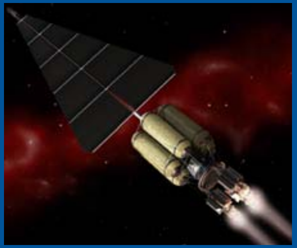
Preliminary study of a 100 kWe space reactor concept for exploration missions



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Overview

- General context of the study
- Requirements
- Methodology of the study
- Technologies selected for final trade-off
- Reactor trade-off
- Conversion trade-off
- Critical technologies and development philosophy
- Conclusion and perspectives

CNES Directorate of Launchers

Space transportation division of the **French space agency**

- Responsible for the development of DIAMANT, ARIANE 1 to 4, ARIANE 5, launchers
- System Architect for the Soyuz at CSG program
- Development of VEGA launcher first stage (P80)
- Future launchers preparation activities
  - Multilateral and ESA budgets
    - To adapt the current launchers to the needs for 2015-2020
    - To prepare launcher evolutions for 2025 - 2030, if needed
    - To prepare the new generation of expandable launchers (2025-2030)
    - To prepare the long future after 2030 with possible advanced launch vehicles
- Future space transportation prospective activities, such as
  - Exploration needs (including in particular OTV missions)
  - Advanced propulsion technologies investigation

General context

- Background
  - Last French studies on space reactors :
    - ERATO (NEP) in the 80’s,
    - MAPS (NTP) in the 90’s
    - OPUS (NEP) 2002-2004

- Since then
  - Nuclear safe orbit to be taken into account
  - Progress in solar cells

  → interest of nuclear electric propulsion for exploration application with high payload, high ΔV requesting very high power

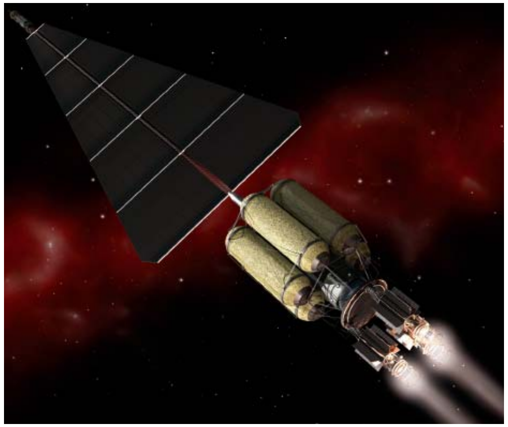
- French know-how and background in ground and on-board nuclear reactors

- European launch capabilities

Requirements

- Study is limited to power generation system (reactor, shielding, conversion, radiators)
- Study is not dedicated to a specific mission
- Main requirements
  - 100kWe
  - Specific mass goal $\leq$ 30 kg/kW
  - Fitting under Ariane 5 fairing
  - <u>Compatible with a mid-term development timeframe</u>
  - 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 of the study

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

Technologies selected for trade-off

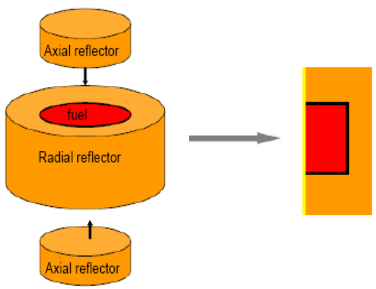
- Reactor : either 1700kWth (low efficiency conversion) or 350 KWth

Coolant	cladding	Moderator (if any)	Fuel
Na-K (1100K)	Steel	ZrH_2	UC 93% UO_2 93% (UC 19,75%) (UO_2 19,75%)
^{7}Li (1500K)	Mo-Re	(fast spectrum)	UC 93% (UC 19,75%)
He-Xe (1500K)	Mo-Re	BeO or Fast spectrum	UC 93% (UC 19,75%) UO_2 93%

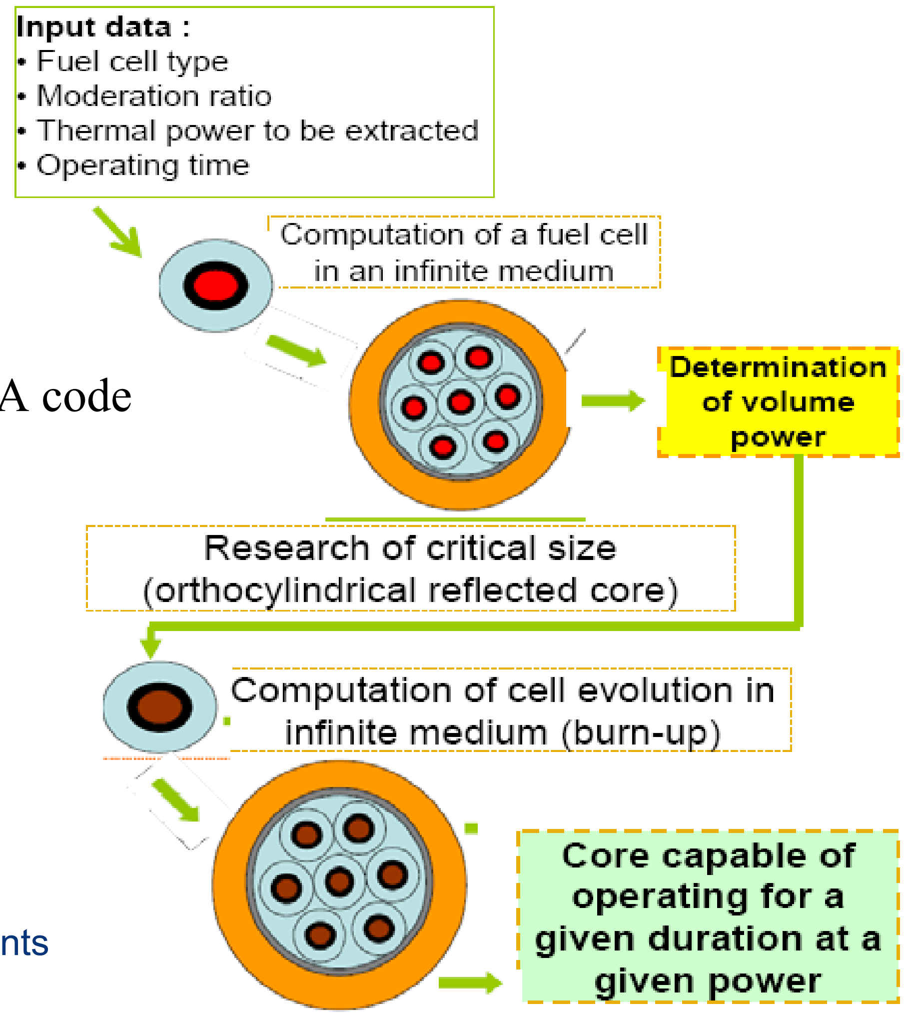
- Conversion :
  - Static option: thermoelectric
    - La_2Te_3
    - Si-Ge
  - Dynamic option: Brayton cycle
  - Radiators: heat pipes or gas circulation

Reactor trade-off

- Neutron physics model for evaluation of reactor options :
  - Homogeneous
  - Axial symmetry



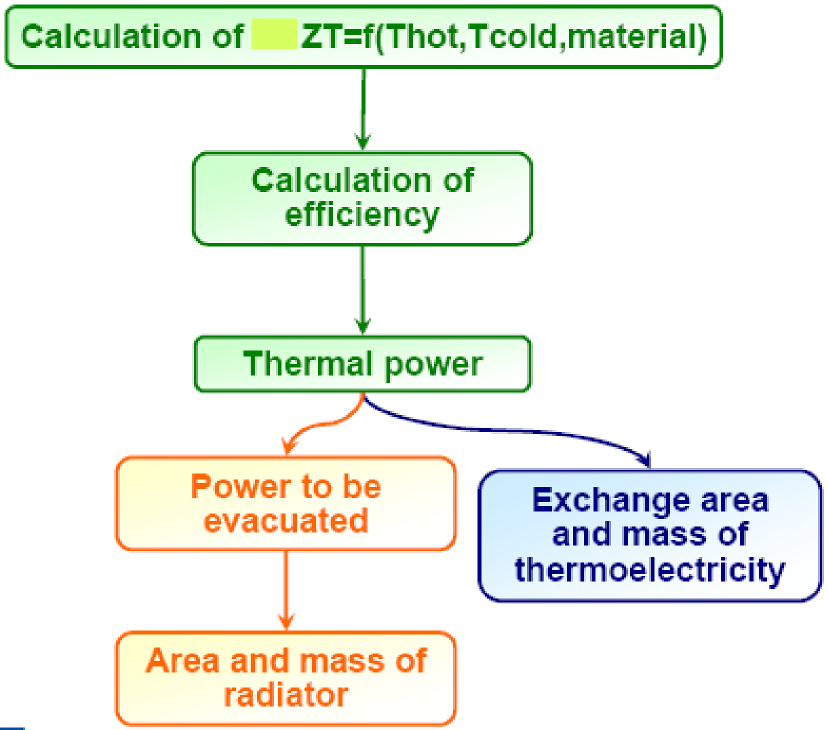
APOLLO 2 CEA code

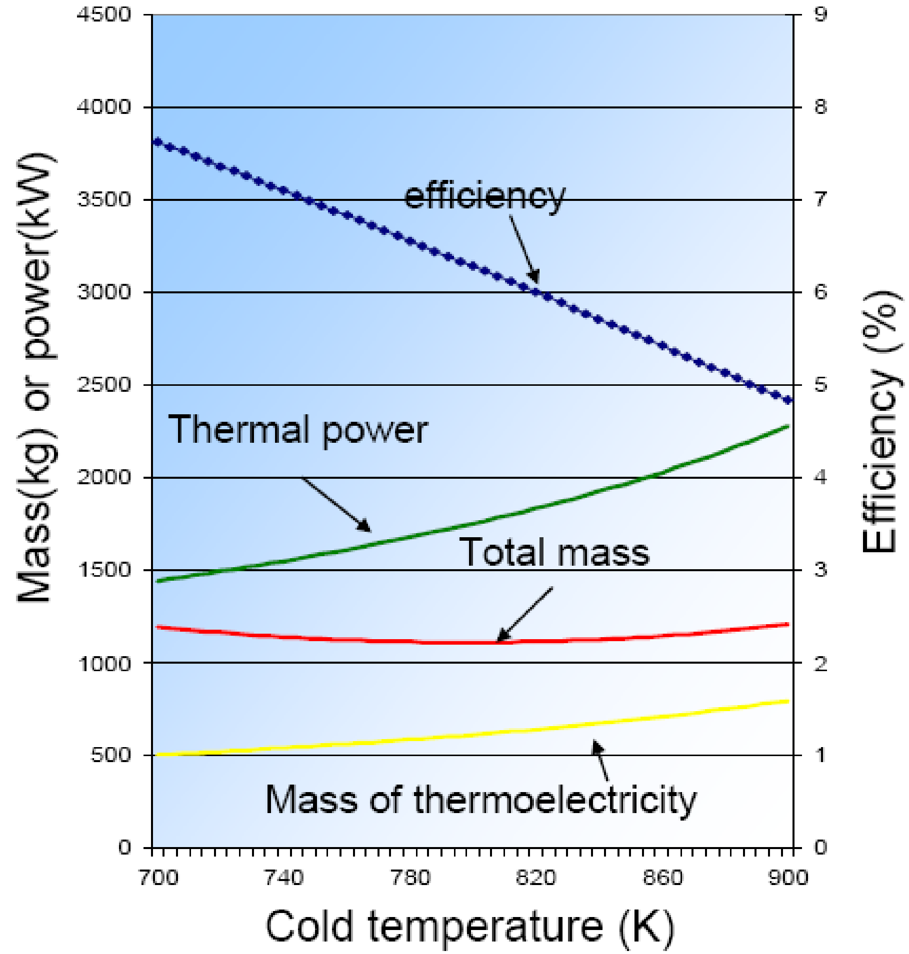


  - Outputs
    - Size
    - Mass
    - Initial reactivity
- Thermal analysis
  - Based on CEA CAST3M code
    - Power distribution in the core
    - Degraded mode studies
  - Outputs :
    - Maximum temperatures
    - Identification of high thermal gradients

Conversion system trade-off for thermoelectric

- Thermoelectric conversion





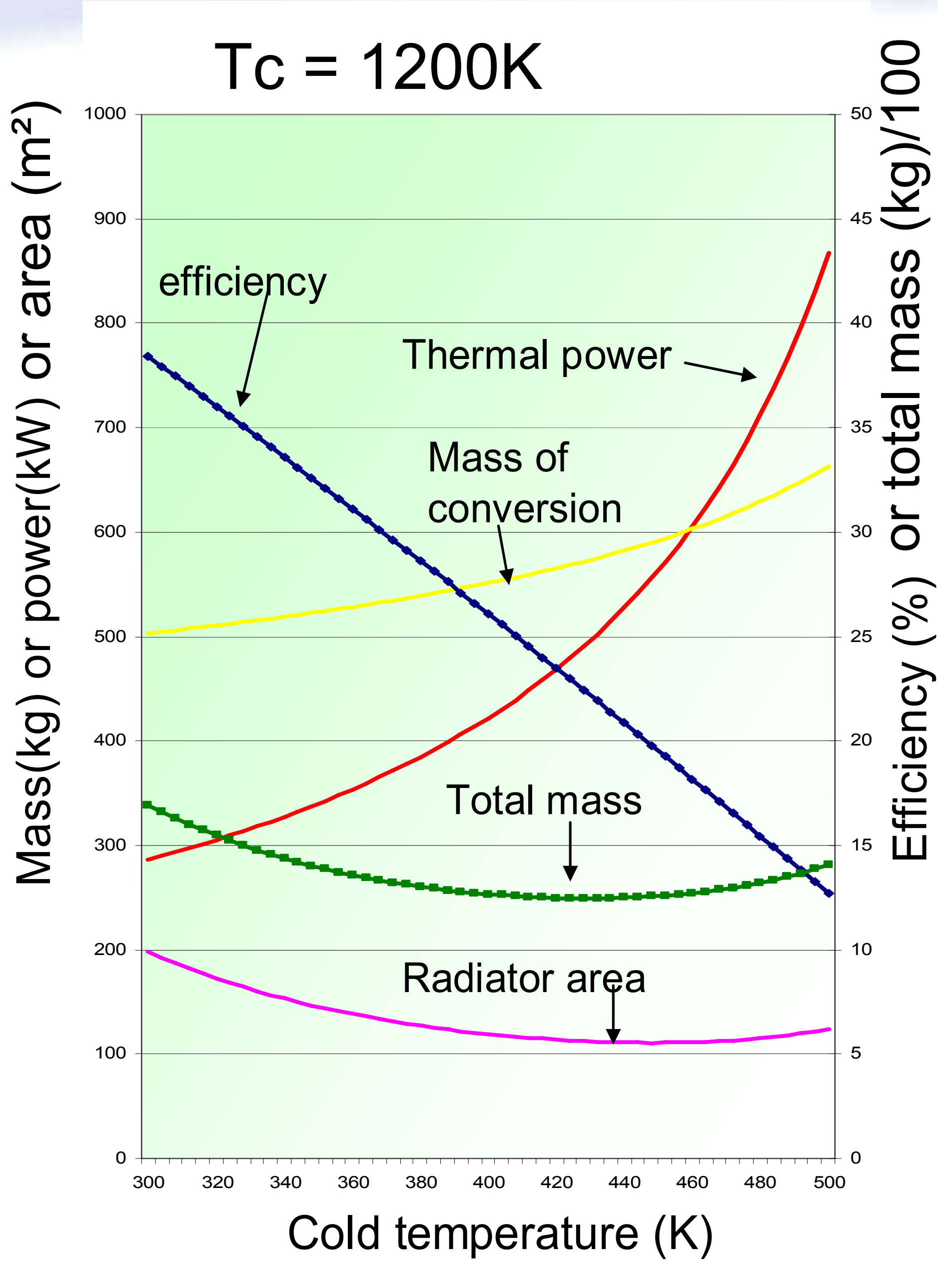
Example of result obtained with simplified model

Radiators : Stefan Boltzman correlations

Various temperature and materials investigated to optimize mass

Conversion system trade-off for Brayton

- Model for cycle based on
  - Perfect gas classic relations
  - Abaqus for main components
- Model for radiators
  - $1/T^3$ law (fluid circulation)
- Allows to estimate impact of operating temperatures on mass

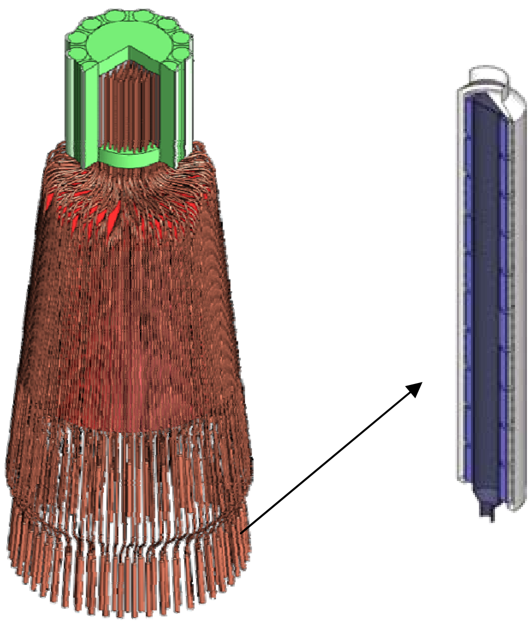


And the winners are..

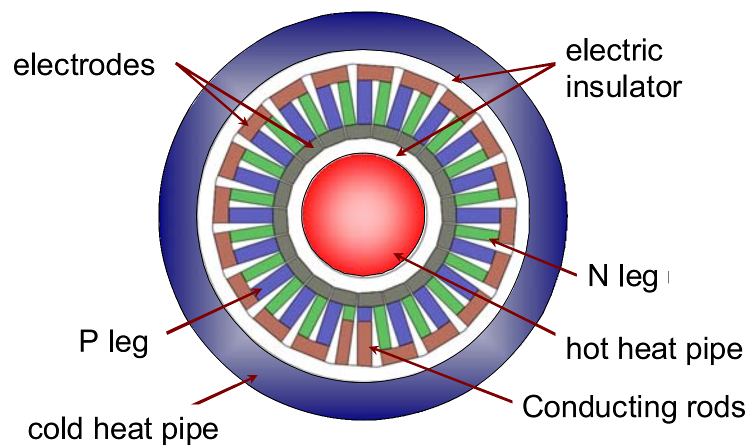
Liquid metal cooled reactor with thermoelectric conversion

- 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



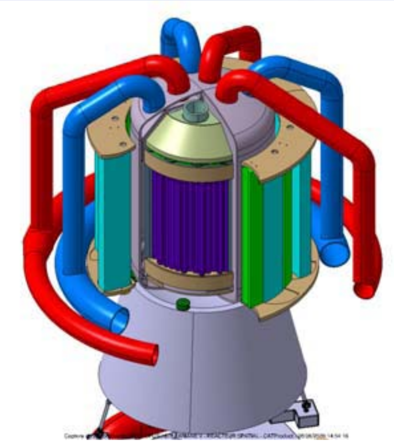
- Conversion :
  - 187 heat pipes x 10 Units of 20 thermoelements (Si-Ge)
  - Optimized leg length
  - Cold heat pipes K

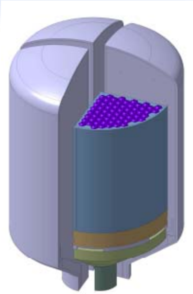


→ reactor + core + conversion : 22.6kg/kW

→ global system mass (including PMAD& miscellaneous) expected around 35 kg/kW

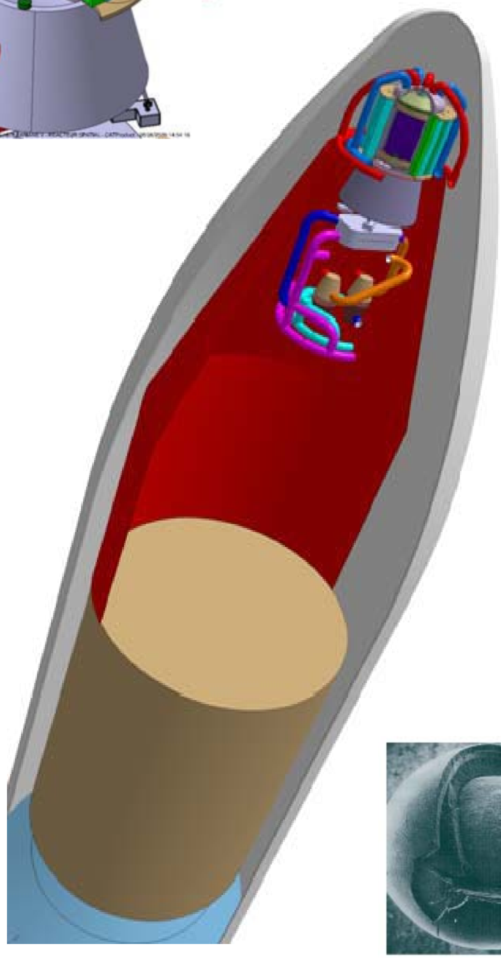
Gas cooled reactor with direct Brayton conversion





- 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

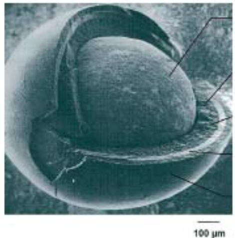
→reactor + core : 16kg/kW



- Conversion
  - 2 turbines+heat exchanger for 100%
  - 2 radiators designed for 50%
  - Heat exchanger for mass optimisation (950K->550K)

→ reactor + core + conversion (including redundancy) : 34kg/kW

→ system mass (including PMAD) expected around 40 kg/kW



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 of such a system
  - 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

Conclusion & perspectives

- This study allowed to evaluate feasibility and performance of a European solution at 100 kWe for mid-term

- Similar specific mass for both concepts between 35-40kg/kW (taking into account large uncertainties)
  - Fully static (TEC) seems better for this power level but has limited growth potential
  - Brayton has a higher growth potential

Other studies on-going :

- Trade-off candidates for high power electric thrusters (under study at SNECMA under CNES contract)

- On-going study for higher power reactors (MW level or more)

- Preparation of a European forum on high power nuclear electric propulsion to identify competencies and cooperation opportunities

- Performance analysis for fast mass transfers to derive requirements for a NEP system
  (2 papers to be published at EUCASS conference in St Petersbourg in July)

Thank you for your attention