MEGAHIT: Update on the advanced propulsion roadmap for HORIZON2020

Dr. Frank Jansen
Frédéric Masson, Elisa Cliquet
Tim Tinsley

DLR
cnes
NATIONAL NUCLEAR LABORATORY

MWE NEP System: The MEGAHIT Project

GENERAL CONTEXT

MEGAHIT: « *Megawatt Highly Efficient Technologies for Space Power and Propulsion Systems for Long-duration Exploration Missions* »

- **European 7th Framework Programme**
  - R&T program of the European Community
- **Horizon 2020**
  - Next EC Research and Technology program starting in 2014
  - Projects with a multi-annual structured agenda allowing to realize ambitious technology demonstrations ("strategic research clusters")
- **Project MEGAHIT**
  - « supporting action », i.e. contribution for the implementation of the FP and preparation of future R&D activities
  - The project objective is to propose a concrete action plan on high power electric propulsion for H2020
  - It is also to create a technical and scientific community in Europe including Russian partners

MEGAHIT contact : megahit@esf.org

MEGAHIT APPROACH

- 4 steps

1. Identify high level requirements and interests for MW NEP with space agencies worldwide → Synthesis of high level requirements
2. Select promising options at system level and identify technology gaps → Reference vision
3. Propose a development plan for each key technology and subsystem, involving stakeholders → Technology plans

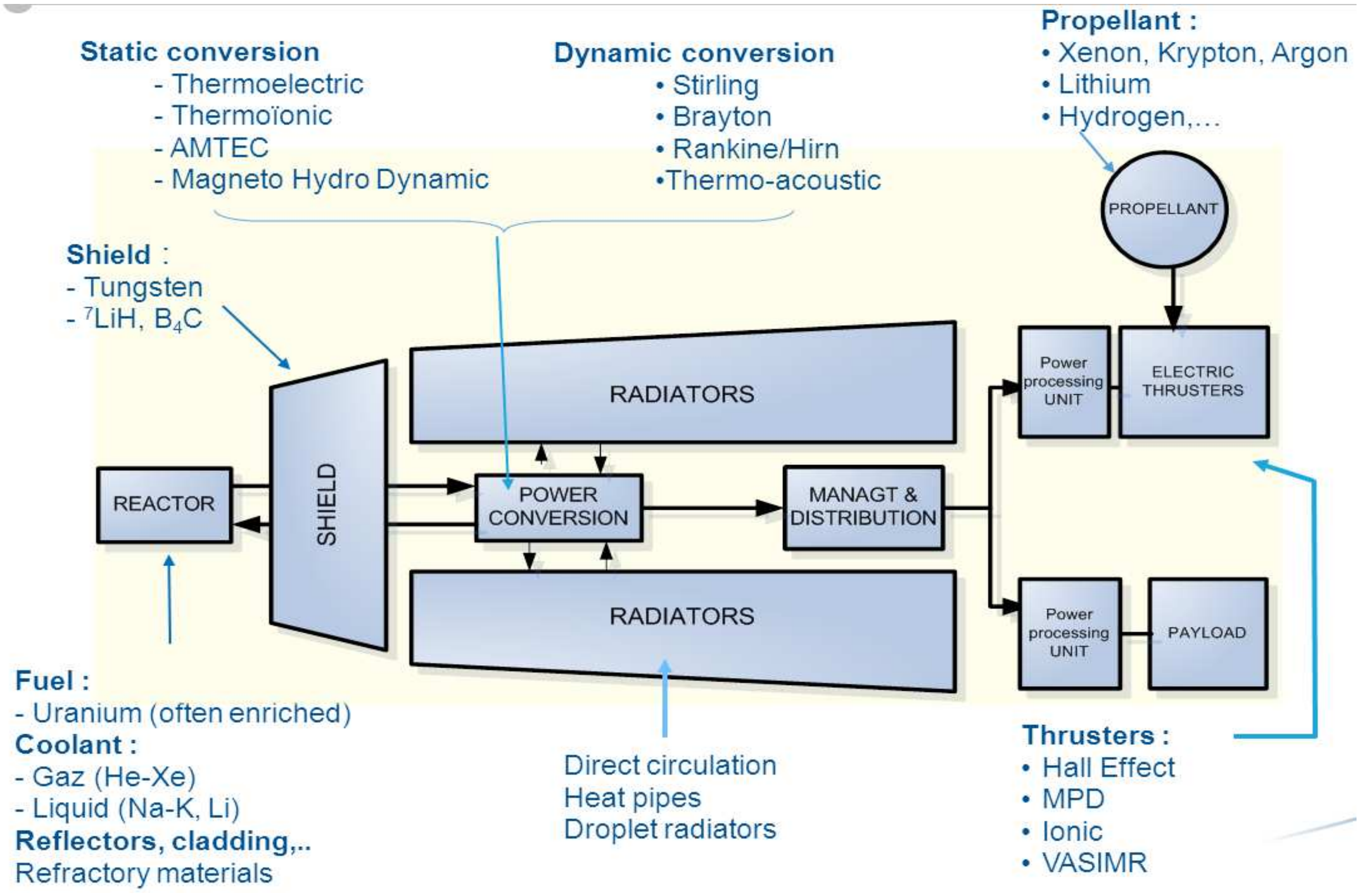
WORKSHOPS

4. Propose a global roadmap with capabilities of stakeholders → ROADMAP

7 topics were discussed in the workshops in Brussels (december 2013)

- Fuel and core (including shielding)
- Thermal control (heat transportation and radiating devices),
- Conversion
- Propulsion (electric thrusters),
- Power management and distribution
- Structure and spacecraft arrangement
- Safety, regulations, public acceptance.

General principle
Candidate technologies for main sub-systems



Static conversion
- Thermoelectric
- Thermoïonic
- AMTEC
- Magneto Hydro Dynamic

Dynamic conversion
- Stirling
- Brayton
- Rankine/Hirn
- Thermo-acoustic

Propellant :
- Xenon, Krypton, Argon
- Lithium
- Hydrogen,…

Shield :
- Tungsten
- ^{7}LiH, B_4C

Fuel :
- Uranium (often enriched)

Coolant :
- Gaz (He-Xe)
- Liquid (Na-K, Li)

Reflectors, cladding,..
Refractory materials

Direct circulation
Heat pipes
Droplet radiators

Thrusters :
- Hall Effect
- MPD
- Ionic
- VASIMR

Reference missions - 1

for 1MWe 20t vehicle

Mission analysis conducted by KerC taking the following hypothesis:

- Departure from a a **sufficiently high orbit** (800km or more)
- Heavy lift launchers capable of putting 20t on a 800km orbit (2 modules) or more classical launchers (ariane) putting more than 2 modules and **on-orbit assembly**
- Spacecraft composed of **2 modules assembled in orbit**: the transport power module with NPPS (20tons) and the module with payload

Reference missions - 2

for 1MWe 20t vehicle

- **NEO deflection**

  deflection by acting as a gravity tractor.

  could deflect **Apophis** trajectory by 1 million kilometer.

  If spacecraft leaves Earth in 2021, would reach Apophis in 200days and deflect it by staying a distance of 300m during 40 days.

Astéroïde Apophis. Crédits : CNES/Ill. P. Carril.

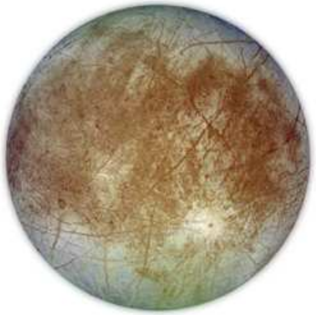
- **Outer solar system missions**
  - for **Europe** (Jovian moon) orbit: 3 to 10t of payload in ~3 years (Isp=7000sec). A chemical stage, without gravity assist manoeuver, would put only 300kg of payload in this orbit.
  - For **Titan** 3 to 12 t of payload in Titan orbit in 3.5 to 6 years (Isp 6000s to 9000s).

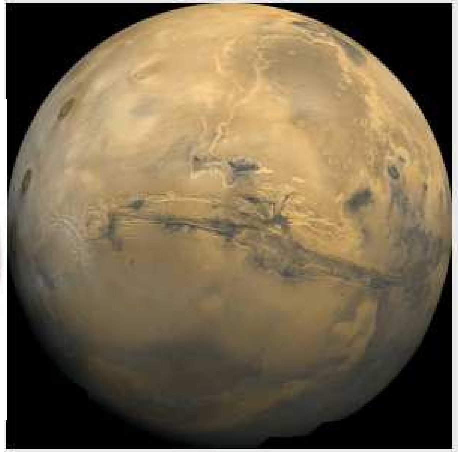
- **Lunar orbit tug**

  With a launcher capable of launching 80t in a 800km orbit 2 times per year, 650t of payload can be brought in lunar orbit in 10 years.

- **Cargo support mission for manned Mars mission**

  Can bring 15t in 400 days (Isp=6000sec)





Main high level system requirements for MEGAHIT

(non exhaustive)

- For 1MWe, **mass of the full system should be lower than 20tons (20kg/kWe)** including :
- **5 years at full power** on a total lifetime of 10 years (**several operating modes**)
- **Radiators** will have to be **foldable** to fit in the launcher
- Safety :
  - the **reactor shall remain subcritical at all times during launch**, even in case of a launch failure, and up to reaching a sufficiently high orbit
  - Compliance with the guidelines of the International Safety Framework for Nuclear Power Source Applications in Outer Space

Nuclear core – 1
Role, challenge, selected fuel

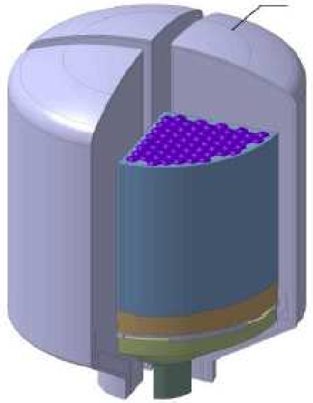
Role in the system and requirements

- For 1MWe of electric power, reactor must provide **3MWth of thermal power** (if 30% efficiency)
- If specific mass of 20kg/kW for full system, minimum **temperature of 1350K at reactor outlet**.

Challenges

- High **temperature level** (even higher than Generation IV reactors).

  safety to guarantee, even in case of launch failure.



Reactor with
4 sub-critical parts

OPUS by CEA

Fuel

➡ **3 fuel candidates UO2, UC and UN retained for reference**

- UO2 wide pre-existing operational experience in Europe, but at lower temp.
- UC and UN denser than UO_2 + better thermal conductivity, but very limited experience in Europe

➡ **High enrichment, fast spectrum, proposed as reference**

- At high temperature, thermal spectrum core is heavier (x2)
- Probably no moderator able to sustain high temperature (ZrH limited to 1000K)
- UN texts recommends highly enriched U as low enriched U produces highly toxic Pu239

Nuclear core – 2
Architecture: Liquid-cooled or gas-cooled reactor

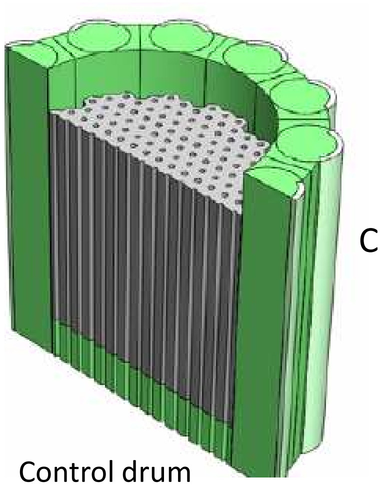
For liquid-cooled:

- Given the level of temperature considered **Lithium** is the only suitable liquid coolant
- **Fuel elements: pins** benefit from pre-existing experience at high temperature on fast reactors (like Superphenix)

For gas-cooled:

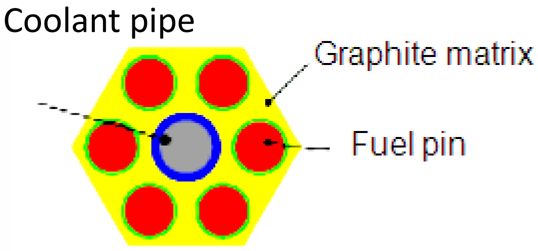
- **He-Xe chosen**. He = good thermal conductivity (for nuclear core), Xe = good density (for turbine)
- **Fuel elements : BISO or TRISO particules** = maximize thermal exchange bw fuel and coolant gas.

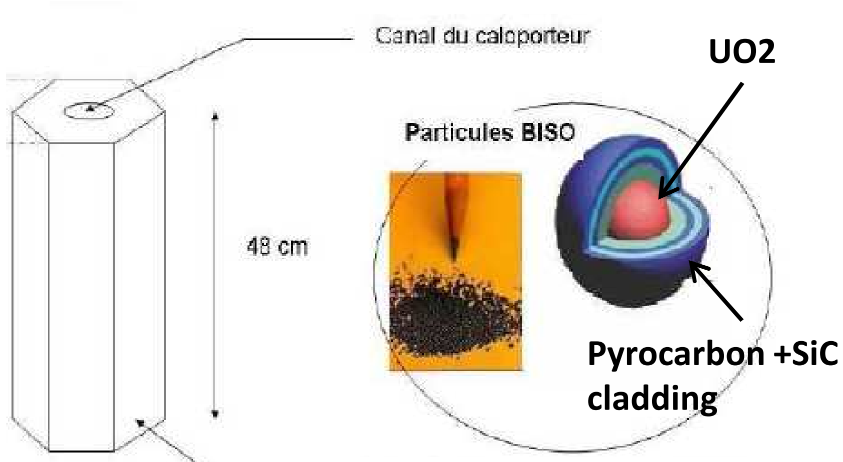
exemple of smaller core: heat pipes could be an option (for lower power levels up to 100kWe)



Control drum
(Be + absorbing part in Be4C)

1 hexagonal element





UO2

Pyrocarbon +SiC cladding

particles in graphite matrix

Reference for conversion

- **Brayton cycle**

Heating performed by nuclear core, expansion by a rotating turbine coupled with an alternator, cooling by a radiator.

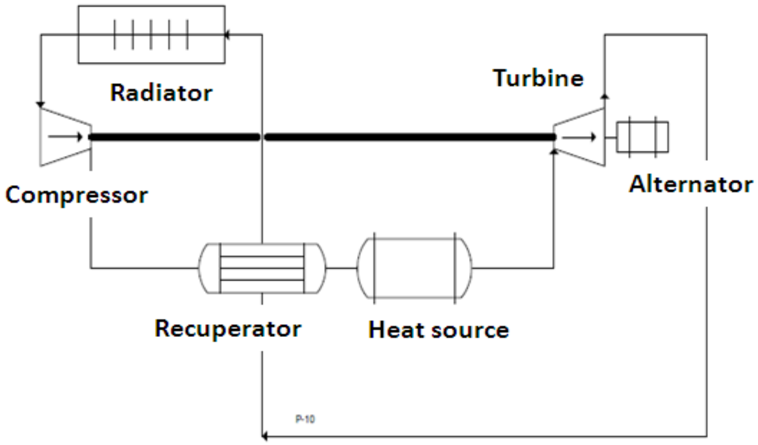
- Could be **direct**: cooling fluid of the reactor is directly injected into the turbine

- Or **indirect:** cooling of the reactor is a liquid (Li) and a heat exchanger separates the primary loop from the conversion loops that uses a gas (He-Xe).

Main identified **challenge is the temperature at turbine inlet** that should be as high as possible (1300K-1600K)

Efficiency is good (31% for Thot = 1600K)

A lot of experience available from aeronautics engine, synergies are possible.



- **Magneto-hydrodynamic conversion :**

A long term alternative

+ : no moving parts

Thermal gradient produces rapid movement of ionized fluid

Passage in a magnetic field induces electrical current.

Reference for radiator

• Heat pipes radiators

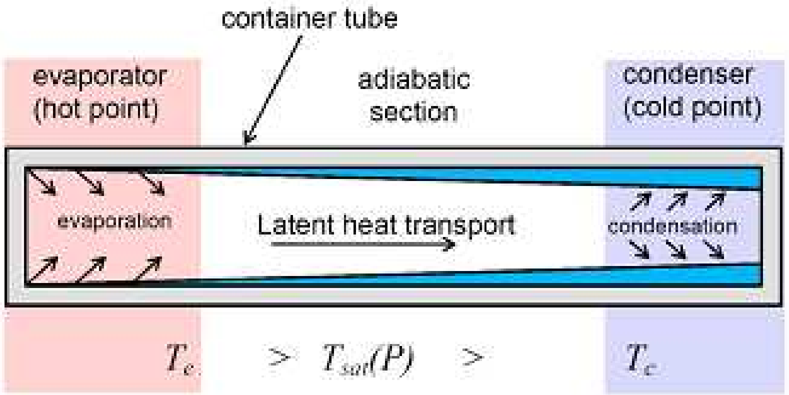
Can be simple heat pipe or loop heat pipe.

- High temperature gradient to manage between radiator inlet/outlet
- High inlet temperature = lower surface tension. Fluid to be chosen accordingly.

\+ Reliable: no need of pumps

\+ Already widely used in ground and space applications.

\+ Performance very attractive (3-5 kg/m2).



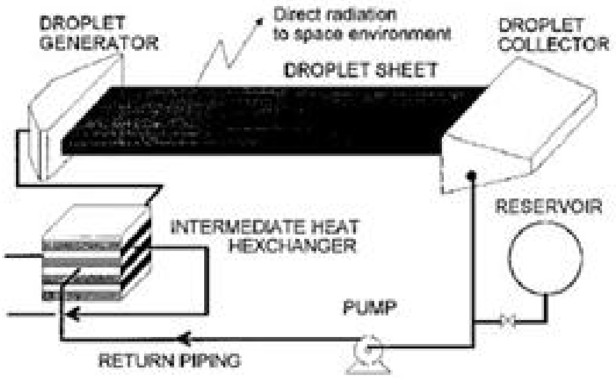
Simple heat pipe – source: espci

• Droplet radiator

A long term alternative

\+ : no metallic exchange surface, lowest mass

A mist of droplet is expelled in space then collected back



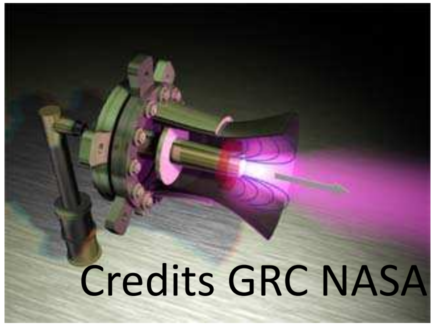
Reference for Electric propulsion

The following thrusters are good candidates for high power

- Cluster of 5 to 20 **Hall-Effect thrusters (Kr or Ar) –** (50 to 200kWe)
  - Currently flying at power levels up to 5kWe
  - Tested in labs up to 72kWe (NASA 457M) with Xe and 150kWe with Bismuth (Russia)
- Cluster of 5 to 20 **Ion engines (electrostatic) –** (50 to 200kWe)
  - Best Isp, but low thrust and thrust density
  - Currently flying at power levels up to 5kWe
  - Tested in labs up to 40kWe (NASA HiPEP).
- Cluster of 2 to 10 **Magnetoplasmadynamic thrusters (Ar or Li)** (100kWe to 500kWe)
  - Best technology for high power level
  - Self field MPD tested in labs between 100 kW-1MWe in Europe
  - Example : Li-LFA 500kWe during 500hours (Russia)
- Other high power thrusters may also be considered but have lower TRL (helicon plasma thruster, etc ..)

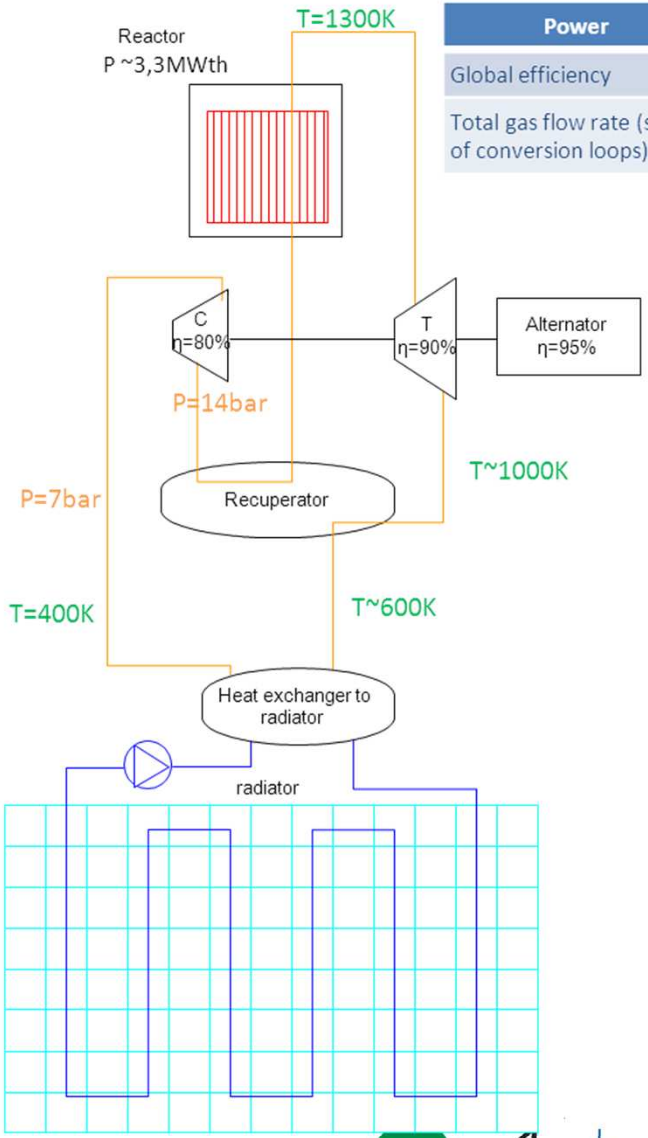

Credits Snecma


Credits GRC NASA


Credits GRC NASA

Thermodynamic maps + mass budget

(near future)



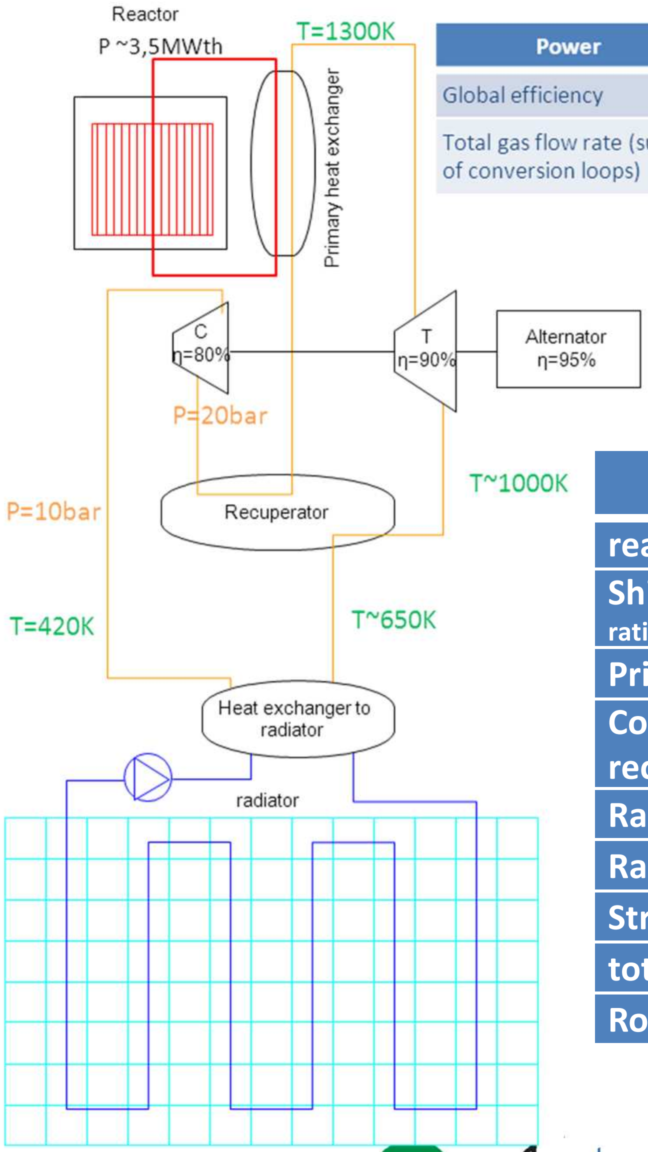
Power	1MWe
Global efficiency	~ 30%
Total gas flow rate (sum of conversion loops)	~45kg/s

Brayton direct 1300K order of magnitude

System	Brayton Direct 1300K
reactor	4,0t
Shield (20° cone angle, 10^{12}n/cm² at 40m behind, elliptical shape ratio of 0.5)	1,7t
Conversion (compressor, turbine, alternator, recuperator)	2,5t
Radiator mass (including radiator heat exchanger)	5,8t
Radiator surface (both sides radiate)	550 m² (1100m²)
Structures & circuits (20%)	2,8t
total mass	16,8 t
Rough specific mass (no PMAD or EP)	17kg/kW

Thermodynamic maps + mass budget

(near future)



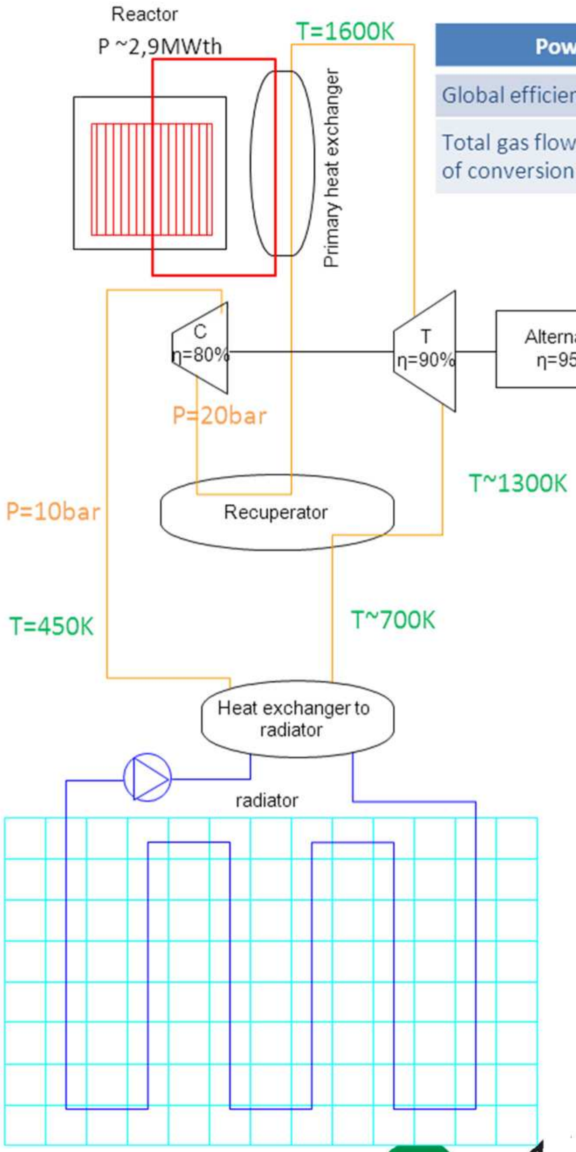
Power	1MWe
Global efficiency	~ 30%
Total gas flow rate (sum of conversion loops)	~45kg/s

Brayton indirect 1300K, order of magnitude

System	Brayton Indirect 1300K
reactor	1,1t
Shield (20° cone angle, 10^{12}n/cm² at 37m behind, elliptical shape ratio of 0.5)	1,1t
Primary exchanger	1,2t
Conversion (compressor, turbine, alternator, recuperator)	2,6
Radiator mass (including radiator heat exchanger)	5,4
Radiator surface (both sides radiate)	500m² (1000m²)
Structures & circuits (20%)	2,3t
total mass	13,0 t
Rough specific mass (no PMAD or EP)	13kg/kW

Thermodynamic maps + mass budget

(far future)



Power	1MWe
Global efficiency	~ 35%
Total gas flow rate (sum of conversion loops)	~30kg/s

Brayton indirect 1600K, order of magnitude

System	Brayton Indirect 1600K
reactor	0,9t
Shield (20° cone angle, 10^{12}n/cm^2 at 28m behind, elliptical shape ratio of 0.5)	1,0t
Primary exchanger	1,0t
Conversion (compressor, turbine, alternator, recuperator)	1,9t
Radiator mass (including radiator heat exchanger)	3,0t
Radiator surface (both sides radiate)	270m^2 (540m^2)
Structures & circuits (20%)	1,7t
total mass	9,4 t
Rough secific mass (no PMAD or EP)	9kg/kW

Proposed reference concept

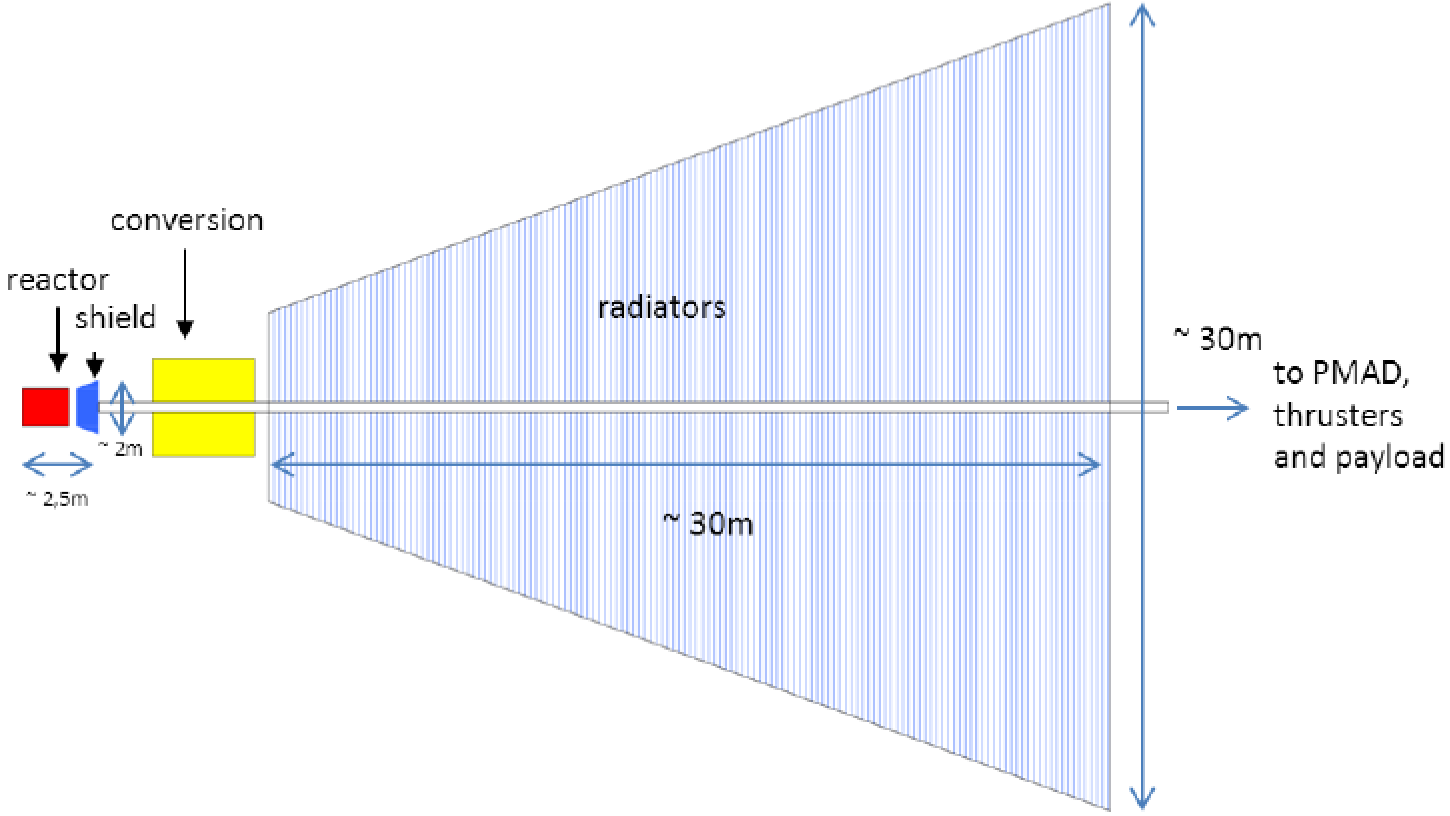


FIGURE 2 - ROUGH SCHEMATIC OF THE 1MW, 1300K, DIRECT BRAYTON OPTION

Some Outcomes from the Megahit workshop

Some choices still need consolidated consideration

- Nuclear fuel (trade-off considering performance, safety, availability, non-proliferation)
- Electric thrusters (type and number of thrusters)
- Direct/ Indirect cycle

Maturations/ new development needed, especially for components compatible with high temperature/ long duration:

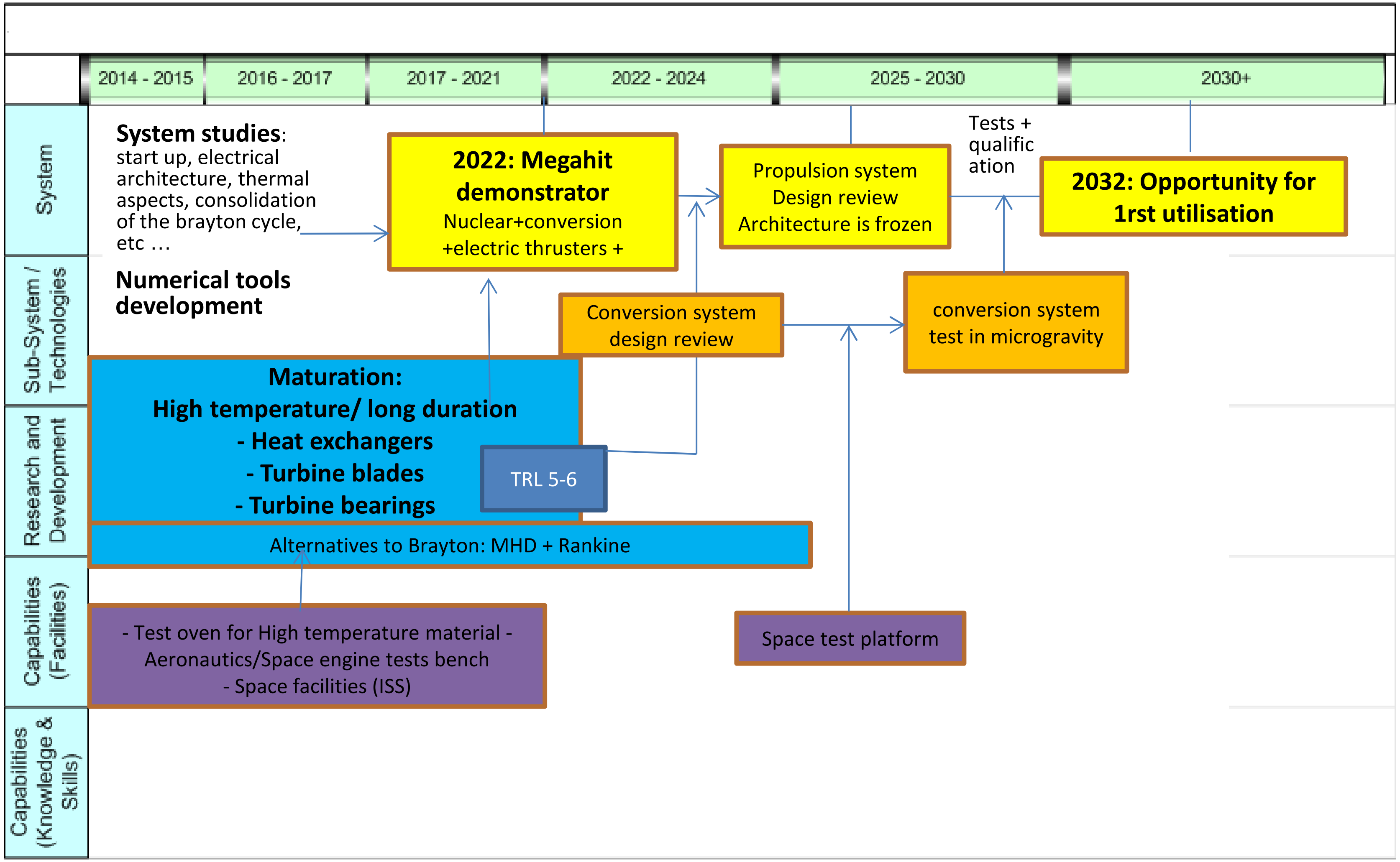
- nuclear reactor,
- the turbine blade and disk,
- conversion bearings,
- heat exchanger between primary and secondary circuit (if a heat exchanger is required).

Need of lower power demonstrators, as part of technologies maturation, and demonstration of correct functioning of the system (for instance, a strategy for transient phases should also be defined, allowing coherent functionning between core, turbine, radiator and thrusters).

The need to assemble many parts in orbit may require **advances in robotics**.

MEGAHIT

Extract of megahit roadmap: high level roadmap for conversion



2014 - 2015
2016 - 2017
2017 - 2021
2022 - 2024
2025 - 2030
2030+

System

Sub-System / Technologies

Research and Development

Capabilities (Facilities)

Capabilities (Knowledge & Skills)

System studies: start up, electrical architecture, thermal aspects, consolidation of the brayton cycle, etc …

Numerical tools development

2022: Megahit demonstrator
Nuclear+conversion +electric thrusters +

Propulsion system Design review Architecture is frozen

Tests + qualification

2032: Opportunity for 1rst utilisation

Conversion system design review

conversion system test in microgravity

Maturation:
High temperature/ long duration
- Heat exchangers
- Turbine blades
- Turbine bearings

TRL 5-6

Alternatives to Brayton: MHD + Rankine

- Test oven for High temperature material
- Aeronautics/Space engine tests bench
- Space facilities (ISS)

Space test platform

Perspectives

- Roadmaps under finalization, taking into account the output of the workshop.
- **Horizon 2020** is Next EC Research and Technology program, starting in 2014, running till 2020.

  Calls for tender have already been issued for 2014-2015

- Megahit consortium will apply to several calls, proposing **demonstrator projects and technology maturation**, related to nuclear-electric propulsion, based on the work already done within Megahit project.
- **Extended International partnerships** will be an asset.