HORIZON 2020

EPIC

Report

D2.1 Database on EP (and EP-related) technologies and TRL

Due date of deliverable:	02/2015
Actual submission date:	
Start date of project:	2/10/2014
Work package/Task	WP2/T2.1
Lead Beneficiary	Centre National d'Etudes Spatiales
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Status	First issue
Dissemination Level	DRAFT – CONFIDENTIAL, (Final version will be Public)
Reference	EPIC-CNES-2.1-RP-D2.1-1.2

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 640199

APPROVAL

Title D2.1 Database on EP (and EP-related) technologies and TRL	
Issue 1	**Rev** 2
Author Nicolas Arcis	**Date**
Approved by	**Date**

CHANGE LOG

Reason for change	**Issue**	**Date**
Creation	1	13/12/2014
Review 1	1.1	16/12/2014
Comments received from THAG delegates and from Advisory Board members	1.2	19/02/2015

CHANGE RECORD

Issue 1			
Reason for change	**Date**	**Pages**	**Paragraph(s)**
Creation			
Addition of Benchmarking of PPUs	16/12/2014	All	7
Comments received from THAG delegates and from Advisory Board members. Removal of annex and transferred in RD7	19/02/2015	All	All

Table of contents:

1 INTRODUCTION

In the frame of the Electric Propulsion Innovation & Competitiveness (EPIC) project, (grant number 640199) and more concretely its Work Package 2 “Technology Mapping & Application Requirements”, this document has been produced with the aim to be the main output of Task 2.1 “Survey of available EP technologies and TRL”.

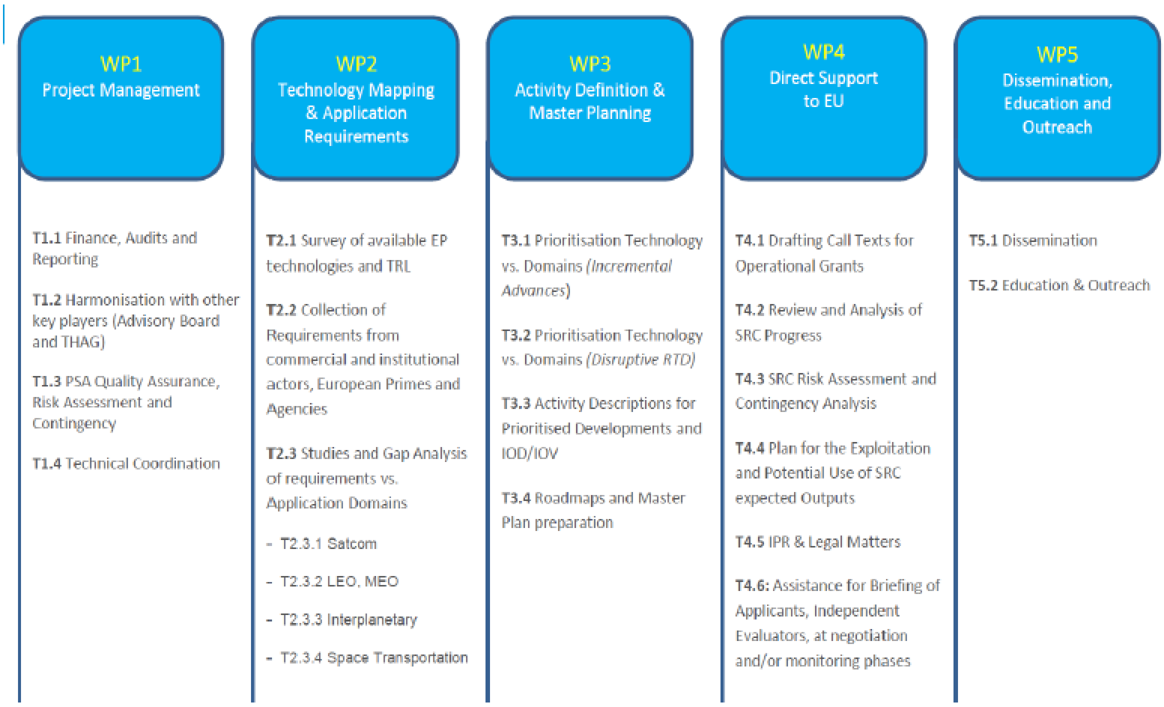

Figure 1-1: EPIC Work Logic

This document aims at providing an overview of EP and EP-related technologies and of their corresponding Technology Readiness Level (TRL). Since it is intended as an input to the elaboration of the roadmap for the H2020 Electric Propulsion Strategic Research Cluster (SRC) (T3.4 on Figure 1-1), the focus has been put on producing a comprehensive overview of European technologies.

In order to be as comprehensive as possible, inputs have been gathered through :

- ESA,
- National Space Agencies partners of the EPIC project,
- the European Space Technology Harmonisation process which ESA coordinates, with the participation of its Member States agencies, industry and research institutions, as well as the European Commission in 2014 [RD1][RD2][RD3][RD4],
- the Preliminary Strategic Design of the EPIC proposal, submitted to the Commission in March 2014 [RD5]
- a survey conducted by Eurospace as part of Task 2.1 of EPIC, with the aim to consult as many relevant stakeholders as possible, and
- a dedicated EPIC workshop held in Brussels on November 25th-28th 2014 on which more than 70 presentations on EP or EP-related technology were received, presented and analysed afterwards [RD6].

Besides the European capabilities analysis, some non-European technologies have also been included in this report, either for comparison purposes (e.g. benchmarking assessment), or because they are deemed promising and have no counterpart in Europe.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 640199

2 REFERENCE DOCUMENTS

[RD1] *European Space Technology Harmonisation Technical Dossier – Electric Propulsion Technologies*, Ref. ESA/IPC/THAG(2014)12, Issue 3, Revision 1, Draft.

[RD2] *European Space Technology Harmonisation Technical Dossier – Space Mechanisms – Electric Propulsion Pointing Mechanisms*, Ref. TEC-MSM-2009-4-In-JML, Issue 2, Revision 2, Technical Note.

[RD3] *European Space Technology Harmonisation Technical Dossier – Power Management and Distribution*, Ref. ESA/IPC/THAG(2013)7, Issue 3, Draft.

[RD4] *European Space Technology Harmonisation Technical Dossier – Chemical Propulsion Components*, Ref. TEC-SGH/2011/97/CPCTD, Issue 3, Revision2, Technical Note.

[RD5] *EPIC Strategic research Cluster Preliminary Strategic Design.*

[RD6] D2.3, *EPIC Workshop 25-28th November 2014 Report*, Ref EPIC-CNES-2.3-RP-D2.3-1.1

[RD7] *EPIC Technology survey Report*, Eurospace, EPIC-EUR-WP2-RP-ID18-1.0

3 LIST OF ACRONYMS AND ABBREVIATIONS

EBB: Elegant BreadBoard

ECRA: Electron Cyclotron Resonance Acceleration thruster

ECSS: European Cooperation for Space Standardization

EOR: Electric Orbit Raising

EP: Electric Propulsion

EPPM: Electric Propulsion Pointing Mechanism

FCU: Flow Control Unit

FEEP: Field Emission Electric Propulsion

GCTD: Game Changing Technology Development

GIE: Gridded Ion Engine

HEMP-T: High Efficiency Multistage Plasma Thruster

HET: Hal Effect Thruster

HPT: Helicon Plasma Thruster

ITAR: International Traffic in Arms Regulations

LIF: Laser Induced Fluorescence

MPD: MagnetoPlasmaDynamic

NGGM: Next Generation Gravity Missions

NSSK: North-South Station Keeping

PCU: Power Conditioning Unit

PCDU: Power Conditioning and Distribution Unit

PSCU: Power Supply and Control Unit

PIT: Pulsed Inductive Thruster

PPT: Pulsed Plasma Thruster

PPU: Power Processing Unit

PR: Pressure Regulator

PSCU: Power Supply and Control Unit

QCT: Quad Confinement Thruster

R&D: Research and Development

R&T: Research and Technology

RPA: Retarding Potential Analyser

SRC: Strategic Research Cluster

TRL: Technology Readiness Level

VAT: Vacuum Arc Thruster

4 TRL DEFINITION

4.1 History and evolution

Although the notion of technology assessment started to loom in the 60s, the TRL methodology was introduced in the USA in 1975 by Stan Sadin and formally defined in 1989 through a 7-level scale. It underwent several changes over the years, growing up to nine levels (Mankins 95 reference, or M95r), and was adopted by many companies of government bodies worldwide.

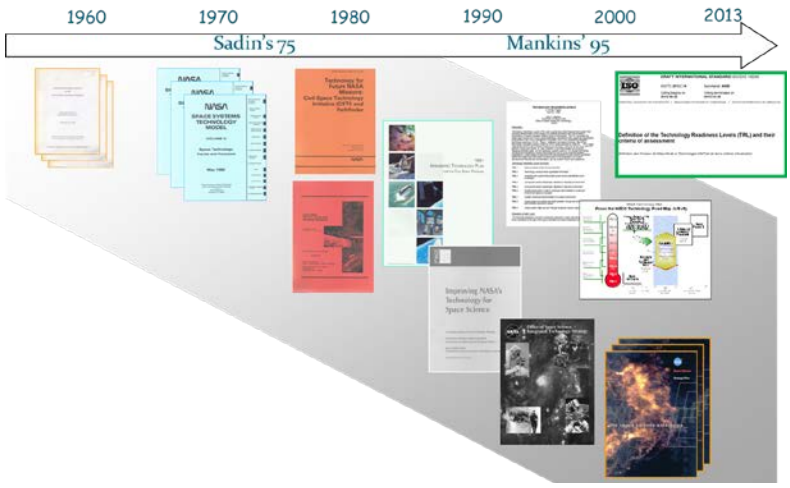

Figure 4-1:overview of TRL history

However, no real international harmonization was carried out in the process, so that its meaning sometimes showed discrepancies between different countries. Through the ECSS, it was decided in 2008 to make a harmonization at European level and then proposed to ISO a global harmonization in 2009. The ISO standard 16290 was published in 2013 and, as a result, TRL are now globally harmonized. The ISO standard concerns the definition and the criteria of assessment; however, the procedure for the TRL assessment or the way to use them within projects is not the object of the standard. The standard is applicable primarily to space system hardware.

It should be noted that the ISO standard introduces some modifications with regards to the M95r previous interpretation by ECSS. which is addressed in the following section

4.2 Differences between M95r and ISO 16290 standards

M95r and ISO 16290 definitions are equivalent for levels 1, 2, 3 and 4. ISO level 5 is a new intermediate level used when models at sub-scales are used, and ISO level 6 is equivalent to M95r level 5. M95r level 6 has been shifted to ISO level 7. M95r level 7 which was "System prototype demonstration in space environment" has been removed in ISO, while M95r and ISO 16290 definitions are equivalent for levels 8 and 9 respectively defining "flight qualified" and "flight proven" for the actual systems. These differences are summarized in Figure 4-2 below. For the remainder of this document, the term TRL is referring to the ISO definition.

	Mankins 95 reference		ISO 16290 standard
TRL 1	Basic principles observed and reported	Equivalent	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated	Equivalent	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-ofconcept	Equivalent	Analytical and experimental critical function and/or characteristic proof-ofconcept
TRL 4	Component and/or breadboard ***validation*** in laboratory environment	Equivalent	Component and/or breadboard ***functional verification*** in laboratory environment
TRL 5	Component and/or breadboard ***validation*** in relevant environment	Split	Component and/or breadboard ***critical function verification*** in **a** relevant environment
TRL 6	***System/subsystem*** model ***or prototype*** demonstration in a relevant environment ***(ground or space)***	Shifted	Model ***demonstrating the critical functions of the element*** in a relevant environment
TRL 7	***System prototype demonstration in a space*** environment	Removed	***Model demonstrating the element performance for the operational*** environment
TRL 8	Actual system completed and ***"flight qualified" through test and demonstration (ground or space)***	Equivalent	Actual system completed and ***accepted for flight ("flight qualified")***
TRL 9	Actual system "flight proven" through successful mission operations	Equivalent	Actual system "flight proven" through successful mission operations

Figure 4-2: differences between M95r and ISO 16290

4.3 TRL basic principle

TRL analysis allows for the assignment of a measure of the maturity of a technology. It is *not* a method to develop technologies. The way to develop, to test, to qualify/verify the development cycle of products, or the model philosophy defined by projects, are not the object of TRL but the purpose of others discipline-specific standards and handbooks, such as the ones provided by the ECSS.

The measure provided by TRL assessment is valid for a given element, at a given point in time, and a given defined environment. It may change if the conditions that prevailed at the time of the assessment are no longer valid. Such a situation may lead to TRL reassessment and re-grading, which can occur in particular when the re-build or re-use of an element is envisioned with variation in the design, development process, targeted environment or operations.

During Research and Development (or Research and Technology) activities, TRL can be used by the specialists developing the technologies to present their development plans (e.g. technology roadmaps) and to communicate with non-specialists or project managers, the costs or risks involved in taking particular technology choices with different TRL.

In the frame of projects, TRL are used during preliminary phases (0,A,B) as a supporting tool to decide whether or not to use or integrate specific technology in a space mission, by allowing such decision to be taken with sufficient knowledge of any risk relating to the degree of maturity.

List of clarifications and limitations:

- TRL assessment is not intrinsic to a technology: if a new target environment has different constraints or performance requirements, a TRL may be reduced (e.g. a level-9 technology in one application may fall even as low as level 4 in another).
- TRL does not take into account capacities of production or technology access constraints (e.g. : International Traffic in Arms Regulations, ITAR).
- TRL does not take into account technology obsolescence; however, obsolescence can drive the need for a TRL re-assessment.
- TRL does not replace development cycle or quality rules although links between the two can be identified.

- TRL is not necessarily incremental: it is not mandatory to achieve level 5 (sub-scale) before proceeding to level 6. More generally, it is not mandatory to go systematically through all levels.
- A TRL may only be reached by a component if all of the sub-components are at least at the same level.
- An R&D (and R&T) action does not necessarily lead to an increment in TRL.
- The time or effort to move from one TRL to another are technology-dependent and cannot be linearly projected along the TRL scale.
- A technology is to be evaluated by an expert not directly involved in its development.

4.4 TRL definition

Figure 4-3 below gives a graphical overview of the 9-level TRL scale.

TRL 1 is the lowest in maturity. It corresponds to scientific activity related to the technology: basic principles are observed and reported through academic-like research. Potential applications are identified but performance requirements are not yet specified. Practical applications are invented/identified at level 2. Applications are speculative and there may be no proof or detailed analysis to support the assumptions.

"Proof of Concept" is verified at TRL 3, through both analysis (modelling and simulation) and experimentation (laboratory-based experiments to physically support the analytical predictions). Then, at TRL 4, a laboratory breadboard is integrated to establish that the "pieces" work together and demonstrate the basic functional performance. The verification is "low fidelity" and is limited to laboratory environment.

TRL 6 is reached when the critical functions are demonstrated in the relevant environment using appropriate engineering models representative in form, fit and function. If necessary, an intermediate step may be reached before with TRL 5, whereby reduced-scale models are built and demonstration is limited to scaling effects. Design (or preliminary design) files can be produced at these stages.

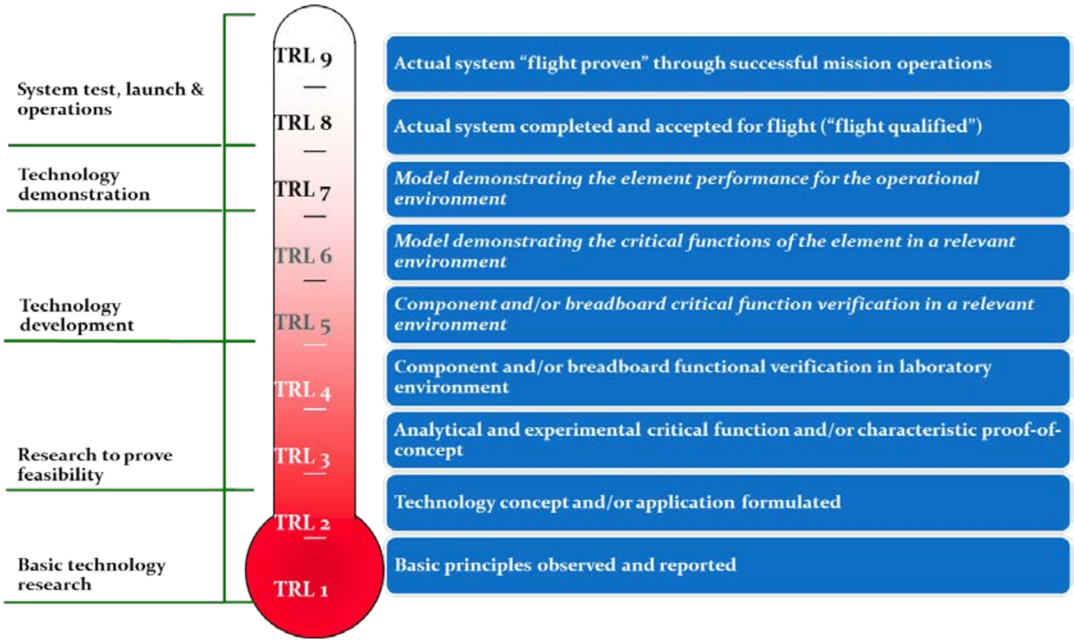

Figure 4-3: overview of the TRL ladder

At TRL 7 performances are demonstrated for the operational environment, on the ground or if necessary in space. A representative model, fully reflecting all aspects of the flight model design, is built and tested with adequate margins. Qualification is achieved on ground, at equipment level.

Levels 8 and 9 are reached in the frame of actual projects. At TRL 8 the flight model is qualified and integrated in the final system ready for flight, while TRL 9 is for a "mature technology" that has been successfully in service in the actual operational environment.

Figure 4-4 shows the correspondence between the different levels and the specific development phases with the associated equipment models, while Table 4-1 summarizes the various milestones and main achievements related to each level of the TRL ladder.

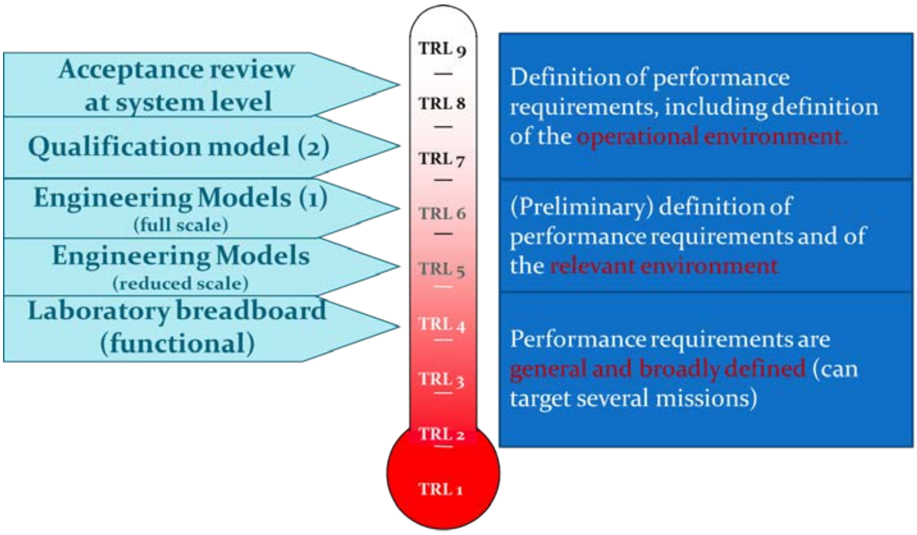

Figure 4-4: development phases and development models

Technology Readiness Level	Milestone achieved for the element	Work achievement (documented)
TRL 1 - Basic principles observed and reported	Potential applications are identified following basic observations but element concept not yet formulated.	Expression of the basic principles intended for use. Identification of potential applications.
TRL 2 - Technology concept and/or application formulated	Formulation of potential applications and preliminary element concept. No proof of concept yet.	Formulation of potential applications. Preliminary conceptual design of the element, providing understanding of how the basic principles would be used.
TRL 3 - Analytical and experimental critical function and/or characteristic proof-of-concept	Element concept is elaborated and expected performance is demonstrated through analytical models supported by experimental data/characteristics.	Preliminary performance requirements (can target several missions) including definition of functional performance requirements. Conceptual design of the element. Experimental data inputs, laboratory-based experiment definition and results. Element analytical models for the proof-of-concept.
TRL 4 - Component and/or breadboard functional verification in laboratory environment	Element functional performance is demonstrated by breadboard testing in laboratory environment.	Preliminary performance requirements (can target several missions) with definition of functional performance requirements. Conceptual design of the element. Functional performance test plan. Breadboard definition for the functional performance verification. Breadboard test reports.
TRL 5 - Component and/or breadboard critical function verification in a relevant environment	Critical functions of the element are identified and the associated relevant environment is defined. Breadboards not full-scale are built for verifying the performance through testing in the relevant environment, subject to scaling effects.	Preliminary definition of performance requirements and of the relevant environment. Identification and analysis of the element critical functions. Preliminary design of the element, supported by appropriate models for the critical functions verification. Critical function test plan. Analysis of scaling effects. Breadboard definition for the critical function verification.
TRL 6 - Model demonstrating the critical functions of the element in a relevant environment	Critical functions of the element are verified, performance is demonstrated in the relevant environment and representative model(s) in form, fit and function.	Definition of performance requirements and of the relevant environment. Identification and analysis of the element critical functions. Design of the element, supported by appropriate models for the critical functions verification. Critical function test plan. Model definition for the critical function verifications. Model test reports.
TRL 7 - Model demonstrating the element performance for the operational environment	Performance is demonstrated for the operational environment, on the ground or if necessary in space. A representative model, fully reflecting all aspects of the flight model design, is build and tested with adequate margins for demonstrating the performance in the operational environment.	Definition of performance requirements, including definition of the operational environment. Model definition and realisation. Model test plan. Model test results.
TRL 8 – Actual system completed and accepted for flight ("flight qualified")	Flight model is qualified and integrated in the final system ready for flight.	Flight model is built and integrated into the final system. Flight acceptance of the final system.
TRL 9 - Actual system "flight proven" through successful mission operations	Technology is mature. The element is successfully in service for the assigned mission in the actual operational environment.	Commissioning in early operation phase. In-orbit operation report.

Table 4-1: milestones and achievements of the different TRL

5 SURVEY OF EUROPEAN EP AND RELATED-EP TECHNOLOGIES

In the following sections, an overview of the EP technologies (and associated ones) with few of their characteristics (TRL, Power, thrust, etc.) will be presented.

This document aims at providing an overview of EP and EP-related technologies and of their corresponding Technology Readiness Level (TRL). Since it is intended as an input to the elaboration of the roadmap for the H2020 Electric Propulsion Strategic Research Cluster (SRC) (T3.4 on Figure 1-1), the focus has been put on producing a comprehensive overview of European technologies.

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6 THRUSTER TECHNOLOGIES

6.1 Gridded Ion Engine

The advantage of this EP technology comes from its high specific impulse capabilities (up to 4000 s), which makes it best suited for:

- interplanetary missions (very high delta-V),
- missions where the operation time of the engine is not a constraint (e.g. NSSK operations),
- formation flying and drag compensation missions, where high controllability is required (micro-Newtons to several milli-Newtons).

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	Power (W)	I tot. (MNs)	Development status, flight opportunities, references
Airbus DS (UK) / QinetiQ (UK)	UK-10	30	25	3000	750	1	Operational on Artemis. No longer in production (obsolete at system level). **TRL 9**
Airbus DS (D)	RIT-µX	Variable (30-100)	0.010-2.5	> 300-3000	< 50	0.025	Demonstration model tested for 2000 hours, Engineering Model under development with National and ESA funding. **TRL 4**
	RIT10	30	15	> 3300	470	>1.5	Operational on ARTEMIS. Life tested for over 20000 hours at ESA Propulsion Laboratory. **TRL 9**
	RIT15		50	> 3300	1500		
	RIT22	35	50-200	4200	4580 - 4740	>20	Engineering Model developed with National and ESA funding. **TRL 4**
QinetiQ / University of Southampton (UK)	MiDGITS	42.5	0.010-2.5	> 2200 s @ 1 mN > 400 s @ 15 µN	<90	0.040	Laboratory demonstration performed with National and ESA funding. **TRL 4**
QinetiQ (UK)	T5	32	0.6-25	417-2926	<600	>3.5	Flown on GOCE. **TRL 9**
	T6	32	30-145, 230 demonstrated for TDA engine	3000 - 4500	1000 - 5000	>13.8	Qualification in progress: HPEPS for GEO comsats and SEP for BepiColombo. **TRL 7**

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	Power (W)	I tot. (MNs)	Development status, flight opportunities, references
	T6 Ring cusp (with Mars Space Ltd)	25	30-180	3000 - 4500	1000 - 5000		Laboratory demonstration performed with National Funding. **TRL 4**
Mars Space Ltd / University of Southampton (UK)	DS3G/DS4G	32 -63	200-400	5000-10000	6-25 kW		Laboratory demonstration performed with National and ESA funding. **TRL 2**
Laboratoire de Physique des plasmas-Polytechnique (F)	PEGASES	30-40	5.5		<200		Several prototypes tested (argon + SF_6 used as propellant). **TRL 3**
TransMIT GmbH (D)	RIT-3.5		0.05 – 2.5				BreadBoard model developed under ESA funding. **TRL 2**
ETSI Aeronautics-UPM-CTA/Aernnova (S)	ALPHIE (Adaptable low power Hybrid ion Engine)	22	0.1 – 4.5	1800 - 2500	< 200		Laboratory demonstration with National funding. Argon. **TRL 3**

6.2 Hall Effect Thruster

The HET technology:

- offers a well proven robustness with a lot of flight heritage;
- has specific impulse around 1500-2000 sec;
- allows lower power consumption than ion engines for a given thrust level due to the lower power to thrust ratio (17W/mN);
- is capable of accomplishing missions in a shorter time due to its higher thrust density;
- is best suited for NSSK and orbit topping operations (power levels below 12 kW) and interplanetary missions where the power to thrust ratio is critical.

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	Power (W)	I tot. (MNs)	Development status, flight opportunities, references
Snecma (F)	PPS® 1350-G	17	40 -88	1650 @ 1500 W	700 - 1500	3.4	Launched on Stentor, not operated due to launch failure. Operated successfully on SMART-1 (5000 hours). Flying on Alphasat. **TRL 9**

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	**Thrust (mN)**	**ISP (s)**	**Power (W)**	**I tot. (MNs)**	**Development status, flight opportunities, references**
	PPS®1350 -E	17	40-140	1670-1800	700-2500	3.4	CDR performed; EM successfully underwent 6,700h lifetest; qualification to begin S1 2015. **TRL 6**
	PPS®1350 -E C2G	17	40-140	1750 @ 2500 W	700-2500	5	Thruster unit includes: PPS + cathode + XFC. Demonstration in progress in the frame of EGEP. **TRL 5** by mid-2015
	PPS® 5000	15-20	90-400	1400-2000	2000-7000	11.6	Laboratory demonstration performed with National and ESA funding; PDR achieved in S2 2014; qualification foreseen by the end of 2018. **TRL 4**
	PPSNG	18	140	1900	1500-3200	5	Development stopped.
	EPS-500 propulsion system	15	15-27	1200-1500	300 -700	0.5	Development in stand-by with National funding. **TRL 3**
	PPS-20k		300-1000	1200-2500	5000-20000	70	Development and testing of a first prototype under EC FP7 HIPER project. **TRL 4**
ICARE (F)	PPI (Petit Propulseur Innovant)	17	20	1200-1400	200		Laboratory model. Xenon and Krypton. **TRL 3**
Airbus DS (UK)	ROS2000	19	71-132	1600-1700	1500-2500	2.9	Development stopped.
Alta SpA (I)	HT-100	20	6-18	1000-1600	80-300	0.05	Development in progress with National and ESA funding to achieve **TRL 6**.
	HT-400	20	20-50	1100-1850	200-1000	0.2	Development in progress with National and ESA funding.
	HT-5k	22	150-350	1700-2800	1650-7500		Laboratory demonstration performed. **TRL 3**
IPPLM (Poland)	KLIMT	20	10-30		200-600		Laboratory demonstration performed. **TRL 3**
European Space Propulsion (UK)	XR-5E	15-18	117-290	1676-2020	3000-4500	> 5.5	European version of XR-5. Flight proven. **TRL 9**
Aerospazio Tecnologie s.r.l. (I)	HET-70		2-5	900-1000	50-100		R&D National funding, efficiency 20 %, coils. A cluster of 4 HET-10 was tested with a single cathode. **TRL 4**
LESIA/GEMaC (F)	μHET						**TRL 3**

6.3 High Efficiency Multistage Plasma Thruster

Europe has a unique expertise in this technology. This technology:

- has a nominal specific impulse of around 2500 s, which can be varied between 2000 and 3000 s;
- allows a lower power consumption than ion engines due to the lower power to thrust ratio;
- has very high life capabilities due to negligible erosion of discharge channel;
- can be operated in clustered configuration with one common anode supply line from the PSCU and has therefore maximum modularity and minimum system complexity.

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	Power (W)	I tot. (MNs)	Development status, flight opportunities, references
THALES Electron Devices GmbH (D)	HTM3050	20-35	10-70	2000-3500	<1450	>4	Development model. Qualification in progress with National, DLR funding. Flight opportunity on next generation of Small GEO platforms, Proba-IP German Heinric Hertz S/C. **TRL 7**
	Sizable HTM 3050		22 – 110 @ 500 V 17 - 84 @ 1000 V		2800		**TRL 3**
	HTM 30250	20-35	140-320	2000-3500	4 k-10 k (anode power)	>20	Laboratory demonstration performed. **TRL 3**
Airbus DS GmbH	µHEMPT		0.021 – 0.312	87-620	1-10		Laboratory demonstration performed. **TRL 3**

6.4 Pulsed Plasma Thruster

This technology is under development in Europe. The smaller versions of PPT are developed to be used on CubeSat platforms for attitude and orbit control applications.

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	Power (W)	I tot. (MNs)	Development status, flight opportunities, references

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	Power (W)	I tot. (MNs)	Development status, flight opportunities, references
IRS University Stuttgart (D)	ADD SIMP-LEX		1.5				Engineering model. Flight opportunity on Perseus and Lunar Mission BW1 (Stuttgart Small Satellite Program). **TRL 4**
University Southampton (UK)	HFB PPT						Laboratory demonstration. **TRL 3**
Quintescience (Poland)	L-μPPT			400-1200	2	> 500 Ns	First prototype tested. Development under EC funding (FP7 activity L-μPPT coordinated by the Spanish company “JMP Ingenieros“). **TRL 3**
Mars Space Ltd (UK)	PPTCUP (34 μN)	58	0.040	600	2	$44\text{-}60.10^{-6}$	Engineering model. Qualification is on-going for the SAMSON mission (Israel). **TRL 8.** Impulse bit: 44 μNs
University Southampton/ Mars Space Ltd (UK)	Nano PPT		0.09	600	5	133.10^{-6}	Breadboard model **TRL 4**. Impulse bit: 90 μNs
FOTEC (A)	μPPT		0.005-0.030	800	2		**TRL 4**

6.5 Magnetoplasmadynamic Thruster

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	Power (W)	I tot. (MNs)	Development status, flight opportunities, references
Alta SpA (I)	SF-MPD		10 k-70 k	10000	300 kW – 5 MW		Development Model. **TRL 3**
	SF-MPD with heated cathode		20 k – 150 k	2000 - 4000	1 MW – 5 MW		Development Model. **TRL 3**
	HPT MPD		Up to 14 k	Up to 2500	100-800 kW		Development Model. **TRL 3**
	AF-MPDT		1000-20000	1500 - 3000	50-250 kW		Under development with ESA and Internal Funding. **TRL 3**

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	Power (W)	I tot. (MNs)	Development status, flight opportunities, references
IRS University Stuttgart (D)	AF MPD ZT1 10 kW (Argon)	40	250	3000	10000		Laboratory demonstration. Basic research, thruster optimization. **TRL 3**
	AFMPD ZT2 100 kW (Argon)	40	2500	3000	100000		Laboratory model in development. **TRL 3**
	ZT and DT thrusters 500 kW	19	26000		500000		Laboratory demonstration. Basic research. Investigation on plasma instabilities. **TRL 3**

6.6 Quad Confinement Thruster

QCT is a novel thruster technology allowing direct thrust beam steering by magnetic field modulation and no moving parts. Its working stability requires no flow control unit (FCU) and its low supply voltage implies lower complexity and lower cost of the PPU. Efficiency of early prototypes needs improving to make it a potential candidate for other applications beyond low cost small satellites.

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	Power (W)	I tot. (MNs)	Development status, flight opportunities, references
University of Surrey (UK) – SSTL (UK)	QCT- 40	12.1	3.3	250	<40		Multipropellant. Prototype being developed under EC FP7 funding. **TRL 3**
SSTL (UK) – Airbus DS (UK)/ University of Surrey (UK)	QCT-200	19.6	10.2	1200	<200		Flight opportunity on NovaSAR. **TRL 5**
Airbus DS (UK)- Surrey Space Centre (UK)/ SSTL (UK)	QCT-1500	15.7	95.6	1600	<1500		Prototype being developed under commercial (Airbus DS) and national funding (NSTP). **TRL 3**

6.7 Resistojet

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	Power (W)	I tot. (MNs)	Development status, flight opportunities, references
Alta SpA (I)	XR-50 (Xenon)	2	100	65	200	≤ 0.036	Engineering model. **TRL 6**
Alta SpA (I)	XR-100 (Xenon)	1	125	63	125	≤ 0.045	Engineering model. **TRL 6**
Alta SpA (I)	XR-150 (xenon)	1	100-250	58-65	<250	≤0.18	Engineering model. **TRL 6**
MOOG ISP (UK) Cheltenham	Resistojet	0.5 1 2	10-100	50 (Xe) 140 (GN2) 200 (NH3)	20-200	0.05	Laboratory demonstration. **TRL 3**
SSTL (UK)	Xenon Nitrogen Nitrous Oxide	2-5	20-100 125	42 100 127		0.038E-3	Flight heritage. **TRL 9**
Mars Space Ltd (UK)	VHTR (Very high temperature resistojets)		100	100	100	> 0.01	**TRL 2**

6.8 Arcjet

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	Power (W)	I tot. (MNs)	Development status, flight opportunities, references
IRS University Stuttgart (D)	ATOS (NH3)	7	115	480	<800	0.4	Lifetime tested (1010 hours including 1010 activations) and qualified with national funding. Flight on AMSAT-P3D. Flight opportunity on TALOS (Stuttgart Small Satellite Program) . **TRL 9**
	MARC 5 kW				5000		Laboratory demonstration performed. **TRL 3**

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	Power (W)	I tot. (MNs)	Development status, flight opportunities, references
	HIPARC 100 kW (H_2)			2000 (1000s at 1 kW 1500s at 10 kW)	100000		Laboratory demonstration. Flight opportunity on Perseus and Lunar Mission BW1 (Stuttgart Small Satellite Program). **TRL 3**
Alta SpA (I)	AT-1k (Ar, He, N_2)	3-8	≥ 100 (Ar) ≥125 (He)	≥ 130 (Ar) – ≥ 590 (He)	<1000		Engineering model. **TRL 4**
European Space Propulsion (UK)	MR-501 including PPU	9	222-258	585-615	<2500	1.45	2 kW - Flown on US satellites. N2H4. **TRL 9**

6.9 Field Emission Electric Propulsion

The FEEP thruster is a pure European technology developed with two different technologies: the slit version and the needle version. FEEP performance in terms of thrust level, noise, thrust accuracy, quantization step , etc., is unique.

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	Power (W)	I tot. (MNs) / lifetime	Development status, flight opportunities, references
Alta SpA (I)	FT-150	Max power consumption is 75 W for 4 thrusters at 0. 1mN	0.0001-0.150	4500 (BOL) – 3200 (EOL)	<6	2E-3 / 4800 h	Qualification Model. Qualification in progress under ESA and National funding. Performance in life verified during endurance test (more than 4800 hours, 2630 Ns). Crucial performance verification such as thrust noise level performed. **TRL 7**
	FT with EMIM-BF4		0.1	3000	4		The IL-FEEP development is funded under EU (FP7 E-sail) and ESA programmes
FOTEC (A)	IFS-N	55-60 W/mN @0.1mN	0.0002-0.150	>5000		3650 h	Indium-Feep Thruster with Needle Emitter technology developed for LISA Pathfinder in collaboration with Airbus DS (D). No further development planned at the moment. **TRL 6**

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	Power (W)	I tot. (MNs) / lifetime	Development status, flight opportunities, references
	IFS-C	50-55	0.001-0.1	>5000		930h (emitter > 9000 h)	Indium-Feep Thruster with Capillary Emitter technology. Capillary emitter technology has TRL9 and the possibility to be integrated in the LISA Pathfinder Propulsion module. **TRL 6**
	IFM-350	60-80	0.0003 – 2	>6000		2000 h	Lifetime testing ongoing, 2000h. Discussions with RUAG (AT) and Selex Galileo (IT) have been initiated to start the development of a breadboard PPU for this thruster. Up to date, this is the only thruster that has demonstrated the capacity to cover a thrust range from >1μN to 1mN. **TRL 4**
	IFM-350 Nano	60-80	0.0003 – 2	>6000		150h	Same Emitter as the IFM-350 without focus electrodes. Thruster Module designed for Nano Satelites (Cubesats). Thruster module including HV-PPU is being developed at FOTEC. This module is the first technology that can equip a Cubesat with a significant deltaV capability (several km/s). **TRL 6**
	IFM-3000		0.05-600	Up to 30000			Highly Experimental Concept using 2-D FEEP arrays (120 needles on 1cm²). Patent granted for 'Ultra-FEEP'. **TRL 1**
Dresden University of technology (D)	NanoFEEP	60-90	0.001 – 0.022	6000		60.10^{-6} (for 4 thrusters)	Gallium as propellant. **TRL 2**

6.10 Colloid and electrospray thrusters

Manufacturer	Model	Technical characteristics				
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	I tot. (MNs)	Development status, flight opportunities, references
Queen Mary University	Array of colloids	22 @ 1000 s	0.23 mN/cm² @ 1000 s	1000 -5000		Current MEMS operation has achieved thrust of ~ 0.02 mN/cm² @ 1000 s. **TRL 3**

Manufacturer	Model	Technical characteristics				
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	I tot. (MNs)	Development status, flight opportunities, references
(UK)		30 @ 5000 s	0.48 mN/cm^2 @ 1000 s			Based on FP7 BBM outputs
EPFL (CH)	Array of colloids	20	2.5 μN/m m2	2500		Laboratory demonstration performed. Cluster built under EC funding (FP7) in collaboration with Queen Mary University. **TRL 4** Application envisaged on future micro-satellites.

6.11 Electrodeless thruster

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	Power (W)	I tot. (MNs)	Development status, flight opportunities, references
CISAS (I)	Helicon plasma thruster HPH.com (Argon)	16-33	0.5-1.5	400-1200	<50		Engineering model. Development under ESA and EC funding. **TRL 4**
SENER and University Carlos III of Madrid (S)	Helicon Plasma thruster HPT	10.1	1480	1009			Prototype being developed under National and ESA funding (GSP). **TRL 2**
Airbus DS (UK)/ Australian National University/ University of Surrey (UK)	GEN III	81-100	5-7	2000 (with argon)			Multipropellant. Prototype developed, final design passed PDR, finalization awaiting flight opportunity on small satellite. Developed by ANU co-funded by Airbus DS.
ONERA (F)	ECRA Thruster	200	0.3-5	1000	30		Laboratory demonstration with Argon. **TRL 3**.
Elwing Company (L)	E-IMPAcT						Laboratory demonstration with Xenon. **TRL 2**.

6.12 Hollow Cathode and neutraliser

Manufacturer	Model	Technical characteristic				
		Media	Mass (kg)	Discharge current range (A)	Flow rate range (mg/s)	Development status, flight opportunities, references
QinetiQ (UK)	5 A	Xe	0.09	≤ 5	0.05 - 0.45	Flight qualified in the T5 Ion Thruster Assembly on GOCE. Tested with mini HET at ESA facilities. Original T5 cathode also fully life qualified for and flown on Artemis IPP. **TRL 9**
	20 A	Xe	0.15	≤ 20	< 0.3-0.7	Qualification in progress for T6 SEPS application on BepiColombo and HPEPS application for GEO telecoms. Pre-qualified for application on the PPS-5000. Qualified for application on the ROS-2000 HET. **TRL 7**
	30 A	Xe	0.18	≤50	0.4-1.2	Laboratory demonstration completed using internal funds. **TRL 4**
University of Southampton / Mars Space/ QinetiQ (UK)	180 A	Xe	0.3	≤180	0.15-10	HiPER cathode- EC FP7 project. **TRL 4**
SSTL (UK)	HCN	Xe	0.18		0.1-1	First iteration to launch as stand-alone thruster on TDS-1. Possible opportunity to fly on NovaSAR. **TRL 6**
Selex-ES (I)	HCA NccA 1000 model	Xe	0.06	0.5 - 1	0.02-0.1	Flown on ARTEMIS. **TRL 9**
	HCA NccA 5000 model	Xe	0.11	2 - 5	0.1 – 0.5	Pre-qualification for the PPS-1350. **TRL 6**
	HCA NccA 15000 model	Xe	0.130	5 - 20	0.3 -0.8	Pre-qualified under ESA funding for possible application with large Ion Engines and Hall Effect Thrusters. **TRL 6**
	Mini HET HCA	Xe	0.09	0.3 - 2	0.1 – 0.2	Development in progress, based on the LP HCA of ARTEMIS. **TRL 5**
THALES (D)	HCN 5000	Xe	0.086	0.1 to 5	0.1 per A	Engineering model, under qualification for a small GEO HEMPT system. Successfully operated with RIT22 (EADS) **TRL 6**
Selex-ES	FEEP Neutraliser	-	0.150	(Nominal) 0.006	-	Flight Model status achieved for LISA PathFinder and Microscope. Thermoionic neutralizer **TRL 7**

Manufacturer	Model	Technical characteristic				
		Media	**Mass (kg)**	**Discharge current range (A)**	**Flow rate range (mg/s)**	**Development status, flight opportunities, references**
Snecma (F)	PPS®1350 cathode	Xe	0.18	≤ 7	0.4-0.7	Used with the PPS®1350-E (already tested up to 7.25 A) **TRL 9**
	PPS®5000 cathode	Xe		5-20	0.4-1.5	Under development; PDR planned in December 2014 **TRL 4**
IOM (D)	RF-PBN (RF plasma bridge neutralizer)					Laboratory model status. Engineering model In development under ESA funding. **TRL 4**
Alta SpA (I)	NeXHT-20 hollow cathode			1-3	0.1-1	**TRL 5**
Mars Space Ltd (UK)	40A HC	Xe	0.2	40		**TRL 3**. 800 W
University of Southampton/JAXA	50-100A HC	Xe	0.2-0.4	50-100		**TRL 2** (being developed for high power HETs(10-20kWs). Also includes heaterless ignition.

6.13 Other

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	**Thrust (mN)**	**ISP (s)**	**Power (W)**	**I tot. (MNs)**	**Development status, flight opportunities, references**
IRS University Stuttgart (D)	TITHUS (hybrid two stage DC/RF thruster)		2000				Laboratory demonstration, basic research, plasma processing. **TRL 3**
CNR IBIMET-Hotwater Srl (I)	Bythrust (Byuon propulsion thruster)						Basic principles under evaluation. Laboratory prototype created with internal funding. **TRL 2**
University of Surrey (UK)/SSTL (UK)/ Airbus (UK)	DC-Halo	26.3	7.6	1600	200		Prototype being developed under national funding (EPSRC). **TRL 2**

Manufacturer	Model	Technical characteristics					
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	Power (W)	I tot. (MNs)	Development status, flight opportunities, references
University of Surrey (UK)/Airbus DS (IK)	RF-Halo	15.7	95.6	1600	1500		Multipropellant. Prototype being developed under national funding (NSTP). **TRL 3**
Mars Space Ltd (UK)	HCT (resistojet mode)		0.9	60	60		**TRL 4**
	HCT (arcjet mode)		1.8	320	190		**TRL 4**
Sodern (F) / ONERA (F)			0.015				Neutron source for ion micro thruster development. Experimental validation with Argon. **TRL 2**
Munich University (D)	VAT for 1U CubeSat		1-30 µNs	139 (Sn) - 1666 (Cr)	2		Laboratory model. **TRL 3**

7 EP SUBSYSTEM COMPONENTS

7.1 Electric Propulsion Pointing Mechanism

EPPMs developments in Europe were initiated in the early 90's as the Electric Propulsion was identified as the most promising technology to provide the specific impulse needed for future Telecommunication, Science and Manned missions.

The following table presents the European EPPM suppliers ([RD2]):

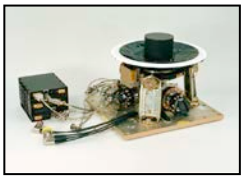
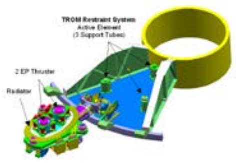
Company/Institution – Nationality	Name of Item	Remarks
RUAG Space Switzerland (CH) RSS	EPMEC TROM TOM	- Smart 1: 3 years operation demonstrated - ConeXpress: ESA programme stopped - Smart Olev: under development – ESA/GSTP (only the mechanism is under development)
RUAG Space Austria (AT) RSA	ITAM TPM TPA EPPM TOM	- Artemis: orbit raising and NSSK - Eurostar 3000: qualified with Astrium – ESA/ARTES-4 - BepiColombo: under development – Astrium/ESA - High power thruster applications: under development–ESA/ARTES-8 - CX2 : under development (phase B0) – ESA/ARTES-4
Thales Alenia Space (FR)	TOM	- SpaceBus 4000: Stentor, Astra 1K → multimedia configuration - Eurostar 3000: Intelsat (Multimedia)

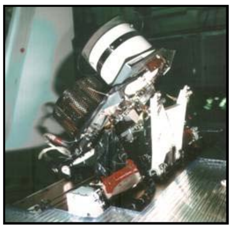
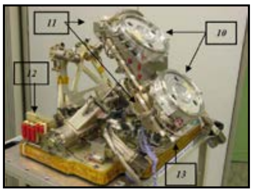
TAS		Inmarsat 4F1, F2 and F3 (Geomobile) Yahsat 1A/1B, Kasat → Under procurement - AlphaBus: being qualified - Multimedia configuration – ESA/ARTES-8 - AlphaSat: qualified - Geomobile configuration – ESA/ARTES-8

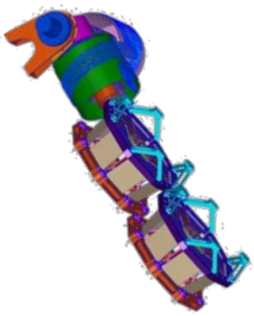
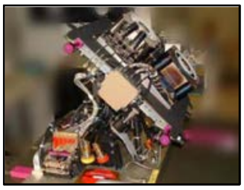
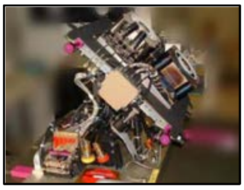
Table 6-1: European EPPM suppliers

It has to be mentioned that Snecma (FR), Thales Alenia Space (FR), Airbus DS Toulouse (FR) have also a strong heritage in thruster module activities which include the EPPM, as well as OHB Sweden, which has also experience in the context of overall architecture of pointing mechanisms, e.g. defining the needs and equipping the bare mechanism with thruster, piping and electrical harness, as well as testing. More recently, QinetiQ (UK) and Airbus DS UK are developing respectively the T6 High Power Electric Propulsion System for telecommunication platforms and, the Solar Electric Propulsion System for BepiColombo.

The following table presents the main technical characteristics of the European EPPMs:

Name of the item	Technical Characteristics	Maturity Status (TRL)	Applicability to Missions
EPMEC - RSZ 	Pointing range: - ± 9.5° half cone Mass : 10 Kg Payload : 1 x PPS1350 Life time: 4 years storage 3 years in orbit	TRL 9	Smart 1 (3 years operation) Science missions Deep space missions Main engine Low Power Electric Thrusters
TROM - RSZ 	Pointing range: - Axis 1: ± 90° - Axis 2: ± 35° - Axis 3: -5 to 95° - Axis 4: 0 to 180°one shot Mass: 22.9 Kg Payload: 2 x PPS1350 Life time: 4 years storage 15 years in orbit	TRL 3	Tailored to ConeXpress / Orbit Life Extension Vehicle Extended pointing range capabilities Full electric Spacecraft Low Power Electric Thrusters Development stopped.
MTOM – RSZ 	Pointing range: - Axis 1: ± 35° - Axis 2: ± 15° Mass: 18 Kg Payload: 2 x PPS1350 Life time: 4 years storage 15 years in orbit	TRL3	Smart Olev Orbit Life Extension Vehicle Science missions Deep space missions Main engine, NSSK and wheel off loading Low Power Electric Thrusters Under development

ITAM – RSA 	Pointing range: - ± 6° half cone Mass: 4.3Kg Payload: - 1 x RIT10 and, - 1 x T5. Life time: 5 years storage 15 years in orbit	TRL9	Telecom platforms Artemis Low Power Electric Thrusters NSSK and orbit raising (not nominal)
TPM – RSA 	Pointing range: - ± 6.5° half cone Mass: 10.7Kg Payload: - 2 x PPS1350 or - 2 x SPT10 or - 2 x ROS2000 or - Any combinations Life time: 5 years storage 15 years in orbit	TRL7	Telecom platforms Eurostar 3000 LX Qualified as part of the ATMA in collaboration with EADS Astrium (FR and UK) Low Power Electric Thrusters NSSK and wheel off loading Qualified at Thruster Module level FM procurement pending
TPA – RSA 	Pointing range: - Axis 1: + 21.09° / - 7.85° - Axis 2: + 21.09° / - 7.85° Mass: 10 Kg Payload: 1 x T6 Life time: 7 years storage 6.6 years in orbit	TRL3	BepiColombo Science missions Deep space missions Main engine High Power Electric Thrusters Under development
EPPM - RSA	Pointing range: - Axis 1: - Deployment : 0 / +120° - Pointing: ± 15° - Axis 2: ± 15° Mass: 12 Kg Payload: - 1 x T6 or - 1 x RIT22 or - 1 x PPS 5000 Life time: 6.5 years storage 16 years in orbit	TRL4	Future high power telecom platforms Extended pointing range capabilities High Power Electric Thrusters Under development Full electric Spacecraft T6 requirement for axis 1 deployment is 0 / +90°

EPPM – RAA 	Pointing range: - Axis 1: - 0 / +90° - ± 15° - Axis 2: ± 15° Mass: 16 Kg Payload: - 2 x T6 or - 2 x RIT22 or - 2 x PPS 5000 or - Any combinations. Life time: 6.5 years storage 16 years in orbit	TRL3	Future high power telecom platforms High Power Electric Thrusters Orbit raising, NSSK and wheel off loading Development stopped
TOM – RAA	Pointing range: - Axis 1: ± 45 mm - Axis 2: ± 60 mm - Axis 3: 180 ° - Axis 4: 30 ° one shot Mass: 20 Kg Payload: 2 x PPS 1350 Life time: 5 years storage 16 years in orbit	TRL3	Tailored to CX2 Small telecommunication platforms Low Power Electric Thrusters Under development Full electric Spacecraft
TOM – TAS 	Pointing range: - ± 8° half cone Pointing accuracy: 0.01° Mass:12 Kg Payload: - 1 x PPS1350 and - 1 x SPT100 Life time: 5 years storage 15 years in orbit Duty cycle: $38x10^6$ motor steps	TRL 8	Telecommunication platforms Stentor Astra 1K SpaceBus 4000 platform Low Power Electric Thrusters Demonstrator Failure of the launchers
TOM – TAS 	Pointing range: - ± 8° half cone Pointing accuracy: 0.01° Mass:12 Kg Payload: 2 x SPT100 Life time: 5 years storage	TRL 9	Telecommunication platforms Eurostar 3000 platform SpaceBus 4000 platform Low Power Electric Thrusters NSSK and wheel off loading

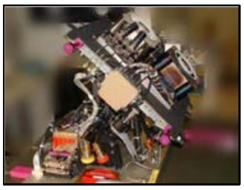
	15 years in orbit Duty cycle: 38x10⁶ motor steps		
TOM – TAS 	Pointing range: - ± 8° half cone Pointing accuracy: 0.01° Mass:14 Kg Payload: 2 x PPS1350 Life time: 5 years storage 15 years in orbit Duty cycle: 38x10⁶ motor steps	TRL 5	Telecommunication platforms Eurostar 3000 platform SpaceBus 4000 platform AlphaBus / AlphaSat Low Power Electric Thrusters NSSK and wheel off loading Under qualification for AlphaSat (early 2010) FMs for AlphaSat under integration.

Table 6-2:Technical characteristics of the Technology Addressed

7.2 Valves

Type	**Manufacturer**	**Model**	**Technical characteristic**				
			Media	**Mass (kg)**	**MEOP (bar)**	**Flow rate range (mg/s)**	**Development status, flight opportunities, references**
Latching Valves	MOOG ISP Europe (UK)	HPLV	Xe		150 (Xe)	< 12	Qualification in progress. **TRL 7**
	Air Liquide (F)	Micro Latch valve		5.10^{-3}	3		
Proportional Flow Control Valves	Selex-ES (I)	LP-RV	N_2, Xe	< 0.2	< 5 bar		Flying on GAIA. **TRL 9**
	MOOG ISP Europe - Bradford (NL)		N_2		< 5 bar		Pre-qualified in the frame of GAIA. **TRL 7**
	MOOG ISP (UK)	MPT	N_2	0.276	< 5 bar	2	Pre-qualified in the frame of GAIA.
Solenoid Flow Control Valves	MOOG ISP Europe (UK)	SVS01-06	Xe	0.075	< 5 bar		Flying on AlphaSat. **TRL 9**
Isolation valves	AST GmbH (D)					150 @ 1 bar	< 1 W – Actuation cycles > 10^9 **TRL 8** (Formosat 5)

Type	Manufacturer	Model	Technical characteristic				
			Media	Mass (kg)	MEOP (bar)	Flow rate range (mg/s)	Development status, flight opportunities, references
	NanoSpace (S)	MIV0M EMS based isolation valve		< 0.08			**TRL 6**
	MOOG ISP (UK) Cheltenham	SVS01-16	Xe, GN2, Propane	0.06	120bar	4g/s	Flying as flow control valve **TRL9**
	MOOG ISP (UK) Cheltenham	SVS01-06	Xe, GN2	0.035	10bar	0.2g/s	Flying as flow control valve **TRL9**
Fill and drain valves	MOOG ISP (UK) Cheltenham	VC03	Xe, GN2, He, Freon, NH3, Propane Hydrazi ne NTO, MMH	0.05	310bar		Flying on many S/C **TRL9**
Piezo Regulator valve	MOOG ISP (UK) Cheltenham	RES01-01	Xe, GN2, He,	0.1	310bar	4g/s	Developed to B/B level **TRL4** Active element in Proportional Electronic Pressure Regulator

7.3 Pressure regulators

7.3.1 Mechanical PR

Manufacturer	Model	Technical characteristics				
		Media	Mass (kg)	MEOP (bar)	Mass flow rate (mg/s)	Development status, flight opportunities, references
MOOG ISP (Ir)	HPR	Xe / N_2 / He		150 (Xe)	10	Development stopped
MOOG ISP (Ir)	MEMS PRM	Xe / N_2	0.45	150 (Xe) 310 (N_2)	10 (Xe)	Mechanical regulator flown in N_2 cold gas application on PRISMA. MEMS component version under development for Proba-3. **TRL 9**
Airbus DS (UK)	XMRS	Xe	7			Operational on Intelsat 10-02. **TRL 9**

Manufacturer	Model	Technical characteristics				
		Media	Mass (kg)	MEOP (bar)	Mass flow rate (mg/s)	Development status, flight opportunities, references
MOOG Bradford (NL)	Mechanical Pressure Regulated Module	Xe		325	Up to 200	Flown on GOCE. **TRL 9**

7.3.2 Electronic PR

Manufacturer	Model	Technical characteristics				
		Media	Mass (kg)	MEOP (bar)	Mass flow rate (mg/s)	Development status, flight opportunities, references
Airbus DS (UK)	XRFS	Xe / He	6	120 (Xe)	10	Operational on Inmarsat-4 F1, F2, F3, satellites and . on Ka-Sat, Yahsat 1A and 1B,. Qualification completed for BepiColombo (600 kg/ 150 bar). **TRL 9**
AST GmbH (D)	mPRS	Xe	< 0.1	12	0 – 25	Development started in 2014 under EC FP7. **TRL 3**
Airbus DS (UK)	HPRA	Xe	6.7	150 (Xe)	7.58	Qualified for BepiColombo mission. **TRL 7**
Snecma (F)	BPRM	Xe	2.75			Operated successfully on SMART-1 (5000 hours). **TRL 9**
IberEspacio/Crisa (E)	PSA	Xe	7	160	0- 200	Qualified for Small GEO. **TRL 7**
Selex-ES (I)	HP-RIV (high pressure regulation valve)	N_2, Xe	< 0.2	150	0-500	EPR Proof of Concept (based on HP-RIV) successfully tested within ARTES 8 contract for Xenon. **TRL 7**
MOOG ISP (UK)	Electronic Pressure Regulator (EPR)	All excluded O_2 and H_2O_2		310	0-200 (Xe EP) 0- 5000 (Xe cold gas) 0-500 (He)	Internal development in proportional valve. **TRL 3**

7.4 Flow controllers

Manufacturer	Model	Technical characteristics				
		Media	**Mass (kg)**	**MEOP (bar)**	**Mass flow rate (mg/s)**	**Development status, flight opportunities, references**
AST GmbH (D)	µFCU	Xenon	0.062	8	0.001 – 0.15	Pre-qualification performed under EC funding (FP7). **TRL 6**
				8	0.1 – 1.0	
				8	1.0 - 10	
MOOG Isp (UK) Cheltenham	XFCU SPS01-01	Xe	0.2	2.5 nom 10 max	0-100	Developed to B/B level **TRL4** Uses in-house valves and TT in a welded package
Snecma (F)	PPS®1350 XFC					Used in flight on SMART-1 and Alphasat. **TRL 9**
NanoSpace (S)	Miniaturised Xenon flow control system	Xenon	0.322		0.005-0.025	Engineering Model developed with National and ESA funding. **TRL 6**
	XFR-MEMS based Flow restrictor	Xenon	<0.1		0.005-0.025	Engineering Model developed with National. **TRL 6**
Air Liquide Advanced technologies (F)	Flow control valve	Xenon / Helium	$< 5.10^{-3}$	190	Up to 20	Flight heritage on Rosetta, Photos Grunt, SAM. Planned to be used on Exomars missions for Helium flow regulation. Adaptation to be used for Xenon under CNES R&D programme. **TRL 3**
Selex-ES (I)	Proportional Flow Control Valve	Xenon	< 0.2	0-150	0-500	Key component of the EPR system: qualified for Xe within an ARTES 8 in 2013. **TRL 7**
MOOG Bradford (NL)		Xenon	< 1.2	10		Flow control units based on MOOG Bradford proportional flow control valve. All components at **TRL 9** (GOCE)
MOOG Isp (UK) Cheltenham	DEC01-01	Xe	0.03	2.5bar nom 186bar max	0-100	Developed to B/B level **TRL4** Active element in Xenon Flow Control Unit

7.5 Pressure transducers

Manufacturer	Model	Technical characteristics				
		Media	Mass (kg)	MEOP (bar)	Mass flow rate (mg/s)	Development status, flight opportunities, references
MOOG - Bradford (NL)	SAPT / HAPT	Xe, N_2, He, H_2O	0.25	1 - 1000 bar	N/A	Qualified product. Flight experience from Rosetta, ATV, GOCE. Will fly on PRISMA, Proba-2, ADM-AOELUS. **TRL 9**
Presens	1560	Xe, N_2, He, H_2O	0.075	1 - 250	N/A	Under development. Will fly on PRISMA .
HERAKLES (F)	SAPT	Xe, He, MON, MMH, N2H4	0.28	1-310	N/A	Flight Proven with Spacebus and Proteus; flying on AlphaSat. **TRL 9**
MOOG-Bradford (NL)	miniSAPT					Qualified and integrated in Small GEO platform.

7.6 Mass flow sensors

Manufacturer	Model	Technical characteristics				
		Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	I tot. (MNs)	Development Status & Flight Opportunities.
Selex-ES (I)	MFS	Xe, N_2	< 0.05	< 5		Flying on GAIA (cold gas thruster application). **TRL 9**
MOOG - Bradford (NL)	XMFS	Xe	< 0.2	< 5	< 1	Qualified and flying on GOCE in Ion Propulsion Feed Assembly. **TRL 9**
MOOG-Bradford (NL)	XFM	Xe	< 0.2	< 150	1 - 10	Under development for Telecommunications S/C propellant gauging applications (ARTES 5)

7.7 Particle filters

Manufacturer	Model	Technical characteristics			
		Media	Mass	Rating	Development Status & Flight Opportunities.
NanoSpace (Sweden)	Advanced particle filters	Xe, N_2, Ar		5-10-20 µm	Development under National and ESA funding (GSTP)
Sofrance (F)	Particle filters	Xe, He		10-20 µm	Flown in the pressure regulator on SMART-1. Flying on Alphasat. **TRL 9**

Manufacturer	Model	Technical characteristics			
		Media	Mass	Rating	Development Status & Flight Opportunities.
AST Advanced Space technologies GmbH (D)	Particle filters			5 µm	Developed within µFCU EC FP7 project. **TRL 6**

7.8 Tanks

The tank is part of any fluidic chain supplying the propellant to the EP thruster(s). It allows storing at high pressure the quantity of Xenon which is needed during the mission duration.

7.8.1 Technologies

In this paragraph, only the technology regarding "thin-wall" tanks for EP will be addressed [RD4].

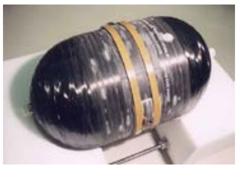
Titanium-lined, Composite Over-Wrapped Pressure Vessels (COPV) for high-pressure helium or nitrogen storage are the state-of-the-art technology for pressurant tanks used for Chemical Propulsion (CP). In fact, the same technology is also utilised for xenon tanks. However due to the physical differences between helium and xenon, the optimal COPV design solutions for these two media leads to two separate tanks – one for helium and one for xenon. However it is possible to design a single tank capable of being used in either a chemical or electrical propulsion system in order to reduce costs, but this leads to the tank design being oversized, i.e. too heavy. Alternative metallic liner materials are being studied to have major improvements in terms of production costs and lead-time reduction, but always there are the technical considerations to be considered as well. Thermoplastic liner technology previously investigated for use in the launch vehicle domain, offers similar advantages for satellite high-pressure vessels, and development is progressing in those specific area. Thermoplastic tanks may have the potential to reduce production time by 15 months (Titanium lined: 25 months, thermoplastic lines: 10 months). There are several characteristics that need to be considered for EP tanks:

- External leakage tightness compatibility with long missions
- Xenon pollution (C, H, O, N) for the liner material.

7.8.2 European EP tank providers

Most of the tanks used in European EP satellites come from Israel or US. However, a few European suppliers exist and have provided tanks for use with EP on European satellites; they are listed below.

Manufacturer	Model / Picture	Technical characteristics					
		Volume (L)	Mass (kg)	MEOP (bar)	Technology	TRL	Remarks - Development Status
Thales Alenia Space (I)		68		150	Over-wrapped	9	Developed for the AlphaBus platform. Flying on AlphaSat

Manufacturer	Model / Picture	Technical characteristics					
		Volume (L)	Mass (kg)	MEOP (bar)	Technology	TRL	Remarks - Development Status
MT Aerospace (Germany)	MT PVG-60	60	12.5	186	Ti-6Al-4V	7	Cylindrical - Integrated on the Small GEO satellite - up to 110 kg of Xenon
SSTL(UK)		7.42	4.5	120	Ti-6Al-4V	9	Flown on Proba-2 Sphere/ cylindrical- capable to store up to 12 kg of xenon
Omnidea (P)					Composite Overwrapped Pressure Vessels (COPV) Liners		R&D
TAS (I)		19	5	150	Titanium T1000 liner with carbon fibre filament winding		Cylindrical – baselined for ESMO mission (ESA)
Airbus DS (F)		68	15.6	150	Ta6V/carbon T1000	8	Launched on Stentor. He version on Rosetta (**TRL9**) – 75x45x45 cm
		70	10.2	190	Ta6V/carbon T800	6	Ground qualification stopped at 80 % completion - 98x34x34 cm

7.8.3 Development trends

The main trends are to develop technologies in order to:

- Reduce the recurring costs (however reduction of non-recurring costs may be the driver un the case of small tank developments in Earth Observation)
- Increase propellant capacity

- Minimise the dry mass
- Improve functional performances.

The standard technology for the manufacturing of propellant tanks are made of Ti-6AL-4V is based on relative thick forgings (25 mm) machined to the final wall thickness (0.8 – 2 mm) and welded to for a complete tank.

To save mass on future platforms, the technology trends leads to COPVs. In the same way as for high-pressure gas tanks, the participation of the metallic liner to the mechanical strength is limited by the use of a composite-over wrapping. This results in overall tank mass savings, as it was demonstrated in Europe with the qualification of the tank for the AlphaBus program. the challenge of rolling out this technology to other programs remains. In addition, Titanium supply for satellite tanks in a general problem.

The overall cost and lead time for a new tank development, particularly for thin walled propellant tanks with internal features (like diaphragms or PMDs), have resulted in a trend away from new tank developments, and reliance is made on existing tank designs that can be “delta-qualified”) after small design changes to meet any new mission requirements (volume changed by changing the cylinder length between the domes only) . This has results in a gauge of competitiveness based on technologies that are already available at tank supplier, hence the design or technology that is the most robust to changes is often more competitive than the optimised solution in preference to an item that just meets some of the requirements sacrificing mass and cost.

8 POWER PROCESSING UNIT

The electric power supply unit of an EP system is called PPU (Power Processing Unit) or PSCU (Power Supply and Control Unit) and is typically providing various high voltage lines, heater lines and complex control functions to the thruster.

Due the complexity of this functionality PPUs are often critical in design and rather expensive (up to 50% of subsystem costs).

The technical characteristics of the power supplies are driven by the type of EP thruster:

- Hall-Effect Thrusters, HEMP-Thrusters and Ion Thrusters: require operating voltages typically from 300V to 2kV, within a power range from a few hundred Watts (SMART-1, Alphabus baseline, GOCE, Proba III) up to 5 kW (high power thruster for EOR, BepiColombo)
- Field Emissions Electric Propulsion (FEEP) needs low power, high voltage power supplies typically with voltage from 10-15 kV at low power levels in the order of few watts per FEEP thruster.
- MPD thrusters require ignition voltage up to 20 kV and discharge voltage in the order of 1300V.

In addtion to valve and pressure control electronics (for those thruster, which use gas supply), there maybe additional very specific power generation needed, for exapmple Radio-Frequency Generation for RIT-Ion engines.

Some FEEP thruster types need clustering of many FEEP emitters to achieve the necessary thrust levels satisfying the mission requirements.

In cases where EP is used for ultra-precise thrust control often the power supplies have to fulfill stringent telemetry and noise requirements.

8.1 Power supplies for Ion Engines, Plasma and Hall Effect Thrusters (High Power, High Voltage power supplies)

Typically, the power to be handled for supplying high power thrusters is in the high range of several 100W to 5 kW (2014 situation).

This implies limitations for use of the existing high voltage insulation materials and components. Furthermore, the high processed power in combination with the High Voltage especially demands for

- Advanced thermal managements, i.e. how to ensure that the heat generated by the power supply is properly controlled and dissipated. Especially for PPU design it is important to remove the heat from the electronic components of the high power transistors, diodes etc, which are often located in high voltage insualtion (potting).
- Increased overall efficiency, since gaining just a few percentage of efficiency in a power supply of some kW reduces the heat dissipated by the unit and constitutes a significant saving in the overall power consumption of the EP system. Especially for PPU the heat dissipation in the high electronic components is critical, increasing the efficiency by 1 or 2 percent can help to drastically simplify the thermal design of the affected electronic circuit.
- High voltage relays/switch to reduce the number of units flown e.g. for redundancy, lifetime or thrust vector.

Most of the past development activities had to spent significant development effort in theses problem areas and is expected that this will continue with the on-going trend to high power of EP thrusters.

Furthermore, the cost of these power supplies remains an important aspect that needs to be addressed.

8.2 Power supplies for FEEP (Low Power, High Voltage power supply)

A large number of FEEP thrusters are needed to be flown on spacecraft requiring fine attitude control. Consequently, the relevant power supplies shall be small, light and cheap.

Moreover, due to the operative modes of FEEP, this kind of power supply shall also have very low stand-by consumption when thrusters are inactive.

High Voltage connectors (practically corona-free) might be needed for testing the power supply during integration.

8.3 PPU Providers

In Europe a number of companies have enough heritage and experience to be able to develop and qualify power supplies for EP.

The companies currently having heritage in this field are:

- Airbus Defense & Space (France),
- Airbus DS (Germany),
- ASP Advanced Space Power Equipment GmbH (Germany),
- CRISA (Spain) an Airbus DS company,
- Selex ES (Italy),
- Sitael (Italy)
- Thales Alenia Space Belgium.

There might be other companies beeing able to enter in the market of PPU based on their heritage buidling power products for airborne equipemet, for example SAGEM (France) and others.

8.4 PPU Overview of actual Products and Developments

Find in the following tables an overview of the PPU providers, their actual products/developments, target and status .

Company Equipment	Max. Voltage	Power	Application/Functionality	Year of Delivery/Use	Status
ASP (Germany)					
PPU for iMPD	20kV&1. 3kV	100W	EBB for thruster research (design & packaging suitable for space)		Elegant Breadboard
CRISA (Spain)					
GOCE IPCU	1200 V	620 W	PPU for the ESA GOCE Mission 2 QinetiQ T5 Ion Engines	Flight since 2009-2013	Full Qualification performed Mission already finished and spacecraft decommissioned without any incident concerning EP.
HPEPS PSCU	1850 V	5100 W	Optional High Power Thruster for the ESA ALPHABUS Platform using the QinetiQ T6 Ion Engines	On-going	Coupling test campaign performed Qualification Program Started
BepiColombo SEPS PPU	1850 V	6400 W	Main Thruster for the ESA BepiColombo Mission using the QinetiQ T6 Ion Engines	Flight in 2016	Qualification still in progress, flight hardware manufactured and ready for acceptance.
EGEP PPU	1850 V	5100 W	Industrialization of the BepiColombo SEPS PPU in the frame of Galileo second generation to drive a T6 thruster.	EM on mid 2016	Industrialization in first stages
Airbus Defence & Space (France)					
Joint development between Airbus DS Elancourt (France) and Airbus DS CRISA (Spain)					
PPU NG for HET thrusters	400 V	4 * 5 kW	Development of a new PPU for EOR subsystems based on HET thrusters.	First flight models will be delivered in Q2 2016	PDR held successful. 2 coupling test campaigns have been performed with SPT140D (Fakel) and PPS5000 (Snecma).
Airbus DS (Germany)					
GOCE MPE	13 kV	10 W	FEEP of AIT Seibersdorf	2003	Breadboard
GOCE IBCV	1200 V	520 W	Ion Beam Converter as part of the ASTRIUM CRISA IPCU (see above)	Flight since 2009-2013	Full Qualification performed Mission already finished and spacecraft decommissioned without any incident concerning EP.
µN-RIT PSCU	1..2 kV	100 W	Predevelopment Power Processing Unit for µ-RIT	2009/2013	Predevelopment Power Processing Unit for µN-RIT
Improvement of Building Blocks for T5 Ion-Beam Supply	2000V	1500 W	Improvement and concept for industrialisation of ASTRIUM PPU (IPCU) for QinetiQ thruster T5	2013	EM for further tests on Subsystem Level
SGEO HEMP PSCU	1050 V	1500 W	ESA SGEO Mission 2 HEMP3050 Thrusters	delivered in 2013, flight opportunity on Heinrich Hertz mission	Coupling test campaign performed Qualification Program Started
HPEPS PSCU Beam Supply Modules	1850 V	4410 W	Beam Supply Unit as part of the ASTRIUM CRISA PPU for the ESA ALPHABUS Platform (see above)	delivered in 2012	Coupling tests campaign thruster performed. Qualification for Beam Supply Modules in progress and Flight Program Started
BepiColombo PPU Beam Supply Modules	1850 V		Beam Supply Unit as part of the ASTRIUM CRISA PPU for the ESA BepiColombo Mission using the QinetiQ T6 Ion Engines	Beam Supply Modules delivered in 2013 Flight in 2015	Qualification still in progress, flight hardware manufactured and ready for acceptance.

Table 7-1: Overview of European Propulsion Electronic Developments and Applications

Company Equipment	Max. Voltage	Power	Application/Functionality	Year of Delivery/Use	Status
Selex ES (Italy)					
Artemis PCU	1200V	600 W	Full power processing for ESA ARTEMIS	Launched in 2002	In flight RIT-10 successfully contributed to ARTEMIS orbit raising into GEO
Microscope PPCU	13 kV	70 W	Full power processing for CNES/ESA Microscope mission	Qualification completed in 2008	Qualification completed
Lisa Pathfinder PCU	13 kV	76 W	Full power processing for ESA LISA Pathfinder mission	Qualification completed in 2010	Qualification completed Flight Models delivered
μN RIT PCU	2 KV	57 W	Full power processing for LISA Pathfinder mission	Completed	Elegant Breadboard Coupling test performed with ASTRIUM RIT-μX and neutralisation concept verified with Selex ES NA
mN RIT PPU	2.5 KV	140 W	Full power processing for a 2.5 mN RIT for Euclid and future space missions	On-going	Design of Elegant Breadboard on going
Sitael (Italy)					
S9093		350W	Low power HET Capable driving 4 HET	Elegant Breadboard	EBB successfully tested
S9032 and S9071	1000V/ 11kV		HV Modules for Induium FEEP Thruster		
S9044 and S9045 HVPS			ALTA FEEP Simulator on Rubin II	Demonstration Model	
MEPS PPU		300W	PPU for Alta HT-100D and Rafael CAM-200 Hall Effect Thrusters	Breadboard 2014	Coupling test with thrusters planned in 2015
5 kW PPU		5 kW	PPU for ALTA HT-5k and Snecma PPS-5000 HET		

Table 7-2: Overview of European Propulsion Electronic Developments and Applications

Company Equipment	Max. Voltage	Power	Application/Functionality	Year of Delivery/Use	Status (for TRL see Figure 7-1)
Thales Alenia Space Belgium (ETCA) (Belgium)					
PPU for SPT-100 and PPS1350-G	350V	1500 W	Full power processing for Fakel SPT-100 and Snecma PPS1350-G Hall Effect Thrusters	Qualification in 1999 Various Flights since 2002	Qualification on Stentor **7 satellites in flight**: Intelsat-10, Inmarsat 4-F1 Inmarsat 4-F2, Inmarsat 4-F3, KaSat, Yahsat-1A, Yahsat-1B 2 satellites to be launched: Direct TV-15, SkyBrazil
SMART1 PPU (Mk1)	350V	1225 W	Flight Program for the ESA SMART-1 mission with Snecma PPS1350-G Thruster	Flight 2003 till 2006	Qualification and **Flight** completed
AlphaBus	350V	1500W	ESA AlphaBus platform	Flight since July 2013	Full Qualification performed and 2 flight models delivered for AlphaSat, satellite in orbit since July 2013
Small GEO	350V	1500W	PPU for the OHB Small GEO platform, with SPT-100 thrusters	Flight in 2014 TBC	2 flight models delivered, satellite to be launched
PPU Mk2	350V	2500W	Full power processing for 2.5kW Hall Effect Thruster	Qualified in July 2014	Qualified in July 2014; Flight Models are being manufactured for delivery in 2015
PPU Mk3	400V	5 kW	Full power processing for 5kW Hall Effect Thruster	Development is on-going	Target of FM delivery in 2016.
HPPU	400V/ 800V	5 kW	Generic Development of High Power PPU for Snecma PPS-5000, Fakel SPT-140, Astrium ROS-2000 compatible with Snecma PPS1350-G and Fakel SPT-100.	Development Model in 2004	Coupling test performed with Snecma PPS-X000
PSCU	2 kV	4.5 kW	Generic Development of High Power PPU for Ion thrusters like Astrium RIT-22 and HEMP-T 3050	Development Model in 2004	Coupling test performed with RIT-22 and Thales HEMP-T 3050

Table 7-3: Overview of European Propulsion Electronic Developments and Applications

In response to the various thruster technologies several power supplies have been developed by the different European Power Supply manufacturers.

8.4.1 ASP, Advance Space Power Equipment (Germany)

ASP developed a PPU for MPD thrusters. The focus of the development is put on a high efficient light weight design.

The PPU provides two independent high voltages for the MPD thrusters. The charge output provides a voltage of 1,3kV to charge up the capacitor of the MPD. This ignition output provides a voltage of 20kV and is connected to the cathode of the MPD in order to ignite the thruster. The input power is 100W max and the Ignition Frequency 1Hz. An EBB was delivered to the scientif reasearch center for coupling test.

8.4.2 Airbus Defence and Space (France)

In 2013, Airbus Defence and Space initiated a project internally called PPU NG. This joint development between Airbus DS Elancourt (France) and Airbus DS CRISA (Spain) began with a 6-months co-engineering phase to define the exact needs in terms of Plasma Propulsion Subsystem resulting in a concept of a PPU capable to be adapted to any near-term EP subsystem configuration. A flexible and modular equipment, same solution able to deliver from 1.5 kW up to 20 kW. PPU NG is thus able to drive six thrusters with max. power of 20 kW (4 thrusters)

The capacity to answer EOR and SK needs, with various operating points: 300 to 400V (optimize ISP vs thrust)

Moreover, 2 successful coupling tests have already been performed between the PPU NG BB, the SPT140D from Fakel and the PPS5000 from Snecma. The static and dynamic behaviors of the PPU NG with real loads have been demonstrated through these tests.

First one was performed in April 2014 between an Anode power supply BB and a SPT140D in Fakel facilities (Kaliningrad – Russia). Anode power supply has been fully characterized and validated at various operating points: 300 to 400V, up to 5kW. Second one was performed in June 2014 with PPS5000 in Snecma facilities (Vernon – France). Full PPU NG Breadboard (all thruster direct interfaces and platform power bus interface representative to the flight model) was successfully coupled with PPS5000 at 5kW, including EPS subsystem supported by Prime, Xenon Flow Control managed by PPU.

Next steps are the CDR is foreseen in Q3 2015, the QR in Q1 2016 and delivery of the first flight set in Q2 2016

8.4.3 Airbus DS (Germany)

Airbus DS (former Astrium GmbH) in Friedrichshafen (Germany) has succesfully qualified the PSCU (=PPU) for the HEMP 3050 thruster - providing a module power of 2x1400W and an output voltage of 1000V. The FM-PSCU has successfully passed E2E-testing controlling and supplying 4 FM-HEMPT3050 Modules friring consecutively as required for the SGEO/HAG1-mission. This supply within the HEMPT3050-EPS will have a flight opportunity on the German H2-Mission (Heinrich-Hertz). This high voltage converter is based on a building block, the "Generic HVPS – Next Generation". This new converter is the result of an improvement of a single stage power conversion concept, enabling a modular power processing unit concept with scalable power and voltage. A power/voltage level up to 1.5kW/2kV can be handled with an overall efficiency 97% per module.

A two-stage converter module (1400W/1.85kV) has been developed and is delivered to CRISA for the Bepi-Colombo PPU and the Alphabus PSCU.

A 600W class module has been delivered for the as part of Astrium CRISAs PPU for the Qinetiq T5 thruster on the GOCE mission. The GOCE mission has been succesfully completed and deorbited at the end of extended life.

Further activities in Astrium were addressing the development of power supplies for FEEP resulting in a breadboard for the GOCE mission (abandoned in an early project phase since a cold-gas thruster system was selected to replace the FEEP) and a development of an elegant breadboard of a PSCU of µN-RIT ion engine. .An EM for µN-RIT is ready and was running in a representative test with a µN-RIT subsystem till mid of 2013. Succesful coupling test has been performed.

8.4.4 CRISA (Spain)

CRISA (an Airbus DS Company) in Spain has developed the Ion Propulsion and Control Unit (IPCU) for the GOCE spacecraft. The system is based in the T5 thruster by QinetiQ.

The IPCU is able to handle up to 750W with voltages up to 1200V with a mass of 17kg.

Within the European Alphabus programme Crisa has also developed the Power Switching and Conditioning Unit (PSCU) for the T6 thruster. A coupling test has been successfully completed. The PSCU is able to handle up to 5.5kW with voltages up to 1850V, besides it is able to drive simultaneously two out of four thrusters.

The same unit design with small variation is used also for the Bepi-Colombo mission, using Qinetiq's T6-thruster .The project is undergoing the qualification program.

Current on going building block optimisation is being performed to the IPCU under an ESA contract. The objective is to apply the conceptual improvements of the PSCU plus T6 system to the IPCU plus T5 system in order to obtain an optimised control unit with a reduction in mass of at least 30% (the basic system to control one T5) but with the capability to be able to supply up to two T5 thrusters out of four simultaneously.

8.4.5 Selex ES (Italy)

Selex ES in Italy has developed the PSCU for the RIT-10 flying in the Artemis Mission. A successful orbit raising into GEO was performed with the RIT-10 rescuing the mission after a launcher failure resulting into a wrong (too low) orbit injection. Furthermore they developed a PCU for FEEP in the frame of an ESA activity. The unit is able to control any thrust in the range 0.1 to 150μN with a thrust resolution better than 0.1μN, providing control and management up to four independent field emission thrusters (hot redundancy) in a cluster structure, providing voltage range varying from 1.8kV to 12kV at very low currents (from 0.1μA to few mA). The PCU allocates 8 High Voltage supplies with voltage/current control and on-board calibration capability and 8 power supplies for propellant heating. It has to be noted that, even though the FEEP power supplies are available at high TRL and basically are ready for flight, the FEEP "engine" technology is still critical. Based on elements from the FEEP PPU and the Artemis PPU for a RIT Selex ES has developed two variant for a PPU for driving small RIT engines.

8.4.6 Sitael (Italy)

SITAEL developed an Elegant Breadboard of a PPU (S9093 PPU) for a cluster of low power HET (75-80W each, 350W total). The PPU has been successfully tested supplying and controlling a cluster of 4 low power HET operating in vacuum environment. The PPU is composed by three sections: Data Processing Unit (DPU), Power Conditioning and Distribution Unit (PCDU) and Flow Control Unit (FCU). Furthmore undeer the names S9032 and S9071 HV modules have been developed to supply ARC In-FEEP Thrusters. S9032 is a switching-type DC/DC converter providing a 0 ÷ –1000 V DC output voltage (HVOUT), S9071 is a switching-type DC/DC converter providing a 0 ÷ +11000 V DC output voltage (HVOUT).

In the frame of a contract with OHB-CGS, SITAEL developed the Power Processing and Control Unit (PPCU) HV power supply system for the ALTA μNewton FEEP to be proven on Rubin II technology demonstrator. The power supply was successfully proven on board of the satellite connected to a simulator of the ALTA FEEP.

In the frame of the ESA/ISA funded project MEPS led by ALTA and RAFAEL, SITAEL is responsible for the development of a PPU for a low power and low costs 300W HET-based propulsion subsystem for small satellites (<300kg).

The MEPS Power Processing Unit (PPU) provides power conditioning and control for Alta HT-100D and Rafael CAM-200 Hall Effect Thrusters. Breadboard availability is exptected end of 2014 and a coupling tests with ALTA and RAFAEL Thrusters planned for February 2015.

In addition SITAEL is developing a 5kW PPU for ALTA HT-5k and Snecma PPS-5000 Hall Effect Thrusters. A breadboard availability is expected end of 2014. Followed by a cCoupling tests with ALTA and Snecma Thrusters planned for January 2015

8.4.7 Thales Alenia Space Belgium (ETCA)

Thales Alenia Space Belgium (ETCA) designs, develops and produces Power Processing Unit (PPU) to supply Hall Effect Thrusters: SPT-100 from Fakel and PPS-1350 from Snecma. A first qualification model, developed for the 50V bus Stentor program, has supplied during 8900 hours an SPT-100 thruster in vacuum chamber simulating space environment. Qualified for the Spacebus 4000 platform, with a 100V regulated bus, SB4000 PPU and Filter Unit EQM have cumulated 6300 hours ground operation with PPS1350-G thruster. Twenty five PPU flight models were delivered for the Stentor, Astra-1K, and Smart-1, Intelsat, Inmarsat, Eutelsat, Yahsat satellites, DirecTV, SkyBrazil. In October 2005, Smart-1 spacecraft reached the Moon after 4958 hours cumulated operation of the PPU and its PPS1350-G thruster.

Fourteen PPU's currently in flight for North South Station Keeping on seven telecom satellites (Intelsat 10-02, Inmarsat 4-F1, 4-F2, 4-F4, Kasat, Yahsat-1A, and Yahsat-1B) have cumulated more than 24 100 hours flight operation.

Following selection of PPS1350-G as baseline thruster for AlphaBus platform, PPU AlphaBus was developed based on SB4000 PPU heritage. Two flight models were delivered for AlphaSat. Launched in July 2013, they have cumulated 350 hours operation. On SmallGEO platform, one EPTA branch has to drive one out of four SPT-100 thrusters. As the PPU drives one out of two thrusters, TAS-ETCA has developed and qualified an External Thruster Selection Unit (ETSU) to be associated to a PPU. Two flight sets (PPU +ETSU) were provided for SmallGEO. In order to propose a more competitive product TAS-B (ETCA) has qualified in July 2014 the new generation of PPU, called PPU Mk2 dedicated to Hall Effect Thruster up to 2.5kW. Twelve PPU Mk2 flight models are already ordered by two different customers. Power modules developed for high power plasma thrusters and ion thrusters were coupled with PPS-X000, RIT-22 and HEMP thrusters. In response the market demand of using Electrical Propulsion for Orbit Raising, TAS-B (ETCA) develops the PPU Mk3 dedicated to 5kW Hall Effect Thrusters.

8.4.8 Others

Past activities of PSCU development were performed in Astrium UK resulting in the PPU of the Qinetiq T5 engine flying on the Artemis mission. The Qinetiq T5 engine was used as an alternative propulsion system to the RIT, however due to anomalies this system was not significantly used. PSCU development was not continued at this point.

Other companies involved in the development of power supplies demonstrators for FEEP in the past are LABEN (I), CAEN (I) – see Sitael, Austrian Aerospace and Magna (Austria).

8.5 European PPUs in an international framework

Although European PPU products have been procured by European Satellite manunfacturers in general up to now, current and future European PPU products are open to competitive bidding on the world market. This can be in combination with a European Electrical Propuslsion Subsystem and as well as a stand-alone product.

PPU manufacturers have reported about several requests for quotation, which they have received in the past from satellite manufacturers in USA, in Russia and Japan. The strategy for such request might have been:

- For benchmarking (comparision to own products)
- For accessing markets (combining an own non-European thruster product with an European PPU in order to easier enter the European markets).
- For avoiding own costly developments of PPU's
- For avoiding conflicts with export restrictions

Therefore in principle it can be stated for the commercial aspect:

- The PPU market in principle is a wordwide market (PPU as part of a EP subsystem or stand-alone)..
- With increasing industrialization of European PPU products, they have chance to be competitive in terms of cost on the world market.

In view of the technical aspects European PPU's can be adapted to Non European Platforms, which typically comprises:

- Adaptation to termo-mechanical and EMC environment (normal work for any space equipment procurement)
- Adaptation to command and control interfaces (although mostly MIL-Bus is accepted standard)
- Adaptation to satellite main bus voltage (European PPU's are mostly 100V and 50V (few cases) and 28V (few cases), while USA is using 70V as well).

The above mentioned adaption can be typically covered by smaller design changes and delta-qualification.

European PPU's can be adapted to Non European Thrusters, which typically comprises:

- Adaptation to output voltage and currents
- Adaptation of valve control

Adapation to non-European thrusters (except the one's already in use like some of the Russian HETs) typically requires design adaptation and full qualification.

In terms of competetiveness of European PPU's only general statements can be given:

- In terms of performance European PPU's are fully competitive expecially in terms of: state-of-the-art of technology and power-to-mass ratio.

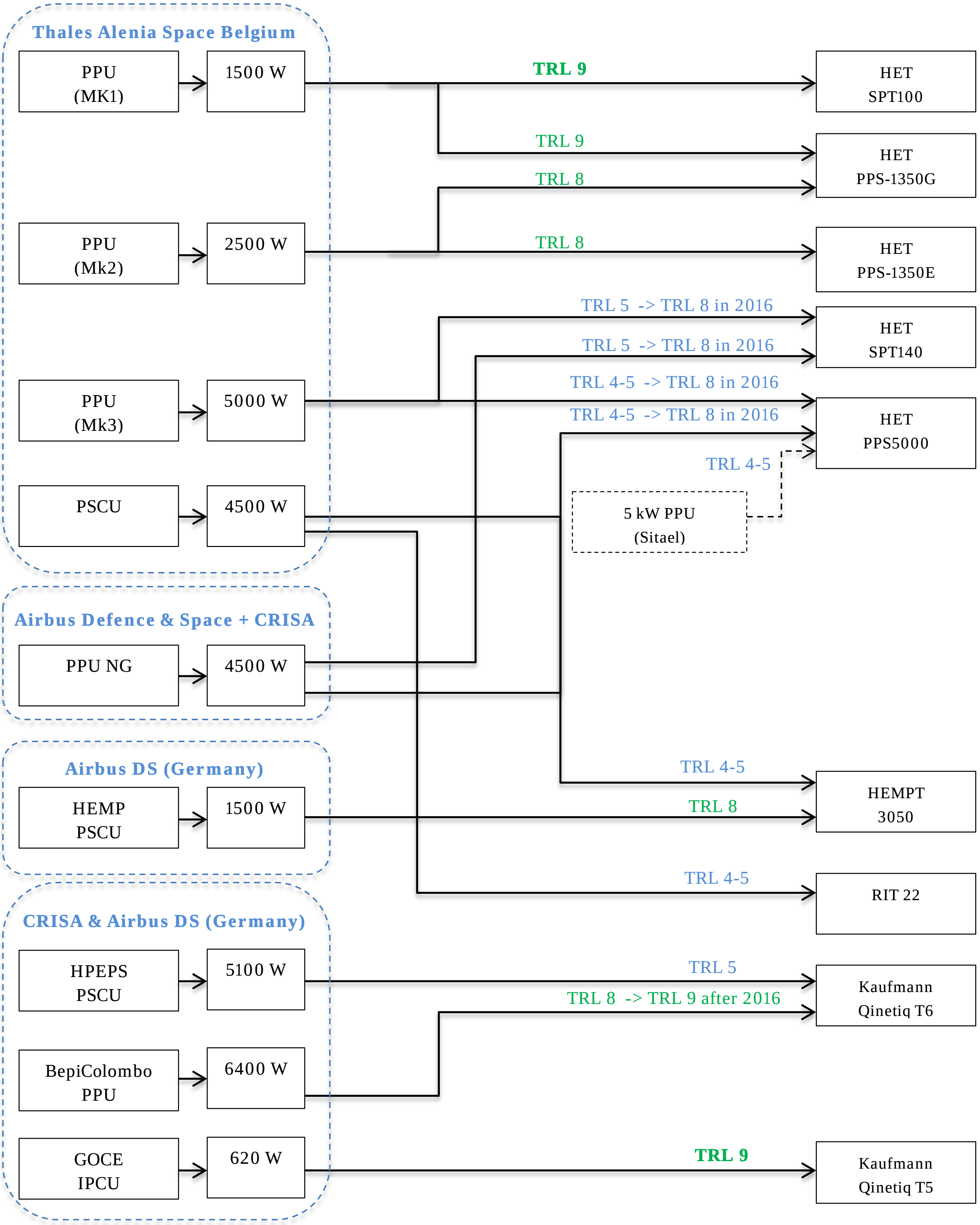
In terms of cost a bench marking is possible as cost figures of competitors are not fully visible, however cost targets for industrialized version of PPU's for telecom or navigations satellites are valid world-wide and therefore European suppliers will have to meet these targets to stay competitive. And finnaly, new PPUs architectures and new industrialation aspects could sensibly improve European position in some markets.

8.6 Summary & Mapping of PPU Products

Concluding, the actual "snapshot" on European landscape of established suppliers for EP power conditioning outlines:

- Thales Alena Space Belgium with PPU´s for Hall-Effect Thruster with good flight heritage on telecom and science missions with their first generation product (1500W), the second generation Mk2 (2500W) is now qualified and the third generation MK3 (5kW) is starting up to qualify and deliver an FM in 2016.
- CRISA's PPU´s having a strong focus on Ion Engines from Qinetiq, flying successfully on the GOCE mission (Qinetiq T5 ion engine) and with a PPU presently completed coupling test on EM level for the HPEPS program and undergoing qualification test for the Bepi-Colombo mission (both Qinetiq T6 ion engine);
- Airbus DS Germany with high voltage, high power modules (beams supply modules) developed for Astrium CRISA´s PPU´s and a complete PSCU for HEMP thruster currently with completed qualification, FM delivered (to be flown on the German Heinrich Hertz mission);
- Selex ES in Italy with current focus on FEEP in the uN-range with successful qualification and and flight model for science mission delivered, all suffering from lack of flight opportunities due to criticality of FEEP technolgy. Derived products now target μN-RIT power units for science missions. Additional activities exploring a range extension for small RITs up to mN. The uN-RIT activity completed with a coupling test on breadboard level, for the mN-RIT activity a breadboard study is ongoing.
- Airbus Space & Defence in France together with CRISA starting a development of a PPU NG (2*5kW) for targeting a flight model in 2016
- Sitael in Italy has built several demonstrators/breadboards for FEEP and high power HET (5kW). Furthermore a PPU for 300W medium power HET has been started.
- ASP in Germany has completed a breadboard PPU for iMPD thruster.

The diagram on the following pages provides an overview over the current PPU products from the various supliers related to available/upcoming thrusters.


Thales Alenia Space Belgium
PPU (MK1)
1500 W
PPU (Mk2)
2500 W
PPU (Mk3)
5000 W
PSCU
4500 W
Airbus Defence & Space + CRISA
PPU NG
4500 W
Airbus DS (Germany)
HEMP PSCU
1500 W
CRISA & Airbus DS (Germany)
HPEPS PSCU
5100 W
BepiColombo PPU
6400 W
GOCE IPCU
620 W
TRL 9
TRL 9
TRL 8
TRL 8
TRL 5 -> TRL 8 in 2016
TRL 5 -> TRL 8 in 2016
TRL 4-5 -> TRL 8 in 2016
TRL 4-5 -> TRL 8 in 2016
TRL 4-5
5 kW PPU (Sitael)
TRL 4-5
TRL 8
TRL 4-5
TRL 5
TRL 8 -> TRL 9 after 2016
TRL 9
HET SPT100
HET PPS-1350G
HET PPS-1350E
HET SPT140
HET PPS5000
HEMPT 3050
RIT 22
Kaufmann Qinetiq T6
Kaufmann Qinetiq T5

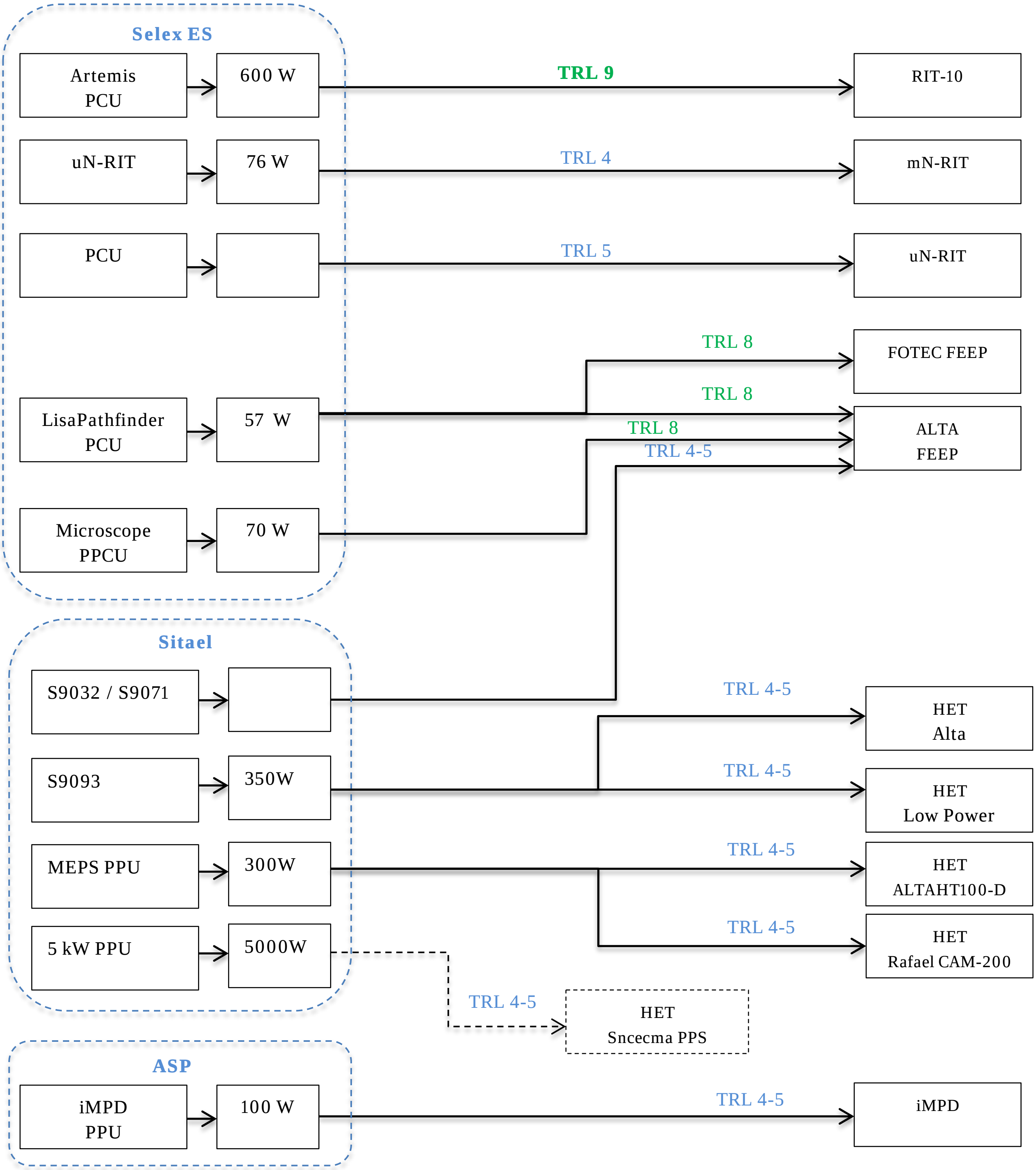


Figure 7-1: Mapping of PPU Products per Supplier w.r.t. Thruster

9 POWER GENERATION AND DISTRIBUTION

Most spacecraft use a single power bus because it eases the management of sources and loads. This bus can be so-called regulated or unregulated. The unit ensuring conditioning of the power sources to provide the bus is generally called a PCU (Power Conditioning Unit) or PCDU (Power Conditioning and Distribution Unit) in case that it also contains the distribution part to the loads.

The following block diagrams show a regulated power bus architecture (Figure 8.1) and an unregulated concept (Figure 8.2) that are the two main architectures used for Power subsystems for space. Note that the battery could be a single one in both cases.

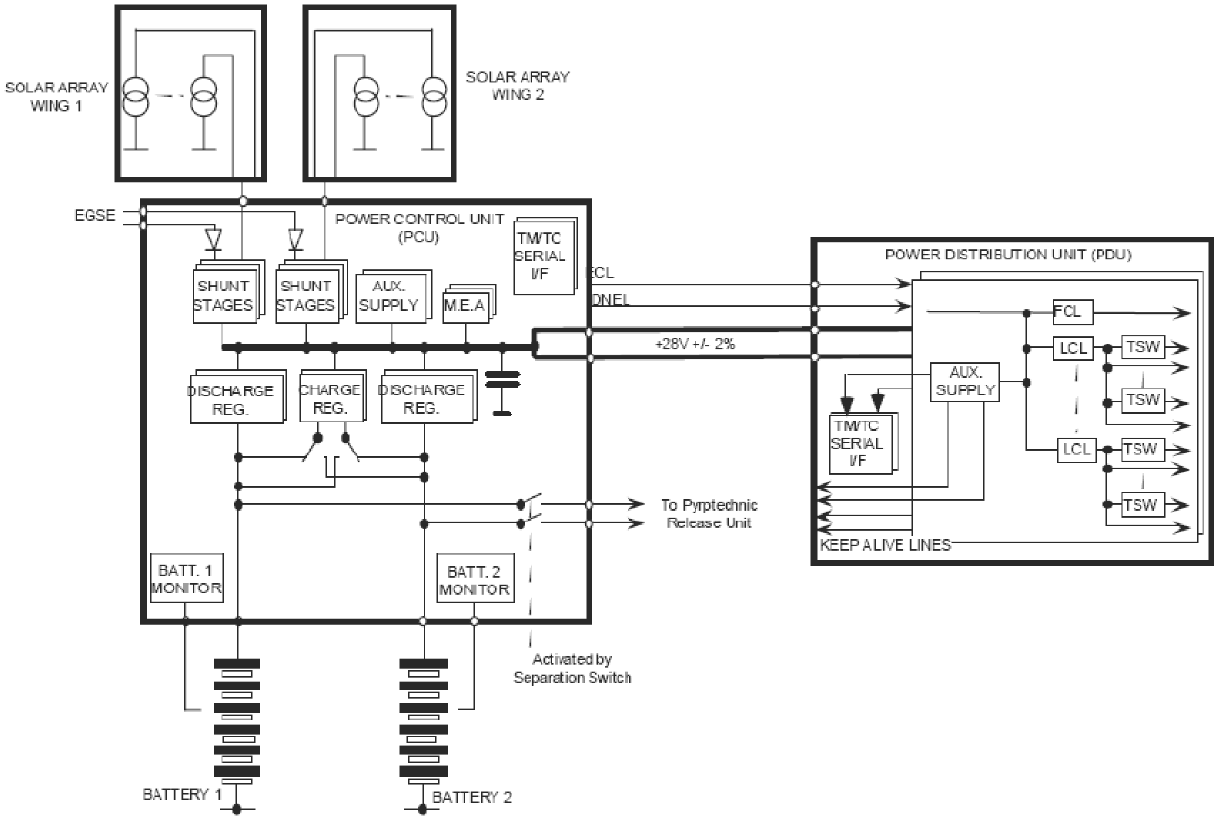


Figure 8-1: Typical Regulated Power Bus Concept

The regulated bus is mainly used for geostationary telecommunication and sciences missions and the unregulated bus for Low Earth Orbit mission (Earth Observation).

On Low Earth missions, the need for a quick recharge of the battery (typically over one hour of sunlight, with an orbital period of 1.5 hours), would require massive chargers if a regulated bus would be used.

Many Earth observation satellites (radar, lidar missions) are characterized by high peak versus average power demand, and a regulated bus option would then require very large discharge regulators.

These are the reasons why generally Low Earth missions use an unregulated bus, e.g. for the minimization of the battery conditioning electronics.

With increasing power demand for EP the regulated power bus could be a disadvantage except in cases, where the regulated bus is needed for the payload anyway (like for telecom satellites).

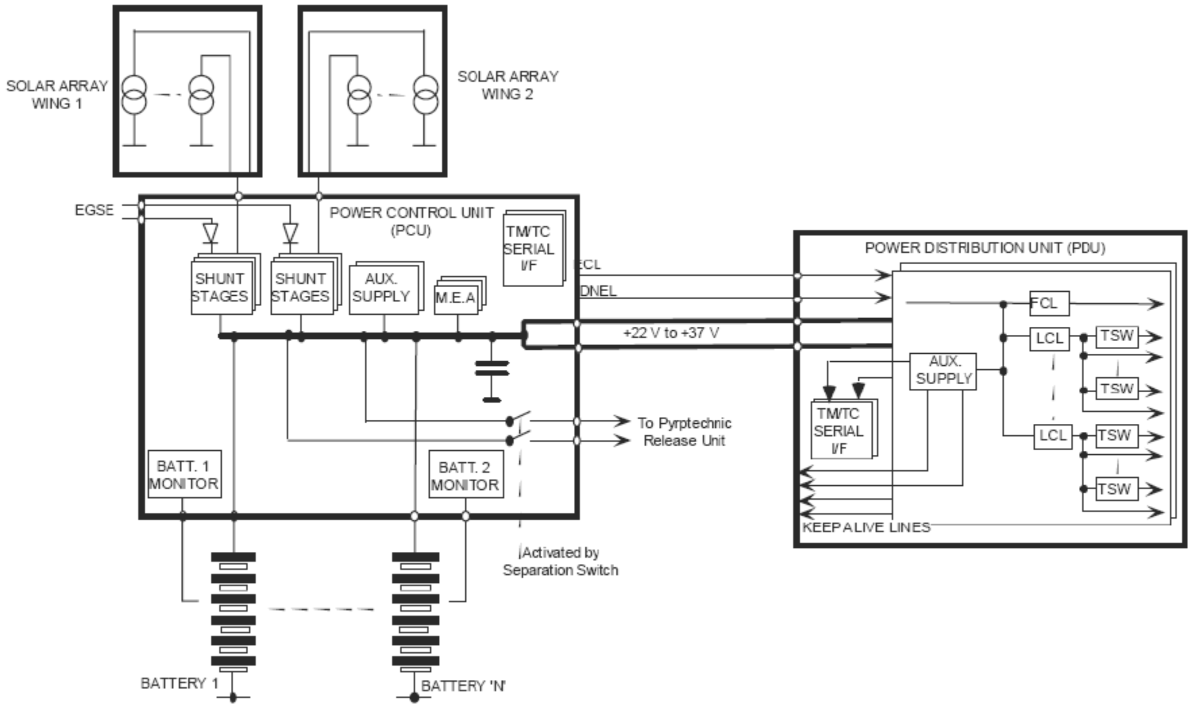


Figure 8-2: Typical Un-regulated Power Bus Concept

In order to route the processed power to the electrical users of the spacecraft, a distribution and protection system has to be provided. At the present time the particular circuit features of this system can range from simple relay and fuse combinations up to comprehensive solid state concepts offering current limitation and load current telemetry.

This distribution function is usually provided by a unit called PDU (Power distribution Unit).

It would appear that the most rationalised and cost effective way of implementing the power subsystem electronic on board a satellite is to centralise it in a single box called PCDU (Power Conditioning and Distribution Unit) which, on the one hand would receive power from the solar array and be backed by the battery(ies), and on the other hand would distribute protected lines to all users on board the satellite.

In the past, there were very often several different boxes to perform this function.

In a most extreme case, you may have a SAR (Solar Array Regulator unit), a BRU (battery Regulator Unit), a PDU (Power Distribution Unit), a PRU (Pyro Release Unit), and a HCU (Heater Control Unit).

At present, we see the consolidation of a single box approach with respect to a multi box one for the PCDU.

The voltage range for buses is typical: 120V regulated (ISS), 100V regulated (most of todays telecom satellites), 70V regulated (US telecom satellites), 50 V regulated (past telecom satellites, still for some of the smaller), 50V unregulated and 28V unregulated (widely used in earth observation and science missions). In a few cases on ESA science mission have been made to accommodated EP, for example for the BepiColombo Mission the low voltage bus was adapted to the 100V input of a PPU.

9.1 Power Conversion and Distribution

Europe has positioned itself well with respect to the technology for electrical power subsystems for space applications, with many novel regulator designs and control principles having been established over the last four decades and applied all over the world.

Currently, after many consolidations, Europe has three Large Satellites Integrators companies – Astrium, Thales Alenia Space and OHB - which have and need to have complete power subsystem definition capability in house as a core competency.

For the actual definition, design and manufacturing of the power subsystem elements, these primes may have different capabilities or policies, also according to the product line, whether it is commercial or institutional. For example, for commercial telecommunication market, Astrium has favoured so far vertical integration, while Thales Alenia Space had a number of partners to provide the elements of their platform.

Power subsystems are considered strategic by primes in relation to their recurrent telecom market, and as such specific power subsystem solution are developed and maintained as part of the satellite platform.

The most remarkable examples of power systems for telecom satellites are on the Spacebus platform by Thales and on the Eurostar platform by Astrium, both fully recurring products. Efforts have been placed to develop also a Large European Platform (Alphabus, with its first mission Alphasat) on the basis of a cooperation within Astrium and Thales Alenia Space, and to cover the low power end of telecom market needs (Small GEO, ARTES 11).

For LEO applications, some generic/recurrent platform has been developed in Europe by Thales Alenia Space (Proteus, PRIMA) and now development activities are running in ESA to support the improvement of the relevant power subsystem for getting a better competitive product for European use (mainly for Earth observation missions) or world-wide use (Globalstar II can be considered as an example).

About efforts presently pursued to develop platforms on the basis of cooperation with Astrium and Thales Alenia Space, it is worth mentioning the CNES project "PF 2012" (multi-mission platform).

For institutional projects (ESA), there is always the consideration of geographical return, which strongly influences the selection of subcontractors. In any case, these prime contractor companies are surrounded by many companies able to provide specific elements of a power subsystem.

Some independent companies (TERMA, DK) succeeded developing and providing very compact, flexible and effective designs for power subsystems used in Science and navigation, responding with excellent results to the big challenges required (Rosetta, Mars and Venus Express, Bepi Colombo, Galileo).

Specific advanced power subsystems were developed for navigation purposes (Galileo) and other challenging missions as BepiColombo and Exomars (both requiring non conventional solutions for the peculiarity of the mission itself – the close proximity to the Sun and the very large electrical propulsion engine for BepiColombo, and the issues of planetary landing for Exomars -).

In today's market the spacecraft power designs was not specifically adapted to the need for EP. PPU were developed as separate units and small adaptation were made just were necessary. Such adapations were in the past:

- Special high power LCL's for the high power demand of PPU's
- Or: removal of LCL in the PCDU and transfer of the protection function into the PPU's
- Increased power regulation due to voltage drops caused by variation of the PPU load (on smaller buses).
- Voltage adaption units, for example to supply a standard high voltage PPU (100V etc.) from a low power bus.

It is obvious that there can be some main drivers to futher integrate PPU with PCDU:

- In order to save cost (less parts)
- Direct driving
- Increasing power demand of EP

- Other power sources: Nuclear power, RTG's

The following table gives an overview of European manafactures providing units or components for PMD (extract for ESA's 2013 harmonisation dossier [RD3]).

Space Unit (SU) Name	Country	Technology Subdomain	Validated through Harmonisation	Validated through Harmonisation - Remarks
RUAG Space GmbH	Austria	3-A Power system architecture	Yes	Power electronics
RUAG Space GmbH	Austria	3-D Power conditioning and distribution	Yes	DC/DC power conversion
Thales Alenia Space ETCA	Belgium	3-A Power system architecture	Yes	Power subsystem (high power solutions for telecom, power system on demand for specific purposes), Power electronics
Thales Alenia Space ETCA	Belgium	3-D Power conditioning and distribution	Yes	Modular centralised PMD for all bus topologies and power classes, DC/DC power conversion, EPCs for TWTA (second european producer), Electrical Power Supplies for Electric Propulsion
Bristol Aerospace Ltd	Canada	3-A Power system architecture	No	
Bristol Aerospace Ltd	Canada	3-D Power conditioning and distribution	No	
DPL Science	Canada	3-A Power system architecture	No	
DPL Science	Canada	3-D Power conditioning and distribution	No	
MDA	Canada	3-A Power system architecture	No	
MDA	Canada	3-D Power conditioning and distribution	No	
ANF DATA	Czech Republic	3-A Power system architecture	No	
ANF DATA	Czech Republic	3-D Power conditioning and distribution	No	
ASICentrum	Czech Republic	3-D Power conditioning and distribution	No	
BBT - Materials Processing	Czech Republic	3-A Power system architecture	No	
BBT - Materials Processing	Czech Republic	3-D Power conditioning and distribution	No	
Brno University of Technology - FEKT	Czech Republic	3-D Power conditioning and distribution	No	
CAS - Institute of Atmospheric Physics	Czech Republic	3-A Power system architecture	No	
CAS - Institute of Atmospheric Physics	Czech Republic	3-D Power conditioning and distribution	No	
CertiCon	Czech Republic	3-A Power system architecture	No	
CertiCon	Czech Republic	3-D Power conditioning and distribution	No	
CTU-Ericsson-Vodafone R&D Centre	Czech Republic	3-D Power conditioning and distribution	No	
Czech Space Research Centre (CSRC)	Czech Republic	3-A Power system architecture	No	
Czech Space Research Centre (CSRC)	Czech Republic	3-D Power conditioning and distribution	No	
Czech Technical University (CTU)	Czech Republic	3-A Power system architecture	No	
Czech Technical University (CTU)	Czech Republic	3-D Power conditioning and distribution	No	
e4t electronics for transportation	Czech Republic	3-A Power system architecture	No	
e4t electronics for transportation	Czech Republic	3-D Power conditioning and distribution	No	
Evolving Systems Consulting	Czech Republic	3-A Power system architecture	No	
Evolving Systems Consulting	Czech Republic	3-D Power conditioning and distribution	No	
FLEXTRONICS	Czech Republic	3-A Power system architecture	No	
FLEXTRONICS	Czech Republic	3-D Power conditioning and distribution	No	
Honeywell	Czech Republic	3-D Power conditioning and distribution	No	
Iguassu Software Systems	Czech Republic	3-A Power system architecture	No	
Iguassu Software Systems	Czech Republic	3-D Power conditioning and distribution	No	
Inter-Informatics Group	Czech Republic	3-A Power system architecture	No	
Inter-Informatics Group	Czech Republic	3-D Power conditioning and distribution	No	
LOM PRAHA	Czech Republic	3-D Power conditioning and distribution	No	
MESIT pristroje	Czech Republic	3-D Power conditioning and distribution	No	
Railway Research Institute (VUZ)	Czech Republic	3-D Power conditioning and distribution	No	
Research Institute of Geodesy, Topography	Czech Republic	3-A Power system architecture	No	
Research Institute of Geodesy, Topography	Czech Republic	3-D Power conditioning and distribution	No	
RETIA	Czech Republic	3-D Power conditioning and distribution	No	
Skoda Auto	Czech Republic	3-D Power conditioning and distribution	No	
Sobriety	Czech Republic	3-A Power system architecture	No	
Sobriety	Czech Republic	3-D Power conditioning and distribution	No	
Solartec	Czech Republic	3-A Power system architecture	No	
Solartec	Czech Republic	3-D Power conditioning and distribution	No	
Space Research Instruments	Czech Republic	3-A Power system architecture	No	
Space Research Instruments	Czech Republic	3-D Power conditioning and distribution	No	
SVM Microwaves	Czech Republic	3-A Power system architecture	No	
SVM Microwaves	Czech Republic	3-D Power conditioning and distribution	No	
SYSGO	Czech Republic	3-A Power system architecture	No	
SYSGO	Czech Republic	3-D Power conditioning and distribution	No	
Technical University of Liberec	Czech Republic	3-A Power system architecture	No	
Technical University of Liberec	Czech Republic	3-D Power conditioning and distribution	No	
Technical University of Ostrava	Czech Republic	3-A Power system architecture	No	
Technical University of Ostrava	Czech Republic	3-D Power conditioning and distribution	No	
TL elektronic	Czech Republic	3-A Power system architecture	No	
TL elektronic	Czech Republic	3-D Power conditioning and distribution	No	
Transport Research Centre (CDV)	Czech Republic	3-D Power conditioning and distribution	No	
TTC TELEKOMUNIKACE	Czech Republic	3-D Power conditioning and distribution	No	
Unis	Czech Republic	3-A Power system architecture	No	
Unis	Czech Republic	3-D Power conditioning and distribution	No	
IR Denmark	Denmark	3-A Power system architecture	Yes	Power electronics
IR Denmark	Denmark	3-D Power conditioning and distribution	Yes	DC/DC power conversion. Connected to the mother company International Rectifiers (US), to date the only producer of Rad-Hard MFETs for Space Applications.
TERMA	Denmark	3-A Power system architecture	Yes	Power subsystem (power system on demand for specific purposes), Power electronics
TERMA	Denmark	3-D Power conditioning and distribution	Yes	Modular centralised PMD for all bus topologies and power classes, DC/DC power conversion
Patria	Finland	3-A Power system architecture	Yes	Power subsystem (mainly power distribution on demand for specific purposes), Power electronics

Space Unit (SU) Name	Country	Technology Subdomain	Validated through Harmonisation	Validated through Harmonisation - Remarks
Patria	Finland	3-D Power conditioning and distribution	Yes	Modular centralised PMD for all bus topologies, DC/DC power conversion.
Astrium SAS	France	3-A Power system architecture	Yes	Power subsystem (high power solutions for telecom) & Power electronics in Velizy; Specification / integration and design & development of Power subsystem (high power solutions for telecom) in Toulouse
Astrium SAS	France	3-D Power conditioning and distribution	Yes	DC/DC power conversion (Velizy, Toulouse). In Velizy: Modular centralised PDM for high power classes, EPC for SSPA, Actuators and motor Drivers.
STMicroelectronics	France	3-A Power system architecture	Yes	Power electronics (EEE components)
Thales Alenia Space	France	3-A Power system architecture	Yes	Specification / integration of Power subsystems (Cannes)
Thales Alenia Space	France	3-D Power conditioning and distribution	Yes	Specification / integration of DC/DC power conversion (Cannes)
ASP	Germany	3-A Power system architecture	Yes	Power subsystem (power system on demand for specific purposes), Power electronics
ASP	Germany	3-D Power conditioning and distribution	Yes	Power Distribution Units, Modular centralized PMD for all bus topologies, DC/DC power conversion, EPCs for TWTA and SSPA, Electrical Power Supplies for Electric Propulsion
Astrium GmbH	Germany	3-A Power system architecture	Yes	Power subsystem specification/analysis, Power subsystem (power system on demand for specific purposes), Power electronics.
Astrium GmbH	Germany	3-D Power conditioning and distribution	Yes	Modular centralized PMD for all bus topologies, DC/DC power conversion for all voltages commonly used in space, EPCs for TWTA, DC/DC or DC/AC/DC supplies for active antenna front-ends, Specail high voltage supplies for scientific instruments on satellites and ISS, Coolers Control and Driving Electronics, Electrical Power Supplies for Electric Propulsion.
Kayser-Threde	Germany	3-A Power system architecture	Yes	Power electronics
Kayser-Threde	Germany	3-D Power conditioning and distribution	Yes	DC/DC power conversion
Tesat-Spacecom	Germany	3-A Power system architecture	Yes	Power electronics
Tesat-Spacecom	Germany	3-D Power conditioning and distribution	Yes	DC/DC power conversion, EPCs for TWTA (major producer in the world of EPCs for TWTAs)
Compagnia Generale per lo Spazio (CGS)	Italy	3-A Power system architecture	Yes	Power electronics
Compagnia Generale per lo Spazio (CGS)	Italy	3-D Power conditioning and distribution	Yes	DC/DC power conversion
SELEX GALILEO SpA	Italy	3-A Power system architecture	Yes	Power subsystem (power system on demand for specific purposes), Power electronics
SELEX GALILEO SpA	Italy	3-D Power conditioning and distribution	Yes	DC/DC power conversion, Tile power supplies and DC/DC power conversion and distribution for active antenna front end, EPCs for SSPA, EPCs for TWTA/Klistron, Actuator and motor drivers, Electrical Power Supplies for Electric Propulsion
SITAEL S.p.A.	Italy	3-A Power system architecture	Yes	Power subsystem (power system on demand for specific purposes), Power electronics
SITAEL S.p.A.	Italy	3-D Power conditioning and distribution	Yes	DC/DC power conversion, Electrical Power Supplies for Electric Propulsion
STMicroelectronics	Italy	3-A Power system architecture	Yes	Power electronics (EEE components)
Thales Alenia Space	Italy	3-A Power system architecture	Yes	Specification / integration of Power subsystems (Roma, Torino). Power Electronics and Power Subsystem (Milan).
Thales Alenia Space	Italy	3-D Power conditioning and distribution	Yes	DC/DC power conversion (Milan). Specification / integration of DC/DC power conversion (Roma).
Astrium CRISA	Spain	3-A Power system architecture	Yes	Power subsystem (power system on demand for specific purposes)
Astrium CRISA	Spain	3-D Power conditioning and distribution	Yes	Modular centralised and decentralised PMD for all bus topologies, Tile power supplies and DC/DC power conversion and distribution for active antenna front end, Actuator and motor drivers, Coolers Control and Driving Electronics, DC/DC Power conversion, Electrical Power Supplies for Electric Propulsion.
Emxys	Spain	3-A Power system architecture	No	
Emxys	Spain	3-D Power conditioning and distribution	No	
GTD	Spain	3-D Power conditioning and distribution	No	
NTE-SENER	Spain	3-D Power conditioning and distribution	No	
Starlab	Spain	3-D Power conditioning and distribution	No	
Thales Alenia Space	Spain	3-D Power conditioning and distribution	No	
Omnisys Instruments	Sweden	3-A Power system architecture	Yes	Power subsystem (power system on demand for specific purposes), Power electronics
Omnisys Instruments	Sweden	3-D Power conditioning and distribution	Yes	DC/DC power conversion
RUAG Space AB	Sweden	3-A Power system architecture	Yes	Power electronics
RUAG Space AB	Sweden	3-D Power conditioning and distribution	Yes	DC/DC power conversion
Montena	Switzerland	3-D Power conditioning and distribution	No	
PMOD/WRC	Switzerland	3-D Power conditioning and distribution	No	
RUAG Space - RUAG Schweiz AG	Switzerland	3-D Power conditioning and distribution	No	
Spectratime	Switzerland	3-D Power conditioning and distribution	No	
Astrium Ltd	UK	3-A Power system architecture	Yes	Specification / integration of Power subsystem
Astrium Ltd	UK	3-D Power conditioning and distribution	Yes	Specification / integration of DC/DC power conversion
Clyde Space	UK	3-A Power system architecture	Yes	Modular power subsystem (LEO)
Surrey Satellite Technology Ltd (SSTL)	UK	3-A Power system architecture	Yes	Power subsystem (power system on demand for specific purposes, LEO, GTO, MEO)

Table 8-1:Industry, Research Institutes and Organisations involved in the PMD Technology

9.2 Power Generation

9.2.1 Solar Generators

Solar Generation cover the range up to 25 kW of large satellites at bus voltage of 100V (Eurostar 3000, Spacebus, AlphaSat) or for the ISS 83 kW at 124 V. Today's technology employs GaAs Triple Junction cells with efficiency up to 29% (BOL)

European manufacturers of solar generators are:

- Airbus DS (in Munich, Germany)
- Airbus DS (in Leiden, The Netherlands)
- Thales Alenia Space (Cannes, France)

An increase of power can be driven by the need of payloads and/or eEP. Scenarios are:

- Increase efficiency of solar cells from now 29% to beyond 40% (BOL) by four or five junctions cells
- Increase of efficiency/cost reduction by concentrator cells
- Increased solar generator surface area by light structures: roll-able or foldable thin structures

An increase of voltage can be driven by need of direct drive for EP. Feasibility has been demonstrated at least on ground in vacuum environment, however the use in space may require an adequate space-based test bed to better assess space vacuum related impact, for example outgassing, spacecraft charging, surface charging. A technology example is shown in Figure 8.3 below.

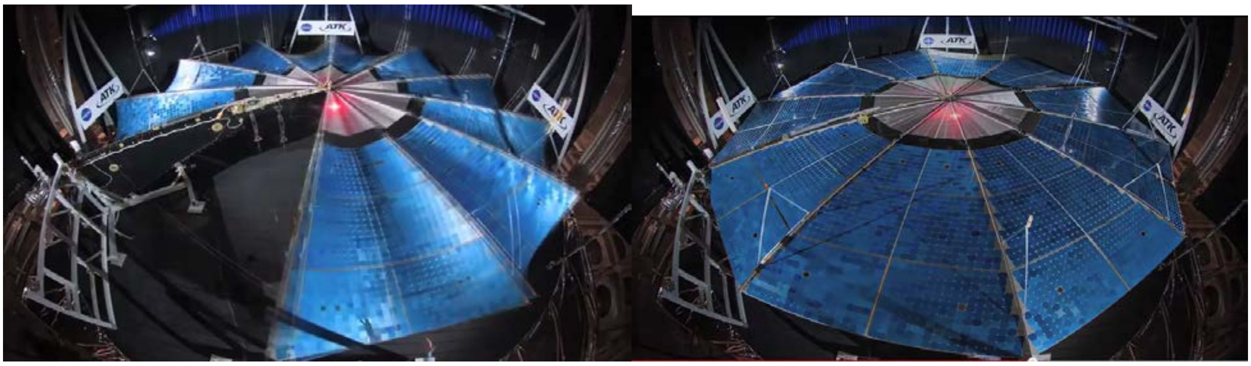


Figure 8-3: Technology Example from US"(ATK) MegaFlex Solar Array Development and Test

The results from Phase 1 of the NASA Game Changing Development (GCD) Program for Solar Electric Propulsion (SEP) Solar Array Systems" - advanced Solar Array system are:

- Objective: design a flexible deployable of 10 kW / wing (https://www.atk.com/wp-content/uploads/2013/05/UltraFlex-2012.pdf)
- Concept:
  - based on existing ATK Ultraflex array with compact stowed packing, low mas, modular architecture using IMM cells
  - SA stowed in a boom and deploy as an fan with motor
  - Currently achieved 10m ø wing (20 kW), 160V typical and up to 300V[1]

[1] Remark: Attention needed to possible discharge effects at higher voltages

- Application for the NASA Solar electric propulstion SEP
- Status/ Roadmap: New design up to 30m ø wing; applications for telecom sat, other.

9.2.2 Nuclear Power Generation

Nuclear power sources for space application are in general based on the following principles:

- Decay Heat Utilization
- Fission Reactors

Both principles have been used for space power systems in US and the Soviet Union, a few US missions with Radio Isotope Generation were shared with European contributions for payloads mainly.

Nuclear power sources in conjunction with EP have not be used up to now. The efficiency of decay heat utilization is poor, so that for medium and high power mission the available power would not be sufficient. Nuclear power from fission reactors is typically higher and at least in theory a possible source for high power EP.

European technology in this field has been covered by the initiative HYPER as part of a European EU Framework Program. As an outcome of this initiative preparatory for a roadmap in advance of the Horizon p2020 program was done under the name of the MEGAHIT activity, see http://www.megahit-eu.org/

9.2.2.1 Electrical Power Generation from Decay Heat

The heat generated by the decay of a radioisotope can be used to generate electricity. The usual way of doing this is via the thermoelectric (Seebeck) effect. Such a device is called a radioisotope thermoelectric generator (RTG). RTGs are an established technology for both space and terrestrial applications. On Earth, RTGs were used most widely in the former Soviet Union to power remote lighthouses and navigation beacons. In space, RTGs have been used most extensively by the USA, with the Soviet Union historically favouring fission reactor power sources.

Since 1961, the USA has flown 42 RTGs. All of these flight models used 238Pu fuel, although other isotopes were used in several development or demonstration models. The NASA RTG missions are summarised in the table below, together with Russian RTG missions highlighted in blue.

The main technical drawback of RTGs is their low power conversion efficiency, which is in the region of 6-7% for modern devices in the >100We power range.

The highest-power space application for radioisotope power generation was the Cassini craft, which used three GPHS RTGs, generating a total of ~880W at BOM. In terms of mass, a 238Pu-fuelled RPS lacks competitiveness (as compared to a fission reactor system), somewhere between 2 and 5kW. In practice, the cost and scarcity of 238Pu also discourages kW-scale RPS usage.

The GPHS RTG is optimised for use in vacuum, and is not suitable for use in planetary atmospheres (it uses light-weight multi-layer insulation). This is one reason why the USA has now developed the Multi-Mission RTG (MMRTG), which is suitable for both environments, but at the cost of a significantly lower specific power (W/kg). The first flight of an MMRTG is on the Mars Science Laboratory (MSL) mission, which is successfully operating on Mars at the time of writing.

Other power conversion technologies have been coupled to radioisotope decay heat sources. The early U.S. system SNAP-1 used a mercury Rankine-cycle heat engine, and SNAP-13 used caesium vapour diodes for thermionic conversion (neither were flown). More recently, NASA’s development of Stirling heat engines for radioisotopic generation has neared maturity, and the U.S agency has publicly stated its intention to fly the ASRG Stirling system in the next few years [Table 8-2]. Heat engines promise greater efficiencies than thermoelectrics, but the dynamic nature of the devices brings challenges in terms of vibration damping and long-term reliability.

Other emerging technologies with potential application to decay heat electrical generation include AMTEC (Alkali Metal Thermal to Electric Conversion), thermophotovoltaics and thermoacoustics.

NASA's current research activities in this field are focussed mainly on thermoelectrics and Stirling engines, and to a lesser degree on thermophotovoltaics and Brayton-cycle turbines.

Year	Mission/ Spacecraft Name	Spacecraft Type	RTG Type & Power (W_e)	Mass of one RTG (kg)	Specific Power (W/kg)	Approx. Efficiency (%)
1961	Transit 4A & 4B	Satellite (Navy Navigation)	SNAP-3B. 2.7W	2.1	1.3	5.1
1963-64	Transit 5BN-1 & 5BN-2. [5BN-3 = launch fail]	Satellite (Navy Navigation)	SNAP-9A. >25W	12.2	2.0	5.1
1965	Kosmos 84 & 90 (USSR)	Satellite (Navigation?)	Orion-1 RTG. ^{210}Po 20W	14.8	1.35	Not known
1969	Nimbus-3	Meteorological satellite	SNAP-19B. 2 x 25W	13.5	1.9	5.4
1969 - 1972	Apollo 12,14,15,16,17.	Lunar Surface (Experiment Package)	SNAP-27. >70W	30.8 (without cask)	2.3	5.0
1972	Transit TRIAD	Satellite (Navy Navigation)	Transit RTG. 35W	13.5	2.6	4.2
1972 - 1973	Pioneer 10 & 11	Interplanetary	SNAP-19. 4 per spacecraft @ 40W each	13.6	2.9	5.4
1975	Viking 1 & 2	Mars Lander	SNAP-19. 2 per lander @ 42W each	13.6	3.1	5.4
1976	Lincoln LES 8 and LES 9	Comms. Satellite	MHW-RTG. 2 per satellite @ 154W each.	38.5	4.0	6.6
1977	Voyager 1 & 2	Interplanetary	MHW-RTG. 3 per spacecraft @ 158W each.	38.5	4.1	6.6
1989	Galileo	Interplanetary	GPHS-RTG. 2@ 288W each	56	5.1	6.6
1990	Ulysses	Interplanetary	GPHS-RTG. 289W.	56	5.2	6.6
1996	Mars '96 (Russia). Launch failure	Mars Landers & penetrators	Angel RTG 150mW 8 in total.	0.5	0.3	1.7
1997	Cassini	Interplanetary	GPHS-RTG. 3@ 295W each	56	5.3	6.6
2006	New Horizons	Interplanetary	GPHS-RTG. 246W.	58	4.2	6.6
2012	Mars Science Laboratory - *Curiosity*	Mars Rover	MMRTG. 125W.	44	2.8	6.25

Table 8-2: RTGs flown in space. 238Pu unless otherwise stated

9.2.2.2 Fission Reactor Systems for Electrical Power Generation

Space nuclear reactors are based on the same fundamental components as terrestrial nuclear reactors in electric power stations: a reactor core, an energy conversion system, and a heat rejection system. However, several key design criteria for space reactors are very different from those for terrestrial ones, including requirements arising from mass and volume limitations, autonomy requirements, impossibility of refuelling, efficiency of heat rejection in deep space, and launch environments. Therefore, the actual designs of space reactors vary substantially from their terrestrial counterparts. Space reactors usually have very small and compact reactor cores with high enrichment ratios, and very high core and conversion system temperatures (in order to allow for small radiator sizes).

Nuclear electric fission reactors in space have been used to provide electric power for on-board instruments as well as for electric propulsion systems. Three reactor types have so far been flown in space: the Russian BUK and TOPAZ reactors and the US SNAP-10A reactor. None of the three reactor types was designed for shut-down and restart in space.

The only U.S. fission reactor to fly in space was the SNAP-10A. This was a thermal2 reactor, using Uranium-Zirconium Hydride (U-ZrHx) fuel, and a sodium-potassium (NaK) liquid-metal primary coolant. SNAP-10A developed 42kWt, and was coupled to a SiGe thermoelectric power converter producing ~600W. The system provided power to the SNAPSHOT spacecraft, which also contained an ion thruster. SNAP 10A operated in space for only 43 days in 1965, until a failed voltage regulator triggered a shutdown.

The U.S. space reactor programme also produced the SNAP-2 and SNAP-8 reactors. These were also thermal reactors with U-ZrHx fuel and Na-K coolant, but were coupled to a Rankine-cycle power conversion system (see Section 8.4). These were ground-tested, but never flown. More recently, between 1978 and 1995, the USA developed a fast reactor design known as SP-100. Although the original mission was an orbital power supply for the US Strategic Defence Initiative of the 1980s, it was designed as a versatile power supply for orbital, lunar, and Martian surface missions as well as for power electric propulsion and was scalable in the power range from 10's to 100's kW. The SP-100 was originally proposed with a SiGe thermoelectric system, but has also been linked, on paper, to closed-cycle Brayton conversion. The SP-100 programme was cancelled before any reactor testing took place, although approximately $1 billion had been invested in design and development.

In 2003, and based on the earlier work within NASA's Nuclear Systems Initiative, the USA started the Prometheus project with two major objectives[3]:

- to develop a nuclear reactor that would provide unprecedented levels of power and to show that it could be processed safely and operated reliably in space for long-duration, deep-space exploration;
- to explore three icy moons of Jupiter (Callisto, Ganymede, and Europa). Although the project was led by the US Jet Propulsion Laboratory, the reactor work was led from 2004 onwards by Naval Reactors, and involved a few dozen US entities and 500 full-time equivalent staff when it was discontinued in 2005 based on a life-cycle cost estimate (including the launch vehicle) of more than $10 billion. Technically, the design centred on a high-temperature gas-cooled reactor directly coupled with redundant Brayton turbo alternators for power conversion with the capability of producing approximately 20kW of electrical power for a 15–20 year nuclear electric propulsion mission. It was foreseen that the reactor would power a very ambitious spacecraft to be launched first in 2015 with a wet mass of more than 36 tons, including 12 tons of xenon propellant, a total length of 58m, and a radiator area of 422m.

The U.S. space nuclear reactors that were actually operated in test or flight are summarised below.

Reactor Name	**Year of operation**	**Power conversion system**	**System unshielded weight (kg)**	**Thermal Power (kW)**	**Electrical Power (kW)**	**Overall efficiency (%) approx.**
				--Data from the latter of 2 tested systems--		
SNAP-2	1959-62 (ground)	Rankine mercury	545	57	5	9
SNAP-8	1963-69 (ground)	Rankine mercury	4545	600	35	8
SNAP-10A	1965-66 (ground and space)	Thermoelectric SiGe	295	42	0.65 BOL 0.54 EOL	1.5

Table 8-3: USA space nuclear reactors. Two models of each system were produced.

[2] Utilising moderated, thermal-energy neutrons to induce fission. As opposed to a *fast* reactor, which has no moderator, and uses high energy neutrons to sustain the chain reaction.
[3] Prometheus project was descoped and re-oriented in 2006

The USSR space programme made extensive use of fission reactors, with 35 believed to have been launched between 1967 and 1988. Most of the Russian reactors have been coupled to thermoelectric generators, and used for short duration low-earth-orbit military satellites. Some higher power systems have used in-core thermionic generation.]

Although the earlier reactor designs used a fast neutron energy spectrum, the later TOPAZ reactor was epithermal. Both relied on NaK liquid-metal cooling and a stainless steel structure and piping (DC induction electromagnetic pumps for the primary and secondary loops). Neutron moderation in the TOPAZ design was based on monolithic ZrH blocks and its energy conversion system used fuel elements with in-core, multi-cell thermionic energy conversion, whereas the BUK reactor used SiGe thermoelectric conversion. The conversion systems had efficiencies of 1.5–2.0% and 5.5% in the BUK and TOPAZ systems, respectively.

Due to the secret military nature of the Soviet space programme, details of the reactor programme are scarce in the open literature, and sources are often contradictory, in particular regarding the earlier reactors in the late 1960s and early 1970s.

9.2.3 Other Power Generation

Other power generation concepts could involve for example plasma current collection from space.

9.2.4 Related activities

DiPoP is an assessment study for the European Space Policy (9.3.5 / SPA.2011.3. 5-01).

Disruptive space power and propulsion technologies as well as their applications are assessed. Recommendations and roadmaps for FP8 for enabling an independent, long term European leadership is the “in fine” goal of the project DiPoP. Disruptive space propulsion and power technologies studied are: continuous detonation wave engine, space and ground nuclear fission (power 30 kWe to 200 kWe, including "Rules for Public Acceptance with Launch & Operations Constrains"), solar and fuel cells, batteries, Power-MEMS (Power Micro- Electro-Mechanical System), Advanced Propulsion Systems and Power Processing Units. Space propulsion and power applications under DiPoP covers EC space work programme areas like propulsion (for entry, interplanetary flight, micro-propulsion systems, robotics), space exploration (mobility on planetary surfaces, habitation, life support),space power long term security and related areas.

10 TEST FACILITIES

10.1 Vacuum Test Chambers

EP testing facilities are requested for long duration tests and acceptance testing. Europe is provided with numerous testing facilities dedicated to electric propulsion. They are located in industry or in laboratories/academia/institute (see Figure 9-1). Most of them are able to host EP components and low/medium power EP thrusters for qualification and lifetime test. They have dedicated pumping systems and diagnostics (including plasma probes, thrust balances, etc.). Today, the biggest facility, IV10, is located in Alta (pumping speed of 1,500,000 l/s Xe) and is able to accommodate 25 kW thrusters. Two companies are also developing facilities for EMC/EMI testing: QinetiQ in UK and Aerospazio in Italy, which will allow European manufacturers to avoid going to the US to perform such kind of tests.

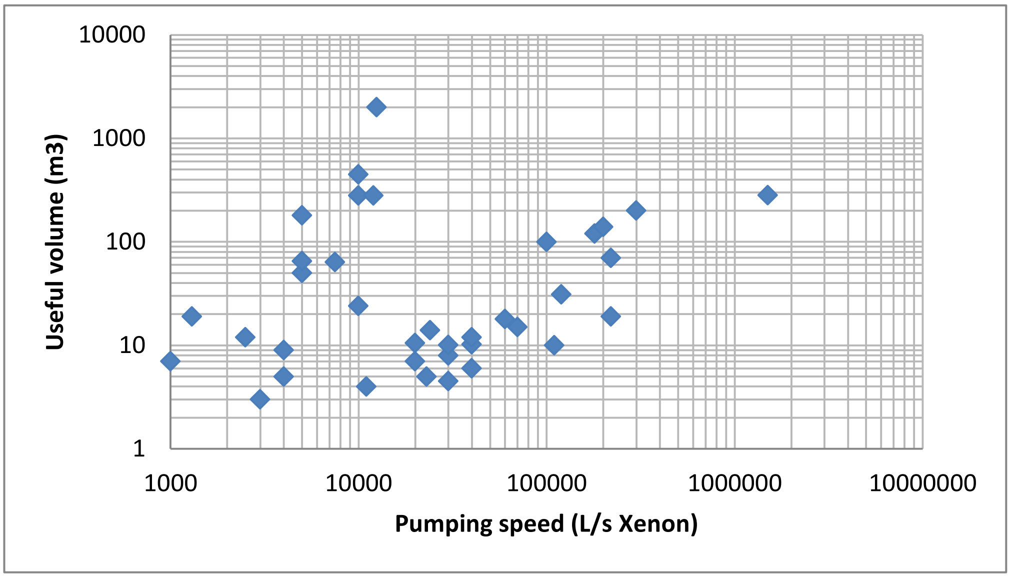


Figure 9-1: Capacity of EP testing facilities in Europe

Product name	Manufacturer and /or Location	Technical Characteristics		
		Pumping capability (L/s)	Volume (m³)/ Dimensions main chamber (m x m Ø)	Development status
Corona	ESA (NL)	70,000 (Xe)	4 x 2	100 W to 2 kW EP thrusters
Gigant		36,000 (Xe)	2.5 x 1.6	
FEEP		4,600 (Xe)	1.3 x 0.8	
Galileo		64,000 (N2)	1.2 x 1	
Micro-Newton		750 (N2)	0.65 x 0.5	
Electron		260 (N2)	0.5 x 0.8	
Small Plasma Facility		60,000 (Xe)	3.35 x 2	100 W to 2 kW EP thrusters
Pivoine – 2G	ICARE- CNRS (F)			100 W to 25 kW EP thrusters
NExET				
LEEP 1	QinetiQ (UK)		3 x 1.6	EMC facility
LEEP 2		80,000 (Xe)	9 x 3.8	5 kW EP testing, twin thruster operation
LEEP 3		200,000 (Xe)	8 x 3.0	5 kW EP testing
Several small facilities				
LIFET 1	FOTEC (A)		1.8 x 1	In-FEEP
LIFET 2			2 x 0.8	In-FEEP
LIFET 3			1.8 x 0.8	In-FEEP
LIFET 4			4 x 2.5	Dual use for In-FEEP and Xe thrusters. Operational in

				2015.
DLR EP Test facility	DLR Gottingen			For thrusters up to 50 kW input power
ULAN	Thales Ulm (D)	70,000 – 120,000 (Xe)	4 x 2.4	
JUMBO	JLU Giessen (D)		30 m³	Cold space simulator down to -100 °C
BigMac			2 m³	Emission spectroscopy
STG-ET	DLR Gottingen (D)		12.2 x 5	For thrusters up to 50 kW input power
High vacuum plume test facility - STG			5 X 1.6	Plume flow and impingement investigations
LVTF-1	Aerospazio Tecnologie (I)	160,000 (Xe)	120 m³ – 11.4 x 3.8	Special test set-up for high power Xenon EP testing (25 kW)
LVTF-2		180,000 (Xe)	200 m³ – 12.5 x 3.8	Special test set-up for high power Xenon EP testing (25 kW) and for thermal vacuum testing on large EUT
EMI/EMC chamber			6.0 x 5.2 x 3.3m	Interfaced to LVTF-2 MIL STD 285 and NSA 65-5 compliant
SVFT-1/2/3				Small vacuum test facilities for cathode/neutraliser testing
Medium vacuum test facility		10,000 (Xe)	4 m³	For EP and thermal vacuum testing
IV 10	Alta SpA (I)	1,500,000 (Xe)	10 x 6	For thrusters up to 25 kW input power
IV 4		130,000 (Xe)	8 m³	
Facilities in Micropropulsion Laboratory				6 ultra-high vacuum chambers, mainly used for FEEP and flight qualification tests
	IPPLM (Poland)	34 m³/s	2 (2 x 1.2)	For low power HET testing
Vacuum tank	Airbus DS (D)	11400 (?)	1.2 x 1.2 x 1.2	
MSCL-1	Mars Space Ltd (UK)	2200	1.5 x 0.6	
MSCL-2		4500	1.5 x 0.6	
Several available	SSTL (UK)			
	UC3M (S)	35,000 (Xe)	3.75 x 2	To be completed by December 2015. Thrusters in 1-1.5 kW range
Arges	University of Madrid (UPM) (S)		2 x 0.8	Basic plasma physics experiments
Balance micronewton	ONERA (F)	500 (Xe)	0.7 x 0.5	
B09		2500	2 x 0.9	
B61		8000	4 x 1	

10.2 Diagnostics

Type	Product name	Manufacturer and /or Location	Technical Characteristics	
			Range (mN)	Development status
Thrust balances		AST GmbH (D)	1-1000	Developed for DLR Gottingen
	Thrust balance		0.1-250	Developed for DLR Gottingen
	Micro-Newton Thrust Balance	ESA (NL)-NPL (UK)	0.001-0.5	ISO 17025 accredited thrust measurements for cold gas thrusters
	MT AX504	ESA (NL)	0.001-500	ISO 17025 accredited thrust measurements for cold gas thrusters
	MT XP2004S		0.001-2300	ISO 17025 accredited thrust measurements for cold gas thrusters
	1-Axis Thrust Stand		1 – 200	ISO 17025 accredited thrust measurements for EP thrusters
	Low Thrust Balance		1-100	ISO 17025 accredited thrust measurements for EP thrusters
	Thrust balance	Aerospazio (I)		
	µNTB	FOTEC (A)	0.001 - 5	
	150 mN single axis inverted pendulum thrust stand	Alta SpA (I)		
	200 mN 2 axis direct pendulum thrust stand			
		Mecartex (Switzerland) - @ IPPLM (Poland)	0.01-100 / Impulse bit: 0.005-50 [mNs]	mechanical rigidity can be adjusted over at least 2 order of magnitude; may also operate with negative feedback in motionless thrust measurement mode
	Micro-Newton thrust balance	Airbus DS (D)	0.0001 - 10	Resolution : 1.10^{-7} N, Bandwidth: 1-1o^{-3} Hz Calibrated via Electro-Static Comb assembly
	Impulsive thrust balance	Mars Space Ltd (UK)	20-1000 [uNs]	Measurement error: 8 %
	MicroNewton thrust balance	ONERA (F)	0.0001-10	
	MicroNewton thrust balance	Dresden University of Technology (D)	6 mN max	Torsional thrust balance Thrust noise < 40-80 nN
	Single axis Thrust balance	QinetiQ (UK) – NPL (UK)	1-500	
	Thrust balance	Thales Ulm (D)	0 - 800	

Plasma / ion Plume diagnostics	ExB probe, Faraday cups, LIF, RPA, Langmuir Probes, Emissive probes, Coherent Thomson scattering (PRAXIS), Laser Photodetachment	ICARE (F)		
	Langmuir Probe, Thrust vector system, RPAs, Faraday cusps, ExB probe, Emissive probe, Infrared thermography (camera and pyrometer)	ESA (NL)		
	EPDP	Selex-ES (I)		Flown on Smart-1. **TRL 9** Qualification up to flight model for FEEP on Lisa PathFinder.
	MM-PDP			Developed for multi-modular applications up to EM
	AEPD (Advanced Electric Propulsion Diagnostic Package)	IOM (D)		8 diagnostics heads for in-situ diagnostics of mechanical parts and plasma properties. In the process to be upgraded for standardisation of EP testing
	Material investigation/sputter yield measurements			Incident angle and energy selective setup
	Faraday cusps, Triple Langmuir probes, RPAs, Thrust vector systems, Emission Spectroscopy, Infrared thermography, microscopy	Alta SpA		
	Thermal probes	University of Kiel (D)		
	Microparticle probes			In development
	Force probes			
	Contact charging experiments			Electrode design, simulation, diagnostics for microparticle thrusters
	Faraday probes, Langmuir Probes, RPA, LIF, Magnetic probes, ExB probe, Emission spectroscopy, Infrared thermography	Aerospazio Tecnologie (I)		
	Faraday Cups, RPA	Airbus DS FN (D)		

	CMM and Digital Photogrammetric Array	QinetiQ (UK)		
	Langmuir Probes, RPA, Emissive probe	University of Madrid (UPM) (S)		
	Faraday probes, RPA	DLR Gottingen (D)		
	RPA, Energy selective mass spectrometer, thrust vector scanner,	Thales Ulm (D)		
	LIF, 3D LIF, Electron beam fluorescence	ONERA (F)		

11 DEVELOPMENT TOOLS

The following table presents a non-exhaustive list of development tools used by European companies, institutions and academia in the area of EP. All European companies have also their own tools that they use to develop the EP components and/or systems.

Product Name	Space Unit name	Comments
SPIS v5.2	ESA/ONERA/FOTEC	www.spis.org- freely available and in continuous development
Battery Electrical Analysis Software Tool (BEAST)	ABSL Space Products (UK)	For detailed cycling performance prediction. BEAST2007 is distributed to ABSL customers and Agencies. Validation has been performed against on-ground testing and in-flight data to give confidence in performance prediction.
Lithium-Ion Fade Evaluator (LIFE)		For long-term battery property prediction. Validation has been performed against on-ground testing and in-flight data to give confidence in performance prediction.
NOMADS	EP2- Equipo de Propulsión Espacial y Plasmas (S)	HET simulation, plasma plumes and spacecraft interactions
EP2PLUS		EP2PLUS still under development
2D DIMAGNO / HELWAVE2		Modelling of Magnetic nozzles and helicon antenna sources
DynaSim	IOM (D)	Material investigation- ion thruster grid erosion modelling
IGUN©		2D code for Ion trajectories
KOBRA3-inp		3D code for Ion trajectories
PROFIL		Plasma densities
FLOOD		Neutral densities
TdNTriaX	Koopos Consulting (F)	
SLIM (Saft Li Ion	SAFT (F)	Model to predict cell performances f=during LEO, MEO, GEO

Model)		missions, for VES and MPS cells.
	ALTA SpA (I)	PiC-DSMC Modelling software for plume simulation and surface-plasma interaction
	University of Bremen (D)	PIC simulations for µHEMPT
F3MPIC, GetDP Wavecode ADAMANT, FEMM, SPICE	University of Padua (I)	Modelling of Helicon Antenna thruster
SDTrimSP	Thales (D)	PIC code for ion thrusters – DSMC for neutral transport - Erosion/deposition – plume interaction with vacuum chamber
	Kornfeld Plasma & microwave Consulting (D)	Based on XOOPIC - For simulation of HEMPT

12 BENCHMARKING

The following paragraphs will present the benchmarking of some European technologies, when applicable.

12.1 Thrusters

A list of the main non-European Industry, Research Institutes and other Organisations involved in the Technology (thruster development) is given in Table 11-1.

Company/Institution – Nationality	Name of Item	Remarks
Boeing – USA	XIPS-13 GIE	Fly on Boeing 601HP platforms
Boeing - USA	XIPS-25 GIE	Fly on Boeing 702HP platforms
Fakel – Russia	SPT-50 HET	Flight proven (350W, 20 mN, 1100 s)
Fakel – Russia	SPT-70 HET	Flight proven (700, 40 mN, 1500 s)
Fakel – Russia	SPT-100 HET	Sold in Europe by Snecma until 2013. Over 15 years of on orbit flight heritage on Russian spacecraft.Operational on Intelsat10-02, Inmarsat 4 F1, F2, F3, SS/L satellites, etc. Embarked in SGEO.
Fakel- Russia	SPT-140 HET	5 kW, for future Space Systems Loral (USA) platforms SPT140-D for western applications
Busek- USA	BHT-200 HET	100-300 W. Flight proven on TacSat-2 and FalconSat-5
Busek- USA	BHT-600 HET	300-800 W
Busek- USA	BHT-1000 HET	500-1500 W
Busek- USA	BHT-1500 HET	1-3 kW
Busek- USA	BHT-8000 HET	4-12 kW
Busek- USA	BHT-20k HET	5-20 kW
Busek- USA	µPPT	Flight proven on FalconSat-3
Aerojet - USA	BPT-2000 HET	2 kW HET and associated PPU, for Telecom platforms
Aerojet - USA	BPT-4000 HET (XR-5)	5 kW HET and associated PPU, flight heritage (AEHF satellites)
Aerojet - USA	MR-510 Arcjet	Flown on A2100™ satellite (US)
Aerojet - USA	MR-509 Arcjet	Low power arcjet system- Flight proven (US)

Aerojet - USA	MR-512 Arcjet	Low power bus arcjet system. Flight proven
Aerojet - USA	PRS-101	PPT system- Flight proven
Aerojet/ NASA GRC - USA	NEXT 6.9 kW	Entire propulsion system- thruster @ Prototype Model – Propellant management system @ EM – PPU @ Laboratory model
Aerojet / NASA GRC – USA	Low power 0.5 kW GIE	
Aerojet- USA	NSTAR-class 2.3kW	Flown on Deep Space 1 and Dawn spacecraft (US)
JPL/Busek - USA	Colloid thrusters	Will fly on Lisa PathFinder spacecraft (planned for launch in 2015)
Rafael- Israel	IHET-300 EP propulsion system	Mini-HET (300 W)
KhAI- Ukraine	SPT-20M7	Mini-HET (100 W)
Keldysh Research Institute - Russia	KM-60 HET	900 W - Qualification on-going - To be flown on “Express-1000”
Lanzkou Institute of Physics (LIP)-China	LIPS-xx GIE series	LIPS-200 flown on SJ-9A satellite
Lanzkou Institute of Physics (LIP)-China	LHT-xx HET series	LHT-100 will be flight tested on XY-2 GEO satellite (2015)
NASA	HiPEP (ECR technology)	20-50 kW class- (6000-9000 s Isp) development stopped – tested at 24.4 kW / 5.6 mg/s /8270 s / 460 mN
MELCO/JAXA- Japan	µ10 ECR GIE	Flown on Hayabusa
Fakel – Russia	SPT-20	

Table 11-1: Main Non-European Industry, Research Institutes and Organisations involved in EP thrusters

Novel concepts for high-power electric propulsion spacecraft are being worldwide pursued to reduce launch size and facilitate in-space transportation of large masses in support of manned space programs, orbit transfer/insertion (e.g. GTO to GEO orbit topping or LEO to GEO reusable tugs) and orbit-to-orbit transfer or SK manoeuvres of commercial telecommunication satellites.

The HEMP, FEEP and Quad Confinement thrusters are pure European Technologies so are not considered in the table above.

12.1.1 HETs and GIEs

12.1.1.1 HET

In the last 15-20 years, HETs have seen a major resurgence in popularity due to their potential advantages over other types of EP for near-Earth missions. In addition, HET have also been considered for robotic solar system exploration missions given the increased deliverable spacecraft mass relative to that achievable using ion thruster systems. In this timeframe, HETs have been generally regarded as 1-5 kW devices operating at specific impulses in the 1000-2000 s range.
In recent years, the range of Isp at which efficient operation has been demonstrated has expanded to 3000 s for xenon propellant and 4500 s for krypton. Even more striking than the gains in Isp is the degree to which the thruster power envelope has widened. Recent works has demonstrated HET operation at power levels as low as 100 W and as high as 75 kW.
The expansion of EP power range – particularly for HET and GIE – seems to be driven by two factors: evolving mission requirements and higher on-board power availability. As a matter of fact, from 1996 to 2013, the average EOL power available aboard commercial GEO satellites more than tripled to values as high as 20 kW, see Figure 11-1 .

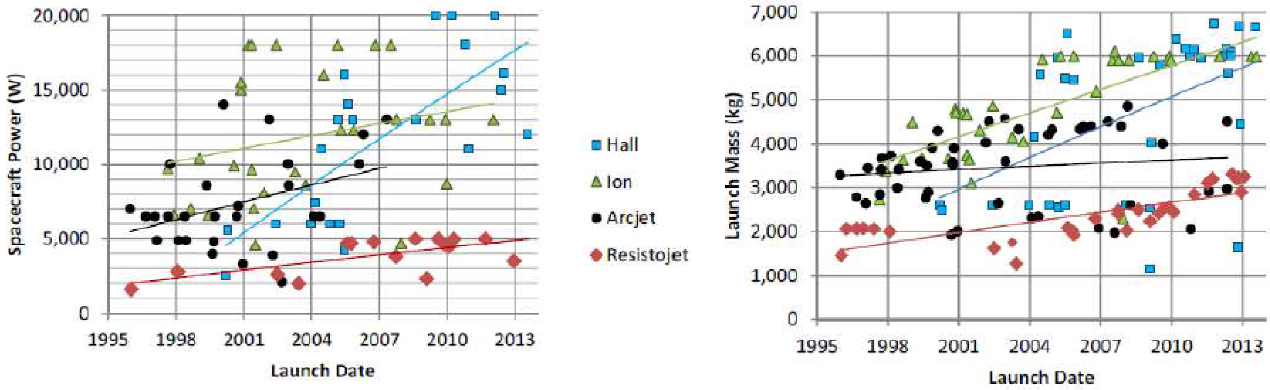


Figure 11-1: Historical trend of total power and launch mass of operational GEO spacecraft with EP

Quite recently, the US government has identified the importance of using very-high power electric propulsion systems (> 10 kW) for NASA's Game Changing Technology Development (GCTD), Innovative Advances Concepts (NIAC) and Space technology Research Grants. Furthermore, the International Space Exploration and Coordination Group (ISECG) has recently release the Global Exploration Roadmap reflecting the coordinated international effort towards human and robotics exploration of the solar system. According to this roadmap, one of the major capabilities needed to enable human exploration beyond LEO is the development of high-power EP systems (30-50 kW). In this context it appears of paramount importance for the European EP community to make significant steps forward in the development of very high-power HETs (≥10 kW).

The development of high-power HETs is strongly supported by the great deal of work performed on the low/medium power range (< 5 kW), which gives a comprehensive background covering both the experimental characterisation of the performance and the technological issues related to these thrusters. In fact, the basis activities in high-power HET design start from the long heritage gained on different devices developed in the US, Russia and Europe.

In the US, the XR-5 (4.5 kW, 280 mN, 1850 s) has successfully propelled two Air Force's Advanced Extremely High Frequency (AEHF) communications satellites into GEO and are currently performing station-keeping duties. At the same time, Space Systems Loral (SSL) is undertaking the qualification of the Russian STP-140 (4.5 kW, 288 mN, 1780 s) for use on western spacecraft.

In addition, although not yet qualified, the US EP market can benefit from the R&D recently carried out by Busek and Aerojet-Rocketdyne in the very high-power range. As a matter of fact, fostered by the renewed interest in NEO and asteroid missions, Busek has developed 8 kW and 20 kW-class HET (BHT-8000 and BHT-20k, respectively) featuring a patented discharge chamber geometry and a unique propellant injection method. These thrusters have been rated for thrust levels ranging from 150 mN to 500 mN (BHT-8000) and from 250 mN to 1300 mN (BHT-20k). Total thrust efficiencies were found to fall in the 50%-65% range for both thrusters. In addition, following the general trend of increasing input power, Aerojet-Rocketdyne has started the development of a 12 kW-class HET (XR-12) capable of providing about 800 mN of thrust and a specific impulse of about 2000 s to support the Lockheed Martin TSAT development efforts.

At even higher power levels, a 50 kW thruster – the NASA-457M_ was manufactured and tested with both xenon and krypton in the frame of the In-Space Transportation Program (ISPT). The thruster was capable of operating at discharge powers as high as 72 kW providing a thrust of 2.9 N and Isp in the range of 1700-3200 s.

In Russia, extensive space applications of EP systems started in the 1970s, mainly for SK manoeuvres on communication satellites. To date, over 240 HETs have been operated on various Soviet and Russian satellites cumulating more than 1.3×10^6 hours of reliable operation in space. Apart the well-known SPT-100 that is largely used on these satellites, all the main Russian manufacturers have oriented their efforts towards high-power devices.

At EDB Fakel. State-of-the-art high power thrusters are in the range of 5-30 kW. SPT-140 and ST-160 are 5 kW HETs rated 290 mN and 260 mN respectively. SPT-200 is a 10 kW HET under development (450 mN, 2900 s) and SPT-290 is a 30 kW HET capable of providing about 1.5 N of thrust and a specific impulse of about 3000 s.

TsNIIMASH activities are mainly focused on TAL devices: TAL D-80 and TAL D-100 are 5 kW HETs while TAL-200 is a two-stage, 35 kW thruster conceived to be operated with bismuth and rated for 1 N and 5000 s.

European industries have been relatively conservative in the adoption of EP technologies compared to US and Russian suppliers. However, in the last decade the use of EP systems on few GEO telecommunication satellites (e.g Inmarsat-4, Intelsat-10 and AlphaBus) has strengthened the European EP market giving impetus to new programs such as NEOSAT and ELECTRA. These new platform will offer a very high power payload capability (16 kW and 12 kW at BOL for NEOSAT and ELECTRA respectively) and will optimise the use of EP for both NSSK and orbit transfer to GEO.

A comparison of the current European industrial situation with key players outside Europe are provided in Table 11-2.

Name of the item	Technical Characteristics of benchmark product				Technical Characteristics of European product			
	Power (W)	Thrust (mN)	Specific Impulse (s)	Others	Name of European Product	Power (W)	Thrust (mN)	Specific Impulse (s)
SPT-100	1350	82	1600	Cheaper, lower total impulse	PPS-1350	1500	88	1650 - 1800
					HEMPT 3050	1600	44	2200-2500
SPT-140	5000	300	1750	higher TRL level (TRL 6)	PPS-5000	5000	230-325	2300-1750
					HT-5k	5000	230	1400-2000
BPT-4000 (XR-5)	1000-4500	290 @ 4500 W /300 V	1790 @ 4500 W /300 V	higher TRL level (TRL9), dual mode operation, ITAR-restricted	PPS-5000	5000	230-325	2300-1750
					HT-5k	5000	230	1400-2000
IHET-300	250-600	≥15	> 1300 @ 300 W	higher TRL level (TRL6)- include Entire EP system- higher total impulse	HT-400	400	20-50	1100-1900
					EPS®500	200-700	15-27	1300-1500
SPT-20M7	100		1500 @ 100 W		HT-100	100-300	5-14	900-1600

Table 11-2: Competitiveness of European HETs (≤ 5 kW). The HEMPT 3050 is also included for completeness.

A new opportunity to use HETs on LEO satellites has pushed the different players to start activities on the low power range. In that regards, KhAI in Ukraine has developed a small HET, the SPT-20M7 based on the SPT technology able to deliver an Isp of about 1500 s at 100 W input power. As well Rafael (Israel) has developed a complete EP system based on the HET, IHET-300 able to provide a minimum thrust of 15 mN for an average power of 300 W.

China started developing their range of HETs very lately, at the beginning of 2000. They today have 3 Ems: LHT-60D, LHT-70 and LHT-100 able to provide thrust between 40 and 80 mN at power ranging from 220 to 1350 W. They have also laboratory models of a low power HET (LHT-35, 250 W, 10 mN, 1200 s) and of a high power HET (LHT-140D, 3-4.5 kW, 170-280 mN, 1700-1900 s).

12.1.1.2 GIE

The concept of ion engine was first developed over 50 years ago. Up to now, they were mainly used for exploration and interplanetary missions (exception of the GOCE mission in Europe where an ion engine was used to compensate for the drag of the Earth atmosphere) due to their high specific impulse capability (> 3000 s).
The first medium power ion engine was flown on the NASA Deep Space 1 mission launched in 1998 and ended in 2001. The NSTAR (NASA Solar Electric Propulsion Technology Applications Readiness) thruster is able to operate over 0.5 to 2.3 kW input power range providing thrust from 19 mN to 92 mN. The Isp is between 1900 s (@ 0.5 kW) and 3100 s (@ 2.3 kW). The NSTAR ion engine is also being used on the US Dawn mission to go to two asteroids. The spacecraft is powered at 10 kW (at 1 AU).

In the US, the NASA's Evolutionary Xenon Thruster (NEXT) program is aimed at building a new ion propulsion system at the Glenn Research Center (GRC) (in collaboration with Aerojet-Rocketdyne) modifying and improving the design of the NSTAR engines: the system is physically bigger but lighter, the system's complexity is reduced to extend its lifetime and the efficiency is also improved. This high power engine can produce up to 236 mN of thrust for an input power of 6.9 kW. Its Isp is 4190 s and it can be throttle down to 500 W. It has today demonstrated in a laboratory a total impulse above 17 MNs (more than 50,000 hours of operation) which is the highest total impulse ever demonstrated by an ion thruster.
The development of such kind of high power GIE is encouraged in the US for missions such as the Discovery Program mission which intend to reach Saturn orbit or to perform a sample return from Mars's moon Deimos.

Russia, even if more known for the development of HETs, is also active in the field of GIE. Up to 2001 ion thruster development was mainly aimed at the thrusters operating in the low power regime (< 500 W). Keldysh Institute have two small ion engines with flight heritage: the IT-50 (2-5 mN, 2300-3500 s, 50-140 W) and IT-100 (150-500 W, 7-18 mN, 1900-3300 s) which are covering a range of 50 to 500 W.
RIAME is working together with Fakel on a 16 cm Radio Frequency Ion thruster (RFIT) which should operate around 2 kW. On the lower range side, an 8 cm thruster is being developed in collaboration with Voronej which should work in the 250-300 W power range. Moscow Aviation Institute (MAI) have also developed two Kaufman type thrusters : a 5 cm and a 10 cm diameter discharge thrusters with more advanced technologies such as cusp field, etc.
L-3 is also developing in the US a 8 cm XIPS ion thruster with the following expected performances: 100-350 W input power, thrust of 2-14 mN, Isp comprises between 2000 and 3000 s for an efficiency of about 76 %.

Their relatively high power-to-thrust ratio condemned GIEs to be embarked only for such kind of missions. However the announcement of Boeing in 2012 on the procurement of 4 telecommunication satellites based on their 702SP platform for 125 million dollars each including launch (thanks to a dual launch on Falcon9) has reviewed the interest of using ion thrusters on telecommunication satellites for orbit raising from GTO to GEO and for SK orbital manoeuvres.
Boeing use the XIPS- 13 and XIPS-25 built by the US company L-3 on the 601HP and 702HP platforms respectively. The XIPS-25 (Xenon Ion Propulsion System) includes two fully redundant subsystems with two 4.5 kW GIEs and one power processor each. On the platform the entire on-orbit manoeuvres can be performed by a single pair of thrusters and autonomously.

Russia has also recently started several activities to develop high and very high power (> 5 kW) ion thruster systems. The Keldysh Institute is working on a 30 cm and a 50 cm Kaufman type thrusters with power up to 37 kW while RIAME is working on a 50 cm RFIT thruster which could also sustain a 35 kW up to 50 kW discharge power.

A comparison of the current European industrial situation with key players outside Europe are provided in Table 11-3.

Name of the item	Technical Characteristics of benchmark product				Technical Characteristics of European product			
	Power (W)	Thrust (mN)	Specific Impulse (s)	others	Name of European Product	Power (W)	Thrust (mN)	Specific Impulse (s)
XIPS-25	2200-4500	79-165	3400-3500	higher TRL level (TRL9)	T6	4500	35-145 (230 demonstrated)	4400
XIPS-13	421	17.8	2585	TRL9	T5	476	0.6-20.6	415-2926
					RIT10	459	15	3400
NSTAR	500 – 2300	19 – 92	1900 – 3280	Higher TRL level (TRL9) wrt T6	RIT22	5000	50-200	4200
					T6	4500	35-145 (230 demonstrated)	4400
NEXT	500-6900	236 (max)	4190	Under qualification	T6	4500	35-145 (230 demonstrated)	4400
XIPS-8	100-350	2-14	2000-3000	Under qualification. TRL level lower then T5 and RIT10	T5	476	0.6-20.6	415-2926
					RIT10	459	15	3400

Table 11-3: Competitiveness of Main European GIEs (power between 500 W and 5 kW)

The Chinese market may be considered a threat in the mid-term to European market share. China started developing its range of ion engine in 1974 and is able to provide through the Lanzkou Institute of Physics (LIP) several models with thrust range between 5 and 200 mN, for power starting from 240 W up to 7 kW, and for Isp above 3000 s. The LIPS-2000 ion EPS is flying on the SJ-9A satellite launched in 2012.

12.1.2 ECR thruster

The ECR thruster is a derivative of an ion engine. The difference comes from the way the discharge is created in the chamber using a combination of microwave and magnetic fields.

The first ECR thruster to be flown was on the Japanese Hayabusa mission in 2003. The µ10 ECR ion engine was manufactured by MELCO in collaboration with JAXA. It is able to provide a thrust up to 8 mN at an Isp of 3000 s and 350 W electrical power consumption. The thruster is a cathodeless ECR thruster and has a 3-grid (carbon-carbon composite) for acceleration of the ions. It is a 10 cm diameter thruster. Regarding the Power processing Units, three units were distributed between the 4 thrusters used for the mission (1.5 kV to screen grid and -330 V to acceleration grid. As well there was a pointing mechanism (two axis gimbal) for each thruster able to point the thruster by ± 5 °.

On the US side, NASA High Power Electric Propulsion (HiPEP) project had the aim to develop a high-power nuclear electric propulsion ion thruster for the Jupiter Icy Moons Orbiter (JIMO) spacecraft. The HiPEP thruster, which was under development at Glenn, is unique in that it has the ability to operate at high power levels in both a conventional hollow cathode configuration and a microwave ECR configuration. The HiPEP ion thruster is currently the most powerful inert gas ion thruster ever built. Early tests in 2004 demonstrated power levels of 40 kilowatts and exhaust velocities in excess of 90,000 meters per second (over 200,000 mph). The thruster itself is in the 20-50 kW class, with a specific impulse of 6,000-9,000 seconds, and a propellant throughput capability exceeding 100 kg/kW. The goal of the project, as of June 2003, was to achieve a TRL of 4-5 within 2 years. On page 8 of the September 2004 HiPEP report NASA/TM—2004-213194 says the pre-prototype HiPEP produced 670 mN of thrust at a power level of 39.3 kW using 7.0 mg/s of fuel giving a specific impulse of 9620 s. Downrated to 24.4 kW, the HiPEP used 5.6 mg/s of fuel giving a specific impulse of 8270 s and 460 mN of thrust.

12.1.3 Colloid

The development of colloid thrusters for propulsive application can be traced to the early 1960s. After lying dormant for over 20 years, there is today a resurgence of interest in colloid engine technology. This is motivated by:

- The new emphasis on miniaturization of spacecraft. The very small thrust per emitter now becomes a positive feature, allowing designs with both, fine controllability and high performance.
- The advances made by electrospray science in the intervening years. These have been motivated by other applications of charged colloids, especially in recent years, for the extraction of charged biological macromolecules form liquid samples, for very detailed mass spectroscopy.

The US company Busek is active in the field. After more than 10 years of pioneering R&D in the field, they built and delivered (in 2008) an EPS based on colloid thrusters clusters to JPL (Jet Propulsion Laboratory, NASA) which will fly on the ESA mission LisaPathFinder planned for launch in 2015.
The technology is based on electrosprays (see Figure 11-2). Such kind of thrusters are characterised by precise thrust control (on the order of nN) and extremely efficient operation (in excess of 80 %)

Figure 11-2: Busek colloid clusters delivered to JPL for the LPF mission (Credit: Busek)

With such kind of thrusters, they have manufactured modules for CubeSats; the module consumes under ½ U and 9 W power to deliver a thrust range up to 1.0 mN, at Isp ranging from 625 s to over 1300 s.

12.2 Tanks

The main competitors outside Europe for the procurement of Xenon tanks to be used for EPS are the US suppliers ATK and ARDÈ, and Rafael Advanced Defense Systems Ltd in Israel.
ARDÈ produce all COPVs and all tanks are metal. They have an extensive portfolio; more than 50 products (including tanks for chemical propulsion) are available "of the shelf".
ATK has a bench of Titanium propellant tanks with flight heritage.

A non-exhaustive list of the major tanks providers and their models is provided in Table 11-4.

Name of company	Model	MEOP (bar)	Volume (l)	Mass (kg)	Remarks
ARDÈ	ARDÈ-D4636	207	27.5	7.7	
ARDÈ	ARDÈ-D4790	180	178	40.4	
ARDÈ	ARDÈ-D4891	125	27.5	7.5	
ARDÈ	ARDÈ-D4898	165	8.3	2.8	
ARDÈ	ARDÈ-D4916	152	2.9	1.5	
ATK	ATK 80386-101	172	32	6.4	
ATK	ATK 80412-1	150	50	7	
ATK	ATK 80458-1	186	133	20.4	
ATK	ATK 80458-101	186	120	19	
ATK	ATK 80458-201	186	54	12.3	
Rafael Advanced Defense systems Ltd	Rafael GSU-1L	700	0.97	1.3	

Table 11-4: Main Non-European Industry, Research Institutes and Organisations involved in EP tanks

12.3 EP Components

12.3.1 Pressure Regulators

Several European companies have in their portfolio pressure regulators: Airbus DS (UK and D) are currently developing these items for BepiColombo and Eurostar. Iberespacio has already qualified a Bang-Bang pressure regulator for SmallGEO. Furthermore, TAS (I) and MOOG Isp (UK) are also developing electronic pressure regulators based in proportional valves. MOOG-Bradford (NL) was involved in the development of the pressure regulator system for GOCE.
Recently, Air Liquide Advanced Technologies has initiated activities with CNES support on the adaptation for Xenon applications of the Helium pressure regulator used on Rosetta and MSL (SAM instrument) and currently integrated on ExoMars mission.
In mechanical pressure regulator systems, Astrium (UK) develops systems based on USA mechanical pressure regulator.

12.3.2 Latching Valves

At this moment all these devices are US components. MOOG and VACCO are the main US providers.

12.3.3 Solenoid Flow Control Valves

MOOG Isp (UK) have qualified components for Alphabus and BepiColombo. MOOG-Bradford (NL) and Airbus DS (D, UK) have also capabilities in this sector.

12.3.4 Pressure Transducers

MOOG-Bradford (NL) is the most important supplier in Europe although USA components are often used. Presens and Herakles (application on Spacebus and Iridium Next) are also active in this field.

12.3.5 Mass Flow Sensors

Selex-ES (I), NanoSpace (Sweden) and MOOG-Bradford (NL) are developing these systems for monitoring and propellant gauging applications.

12.3.6 Flow control units

NanoSpace (Sweden) and AST (D) have started developing miniaturized flow control units mainly for miniaturized thrusters. In the US, VACCO have already qualified similar systems for Xenon applications for mass flow rates in the range of 0.01 mg/s to 8 mg/s.

12.4 Test facilities

Today EP thrusters manufacturers are obliged to go to the US, concretely to Aerospace Corporation which has the capabilities for EMC/EMI characterisations.