Assessment of a 10kWe small reactor system

Elisa Cliquet Moreno, Jean-Marc Ruault*, Jean-Pierre Roux**, Brice Cazale**, Laurent Manifacier***
**CNES Launchers Directorate,*
52 rue Jacques Hillairet, 75612 Paris Cedex, France
*** AREVA TA, Research & Modular Reactors*
CS50497, 13593 Aix en Provence, France

Abstract
This paper addresses the main design options for a reactor system in the 5-10kWe power range. Radioisotope power systems are intrinsically limited by the amount of fuel, which is proportional to the power. Due to several factors such as specific mass increase, limited availability, the high cost of fuel and safety issues, radioisotope power systems producing over 1kWe are unlikely. The nuclear option is then fission-based systems, of which SNAP10, BUK, TOPAZ were the first of their kind. The objective of the study presented in this paper is to assess a small fission reactor in terms of technological options and corresponding levels of performance.

1. Introduction and Rationale

CNES (the French space agency) and AREVA have been leading studies in the past few years on nuclear power generation systems for space exploration missions. Indeed, for some space exploration missions nuclear power is an absolute necessity, since they are either too far from the Sun or exposed to night if on a planet. The goal of these studies is to evaluate technologies that could be relevant for various power levels and to assess their specific mass and readiness levels in France and in Europe. The findings for higher power levels (100kWe and multi-MWe) have been presented previously[2,3]. This paper focuses on lower power levels.

Space missions are currently powered by Radioisotope Power Systems (RPS), from single-watt systems (Russia) to hundreds of watts (USA). The spacecraft with the highest power is Cassini-Huygens with almost 1000We on board. For multi-kWe missions, RPS are probably not the best option since the amount of fuel is directly proportional to the required thermal power. This leads to a limit in terms of achievable minimum specific mass, and it is probable that what has been achieved in the USA represents the best performance we can expect from RPS. This also leads to high costs for the mission, as the radio-isotope is scarce and very expensive. Finally, this raises issues with nuclear safety: regardless of the protective systems in place, the risk increases with the source term.

Over 5kWe, we consider fission-based systems to be mandatory. Fission reactors have flown in the past, mainly on Russian spacecraft (only one flight experiment in the USA). The designs were excellent and varied, with many options explored. Four types of fuel (UC, UMo, UO2, UZrH) were used experimentally for these reactors, as well as two types of conversion – thermoelectric and thermionic.

The question is then: what might a small reactor for the 21st century be? Besides performance, the design trade-off must also consider scalability in order to integrate small reactors within a long term technological road map. Indeed, the effort needed for the development of a reactor for space means that a multiplicity of options is not possible..

2. Trade-off at subsystem level

A trade-off approach is necessary for analyzing the performance of the system. Each subsystem option is assessed independently and performance is then consolidated at system level. The subsystems assessed are:

- the reactor
- the shield
- the balance of plant

Other components, such as power management and distribution system, structure, instrumentation and control, have not been assessed.

2.1 Reactor

UO2 was selected for the fuel because of its availability and the wide pre-existing operational experience. UMo allows more compact cores (see NASA-DOE study [4] or the flight-proven Russian reactor BUK) but it was not considered on account of a lack of operational experience in France and Europe.
The first question regarding the reactor is the spectrum, fast or thermal. Previous studies <1> carried out under ESA contract (LuNPS-FPS) have shown that thermal reactors are more attractive in terms of critical diameter and mass. For example, the figure below shows a critical diameter of 32cm for a fast neutron reactor with a Beryllium reflector (red triangle), while the diameter is limited to roughly 22cm for a moderated reactor (blue triangles, also with a Beryllium reflector).

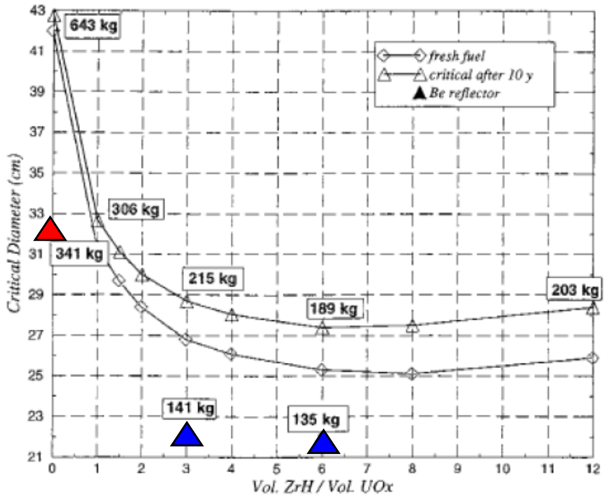

Figure 1: LuNPS-FPS by AREVA: concept (left)– Critical diameter vs moderator (right)

However, the operating temperature of thermal reactors is limited by the moderator. So, if high temperature is required, the only option is the fast reactor. It is heavier but has the advantage of low core wear (-70 pcm/GWd/t).
The fuel configuration selected for the trade-off phase consists of hexagonal fuel elements, based on the rods or pins developed in France for fast reactors. The reactor is cooled by liquid metal heat pipes. Indeed, at this power range, heat pipes are the best option: the power per pipe is reasonable and a completely passive, simple device is preferred to pumps even if the latter are electromagnetic. The preliminary assumption for the fuel elements is shown in Figure 2. Their manufacture has not been addressed at this stage, nor thermal analysis. Deeper analysis is necessary.

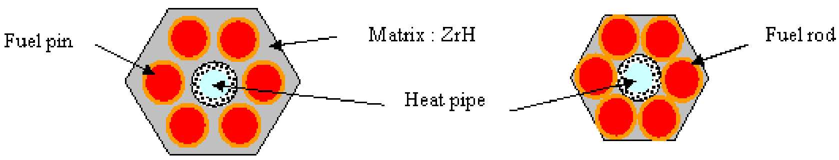

Figure 2: Fuel configuration: thermal on left (vol ZrH/vol UO2=2), fast on right

A neutronic model for the fast neutron option, based around an orthocylindrical core, has been completed. This model confirms previous studies and refines some parameters. The reactivity margin is only 4300pcm roughly for a core diameter of 33cm with a 10cm reflector. Thus, in order to have sufficient reactivity margin, this leads to a Beryllium reflector thickness of 8cm minimum. The mass of the reactor has been calculated on this basis. It gives from 178kg for a thermal reactor (25cm in diameter) to 250kg (40cm in diameter), and 340kg to 365kg for a fast neutron reactor (32 cm in diameter) depending on the cladding materials.
The reactivity control system has not been designed. At this stage of the trade-off, it is considered to be included in the reflector mass (i.e. moving parts such as drums, shutters, or a sliding reflector), and different options should not have a significant impact on the assessment.

2.2 Shielding

The shield has a conical shape. The material options are conventional: LiH for neutrons and tungsten for gamma protection. From previous studies [1], a density of 1.89 was assumed and the following simple model for neutron attenuation was used:

$$\phi_{OUT} = \phi_{IN} \times e^{-kx} \quad \text{where x is the thickness of the shield} \qquad \textbf{(1)}$$

This model, consistent with previous studies [1,2], is satisfactory for a trade-off but it gives values slightly higher than the Russian reactors and those in the literature, notably [4]. The comparison is not easy since many parameters drive the shield mass. Whatever the accuracy of the model, the objective is to carry out a parametric analysis. This analysis has been performed, with assumptions as to the reactor geometry (H/D), permissible flux (1011 or 1012 n/cm^2), the boom length, and the diameter of the protected area.

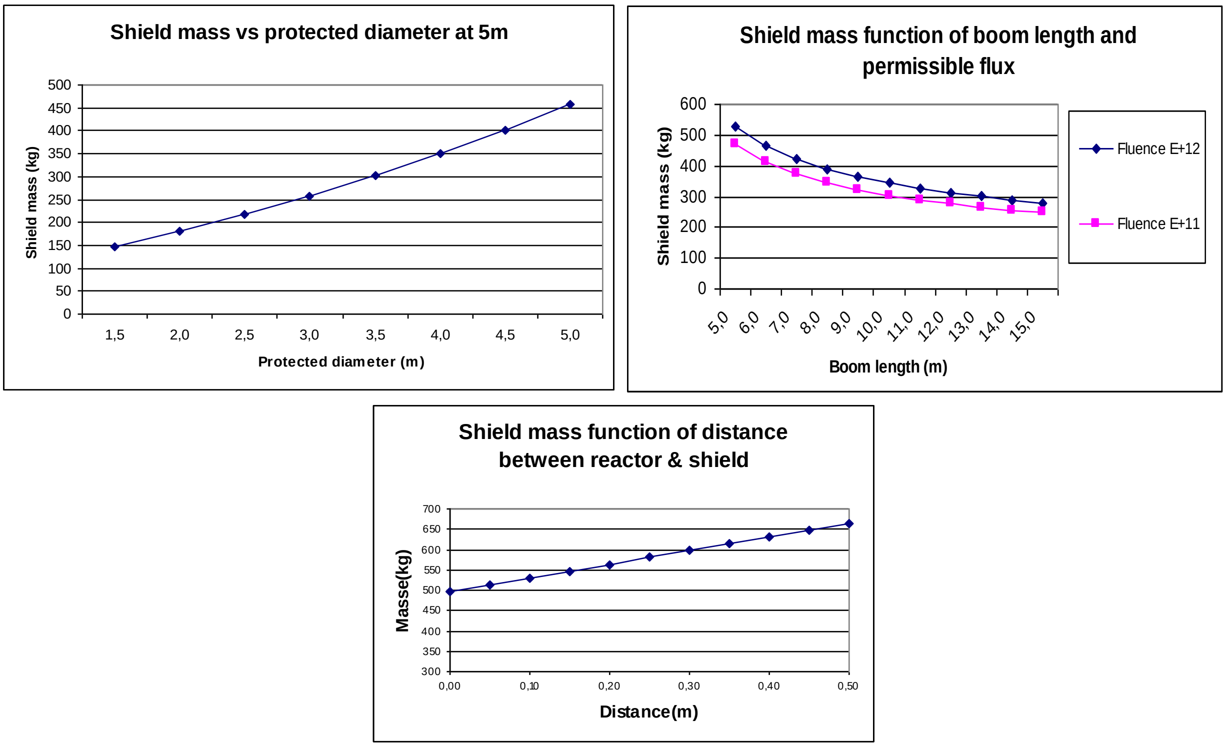

Figure 3: Shield mass assessment

One conclusion is that the main shield mass driver is the geometry of the spacecraft. Indeed, while, on the one hand, protection of a large area is very costly in mass, on the other hand, reducing the distance between shielding and payload can save a significant mass, as shown in figure 3. Neutron fluence has less of an effect.

2.3 Balance of plant

The balance of plant is a critical issue. By balance of plant we mean the thermal to electric power conversion system, including the cold source. Many technological options have been examined, but the options finally selected are standard: thermoelectricity, Stirling cycle machines and Brayton cycle machines. Thermionic generation has been discarded because of the lack of technology in Europe, where R&D stopped about 20 years ago. Other options such as thermophotovoltaics are not considered mature enough.

The Rankine cycle could be considered as a good candidate, but its feasibility is too uncertain. Managing a two-phase flow cycle in microgravity is possible, but this would require a number of devices, lowering the system robustness and making the operations very complex.

Thermoelectricity has the advantage of being passive, without moving parts. Despite its low efficiency, it has been considered as a very good candidate at this low power range where, regardless of the efficiency, the rejected heat remains low. It has been assessed by existing models at medium temperature (850K) for which a solution is available in France (MgSi-MnSi), and high temperature (1100 to 1300K) based on SiGe. The mass assessment is based on a draft design, where the radiators are based on heat pipes.

Assessment of the Stirling generator is based on American data, since no Stirling generator is currently available in Europe. Efficiency was taken to be 50% of Carnot, which is conservative. The design is based on the NASA-DOE study [4] and mass assessment is based on projections of the study [5] of the Space Research Institute. The hot temperature is 850K for the baseline, then 1100K. An operating temperature of 850K was used to allow coupling with a thermal reactor. The 1100K case, closer to ASRG US technology, needs a fast reactor. The radiator is also based on heat pipes.

A Brayton loop has also been modeled, though with significant uncertainties due to the lack of experimental data. A first assessment has been carried out on the basis of a preliminary design. The turbine temperature is taken to be 1300K, and the radiator is a direct circulation type. The uncertainties are more significant for the balance of plant based on the Brayton cycle than for the other technologies where experience or data are available. However it is considered relevant at this stage in the trade-off process.

All models provide the specific mass and efficiency functions of the cold source temperature, then the optimum operating point of the conversion subsystem. The results of the assessment are given in Figure 4 below. The figures relate to the draft design of each conversion system, and are probably not optimized. A more accurate design could give different figures. Consequently these figures are to be taken as orders of magnitude only, and the analysis must consider them as relative, rather than absolute, values.

A Stirling machine at 850K and medium temperature thermoelectric converters appear to have the same specific mass. The best specific mass is attained using high temperature technologies, which is to be expected. Thermoelectric conversion at 1300K appears to have the best specific mass, but at this temperature Brayton also seems to be an attractive option. The specific mass of the Stirling machine at 1100K appears to be close to that for Brayton.

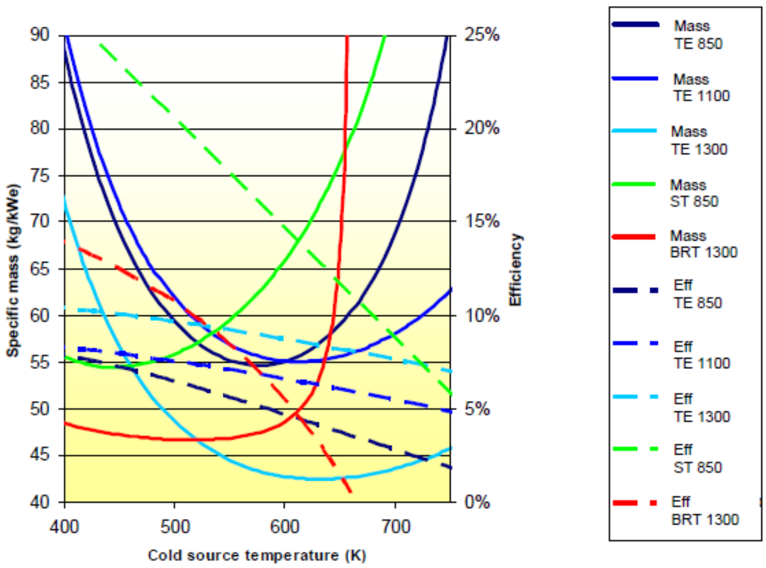

Figure 4: Balance of plant assessment (at 5kWe)

3. Trade-off at system level

The overall system performance is assessed on the basis of the subsystems' figures. Performance of the balance of plant is integrated with reactor and shielding, whose mass will depend on the temperature (fast or thermal spectrum) and the thermal power needed, with due regard to the conversion efficiency. PMADs which have not been modeled have been set at 100kg. I&C is taken to be 75kg for thermoelectrics, and 150kg for Stirling and Brayton, which are significantly more difficult to control (starting sequence, synchronization, redundancy, etc.). Brayton needs to be equipped with a starter, which adds a mass penalty. Structure and margin are fixed at 20% of the calculated mass. These assumptions are entirely approximate, but it is assumed that they are not so important at the trade-off stage, whose purpose is to compare the different options.

Several cases are calculated, with different assumptions relating to the geometry of the system (boom length, protected area), in order to assess the sensitivity of these parameters within the options selected.

3.1 Baseline

The first case is a 5m boom, i.e. where the payload is directly mounted after the conversion system (the conversion system is assumed to need about 5 meters behind the shielding). This is the most compact monolithic option (the boom is fixed, and there is no deployable structure). The diameter of the area protected at 5m behind the shielding is 2m.

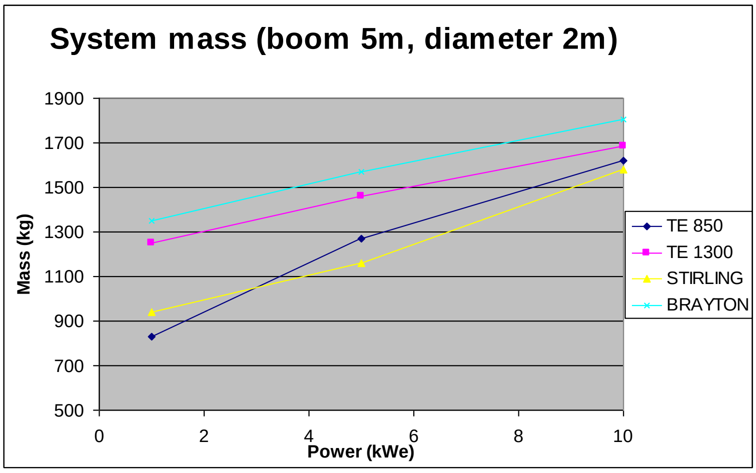

Figure 5: System mass - Baseline

The Stirling machine is the most attractive, and has the advantage of good efficiency when coupled with a thermal reactor. At 10kWe, 1300K thermoelectric generation becomes competitive. A 1100K Stirling based system has been assessed, with a mass close to, but slightly greater than, the 850K case: the penalty due to the higher mass of the fast reactor is partially balanced by the better conversion efficiency.

To assess the impact of the spacecraft geometry, two other cases have been studied. The order has not been changed, but if a large protected area is needed, then the thermal spectrum option is clearly the best candidate. Indeed if the performances of 1300K thermoelectric generation and 850K Stirling were equivalent for the baseline case, then with a large protected area, the thermoelectric option is no more competitive.

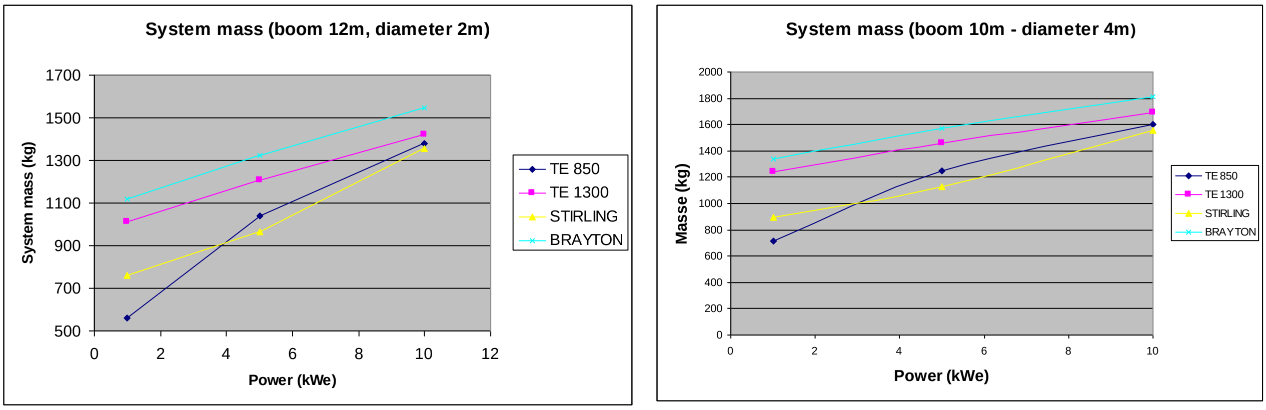

Figure 6: System mass –effect of boom and protected area

4. Conclusion

This study gives orders of magnitude for the performance of the candidate technologies for a space fission power system within the range from 1kWe to 10kWe. Our conclusions are:

- spacecraft geometry is a significant parameter for system optimization, and should also be taken into consideration for the selection of the system technology,
- The Stirling option is attractive, especially when using a thermal reactor. Brayton is less attractive in this power range, and the Stirling machine's nearest competitor is thermoelectric generation.

Besides the system performance, a road map towards higher power systems must be considered. This leads us to consider the Stirling as also being useful for radioisotope power systems and to conclude that high temperature fast reactors will be unavoidable for the higher power ranges. Hence we recommend selection of a Stirling system coupled with a fast reactor technology rather than a thermal reactor. The mass penalty incurred by this choice at 10kWe is insufficiently great to lead to the selection of a thermal spectrum which would be used only in this power range.

A draft design of the complete system, as illustrated below, has been completed. The option is not a conventional Stirling machine, in which pistons are a disadvantage, but rather a Stirling-based thermoacoustic system.

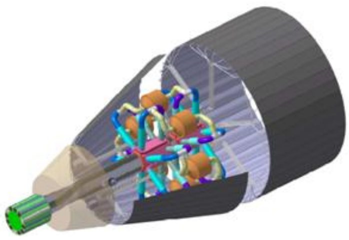

Figure 7: Draft design

Acknowledgments

This study was carried out by AREVA TA in Aix-en-Provence, under funding from CNES and AREVA.

References

[1] X.Masson, Future Power System, Derivation of parametric models – TA22612A – 2001
[2] E.Cliquet, JM.Ruault, JP.Roux, L.Lamoine, T.Ramee², A.Lokhov, C.Poinot Salanon, S.Pascal, Study of a 100kWe space reactor for exploration missions, Space propulsion 2010
[3] E.Cliquet, JM.Ruault, JP.Roux, N.Paris, B.Cazalé, Study of a Megawatt level power generation system for exploration missions, Nuclear and Emerging Technologies for Space 2012, The woodlands, Texas

[4] Lee Mason et al., A Small Fission Power System for NASA Planetary Science Missions, Nuclear and Emerging Technologies for Space 2011, Albuquerque, New Mexico
[5] Henry W. Brandhorst, Jr., New 5 Kilowatt Free-Piston Stirling Space Convertor Developments, Nuclear and Emerging Technologies for Space 2011, Albuquerque, New Mexico