Study of nuclear space reactors for exploration missions

Elisa CLIQUET*, Jean-Marc RUAULT*, Frédéric MASSON*
,
Jean-Pierre ROUX**, Nicolas PARIS**, Brice CAZALÉ**, Laurent Manifacier**

Christine POINOT-SALANON***

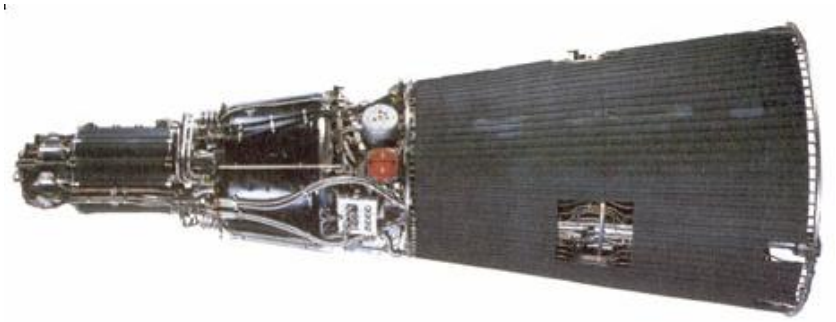
Novembre 2013

Introduction

We considered **nuclear electric propulsion based on fission**
Power density of nuclear fission much higher than chemical process

→ **For many interplanetary missions, nuclear electric propulsion the only option** offering a reasonable mass in low earth orbit.

Existence of low power experiences - SNAP10 in the 60's or Buk/Topaz in the 60-80's – but no high power reactor developed (<10kWe)



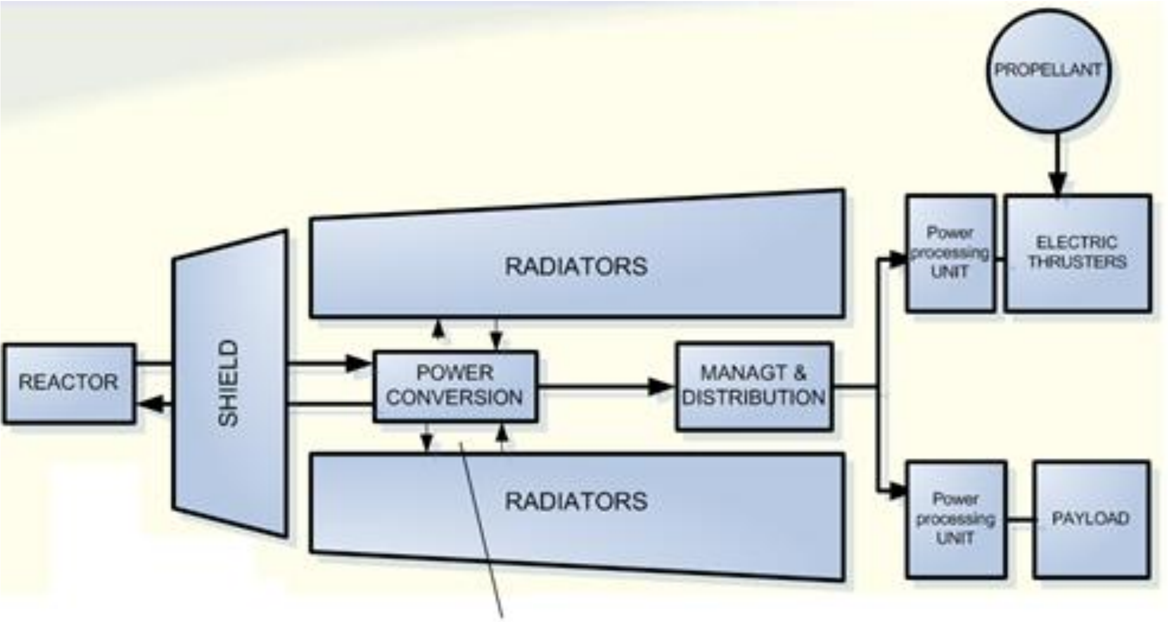
TOPAZ – 5kWe

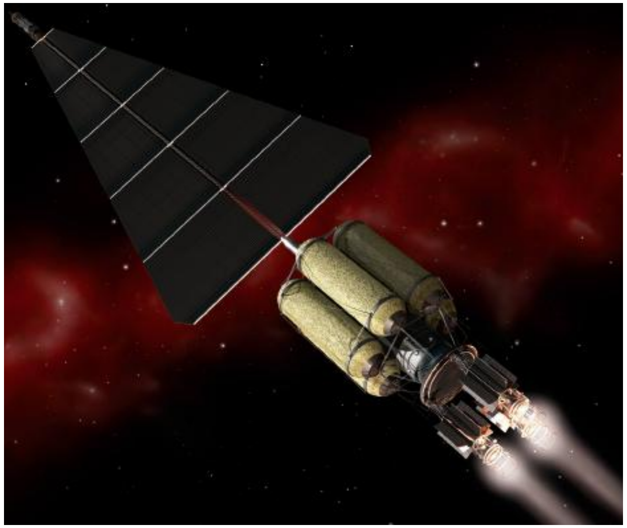
From 2005, studies going on in France and Europe, on space reactors for exploration.
3 classes of power considered recently: 10kWe, 100kWe, and > 1 megawatt
Results: preliminary designs + list of critical technologies needing maturation activities

French know-how and background:

- In ground and on-board nuclear reactors (CEA, Areva)
- Conversion system and electric thrusters (Snecma)
- European launch capabilities (Ariane in guyana: CNES, Astrium, Arianespace)

Architecture of nuclear-electric propulsion





- **Nuclear core** provides thermal energy via the coolant fluid
- **Conversion** converts thermal energy into electric energy
- **Radiators** provide the cold source of the cycle
- Electric energy feeds **electric thrusters**
- **Shield** protects all the parts downstream of the core

100 kWe system study

- limited to power generation system (reactor, shielding, conversion, radiators)
- not dedicated to a specific mission

Main requirements

- Specific mass of about 30 kg/kW
- Fitting under Ariane 5 fairing
- 3 years of operation at full power and 10 years of mission

Criteria for technology selection

1. specific mass, cost and operating versatility
2. reliability and safety
3. maturity of technologies
4. European independence

Methodology

1. Screening of possible technologies (supported by large bibliography)
2. Simplified modeling of candidates technologies
3. Trade-off at system level based on coupling of those models
4. Preliminary design of two options Gas cooled reactor and Liquid metal cooled reactor

Technologies selected for trade-off

- **Reactor : either 1700kWth (low efficiency conversion) or 350 KWth**

Coolant	cladding	Moderator (if any)	Fuel
Na-K (1100K)	Steel	ZrH_2	UC 93% or 20% UO_2 93% or 20%
^{7}Li (1500K)	Mo-Re	fast spectrum	UC 93% or 20%
He-Xe (1500K)	Mo-Re	BeO or Fast spectrum	UC 93% or 20% UO2 93%

- **Conversion :**
  - **Static**: thermo-electric (La_2Te_3, Si-Ge), thermo-ionic, Alkali-metal thermoelectric
  - Or **dynamic**: Stirling, Brayton, Rankine/Hirn, thermo-acoustic

- **Radiators:**
  - **heat pipes**,
  - gas circulation with pumps,
  - or droplet radiators

system sizing and trade-offs

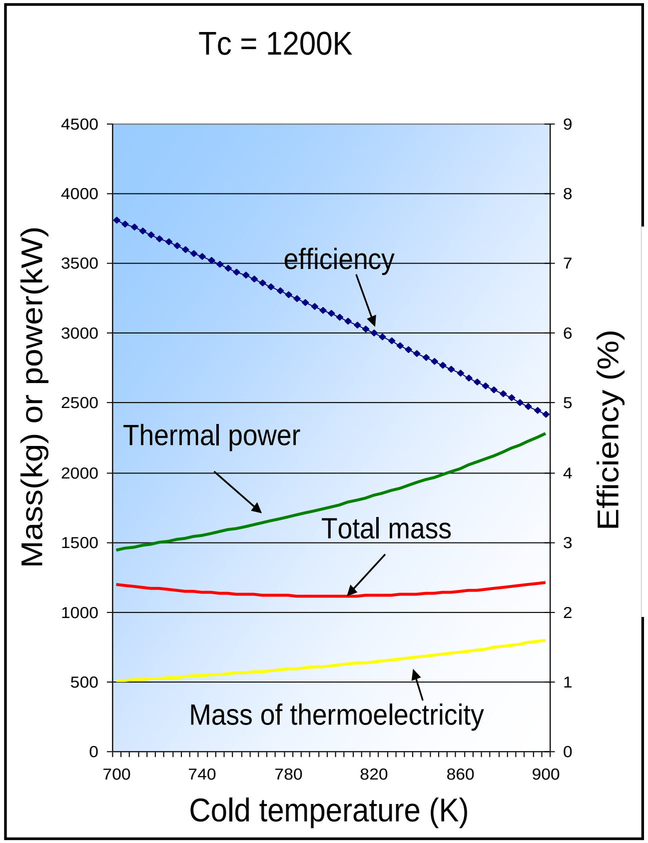
- **For fuel: UO2 :** available and wide pre-existing operational experience in France

It requires a **fast spectrum with highly enriched** fuel to optimize the mass

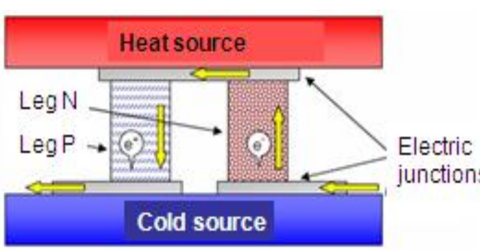
- **Highest possible core temperature** is the best: better cycle efficiency ⟶ use of Li or He-Xe as coolant.

- For conversion, **thermo-electric and Brayton** seems the best options.

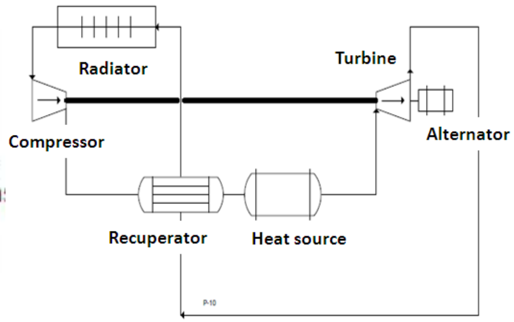
- **Temperature of the cold source** is a compromize between high temperature/ high radiator performance and cold temperature/high carnot efficiency.



Optimisation of the cold temperature for a system using Brayton conversion



Thermo-electric conversion



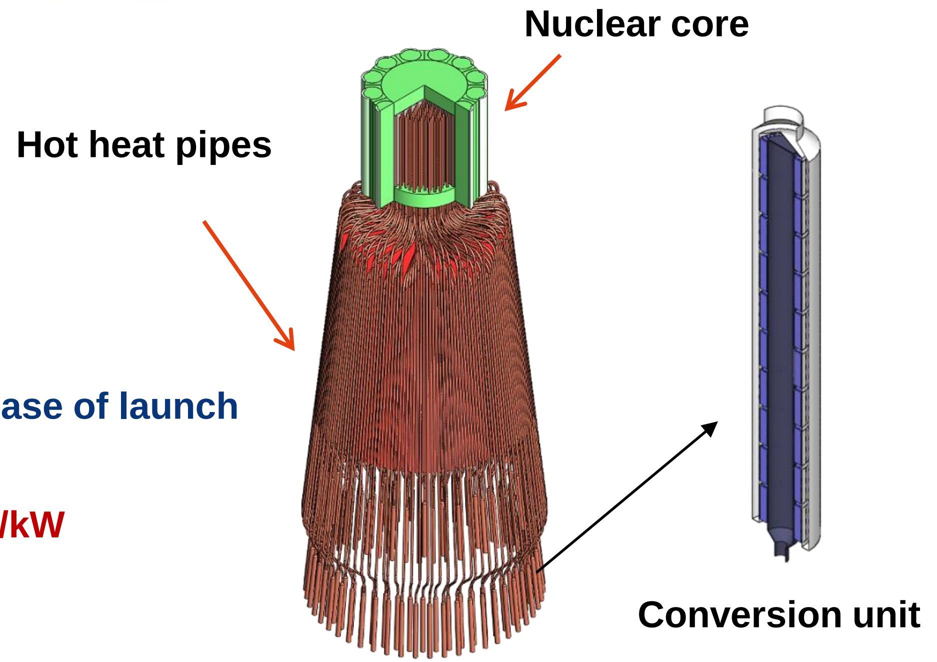
Brayton conversion

Liquid metal cooled reactor with thermoelectric conversion

- Core
  - Highly enriched UO_2 needles
  - Fast spectrum
  - Li cooled (Heat pipes with NbZr wall)
- Reactivity control drums: Be-B_4C
- Core to be separated in subcritcal parts in case of launch failure

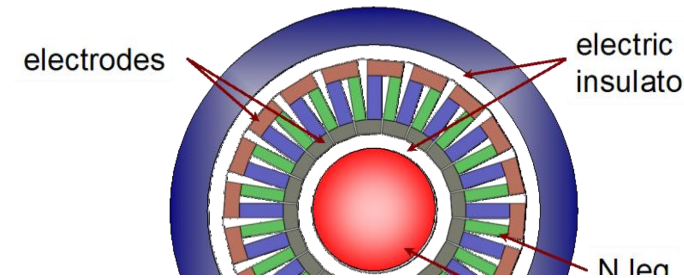
→ **reactor + core : 13kg/kW**

- Conversion :
  - 187 heat pipes x 10 Units
    of 20 thermoelements (Si-Ge)
  - Optimized leg length
  - Cold heat pipes K



→ **reactor + core + conversion : 23kg/kW**

→ **system mass (including PMAD& miscellaneous) expected around 33 kg/kW**



Gas cooled reactor with direct Brayton conversion

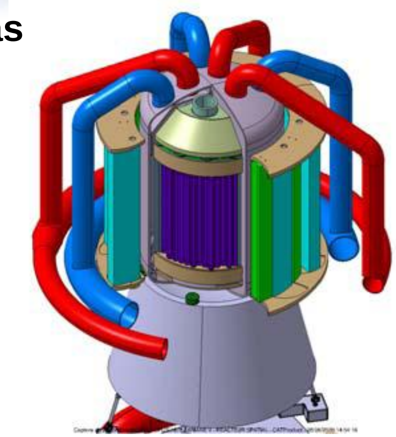
- Core (based on previous opus study)
  - Highly enriched UO_2
  - BISO particules in graphite matrix
  - Fast spectrum
  - 4 separable sub-criticical parts for safety at launch
- Reactivity control : mobile shutter in Be, main reflectors in BeO

→reactor + core : 16kg/kW

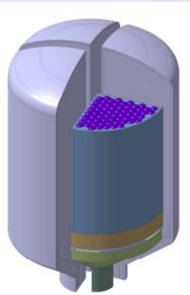
- Conversion
  - 3 turbines designed for 50%
  - 2 radiators designed for 50%
  - Heat exchanger for mass optimisation (950K->550K)

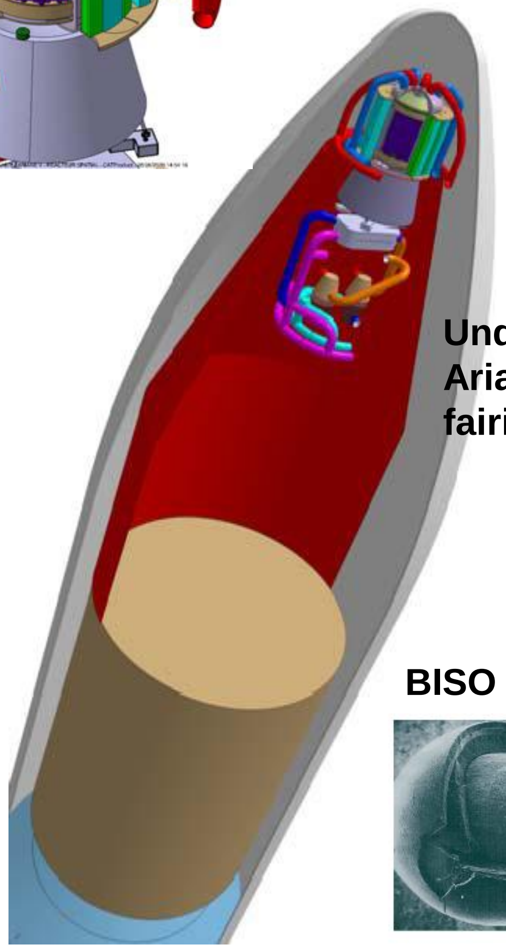
→ system mass (including PMAD) expected around 33 kg/kW

Core with gas inlet/outlets



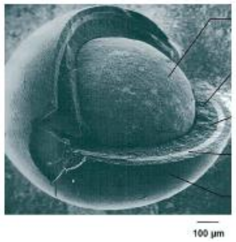
4 subcritical parts





Under Ariane fairing

BISO particle



Critical technologies and development philosophy

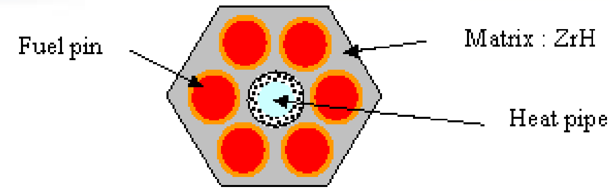
- Critical technologies
  - General :
    - Very high temperatures required whatever the solution
    - Command mechanisms (high temperature and high reliability)
    - Fuel assemblies
    - Radiators
    - Specific instrumentation
  - Gas cooled
    - Gas turbine
  - Liquid cooled
    - Heat pipe performances

- Development philosophy
  - Conversion technology mock-ups with non nuclear heat source to validate critical aspects
  - Core prototype for fuel qualification
  - Full system on-ground prototype
  - Final flight system

10 kWe study - Core and Shield design

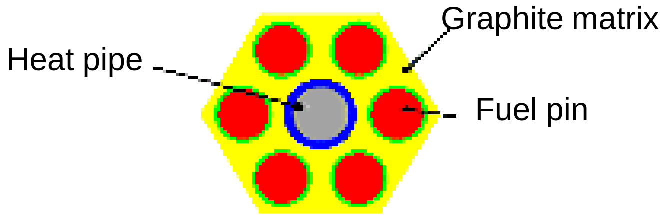
Core description

- Hexagonal, based on pins developed in France for fast reactors
- Cooled by liquid metal heat pipes
- Beryllium reflector
- Thermal power from 5kWth to 200kWth



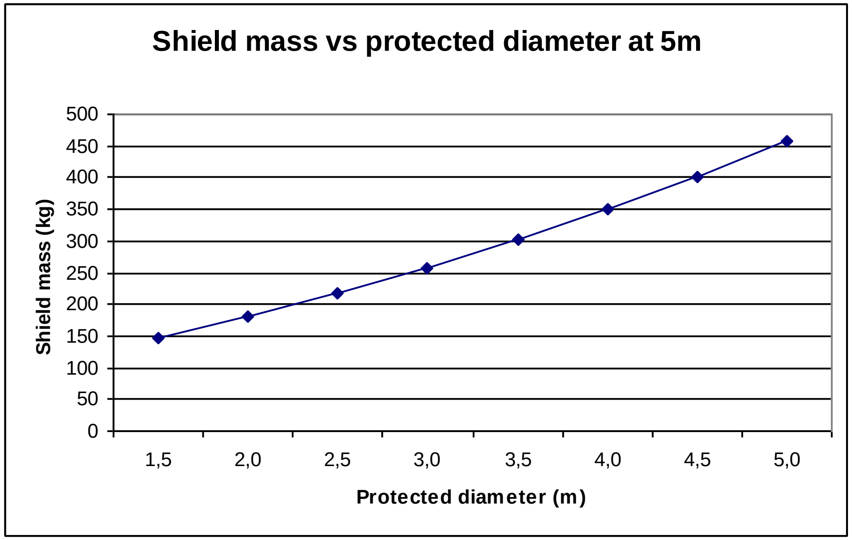
Thermal version moderated by ZrH

T ≤ 900K



Fast version

1100K < T ≤ 1300K



Shield

Classical shielding materials

- LiH for neutrons
- W for gammas

Spacecraft geometry is a key driver for performance

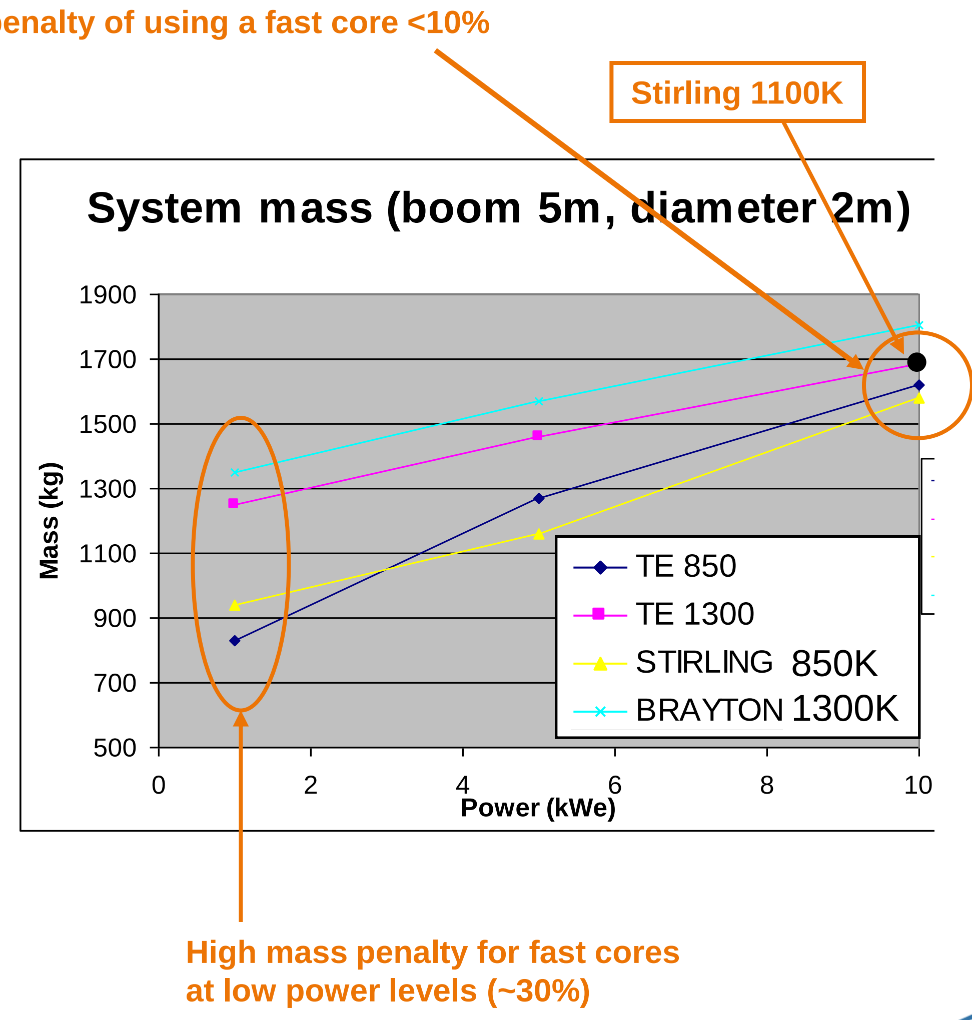
Mission duration and permissible flux impacts slightly the shield mass (10%)

SYSTEM LEVEL TRADE-OFF

Stirling is the best option, especially when using a thermal reactor.
Brayton is less attractive in this power range, Stirling machine's **nearest competitor is thermoelectric generation**

Thermal spectrum option is better for low power range, but the mass saving seems rapidly less significant when the power increases.

Even if there is a mass penalty due to the reactor **we recommend the Stirling + Fast reactor option for growth potential:**
the development of a thermal reactor only for this power range would not be worth the effort



MWE System: The MEGAHIT Project
GENERAL CONTEXT

SEVENTH FRAMEWORK PROGRAMME

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

cnes

DLR

EUROPEAN SCIENCE FOUNDATION
SETTING SCIENCE AGENDAS FOR EUROPE

NATIONAL NUCLEAR LABORATORY

ThalesAlenia Space

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

WORKSHOPS

SEVENTH FRAMEWORK PROGRAMME

7 topics to be 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.

MEGAHIT - Reference missions

for 1MWe 40t vehicle – study performed by KerC

- **NEO deflection**

  deflection by acting as a gravity tractor.

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

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

- **Lunar orbit tug**

  Several hundredths tons of payload can be brought in lunar orbit in 10 years.

- **Outer solar system missions**

  for **Europe** (Jovian moon) orbit :3 to 10t of payload

  for **Titan** 3 to 12 t of payload in Titan orbit

- **Manned Mars mission cargo support mission**

  Can bring 15t in 400 days