Advanced Space Technologies GmbH

Doc.Nr AST-µFCU-0002

Miniaturized Flow Control Unit - µFCU

Mission Scenario Description

Technical Document

hpharmann / 1.0
24.02.2012
draft

Project: µFCU
Project-N°: 28410
Responsible Partner: AST
Deliverable: D6.1
Dissemination Level: PU

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"µFCU" is funded by the European Commission within the FP7 Program

Distribution List

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M. Berger	EADS Astrium, Friedrichshafen	eMail
M. Lyszyk	Thales Alenia Space, Cannes	eMail
	REA	via SESAM

Change List

Date/Version	Changed Pages	Changed by	Remark
24.02.2012 / 1.0			Initial Version

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Content

1 Scope

This document describes scenarios of reference space missions using electric propulsion systems that could benefit from a µFCU component. The reference missions are chosen from different mission classes. For each mission a short specification is given. The whole spectrum of specifications is analysed and grouped into two FCU types to cover the large range of applications.

This document shall be used for the µFCU requirements engineering process.

2 Documents

2.1 Applicable Documents

ID (AD-xxx)	Title	Doc-Nr.	Release / Date
	none		

2.2 Reference Documents

ID (RD-xxx)	Title	Doc-Nr.	Release / Date
[RD-1]	Project Abbreviation List	AST-µFCU-003	1.0/ 16.02.2012
[RD-2]	Laser Interferometer Space Antenna (LISA) Mission Concept	LISA-PRJ-RP-0001	0.0/ 04.05.2009
[RD-3]	Microthrust Propulsion for the LISA Mission	AIAA-2004-2221	2004
[RD-4]	Propulsion Options for the LISA Mission	AIAA-2004	2004
[RD-5]	RIT MicroPropulsion System on Lisa Pathfinder	IEPC-2011-325	2011
[RD-6]	Microthruster Propulsion for the Space Technology 7 (ST7) Technology Demonstration Mission	AIAA 2006-4320	2006
[RD-7]	Assessment of a Next Generation Mission for Monitoring the Variations of Earth's Gravity	NG2-ASG-FR	2011
[RD-8]	Oberflächentechnologie mit Plasma- und Ionenstrahlprozessen	Workshop Mühlleiten	10.-12.März 2009
[RD-9]	Performance verification of the µNRIT-2.5 thruster on the Nanobalance facility	IEPC-2011-013	2011
[RD-10]	The dynamical environment of Dawn at Vesta	Planetary and Space Science Volume 58, Issue 12, October 2010, Pages 1516–1525	2010
[RD-11]	Simplified Ion Thruster Xenon Feed System For NASA Science Missions	IEPC-2009-064	2009
[RD-12]	Qualification of Commercial Electric Propulsion Systems for Deep Space Missions	IEPC-2007-271	2007
[RD-13]	Implementation of the Dawn Ion Propulsion System	AIAA 2005-4071	2004

[RD-14]	The Dawn Ion Propulsion System – Getting to Launch	IEPC-2007-083	2007
[RD-15]	Systems-Level Trade Studies of a Dual-Mode SPT for Geosynchronous Communications Satellites	IEPC-01-172	Oct. 2001
[RD-16]	Spacecraft Electric Propulsion—An Overview	JOURNAL OF PROPULSION AND POWER,Vol. 14, No. 5	1998
[RD-17]	IMPACT OF ION PROPULSION ON PERFORMANCE, DESIGN, TESTING AND OPERATION OF A GEOSYNCHRONOUS SPACECRAFT	AD-A237 028	June 1990
[RD-18]	CLUSTERING OF HALL EFFECT THRUSTERS FOR HIGH-POWER ELECTRIC PROPULSION APPLICATIONS	Dissertation, Univ. of Michigan	2004
[RD-19]	Understanding the Orbital Transfer Vehicle Trade Space	AIAA 2003-6370	2003
[RD-20]	COMBINED FLIGHT PROFILE TO INSERT TELECOMMUNICATION SATELLITE INTO GEOSTATIONARY ORBIT USING ROCKOT LIGHT-WEIGHT CLASS LAUNCH VEHICLE	IAF-00-V_2_09.pdf	2000
[RD-21]	ELECTRIC PROPULSION MISSION TO GEO USING SOYUZ/FREGAT LAUNCH VEHICLE	IAF-01-V_3_02.pdf	2001
[RD-22]	Optimization of Electric Propulsion Orbit Raising	Master thesis, MASSACHUSETTS INSTITUTE OF TECHNOLOGY	2002

3 Acronyms and Abbreviations

Abbreviation	Full text
AST	Advanced Space Technologies GmbH
BB	Breadboard Model
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.
DS1	Deep Space One - Name of a NASA mission
EO	Earth observation
ESA	European Space Agency
FCU	Flow Control Unit
FF	formation flying
FM	Flight Model
FP7	7^{th} Framework Programme
F.S.	Full scale
GEO	Geostationary (Earth) Orbit
GOCE	Gravity and Ocean Circulation Explorer
GTO	Geostationary Transfer Orbit
LEO	Low Earth Orbit
LISA	Laser Interferometer Space Antenna
MAIT	Manufacturing, Assembly, Integration and Test
MEOP	Maximum expected operational pressure
µFCU	Project Acronym: Miniaturized Flow Control Unit
NGGM	Next Generation Gravity Mission
NOP	Non-operational
NTR	Neutralizer
OP	Operational
PFM	Protoflight Model
QA	Quality Assurance
QM	Qualification Model
THR	Thruster

4 Mission Classes

Four classes of missions are described below in more detail:

- Telecom Satellites
- Formation Flying Satellites
- Earth Observation
- Deep Space Missions

4.1 Mission Class: Telecom Satellite

The task of telecom satellites is to provide a telecommunication link between at least two points on ground. Typical applications are direct TV, direct radio, internet backbone, international telephone lines etc. Telecom satellites are the type of spacecraft for which electric propulsion is actually used most. The class can be subdivided into midsize satellites and heavy satellites. Small satellites are typically not used for telecom purpose.

The most common EP-systems on such satellites are resistojets and arcjets followed by ion thrusters (gridded ion thrusters and hall effect thrusters). While resistojets and arcjets are used for all spacecraft sizes, ion thrusters are limited to large satellites. A new ion thruster development, the HEMP thruster, tries to enter also the medium sized satellite segment.

Reference mission: North-South-Stationkeeping (NSSK) of a large GEO telecom satellite
Reference mission: Orbit transfer of a large GEO telecom satellite

4.2 Formation Flying Satellites

Formation flying is a promising method for high precision scientific mission. Two or more spacecrafts are placed in well controlled distances to each other. Such formations are used to investigate e.g. earth's gravity field or fast changes in the magnetic field. Very sophisticated mission designs use formations to set up a space based interferometer telescope to achieve ultra high resolutions. To control the satellites in formation very small and precise forces have to be delivered by the propulsion system creating challenging requirements for the flow control system. The FF mission class shall be used for all formation flying missions that are NOT earth observation missions.

Reference mission: Laser Interferometer Space Antenna (LISA)

4.3 Earth Observation Missions

The focus of Earth Observation (EO) missions is to learn more about our planet. Many scientific satellites have been started in the past to investigate global aspects like weather, climate etc. During ESA's GOCE mission, electric propulsion has demonstrated its capability to enable new concepts that are not possible using chemical or cold gas propulsion. For more sophisticated EO missions also formation flying configurations will be used e.g. to improve the measurement of Earth's geoid.

Reference mission: Next Generation Gravity Mission (NGGM)

4.4 Deep Space Missions

Deep space missions describe scientific missions to planets or objects outside the earth-moon system. Such missions typically have a long coasting phase. During the coasting the spacecraft and it's instruments are in "hibernation" and have to survive extended environmental conditions. At the end of the hibernation phase the spacecraft executes a wake-up sequence to come back to its nominal operational environment (e.g. thermal control).

Deep space mission take place far from earth's magnetic shield. Therefore large doses of high energy particles have to be assumed. For missions to the large planets like Jupiter or Saturn the radiation levels can be further increased.

Reference mission: DAWN

5 Reference Missions

For each reference mission, a mini specification for the flow control system is either directly taken from the related study report or is derived from the baselined propulsion system. For each requirement a "minimum" requirement level is defined, that has to be matched by the FCU. If possible, a second "optimum" requirement value outlines a possible further improvement of the mission. Not all requirements have been defined for each reference mission.

The results from the different reference missions are grouped into three FCU specifications covering the different requirement ranges.

5.1 Next Generation Gravity Mission (NGGM)

Related documents: [RD-7], [RD-9]

NGGM is the acronym of a current mission study for a mission to measure variations in Earth's gravity field. The mission uses at least one pair of satellites flying in formation. Due increase resolution and accuracy of the measurement, it is required that the spacecrafts fly in orbits as low as possible. This requires continuous drag compensation like demonstrated on GOCE. A mission analysis study [RD-7] performed for ESA has been reviewed to derive a requirement envelop for the µFCU development. The results of an investigation for a second study described in [RD-9] have also been used as input. Both studies propose an electric micropropulsion system like µN-RIT to compensate the air drag. The required thrust ranges from some hundred µN to a maximum of approximately 7 mN. This thrust level can be provided by RIT-2 or RIT-2.5 and RIT-4 thrusters currently under development at Giessen University.

In addition to the aforementioned study report EADS Astrium, Friedrichshafen provided additional background information on FCU requirements.

ID	Requirement	min. req.	opt. req.	remark
1-01	Number of controlled flow lines	2	4	
1-02	Type of thruster	RIT-2 or RIT-2.5, RIT-4		
1-03	Thruster configuration	single thruster		
1-04	Propellant	Xenon		
1-05	Flow range [sccm]	0.1 … 1.0	0.01 … 1.0	estimated from thruster performance data [RD-8]
1-06	Flow accuracy	10%	1%	estimated from min. thrust step requirement
1-07	Flow linearity	10%	1%	estimated from min. thrust step requirement
1-08	min. flow step	10%	1%	estimated from min. thrust step requirement
1-09	max. power consumption (OP)	1 W		estimate assuming no heater required
1-10	internal leakage	1.4×10^{-5} scc/s GHe		lower will be better
1-11	external leakage	1×10^{-6} scc/s GHe		lower will be better
1-12	Temperature range (OP)	-50 … +100		
1-13	Temperature range (NOP) [°C]	-60 … +110		
1-14	Operational inlet pressure [bar]	< MEOP		
1-15	MEOP [bar]	10		higher will be better
1-16	Burst pressure	2.5xMEOP		
1-17	max. mass [kg]	0.73	0.59	lower will be better
1-18	max. dimensions [mm]	60x30x30		smaller will be better
1-19	Orbit	LEO		
1-20	Launcher compatibility	VEGA		

1-21	min. lifetime (OP) [years]	10		
1-22	min. storage time [years]	3		
1-23	min. Xenon throughput	10 kg/flow line		calculated as: tank capacity / 2 thr.

5.2 Laser Interferometer Space Antenna (LISA)

Related documents: [RD-2], [RD-3], [RD-4], [RD-5]

The Laser Interferometer Space Antenna (LISA) is an ESA mission to design, build and operate a spaceborne gravitational wave detector. The primary objective of the Laser Interferometer Space Antenna (LISA) is to detect and measure as yet unobserved gravitational waves produced by compact binary systems and mergers of super massive black holes‡. Only interplanetary space can provide the relative disturbance free environment suitable for these long time scale (1-10,000 s) measurements that could lead us to a better understanding of the beginning and current state of the universe. Yet, even interplanetary space is subject to minute disturbances, such as solar wind, radiation, and photon pressure that could mask the influence of gravitational waves on free-floating proof masses. To shield the gravitational wave instrument, LISA consists of a precisely controlled set of spacecraft that follow the array proof masses within approximately 10 nm and provide a disturbance free environment. Calculations have shown that to reach the sensitivity level of interest, the disturbances to the proof masses can be no more than 3×10-15 m s-2 Hz-1/2 in the 10-4-1 Hz bandwidth.

The Disturbance Reduction System (DRS) for each spacecraft consists of position sensors in the GRS, micro Newton thrusters as actuators, and dragfree control laws that maintain the spacecraft orbits and cancel out the environmental disturbances (mainly solar photon pressure) to the spacecraft. To observe gravitational waves effectively, the LISA instrument must operate in a drag-free environment with stringent, high-resolution requirements on both the pointing and the translation of the spacecraft.

In the beginning of the mission design, FEEP thrusters had been the baseline. Since delays in providing the propulsion system endanger the project, other thrusters like µN-RIT are under investigation. While FEEPs do not need a gas flow control unit, the investigated alternatives will require controlled flows in the sub-sccm range. The further investigation is focusing on a µN-RIT propulsion system.

In the preface to LISA a technology demonstration mission called LISA-pathfinder (LPF) is prepared to verify the feasibility of the concepts. The actual status of the µN-RIT propulsion system is described in [RD-5]. The performance data have been compiled together with LISA overall mission requirements.

ID	Requirement	min. req.	opt. req.	remark
2-01	Number of controlled flow lines	4		
2-02	Type of thruster	RIT-2.5 or RIT-4		
2-03	Thruster configuration	4 thusters in a pod		
2-04	Propellant	Xenon		
2-05	Flow range [sccm]	0.01 ... 0.25	0.005 ... 0.5	estimate from mission thrust requirements
2-06	Flow accuracy	10%	1%	estimated
2-07	Flow linearity	10%	1%	estimated
2-08	min. flow step	10%	1%	estimated
2-09	max. power consumption (OP)	N/A		
2-10	internal leakage	N/A		lower will be better

2-11	external leakage	N/A		lower will be better
2-12	Temperature range (OP)	N/A		
2-13	Temperature range (NOP) [°C]	N/A		
2-14	Operational inlet pressure [bar]	N/A		
2-15	MEOP [bar]	N/A		higher will be better
2-16	Burst pressure	N/A		
2-17	max. mass [kg]	0.48		lower will be better
2-18	max. dimensions [mm]	N/A		smaller will be better
2-19	Orbit	Deep Space		
2-20	Launcher compatibility	N/A		
2-21	min. lifetime (OP) [h]	55 000	88 000	increasing during mission planning
2-22	min. storage time [years]	N/A		
2-23	min. Xenon throughput	N/A		

5.3 DAWN

Related documents: [RD-10], [RD-11], [RD-12], [RD-13], [RD-14]

Dawn is the ninth project in NASA's Discovery Program. The Dawn spacecraft is being developed to enable the scientific investigation of the two heaviest main-belt asteroids, (4) Vesta and (1) Ceres [1,2]. To accomplish this investigation the spacecraft will rendezvous with and go into orbit about each of these asteroids. Dawn will be the first mission to orbit two different extraterrestrial (and nonsolar) bodies, and the first to orbit a main-belt asteroid. The mission is enabled by Dawn's ion propulsion system which provides all of the post-launch deltaV including the heliocentric transfer to Vesta, orbit capture at Vesta, transfer to the Vesta science orbits, departure and escape from Vesta, heliocentric transfer to Ceres, orbit capture at Ceres, and transfer to the Ceres science orbits.

ID	Requirement	min. req.	opt. req.	remark
3-01	Number of controlled flow lines	3		
3-02	Type of thruster	NSTAR		
3-03	Thruster configuration	single thrusters		
3-04	Propellant	Xenon		
3-05	Flow range [sccm]	6.1 … 23.4 2.4 … 3.7 2.4 … 3.7		different flows in the three lines
3-06	Flow accuracy	3%	1%	from DS1
3-07	Flow linearity	N/A		
3-08	min. flow step	3.5%		
3-09	max. power consumption (OP)	N/A		
3-10	internal leakage	6×10^{-5} scc/s Xe		lower will be better
3-11	external leakage	N/A		lower will be better
3-12	Temperature range (OP)	N/A		
3-13	Temperature range (NOP) [°C]	N/A		
3-14	Operational inlet pressure [bar]	2.65		
3-15	MEOP [bar]	N/A		higher will be better
3-16	Burst pressure	N/A		
3-17	max. mass [kg]	6		including some high pressure parts

3-18	max. dimensions [mm]	N/A		smaller will be better
3-19	Orbit	Deep Space		
3-20	Launcher compatibility	N/A		
3-21	min. lifetime (OP) [h]	> 20 000		
3-22	min. storage time [years]	N/A		
3-23	min. Xenon throughput [kg]	200		400 kg / 2 thrusters

5.4 North-South-Stationkeeping (NSSK) of a large GEO telecom satellite

Related documents: [RD-15], [RD-16], [RD-17], [RD-18]

The term "North-South Stationkeeping (NSSK)" is not linked to a specific mission but refers to a task of the AOCS system of every geostationary satellite. Different NSSK strategies have been developed in the past to reflect the large variety of propulsion systems. The most common approach is to perform a thrust arc twice a day around the ascending and descending orbital node. The specification values given below are a compilation of requirements for RIT-22, SPT-100 and HEMP3050.

ID	Requirement	min. req.	opt. req.	remark
4-01	Number of controlled flow lines	2	4	
4-02	Type of thruster	RIT-22, SPT-100, HEMP3050		
4-03	Thruster configuration	single thrusters + neutralizer		
4-04	Propellant	Xenon		
4-05	Flow range [sccm]	5 … 60 0.5 … 2	1 … 100 0.1 … 3	different flow for THR and NTR
4-06	Flow accuracy	5%	1%	
4-07	Flow linearity	1%		more important is the monotonic behaviour as the SPT and HEMP use the flow to control the anode current
4-08	min. flow step	1%	0.5%	
4-09	max. power consumption (OP)	<2W		assuming no heater required
4-10	internal leakage	$<10^{-6}$ scc/s		lower will be better
4-11	external leakage	$<10^{-6}$ scc/s		lower will be better
4-12	Temperature range (OP) [°C]	-15 … 110		
4-13	Temperature range (NOP) [°C]	-40 … 120		
4-14	Operational inlet pressure [bar]	2 … 2.5		
4-15	MEOP [bar]	8		higher will be better
4-16	Burst pressure [bar]	28		
4-17	max. mass [kg]	0.40		
4-18	max. dimensions [mm]			smaller will be better
4-19	Orbit	GEO		
4-20	Launcher compatibility	all		
4-21	min. lifetime (OP) [h]	18 000		
4-22	min. storage time [years]	5		
4-23	min. Xenon throughput [kg]	150		
4-24	Flow control step response (90%)	within 100 ms		

5.5 Orbit transfer of a large GEO telecom satellite

Related documents: [RD-19], [RD-20], [RD-21], [RD-22]

Orbit transfer for GEO satellites is not covered by today's electric propulsion systems. Large thrust level in the order of 1N and above are required to keep the transfer duration within a commercially acceptable limit. First experiences with orbit transfer within Earth's gravitational field have been gained by scientific missions like SMART-1. A further milestone was the unintended orbit transfer mission performed by ESA's ARTEMIS satellite. After a partial upper stage failure of the launcher the satellite was put into an orbit lower than required. By using a combination of the onboard chemical propulsion and the electric propulsion system which was designed for NSSK, the orbit could be sufficiently raised to allow the satellite operation.

Future scenarios of "all electric" satellites investigate the possibility to perform the orbit injection from GTO to GEO and inclination change.

ID	Requirement	min. req.	opt. req.	remark
4-01	Number of controlled flow lines	2	4	
4-02	Type of thruster	HEMP 30250, SPT-140		
4-03	Thruster configuration	(cluster of) single thrusters + neutralizer		
4-04	Propellant	Xenon		
4-05	Flow range [sccm]	20 … 160		
4-06	Flow accuracy	5%	1%	
4-07	Flow linearity	1%		more important is the monotonic behaviour as the SPT and HEMP use the flow to control the anode current
4-08	min. flow step	1%	0.5%	
4-09	max. power consumption (OP)	<10W		
4-10	internal leakage	N/A		lower will be better
4-11	external leakage	N/A		lower will be better
4-12	Temperature range (OP)			
4-13	Temperature range (NOP) [°C]			
4-14	Operational inlet pressure [bar]	2 … 2.5		
4-15	MEOP [bar]	N/A		higher will be better
4-16	Burst pressure	N/A		
4-17	max. mass [kg]	0.40		
4-18	max. dimensions [mm]	N/A		smaller will be better
4-19	Orbit	GTO, GEO		
4-20	Launcher compatibility	all		
4-21	min. lifetime (OP) [h]	5000		increased if EP is used for reallocation etc.
4-22	min. storage time [years]	5		
4-23	min. Xenon throughput [kg]	N/A		

6 Summary

The functional requirements for the FCU span over a large range of values. Some requirements like leakage, inlet pressure and temperature are mostly independent from the reference mission. Others like flow range and accuracy depend strongly on the mission and the involved thrusters.

The requirements can be grouped depending on the type and the size of the supplied thrusters.

	RIT	HEMP/SPT
microthruster	1.0 sccm (F.S.) , less demanding requirement on accuracy and linearity	
standard thruster	40 sccm (F.S.), less demanding requirement on accuracy and linearity	60 sccm (F.S.), demanding requirement on accuracy and linearity
high power thruster		160 sccm (F.S.), demanding requirement on accuracy and linearity

The less demanding accuracy and linearity requirement can be included in the more demanding requirement. For the different flow ranges different µFCUs are required. The large flows (40, 60 , 160 sccm) may be achieved with the same operational principle and therefore FCU design as up-scaling can be done easily. For the ultra low flows a dedicated design seems to be required.

The reference missions' requirements have been compiled into two FCU targets as shown below. These targets will be input for a detailed analysis that shall deliver a µFCU Unit Specification (deliverable D.6.2)

6.1 Target A - micro flow range

ID	Requirement	min. req.	opt. req.	remark
A-01	Number of controlled flow lines	4		
A-02	Type of thruster	RIT-2 or RIT-2.5, RIT-4		
A-03	Thruster configuration	single THR or 4 THR pod		
A-04	Propellant	Xenon		
A-05	Flow range [sccm]	0.01 … 1.0	0.005 … 1.0	
A-06	Flow accuracy	10%	1%	
A-07	Flow linearity	10%	1%	
A-08	min. flow step	10%	1%	
A-09	max. power consumption (OP)	1 W		
A-10	internal leakage	1.4×10^{-5} scc/s GHe		lower will be better
A-11	external leakage	1×10^{-6} scc/s GHe		lower will be better
A-12	Temperature range (OP)	-50 … +100		
A-13	Temperature range (NOP) [°C]	-60 … +110		
A-14	Operational inlet pressure [bar]	< MEOP		
A-15	MEOP [bar]	10		higher will be better
A-16	Burst pressure	2.5xMEOP		

A-17	max. mass [kg]	0.48		lower will be better
A-18	max. dimensions [mm]	60x30x30		
A-19	Orbit	LEO, Deep Space		
A-20	Launcher compatibility	VEGA	all	
A-21	min. lifetime (OP) [years] operational hours [hours]	10 >88 000		
A-22	min. storage time [years]	3		
A-23	min. Xenon throughput	>10 kg/flow line		

6.2 Target B - large flow range

The large flow range focuses on the NSSK task and deep space missions. Orbit transfer and high power thrusters are covered by "opt.req".

ID	Requirement	min. req.	opt. req.	remark
B-01	Number of controlled flow lines	4		
B-02	Type of thruster	NSTAR, RIT-22, HEMP3050, SPT-100		
B-03	Thruster configuration	single thruster		
B-04	Propellant	Xenon		
B-05	Flow range [sccm] Line 1: Line 2: Line 3: Line 4:	 5.0 … 60.0 5.0 … 60.0 0.5 … 4.0 0.5 … 4.0	 5.0 … 160 5.0 … 160 0.5 … 8.0 0.5 … 8.0	
B-06	Flow accuracy	3%	1%	
B-07	Flow linearity	1%		
B-08	min. flow step	1%	0.5%	
B-09	max. power consumption (OP)	<2W		
B-10	internal leakage	1×10^{-6} scc/s Xe		lower will be better
B-11	external leakage	1×10^{-6} scc/s Xe		lower will be better
B-12	Temperature range (OP)	-15 … 110	-30 … 120	
B-13	Temperature range (NOP) [°C]	-40 … 120	-50 … 130	
B-14	Operational inlet pressure [bar]	2 … 2.65	1 … 3	
B-15	MEOP [bar]	8		higher will be better
B-16	Burst pressure	28		
B-17	max. mass [kg]	0.40		
B-18	max. dimensions [mm]	100 x 100 x 50		
B-19	Orbit	GEO, Deep Space, GTO		
B-20	Launcher compatibility	all especially VEGA, Ariane 5, Sojus		
B-21	min. lifetime (OP) [h]	> 20 000		
B-22	min. storage time [years]	5		
B-23	min. Xenon throughput [kg]	200		