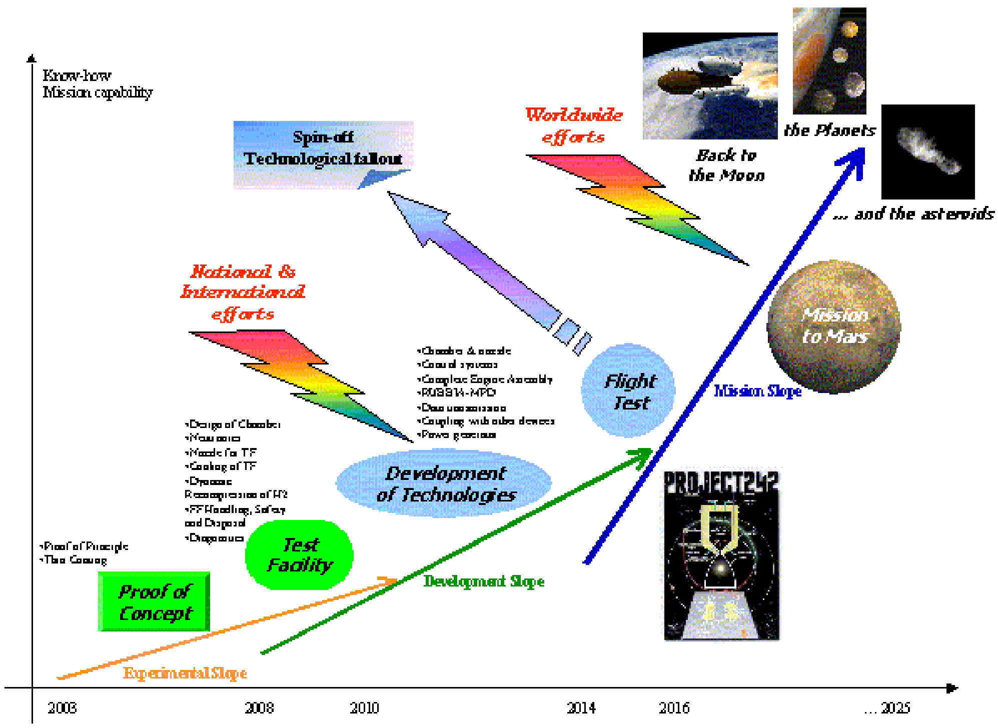
Development plan and estimated effort - Total costs are at this point very difficult to estimate, as they will also depend on the likely coupling between the Rubbia's Engine concept with electric thrusters and on the issue of on-board power generation. Figures of the order of several billion € may be anticipated if Am 242 technology must be developed from scratch. Rubbia's Engine is an innovative and attractive concept; after studying its principles, proof-of-principle tests are now being planned by ASI in Italy. Following this, the first step toward testing its propulsion application is the design and fabrication of a single module of the engine in a ground Test Facility. The complete program lasts 7 years, divided into 3 years for phase A and 4 for phase B.

Phase A has two major subtasks:
- Proof of principle tests
- Thin fissioning coating development

Phase B has seven major subtasks:
- Chamber design
- Neutronics
- Nozzle for TF
- Cooling of TF Dynamic recompression of H2 flow
- Fission Fragments handling, safety and disposal
- Diagnostics

About 10-12 organizations participating in this Project can be forecast. An estimate of overall manpower costs is between 37 and 62 M€. This budget does not include materials and fabrication costs.

Roadmap and vision - Below a proposed roadmap for the Rubbia's engine scenario is shown.



Suggestions and recommendations - Rubbia's engine is a European idea and should be pursued in order to reach a leadership role in such a field. Also this technology can increase mission capability and disclose new missions and has great spin-offs in other areas (industrial power generation and so on)
One result: Four Rubbia's missions for the price of one chemical mission has been estimated!
It is strongly suggested to pursue development of Rubbia's engine, for its wide-range potential applications at least. Mission capability could be proven by an initial development phase in order to perform a concept validation and a preliminary development path.

5. ADVANCED CONCEPTS

In this section we will discuss about advanced concepts, such as electromagnetic railguns, miniaturised propulsion, superconductivity, solar sails, solar thermal, laser, ISRU.

5.1 ELECTROMAGNETIC RAILGUNS (DMA)

Scenario - Railgun accelerators and MAGLEV systems such as INDUCTRAC rely on a ground electric power source, a very attractive feature in that its technology is known and ubiquitous. Electromagnetic railguns replace the first stage of future launchers: Lorentz's force accelerates a sled (sliding over, or on, a rail) accelerating the payload. Basic Advantages are: no mass consumption, fixed installation (low recurring costs) and could increase launch rates by large factors (faster investment recovery, lower cost). Major constraints:

- cost of land area
- raising a vertical tower (2-10 km)
- on-board rocket propulsion to adjust the rail-imparted trajectory
- high terminal speed (10-15 km/s): 7 km/s is historically max speed reached (plasma contact is limiting)
- track length: short track / lower cost, but: more acceleration, stress and power

Key technologies - A list of enabling technologies for both Railgun and Maglev is shown below (including TRL for US and Europe):

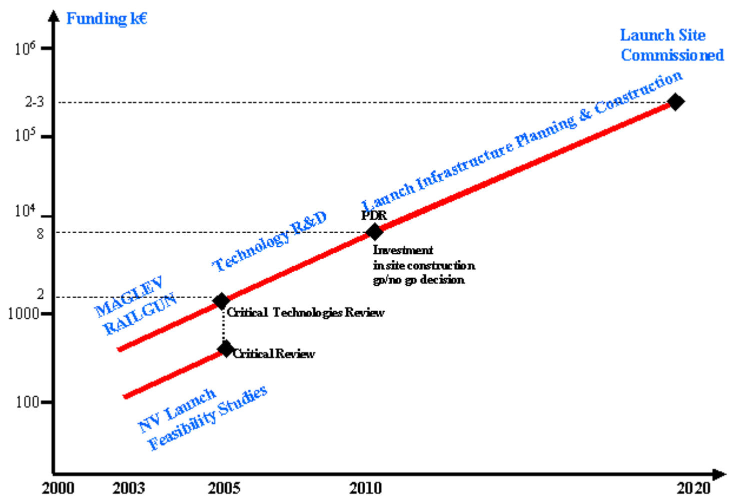
RAILGUNS	US TRL	EU TRL
Accelerator Sliding Contact	4	1
Aerodynamics and Drag Reduction	5	2
Accelerator Braking	6	3
Track and Sled Sizing as a Function of P/L	2	2
Power Requirement and Power System	4	2
Power Switching	1	1
Total Cost Estimate as a Function of Mission	3	3
MAGLEV		
Inductive Magnet Sled/Track Coupling	4	1
Aerodynamics and Drag Reduction	4	2
Accelerator Braking	6	3
Track and Sled Sizing as a Function of P/L	2	2
Power Requirement and Power System	4	2
Power Switching	1	1
Total Cost Estimate as a Function of Mission	2	2

A way of solving some of the track-related problems is to revisit concepts based on vertical or near-vertical (NV) acceleration. NV acceleration worsens initial stresses BUT:
- acceleration typical of reasonably short tracks will be many "g", adding so that weight stress will not substantially affect total stresses
- minimal land requirement
- shorter path through the atmosphere / improves the energy budget

A potential viable and economical solution: the gun shaft may be put underground or undersea shorter. This means a shorter atmospheric path and a lower final speed.

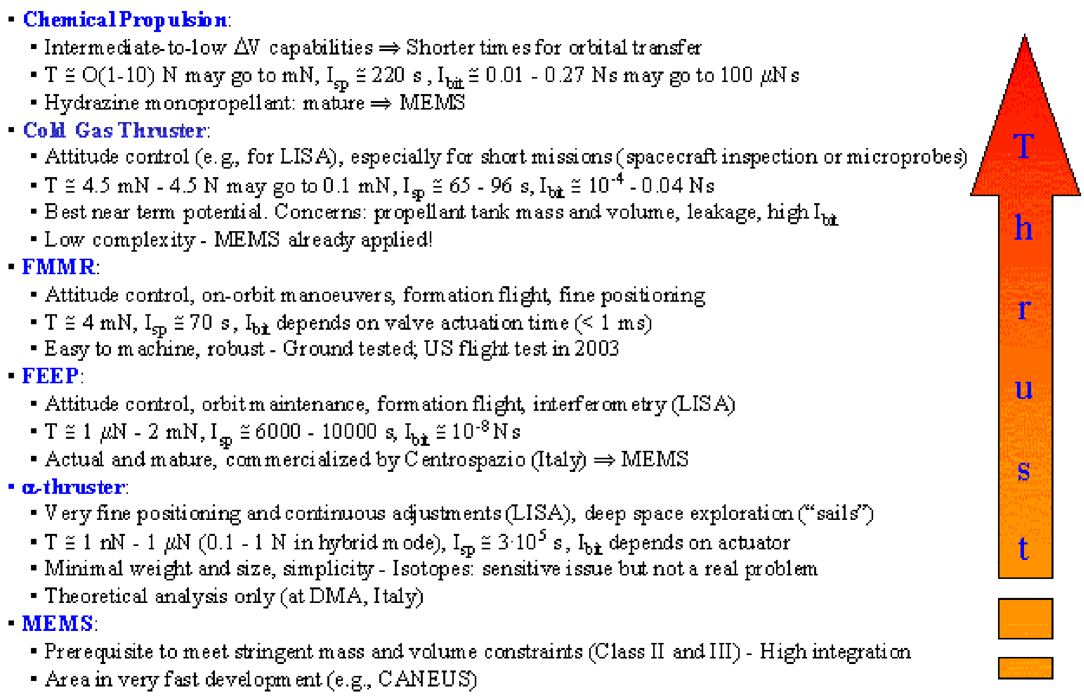
Development plan and estimated effort - Preliminary studies are necessary and will take two years (250 k€).
- Analysis of NV acceleration system (mid-term)
  Goal: Evaluate feasibility of NV accelerators and compare them with traditional railgun
- Maglev/Railgun Technology Requirement Analysis and Definition (mid-term)
  Goal: Have a complete critical technologies review

Roadmap and vision - Below a proposed roadmap for Railguns is shown.



5.2 MICROPROPULSION (DMA)

Scenario - This scenario is focused on several micropropulsion concepts which have as main advantages the following: Reduce payloads mass (microsatellites and constellations) and Reduce mission risks (off-load scientific instruments onto a fleet of microspacecrafts). As regard the markets we have Communications, Satellite imaging, Scientific Missions, Defense, Civil, Entertainment. A brief overview on such a scenario is shown below:



Key technologies - Technology Scenario is represented by:

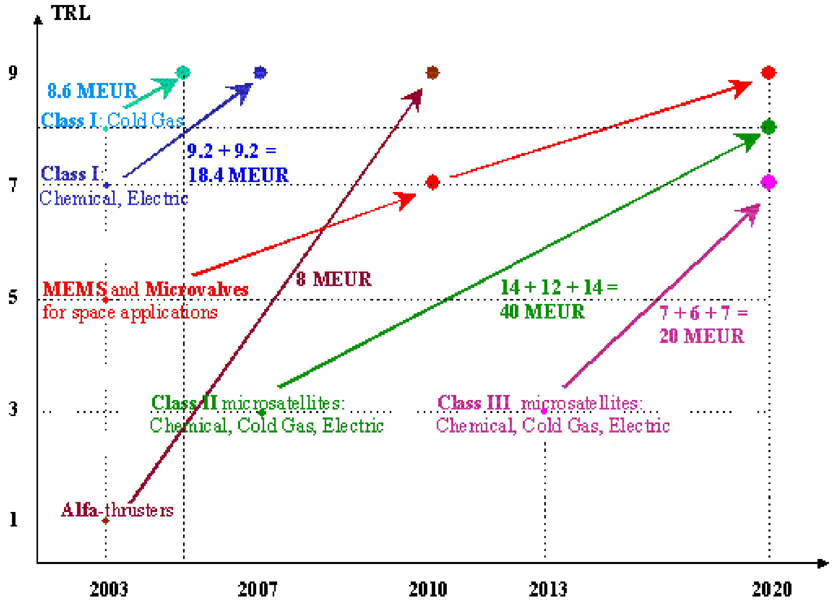
- Microspacecrafts: Class I (5-20 kg), Class II (1-5 kg), Class III (<1 kg)
- Thrust: < O(1) mN for attitude control and precise positioning, O(1) N for primary propulsion
- Ibit: <O(10) µNs
- High Isp important only for primary propulsion
- Bus voltage: 3.3-5 V
- Mini- or MEMS systems
- High level of integration
- Payload cost: 100 EURO/kg

Technologies are related mainly to Materials, Contamination, Valve leakage and Ducts clogging. Anyway below there is a list of selected technologies to be pursued by Europe to acquire leadership in such a field:

- Chemical monopropellant thrusters: new propellants, scaling laws needed, microvalves.
- Cold Gas Thrusters: scaling laws needed, microvalves.
- FMMR (Free Molecule Micro Resistojet): transfer technology from US to Europe. Possible development at Centrospazio (Italy).
- FEEP (Field Emission Electric Propulsion): MEMS emitter arrays
- α-Thrusters: basic theory developed; need feasibility analysis.

For all the systems are required studies / testing on: spacecraft contamination, actuator transient dynamics, optimization with respect to an entire mission, compatibility between MEMS materials and propellants, integration of propulsion and payload.

Roadmap and vision - Below the proposed roadmap for the Micropropulsion scenario is shown. Also on this roadmap the estimated effort activities have been estimated.



Suggestions and recommendations - The choice of micropropulsion system is a compromise between satellite lifetime, safety, costs and resources available. The extent of technology development can have a large impact on mission costs. Actually MEMS is the next future technology.

5.3 SUPERCONDUCTIVITY (DMA)

Scenario - Superconductivity seems to have a broad applications spectrum in terrestrial applications: Magnetic Resonance Imaging (MRI), Nuclear Magnetic Resonance (NMR), Thermonuclear Fusion, Superconducting Magnetic Energy Storage (SMES). Propulsion applications in all EP systems using high B fields are related to:

- GEO telecommunication satellites: station keeping, μ-thrusters and for orbit insertion
- LEO telecommunication constellation satellites: μ-thrusters
- Interplanetary missions (Mars, Europa), integrated with advanced propulsion (e.g., Rubbia's Engine, Nuclear Electric Propulsion)

Main benefits using SC-EP systems are mainly related on high B fields [performance (T, Isp) and efficiency improvement] and Lower mass.

Key technologies - Enabling technologies are related to:

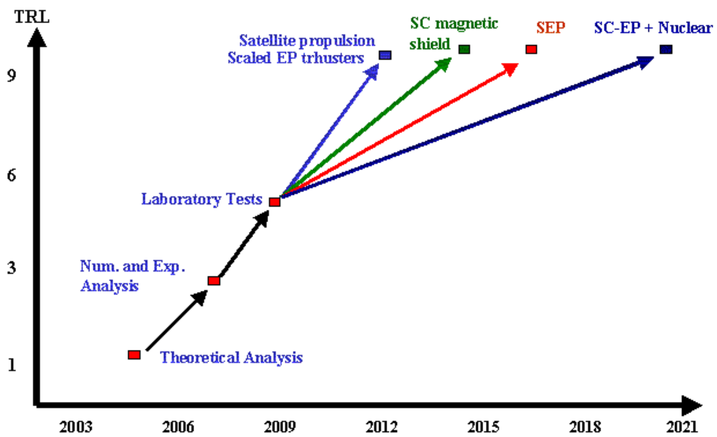
- Dry cryocoolers
- High Temperature Superconducting Materials
- High current switching
- SC-NC interface

Also EU research/industrial capability exists: SCENET (Super Conducting European NETwork), Oxford Magnet Technology (Siemens-Oxford Instruments joint venture, UK), Magnex Scientific (UK): specialist in high field magnets, Ansaldo, Pirelli Cables, Europa Metalli.

Development plan and estimated effort - Short term development plans (2003 – 2006) for the EP systems are focused on Theoretical Analysis, Numerical Analysis and Experimental Analysis.
As regard the timeframe 2006-2020 we have considered the following development plan.

- Laboratory Tests: 2006–2009 / 3 M€
- Electric micropropulsion (Micro-satellites): 2009–2012 / 4 M€
- Satellite Propulsion (Communication Satellites): 2009–2012 / 10 M€
- SC Magnetic Shields (High proton wind missions): 2009–2015 / 20 M€
- Solar Electric Propulsion (Interplanetary missions): 2009–2017 / 42 M€
- SC-EP + Nuclear (Interplanetary missions): 2009–2020 / 274 M€

Roadmap and vision - Below the roadmap for the Superconductivity scenario is proposed.



Suggestions and recommendations - This scenario should be strongly pursued thanks to its commonalties with other concepts such as nuclear propulsion and electric propulsion systems. Also the wide-range perspectives offered by superconductivity should be carefully considered for the future.

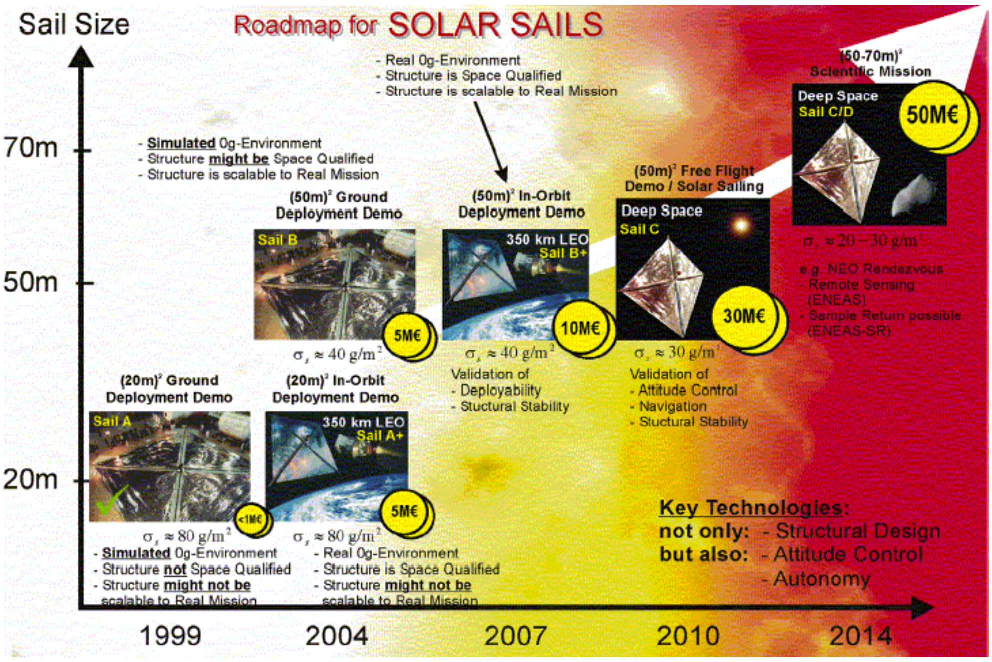
5.4 SOLAR SAILS (DLR)

Scenario - Solar sails are large and light-weight, generally deployable or inflatable, space structures, which reflect solar radiation and thereby utilize the freely available radiation pressure for propellant-free space propulsion. Solar sails provide a wide range of opportunities for low-cost interplanetary missions with large ΔV-requirements, many of which may be difficult or even impossible to be carried out with other types of spacecraft. Based on the experience gained with the ground deployment demonstration of a 20 m x 20 m solar sail, performed in December 1999 at DLR, the future development of solar sails is currently under investigation at DLR and ESA. As a possible next step for solar sail technology verification a space experiment is considered in co-operation between DLR and ESA.

Key technologies - The following list summarizes the identified most critical and challenging technologies:

- building large sails (order of 100m) with low sail assembly loading (around or less than 10 g/m2);
- Carbon Fiber Reinforced Plastics (CFRP) booms
- developing autonomous sailcraft navigation and attitude control (including intelligent S/W);
- dealing with short time-scales for attitude maneuvers in planetocentric orbits;
- keeping sail degradation due to electromagnetic and particulate radiation within acceptable limits;
- establishing long system and component lifetimes (order of 5-10 years);
- solving conflicting pointing requirements for communication, observation and propulsion;
- handling the restricted payload capability
- deployment module

Roadmap and vision - Below a proposed roadmap for solar sail development is shown including cost.



Suggestions and recommendations -

- Asap development of larger booms and sails including space qualification
- Asap development of autonomous navigation and attitude control (incl. SW!)
- Development and demo of (50 m2) solar sail incl. ground deployment demo (space qualified HW)
- In-orbit deployment demo of (20 m2) and/or (50 m2) solar sail [skipping of (20 m2) sail demo is possible but saves not the total € and increases risk]
- Test degradation of sails due to space environment
- Identify and study promising scientific (and commercial) missions with solar sails (in progress at DLR).
- No free-flying solar sail missions in near-Earth orbit (≥ 1000 km altitude) if a controlled de-orbiting can not be guaranteed (space debris!)

If acquired this technology could enable Europe as worldwide player.

5.5 SOLAR THERMAL PROPULSION (DLR)

Scenario - Two main scenarios have been considered for STP.

- Orbit Transfer LEO - GEO: main commercial (possibly military) interest in solar thermal propulsion due to the increased Isp hence ΔV potential combined with acceptable trip times.
- Interplanetary Transfer: STP with or w/o chemical propulsion offers considerably reduced trip times or launch mass savings. – Enables autonomous outer planets capability for Europe by solar power concentration w/o RTG technology.

Key technologies - Enabling technologies are the following:

- Long term cryogenic propellant storage: effective multi-layer-insulation (MLI), thermodynamic vent system (TVS)
- Absorber / receiver assembly: selection of suitable materials for operation temperature above 2000 °C, advanced coatings required, light weight super-insulation
- Concentrator / mirror: rigid, segmented structures (extremely low mass, deployment process), inflatable structures (accuracy/aging concerns, no experience in Europe)
- Pointing and autonomous attitude control: thrust vector control and mirror pointing is extremely demanding for continuos firing orbit-transfer missions, fully autonomous navigation, attitude- and STP-firing-control (verification of adequate software)

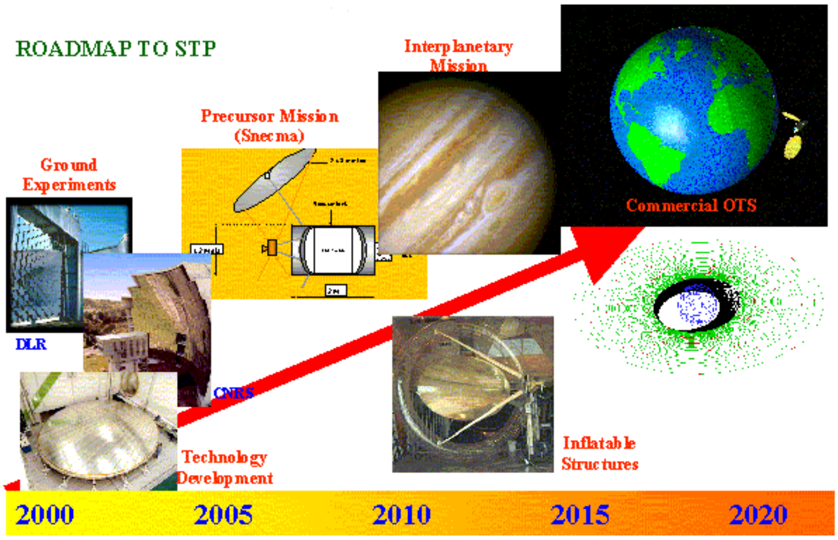
Also we have to take into consideration all major technological synergies, such as:

- Primary mirrors: millimeter wave astronomy, solar energy focusing device

- Absorber / receiver assembly: managing of high temperatures above 2000 °C for other propulsion applications like nuclear thermal, LH2-tank, cryogenic upper stages for interplanetary missions, composite tank technology
- Autonomous attitude control and trajectory optimization: similar requirements exist for other low-thrust orbital transfer missions (e.g. electric propulsion)

Development plan and estimated effort - The development path (2003-2018) is focused on technology development, ground demonstrators and in-flight simulations, while development costs can be considered within five principal areas:
- STP operations: 398 M€
- Space flight experiment: 173 M€
- Ground experiment: 18.2 M€
- Technology development: 16 M€
- System studies / management effort: 28 M€

Roadmap and vision - Below the roadmap proposed for STP is shown.



Suggestions and recommendations:
- STP is a promising technology to reduce specific launch costs for commercial GEO satellites, and to raise performance for some interplanetary scientific missions.
- Technology roadmap focuses on technology development and ground experiments.
- Receiver/Accumulator is on critical path, and therefore this development requires immediate funding.
- Overall financial amount is quite modest.
- Cost optimization is key to commercial success. System studies should address, how much reduced performance can improve STP's commercial competitiveness.

5.6 LASER PROPULSION (DLR)

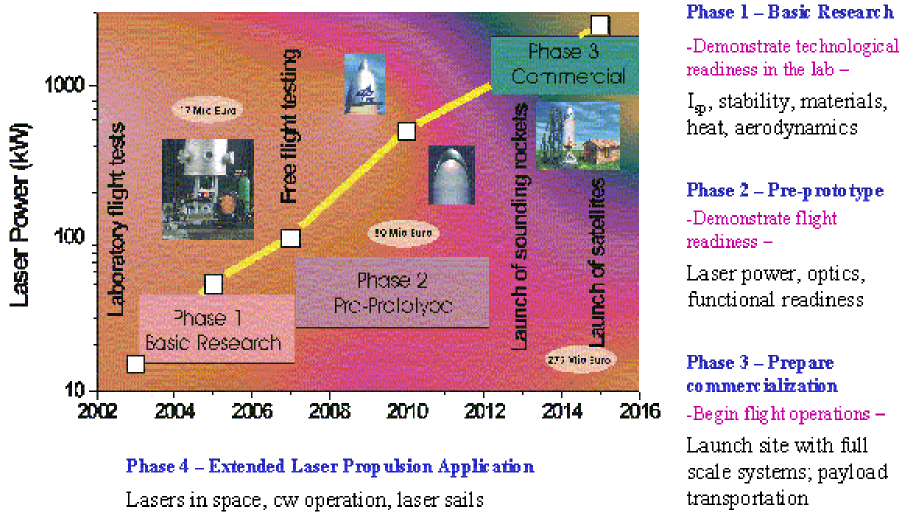
Scenario - Laser propulsion builds upon the following principles:
- Transmission of the propulsive power to the spacecraft from a remote power source (laser) that is in general not located on board of the spacecraft. The laser source may either be located on Earth or in space.
- Raising the enthalpy and thus the exhaust velocity of the propellant to values well beyond those achieved by chemical combustion.
- Propellant can be in any phase (solid, liquid, gaseous) and of any appropriate kind, including air (ram-type) and chemically reactive substances (hybrid propulsion).

Depending on the mission the required power may range from Watts to Gigawatts. However, the transportation of payloads demands Megawatt power level and higher. Continuous and pulsed propulsion are possible and presuppose different laser types. Market scenario is focused on nanosats with payload 5-10 kg and orbit altitude 350 km. Launch price < 5.000 €/kg. The advantages associated with this technology are: High thrust to weight ratio, High payload fraction, Low launch costs, Rapid turn around, Convenient propellants, No atmospheric pollution, Simple thrust modulation.

Key technologies - Enabling technologies are focused on:
- Flyer (Lightcraft)
- Repetitively Pulsed Laser
- Telescope with adaptive optics
- Active Tracking System
- Flight and Attitude Control

Development plan and estimated effort - In the timeframe 2003-2014 four main phases have been addressed:
- Phase 1 – Basic Research and System Demonstration: 17 M€ / 4 years
  Gathering of basic data contd., Technology developments 1st step, Improved model design, Laser power upgrade, Technological development 2nd step
- Phase 2 – Pre-prototype: 80 M€ / 6 years
  Laser upgrade (500 kW), Larger lightcraft, Larger telescope
- Phase 3 – Commercialization: 275 M€ / 4.5 years
  Begin construction of launch site, Install systems at launch site, Launch sounding rockets with small payloads, MW-laser – orbital flights
- Phase 4 – Global laser based infrastructure

Roadmap and vision - In the following roadmap the main development phases are shown.



Suggestions and recommendations -
- Establish a sound data base on possible lightcraft performance data. Understand the thrust production mechanism and losses. Demonstrate a vacuum specific impulse of 600 s in a realistic configuration.
- Identify and quantify the problem of heat management and materials, flight dynamics and stability, attitude control and steerability, and provide solutions.
- Calculate and select possible flight trajectories on the basis of the currently foreseeable pulsed laser development, i.e. the CO2 laser.
- Look into micro-propulsion and initiate basic experiments on thrusters with available laser sources.
- Support research for short wavelength pulsed lasers in small scale experiments.

Finally, why should we develop these technologies?
- New and promising launch technology
- Expand Europe's access to space
- Dual use technology
- First steps done and capabilities available
- Low starting costs – mediocre system costs

International cooperation can be helpful.

5.7 IN-SITU RESOURCE UTILIZATION (FiatAvio)

Scenario - Starting point is about methods for reducing cost in Mars Exploration. ISRU could be the answer:
- We can use resources that already exist on Mars in an innovative approach to reduce the need (and expense) to bring everything from Earth.
- Among these resources are oxygen and nitrogen to breathe and water to drink.
- Propellants can be manufactured.
- Bricks and panels from in-situ rocks may be manufactured to build habitats.
- In short, much needed for life on the new frontier can be produced from local resources.

ISRU can provide a reduction in cost and can increase our capabilities significantly as we develop and expand a Mars outpost. However, using Mars resources can have a major effect on the way we proceed, the cost of the program, its timetable, milestones along the way, and ultimately on whether the program is successful or not.

Key technologies - Enabling technologies are mainly related to the following areas:
- Chemical Plants: Zirconia cell, Electrolysis, Bosch process and Sabatier cycle, …
- Associated Component Technologies: energy power generation system, liquefaction system, filters, control systems, …
- Combustion: combustion stability, oxidizing process of Mg powder
- Power supply for ISRU and ISPU (In-Situ Propellant Utilization)
- Requirements on Materials
- Autonomous controls
- Integrated missions: the coupling with other mission phases is an important issue for ISPU
- Several propellants pair are suitable (H2, CH4, CO, SCO, SCH4, …)
- Use of hydrogen in Sabatier process (from Earth or Mars)

Finally we have to take carefully into account mission constraints: ISRU is not only a propulsion system.

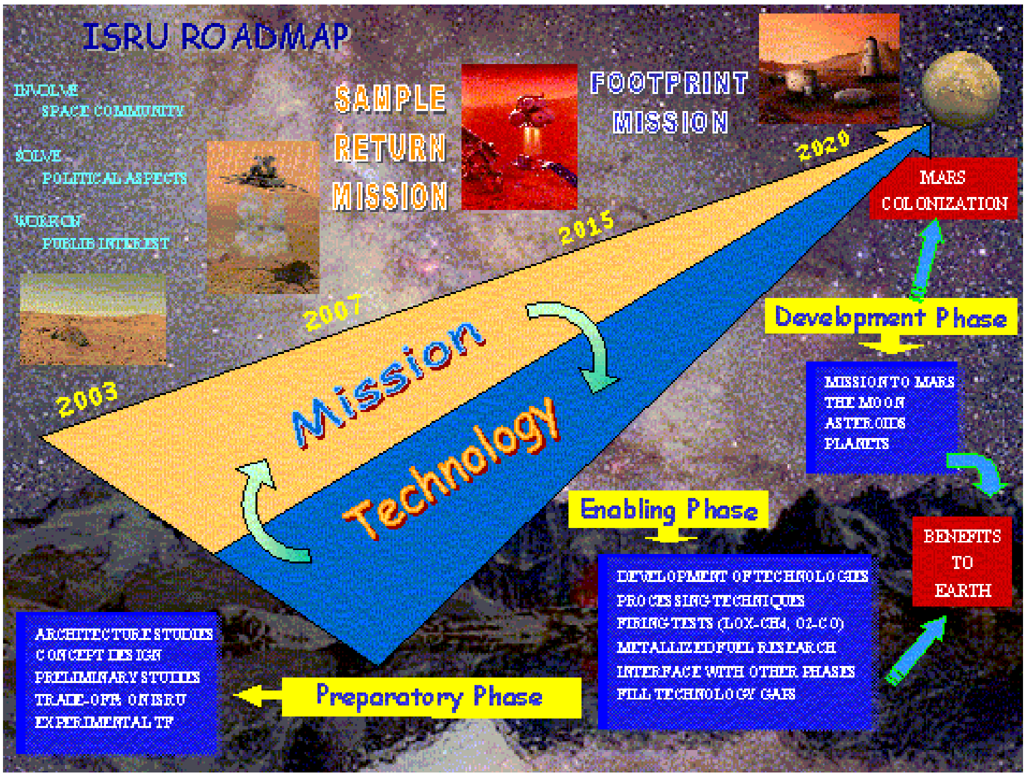
Development plan and estimated effort - Several propellants pairs on-going worldwide. In Europe we could move toward CH4-LOX systems, in order to avoid both overlapping with other programs and the only-one-option case, so benefits from/to LOX-HC programs can occur.
Development costs are very different (ranging from 118 $M to 21.4 $B; cost models are strongly dependent by the mass, the mission complexity and the technological maturity of the project).
A significant amount of technology development in space-qualified ISRU processing systems will be necessary and should begin now! ISRU development by four complementary phases (for a manned Mars mission):
- Architecture Studies (ISRU is directed linked with the whole mission to Mars)
- Concept Design (a lot of technologies are involved and we have to design each one)
- Preliminary Studies (we have to perform concept validation and preliminary analysis)
- Trade-Off on ISRU (propellant pair selection)
- Experimental Test Bench (small scale firing tests of selected propellants)

A Program Preparatory Phase (2.5 M€ / 3 years) is proposed: in this phase one should build-up the knowledge able to develop future technologies and to permit to start with a first mission: sample return from Mars.

Roadmap and vision - The proposed roadmap for ISRU is shown hereinafter together with enabling missions.

Suggestions and recommendations:
- Liquid CO/O2 offers many benefits: CO2 in the Martian atmosphere / safe and storable liquid propulsion / easy to manufacture in a propellant production plant / using today's technology
- LOX-CH4 more indicated for synergies with LOX-HC Programs / excellent for large orbital operations
- Significant technology development will be required before the Mars ISRU architecture can be put into place: small-scale rocket engine test firings as first priority
- Likely need nuclear power systems in many sizes
- Needs for concept design on vehicles and process equipment to arrive at correct answer

From a general point of view we cannot forget the advantages coming from this technology:
- ISRU will be a significant benefit to the Mars Exploration Program
- ISRU could enable a new approach toward the use of local resources
- Novel opportunities on Earth: if one is able to use local resources on Mars, maybe one is able to learn how to use local resources on Earth



6. CONCLUSIONS

Each of the 21 considered propulsion systems has been investigated and assessed, by a European industrial team, in terms of:

- Scenario on which such a concept is involved
- Projected missions foreseen for that technology
- System analysis & requirements related to that concept
- Definition of key technologies, TRL and competencies worldwide
- Focus on European competencies
- Development costs & timeframe
- Rationalization of the final vision in form of Roadmaps

Also, if development plans will be implemented several benefits for Europe will be disclosed, such as:

- Increasing mission capability / flexibility
- Increasing access to space
- European integration and synergy
- Increasing performance and RAMS
- Expanding European leadership in Space Propulsion
- Enabling ISS servicing and technologies
- Spin-off on other areas / increase quality of life
- Enabling new frontiers / disclose new opportunities

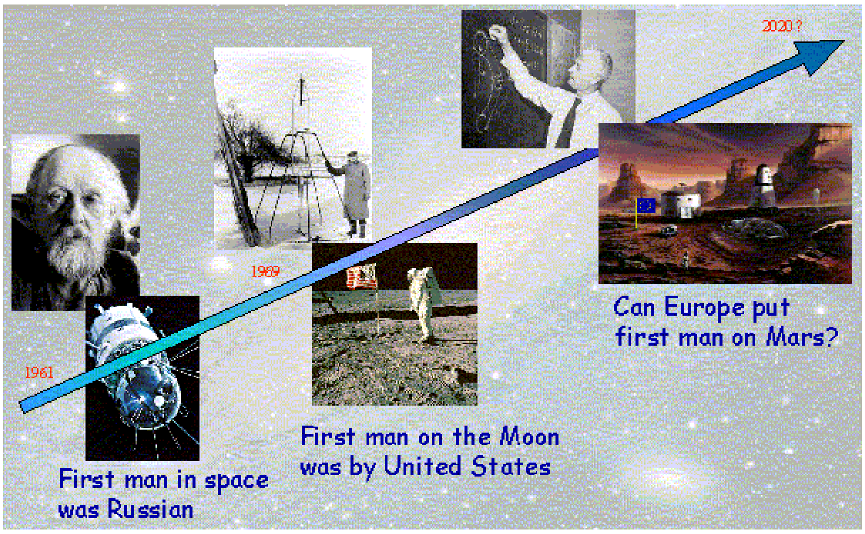
Conclusions and recommendations, which can be addressed at this point, are suggested approaches for future strategy and development paths:

- Synergy between European entities (industries, agencies, universities and research centers) in order to maximize the investment while reducing risk.
- Synergy between Technologies in order to have maximum gain for each investment (i.e. LOX-CH4, VASIMR, Superconductivity, …)

- Wide-range perspectives toward European enrichment in the field of advanced propulsion system development should be targeted.
- Being in the phase of new developments we suggest to involve the new entries in ESA space propulsion community.

Finally there are some open questions, which can be considered as starting point for any future phase:
- How does Europe sustain the leading edge of technology?
- How does we contribute to the evolution/revolution of the Space?
- We will have a European RLV?
- Can we develop new frontiers?
- The most important breakthrough: can we merge aeronautics and space?

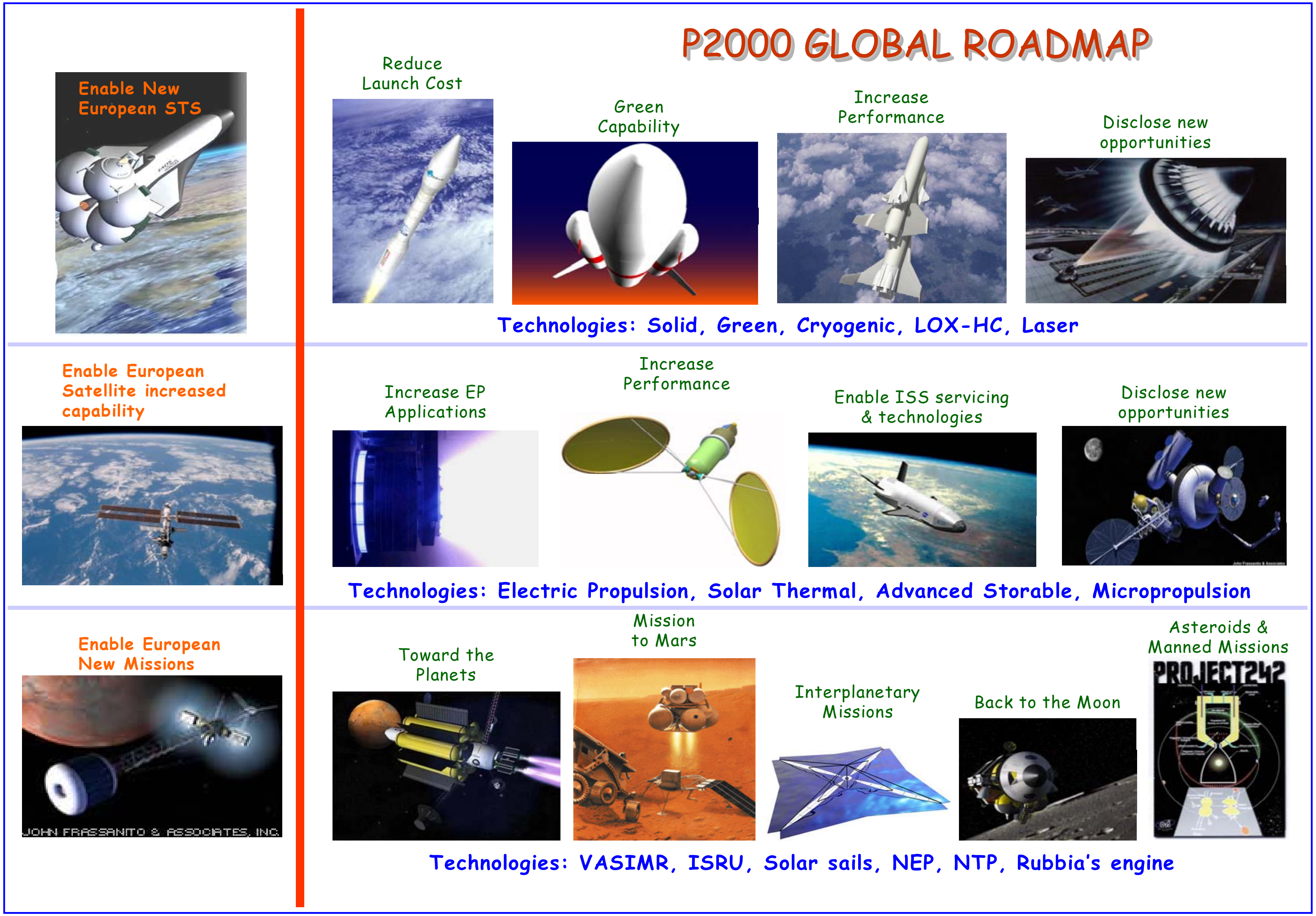
Not only, all the selected technologies from Propulsion 2000 can be used as starting point for new space applications, among them we can cite outer solar system missions, Mars colonization, astroengineering techniques, space tourism and so on. Answering these questions is not an easy task, nevertheless most of the selected technologies are well on progress while other can be considered far away from 2020. One thing should be clear: if we want to realize a 2020 scenario we must to start now, because space is a very complex environment halfway between experimental and pioneering activities! This means that we need to focus hardly our attention on key technologies, RAMS, and testing activities as first priority.
A Global Roadmap on Propulsion 2000 Program at the beginning of the 21st century is shown in the last page of this executive summary (in red the main scenarios, in blue the technologies, in green the strategic goals).



Reference: RAP PRP 10000 Is.1, "Propulsion 2000 Program – Phase 2, Final Report" (four volumes)

Acknowledgements: Special thanks to European Space Agency for its support and suggestions, and to all the people which have been involved on the Program:

Alessandra Negrotti	(DRG, Italy)	German Kalmicov	(Keldysh Institute, Russia)
Monika Auweter-Kurtz	(IRS, Germany)	Giorgio Saccoccia	(ESTEC, The Netherlands)
Paola Rossetti	(Centrospazio, Italy)	Jose Gonzalez del Amo	(ESTEC, The Netherlands)
Tanya Scalia	(FiatAvio, Italy)	Leonardo Biagioni	(Centrospazio, Italy)
Alessandro Congiunti	(DMA, Italy)	Leonardo De Rose	(FiatAvio, Italy)
Alessio Del Rossi	(DMA, Italy)	Martin Sippel	(DLR, Germany)
Antonio G. Accettura	(FiatAvio, Italy)	Massimo Saverdi	(Centrospazio, Italy)
Bernd Dachwald	(DLR, Germany)	Matteo Berti	(Centrospazio, Italy)
Berrie Mellor	(Edotek, England)	Mauro Varetti	(FiatAvio, Italy)
Boris Palenov	(Keldysh Institute, Russia)	Paul Williams	(ISP, England)
Claudio Bruno	(DMA, Italy)	Roberto De Amicis	(FiatAvio, Italy)
Daniele Casali	(DMA, Italy)	Ubaldo Staffilano	(FiatAvio, Italy)
Dirk Greuel	(DLR, Germany)	Valery Musiyenko	(Keldysh Institute, Russia)
Eugenio Giacomazzi	(DMA, Italy)	Wolfgang Schall	(DLR, Germany)
Fabio Caramelli	(ESTEC, The Netherlands)	Wolfgang Seboldt	(DLR, Germany)
Francesco Betti	(FiatAvio, Italy)		



Propulsion 2000: a wide-angle perspective on Advanced Propulsion Systems for Europe