Propulsion 2012

Bordeaux

High Power Nuclear Electric Propulsion

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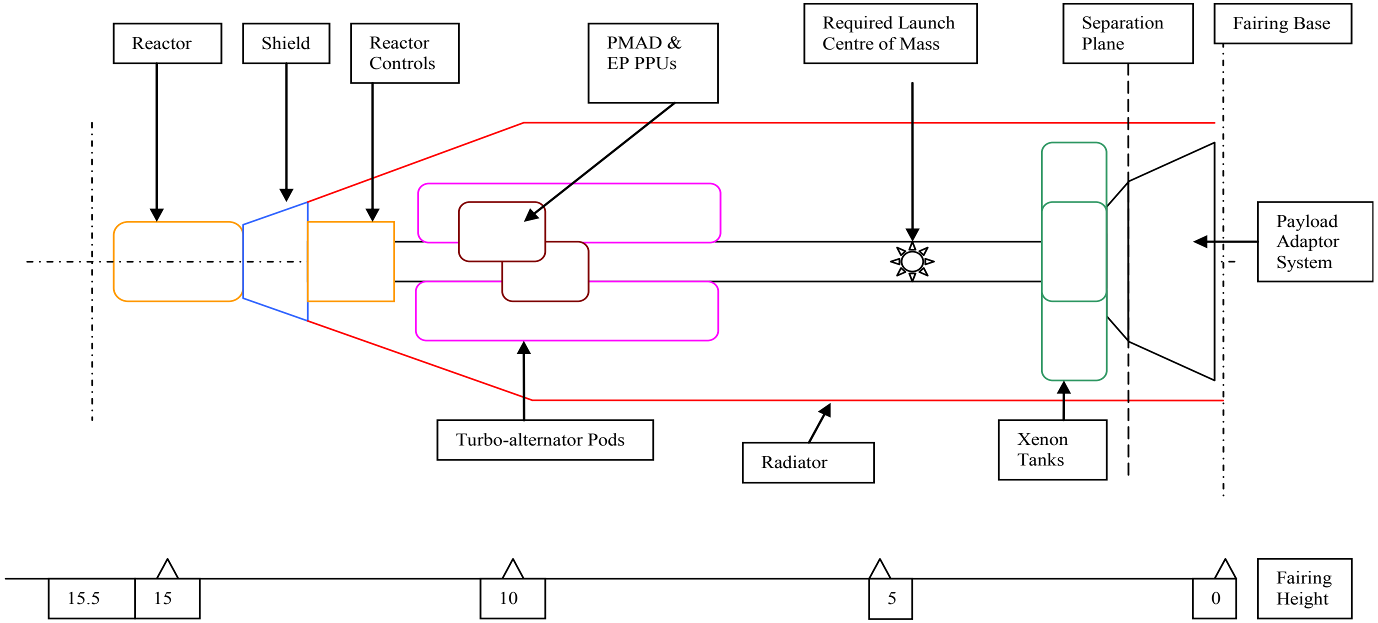
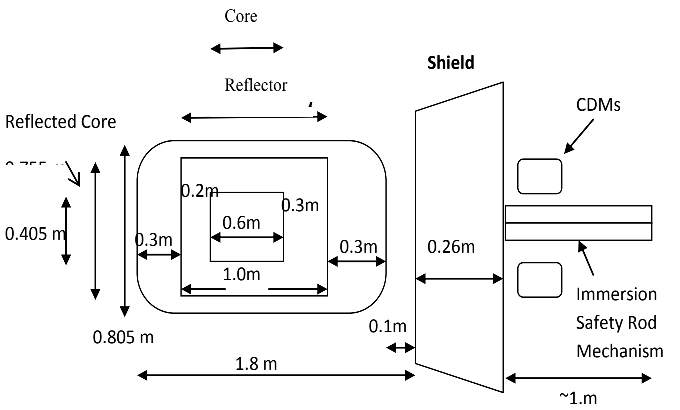
INITIAL ASSUMPTIONS

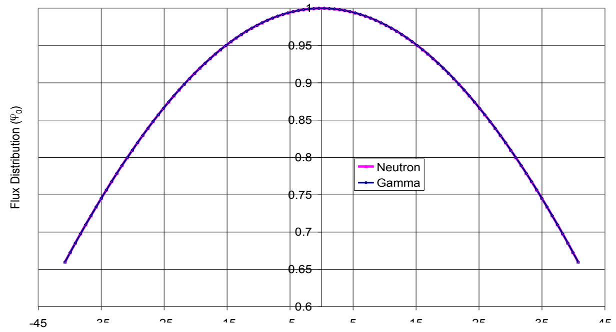
- Compatibility with high power GIE, HET an MPD.
- Compatibility with Ariane 5 ECA fairing and lift capability.
- Specific mass the main design driver – target 25kg/kWe,
- Space tug concept with payload attachment at the end of a 22.5m boom,
- 200 kWe power generation target.
- Either direct cycle gas cooled or indirect fast liquid metal cooled Brayton.

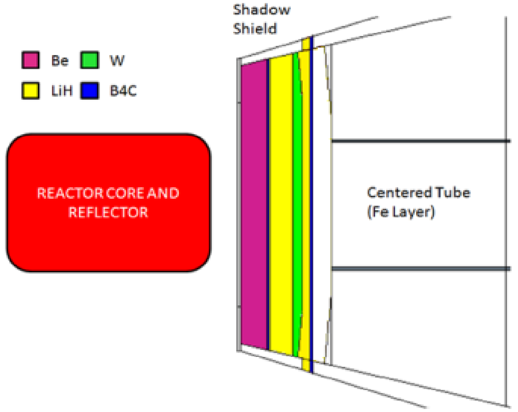


REACTOR SHIELD AND CONTROL SYSTEMS

- Initial design modelling gave excess reactivity for ten year life and met safety requirements (eg water immersion).
- Fuel enriched UO_2 (pins Fast, pellets epi-thermal)
- Dimensions for both fast and epi-thermal reduced ~ 10% with useful mass savings.
- Control mechanism penetration of shield tolerated for mass saving of small gap.
- Neutron and gamma ray flux distribution permits shield shaping for further significant mass savings.
- Shield design using US Government MCNP-MCNPX code gave minimum end of life gamma and neutron dose margin 20%.
- Requirement (from SP100) 1.6 mrad s^{-1} and 31700 n cm^{-2} with 22.5m boom.

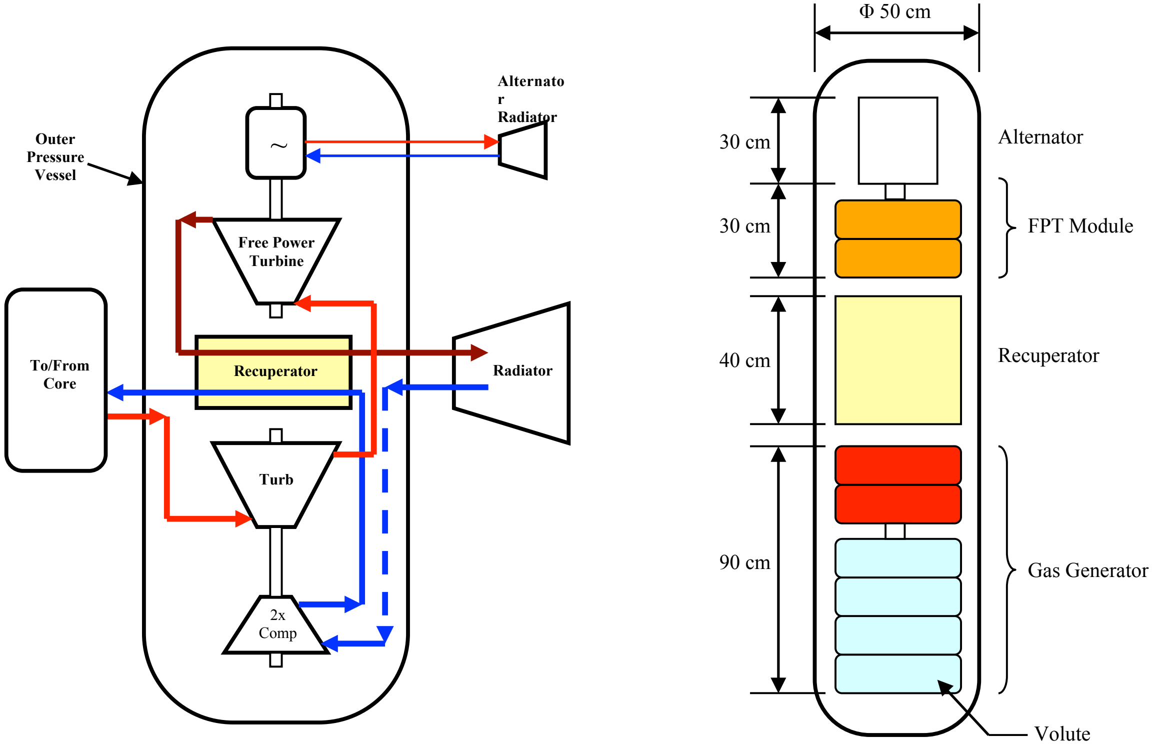






POWER CONVERSION

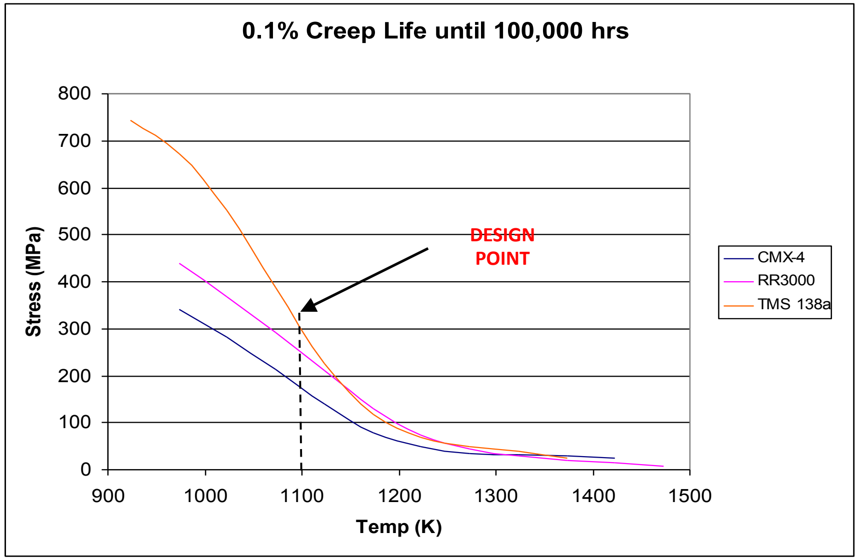
- Brayton radial turbo-alternator optimised for specific mass.
- Indirect cycle (19%) more efficient than direct cycle (17%).
- Smaller radiator but ‘pods’ are larger and greater mass.
- Specific mass driven by radiator size; 300°K increase halves size.
- Temperature limited by creep life of HP turbine materials.
- Separate cooling required for alternator (<470°K).



Example of Direct Cycle Turbo-alternator Arrangement

HIGH TEMPERATURE TURBINES

- *Turbine Inlet Design*. Turbine rotor rather than the guide vanes is the vulnerable. Rotation allows stagnation temperature margin ~80ºK, or higher, permitting the turbine inlet gas temperature to rise to ~1180 to 1300ºK.
- *Turbine Blade Cooling* . Bleed cooler gas from the compressor onto the turbine rotor blades may enable them to remain at up to 200ºK below the inlet gas temperature.
- *Refractory Metal Alloys*. Research into refractory metal alloys shows promise particularly as the working gas on xenon and helium is not oxidising.
- *Ceramic Materials.* Ceramic materials have thermal and creep properties to offer a very high temperature solution but tend to be prone to stress fracture.

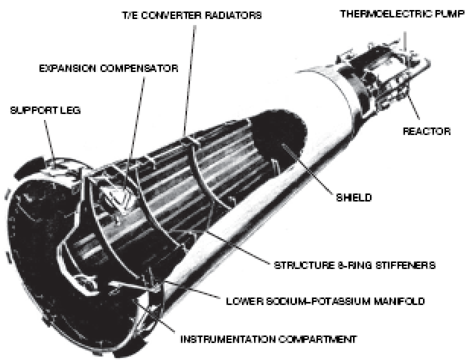


Creep Life Characteristics for Single Crystal Alloys.

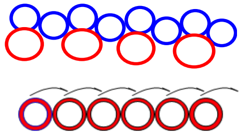
Alternatively it may be worth investigating other emerging terrestrial techniques such as coating alloys with a thin ceramic layer.

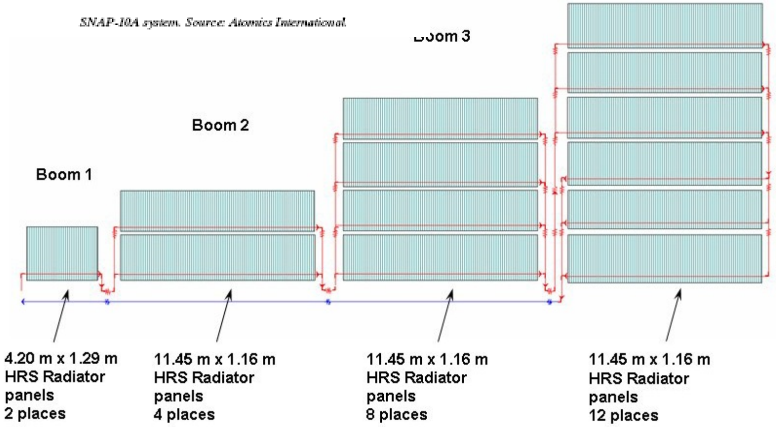
RADIATORS

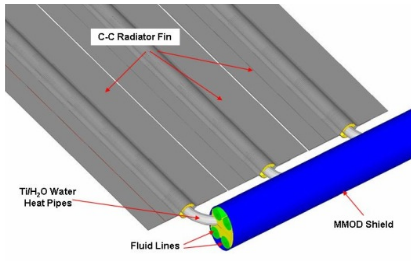
- Fixed radiator. Classical design as illustrated by SNAP10A design.
- More compact and only one (direct) or 2 (indirect) coolant loops. 1300K° turbine inle for area to fit in Ariane 5 fairing.
- Nickel alloys at 8.25 kgm^{-3} may be replaced by carbon at > 2 8.25 kgm^{-3} if helium porosity is solved.
- Micro-meteoroid protection by barrier tubes or shaped fins.
- Deployable radiators. Bigger area but lower temperature operation.
- Require second or third coolant loop and use heat pipes and fins.
- Micro-meteoroid protection from foam.
- Hybrid options may also work.

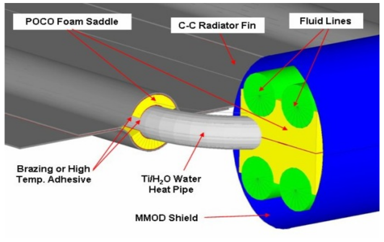


SNAP-10A system. Source: Atomics International.









DESIGN OPTIONS

- Direct and Indirect concept fixed radiator (nickel alloy) designs.
- Add micro-meteoroid protection:
  - Direct area 140m^2,
  - Direct mass 2589 kg
- Carbon tubing with liners reduces mass to ~1245 kg.
- Indirect is only feasible with a deployable radiator

SYSTEM & BASELINE EXAMPLE	**Recuperated Direct Brayton (Epi)**	**Indirect Brayton (Fast)**
T hot, ºK	**1300**	**1200**
Power **MWth** **MWe**	 1.18 0.200	 1.12 0.200
η	0.169	0.175
Reactor Mass kg	**1627** *8.14*	**528** *2.64*
Shield kg	**800** *4.0*	**600** *3.0*
Reactor Control kg	**42.6** *0.21*	**31.1** *0.16*
IHX kg		**366** *1.83*
Generation kg	**1656** *8.28*	**1612** *8.06*
Radiator Area m^2 Mass kg	 **110** **1523** *7.62*	 **128** **1770** *8.85*
Total Mass	**5648**	**4907**
Sp. Mass, kg/kWe	**28.2**	**24.5**

SCALING

- Scaling example 100 kWe to 2 MWe.
- Based on 1500°K ceramic turbine inlet temperature with nickel alloy fixed radiator and micro-meteoroid protection.
- Carbon radiator brings the 200 kWe specific mass ~ 25 kg/kWe operating at a mean temperature ~ 950°K .

T hot, K	**1500**			
Power **MWth** **MWe**	0.592 0.100	0.888 0.150	1.183 0.200	11.83 2.0
η	0.169	0.169	0.169	0.169
Reactor Mass kg	**1226**	**1436**	**1627**	**6468**
Shield kg	**598**	**708**	**800**	**2306**
Reactor Control kg	**33**	**38.3**	**42.6**	**113**
IHX kg				
Generation kg	**1229**	**1449**	**1656**	**7693**
Radiator Area m^2 Mass kg	**40.5** **750**	**60.6** **1098**	**80.8** **1441**	**808** **12768**
Total Mass kg	**3856**	**4729**	**5566**	**29349**
Sp. Mass, kg/kWe	**38.6**	**31.5**	**27.8**	**14.7**

TECHNICAL ROADMAP

- Common to Direct and Indirect Cycle Brayton:
  - Higher turbine inlet temperature (Direct 1300/1500°K, Indirect 1200°K),
  - Turbine efficiency from 85% to 88%,
  - High temperature radiator (from mean ~550 °K to 700 °K or 950 °K,
  - Low mass radiator materials and micro-meteoroid protection,
  - Efficient routing of coolant pipes around the shield and control drive mechanism location and operation.
  - Mass efficient low loss PMAD (thruster location, temperature, AC or DC, battery for commissioning and re-start, load shedding protection, regulation and rectification optimised for whole system, etc.),
  - Emergency shut-down, by-pass function, low-power operation, etc.
- Direct cycle: Higher operating pressure and greater TRISO particle density and control rods in place of drums to reduce size, mass and shadow angle.
- Indirect Cycle: ‘Hot launch’ strategies to reduce mass of power plant to heat reactor and surrounds to an initial operating temperature.

DISRUPTIVE TECHNOLOGIES FOR POWER AND PROPULSION (DiPOP)

- One year study asking why Europe might invest in NEP.
- Considering:
    - Potential applications:
        - Planetary outpost power,
        - High power ground penetrating radars and ice-melting lasers,
        - Long distance high data rate communications,
        - Propulsion for deep space exploration, exploitation or counter NEO threat,
    - How many missions a decade to attract industry?
    - Government motivation: prestige, economic benefit, security?
    - Existing expertise and infrastructure and investment required?
    - How do we win public acceptance and ensure safety?
- Team: Kopoos Consulting, DLR, ISIS_R&D, USTUTT, Kiel Uni, SEP.
- Advisory Board: Europe, Russia US.
- Progress: Draft roadmap, AB Meeting, assessing expertise and infrastructure.
- Deliverables: Roadmap and supporting documentation October 2012.

Rolls-Royce

SPACE ENTERPRISE PARTNERSHIPS

ACTA BEYOND THE RESEARCH

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