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A new HTGR design for Interplanetary Space Applications

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ABSTRACT

A preliminary feasibility study of a high temperature nuclear fission reactor for space applications is here presented with the following requirements: high reliability, R&D program of moderate cost, development in a reasonable period of time, 10 years without human intervention operability and controllability, terrestrial applicability, or at least common technology sharing, applicability for human settlements on a solar system planet. The driving idea is to extend as much as possible the HTGR technology, nowadays under development on Earth and able to produce high power levels in terrestrial applications, to the design of a reactor suited for space conditions. Two different options are evaluated for the electricity production: a Brayton cycle and a Thermoelectric conversion device. The neutronics calculation is based on WIMS code benchmarked with MCNP code. The resulting system appears viable and of reasonable size, well fit to the present space launchers capabilities. Finally, a set of R&D needs has been identified for some critical components and system research plan interesting the new high temperature gas reactor is proposed.

Introduction

Near future space exploration programs will require power systems able to provide hundreds of KWe[1,2]. Fission power systems seem to be well suited to provide safe, reliable, and economic power within this range. The goal of this research program, developed within an ESA research contract, is to carry out a preliminary feasibility study of a nuclear fission reactor for space applications. These refer to electrical power production to feed either the electric engines on board of a spacecraft mainly (Nuclear Electric Propulsion, NEP) or stationary settlements, manned or unmanned, on planets or satellites of the Solar system.

Main requirements for the design of the reactor are: the extreme reliability, the moderate cost R&D program, the implementation within a reasonable period of time and the long time operability without intervention.

The first three items mean that the chosen reactor must be already extensively and positively used or tested in terrestrial applications, and then too innovative proposals are a priori excluded, at least in the medium range time. The last item too is in favour of simple and reliable solutions.

Moreover it seems reasonable and probable to apply some technologies here suggested for space to terrestrial nuclear and non-nuclear systems.
In conclusion the reactor here proposed should be based on the under study technology for terrestrial reactors and in principle suitable for propulsion and stationary applications.
Specific requirements, besides the general ones presented above, are:

- electrical power around 100 KW;
- operating life time of around 4000 days, without intervention and fuel supply;
- minimal overall mass and volume;
- high enriched uranium fuel;
- low core power density substantially lower than nowadays reactors;
- no leakage of fluids or presence of a recovery system.

Usual safety requirements for terrestrial reactors are to be adopted, able also to assure no irradiated fuel at launch; core subcriticality in case of launch abort (flooding); radiation protection without impairing mass requirements; easy decommissioning in space.
The reactor considered in this study is an HTGR.
As known the High Temperature Gas reactor, HTGR, is adopted for producing high powers in terrestrial applications and widely considered for nuclear thermal propulsion for its unique capability of using Brayton cycle and its extreme reliability[3].

The HTGR Design

The most significant modifications to be drawn to a terrestrial HTGR to make it fit to space applications are listed below.
Fuel composition adopted is conventional 93% enriched powder of uranium oxide, sintered in micro spheres. Fuel micro sphere diameter chosen is 350 µm. The fuel micro spheres are protected by four carbon based layers: a low density pyrolitic carbon buffer, high density inner pyrolitic carbon layer, silicon carbide layer, high density, outer pyrolitic carbon layer that are the cladding material. The overall thickness is assumed equal to 400 µm. For the neutronic calculations the layers are assumed to be equal to pure graphite (density 1800 kg/m^3). Overall micro sphere diameter turns out to be 750 µm.
The micro spheres are mixed with a graphite powder and then compacted to form an hexagonal rod or *compact* having the apothem of 4.1 mm, while the length is that of the reactor height and then it is the result of the neutronic calculations to define the core size. Taking into account the graphite layers of the fuel micro spheres and the graphite powder, the overall uranium oxide volume content in the compact is 9.4 %.
The moderator is graphite under the form of hexagonal blocks having the same length of the reactor height. The blocks have an apothem that depends on the moderation ratio. The blocks are drilled by two types of hexagonal holes: six of them are for the compacts and one for the coolant. The six are symmetrically located in the hexagon, while the coolant one is located in the centre as shown in Fig. 1. The blocks are then assembled together to form the reactor core. The moderator is then made by these blocks and by the graphite already in the compacts.
Fuel burnup has an average value of 100 MWd/kg. Temperatures and pressures: the maximum reactor temperature at the outlet is a parameter of paramount importance both for the thermodynamic efficiency and for the technological constrains of the system. A reasonable and well-experienced value is 800 °C, however the several designs for terrestrial reactors now under development foresee higher values up to 900 °C and beyond. In this study the value of 900 °C has then been adopted. For the time being the minimum pressure has been assumed a rather usual value equal to 3 Mpa[4], while the maximum one depends on the optimum compression ratio (1.6 in the chosen cycle, giving a maximum pressure of 4.8 MPa).
Cold well temperature definitions imply a preliminary optimisation in order to minimize the overall mass as lower

temperature means higher efficiencies, but higher cold well size. Electrical generator has been chosen among [two alternate designs thermoelectric generator, and Brayton cycle. Core geometry and reflector: the core height to diameter ratio is 1; it is rounded by a 12 cm thick radial reflector.

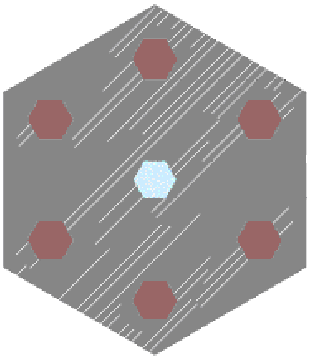


Figure1 - hexagonal block of graphite

Minimum fuel quantity: set the thermal power, the burnup, the full power duration (4000 days), we obtain for the thermal powers the minimum fuel masses: 85.76 kg for the themoelecric reactor and 16.68 kg for the brayton one. The possibility to adopt the minimum masses however, is strictly connected to the reactor neutronic design. In fact, the small size of these reactors, roughly two orders of magnitude lower than those of conventional HTGRs, implies big fractions of escaping neutrons from the core surface. Present calculations show that these minimum masses are not enough for 93% enriched fuel to satisfy the imposed fuel life, unless a rather thick reflector is adopted (see below). This means that the maximum fuel burnup is lower and this can be positive for a better fuel performance.
Two reactors have been designed in this work a Brayton 417 KWth HTGR and a Thermoelectric 2144 KWth HTGR.

Core neutronic design

The neutronic design has been realized using the deterministic code Winfrith Improved Multi group Scheme, WIMS[5,6].
WIMS gives the reactivity in an infinite mean: to obtain the reactivity of a finite reactor, the value of axial and radial buckling, which is a crucial parameter in this small size reactor, is required[7]. Because of the strong dependence of the effective multiplication from the buckling values, WIMS. results were compared with a Monte Carlo program, MCNP-4C[8], known as an exact program. The comparison was made in four specific points and namely: infinite lattice and actual reflected reactor at Beginning of Life, cold and hot conditions, different moderation ratio. Monte Carlo results show that WIMS should converge at the End of Life to a reactivity of 1.00 with a reasonable margin of 0.73 $.
The Monte Carlo MCNP-4C and WIMS k_∞ values, versus moderation ratio from 1 to 20, both in cold and hot conditions, have been obtained. The differences between the values obtained is shown in figure 2

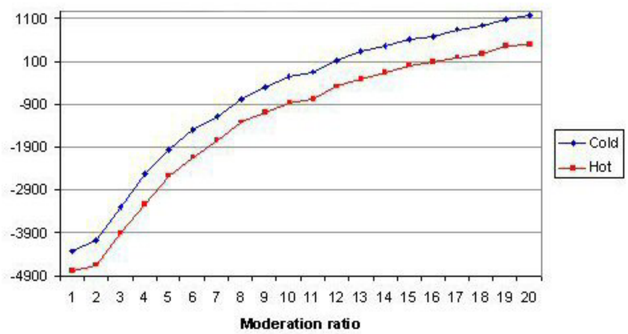


Figure 2 - Delta k_∞ MCNP-4C/WIMS

From these first results it is clear that WIMS shows a reasonable agreement with the *exact* Monte Carlo program, in spite of being applied outside of its range of validity both in terms of enrichment and compact size.
The Monte Carlo k_{eff} values, versus moderation ratio from 7 to 11 (which is the range of the foreseen solution), are shown in figure 3. These results have been obtained for a 100 kg-fuel reactor. The data presented refer to both the 2144 and the 417 KW core.
The WIMS k_{eff} values, versus moderation ratio from 7 to 11, are shown in figure 4.
The MCNP-4C/WIMS k_{eff} difference is detailed in figure 5.

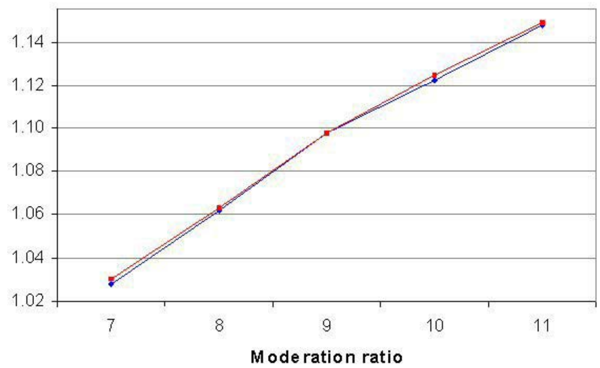


Figure 3 - k_{eff} values obtained by MCNP-4C

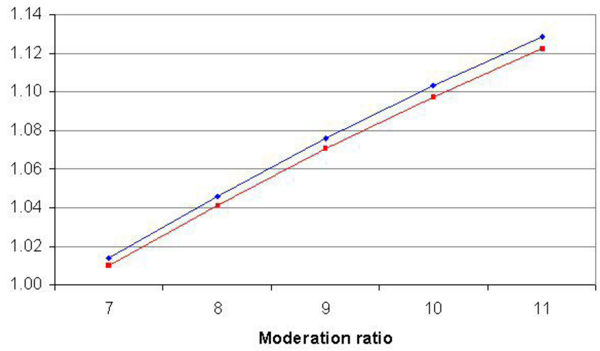


Figure 4 - k_{eff} values obtained by WIMS

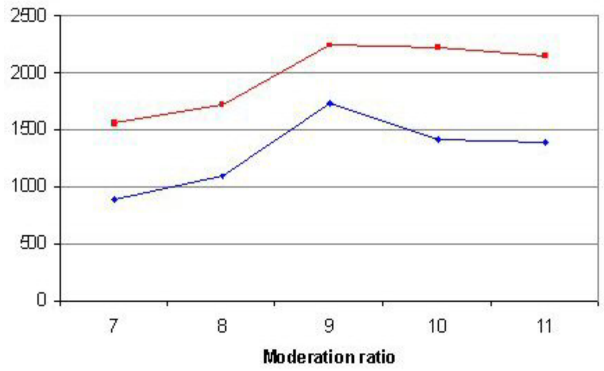


Figure 5 - Delta k_{eff} MCNP-4C/WIMS

The k_{eff} is calculated for both powers with 100 kg of fuel, the core k_{eff} at BOL does not depend on power but only on the moderation ratio, this is the reason why this result is valid for both reactors

In conclusion, in these particular conditions the WIMS program can be judged sufficiently reliable for the goals of this feasibility study.

Present calculations show that the minimum mass calculated is not enough for the 417 KWth core, to satisfy the imposed fuel life. Furthermore, neutronic calculations have also shown that the optimum fuel quantity to minimize the overall reactor mass is equal to 100 kg in both cases.

The moderation ratio to satisfy these requirements are 7.5 for the 417 KW reactor and 9 for the 2144 reactor.

Brayton Gas Reactor

The core of the 417 KWth reactor is composed by 281 hexagonal graphite blocks. Each block is drilled with a central hole of 40 mm radius surrounded by six holes for the fuel compacts. The core is surrounded by a 120 mm thick reflector.

Figure 6 shows that the constrain to have a reactivity of 1.00 at the End of Life is satisfied choosing a moderation ratio of 7.5 for the 417 KWth reactor. Regulation of the neutron flux during the 10 years reactor life will be performed with control drums, made of a neutron absorber in a portion of the drum and of a neutron reflecting material in the other portion. They will be placed into the radial reflector region to limit their high temperature exposure; a first attempt to develop this control strategy shows that a large number of drums are needed and that an optimization of the core is required to perform the reactivity control with a reasonable margin.

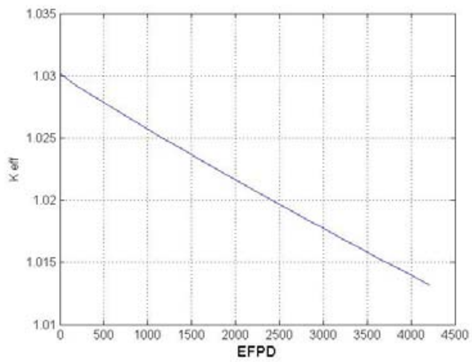


Figure 6 - K-effective 417 KWth Reactor

The reactor vessel is a cylinder with hemispherical domes.
Reactor dimentions are shown in table 1.
Stainless steel SA 508, Tp.3, Cl.2, with an allowable stress of 205 MPa, has been considered as vessel material for a preliminary design. An insulated vessel design or a vessel cooling by helium returning from the power conversion system is needed[9]. Setting the design pressure of the primary system equal to the operating one multiplied a factor 1.1, which takes into account the value of the safety valve setting, a thickness of 12 mm, for the brayton reactor, and 13 mm for the thermoelectric one, for the cylindrical region and a value of 6.5 mm for the first and 6 mm for the second, for the domes have been obtained.
A simplified but sufficiently reliable calculation program for the Brayton cycle has been implemented and applied to the following input data:

- Outlet reactor temperature: 900 °C;
- Minimum cold well temperature: 135 °C;
- Turbine efficiency: 0.80;
- Compressor efficiency: 0.80;
- Regenerator efficiency: 0.95;
- Minimum pressure: 3 MPa;
- Pressure drops over fluid pressure ($\Delta p/p$) in reactor, cold well, regenerator (two sides): 0.01.

The conceptual layout of this reactor is shown in figure 7, its data are detailed in figure 8.

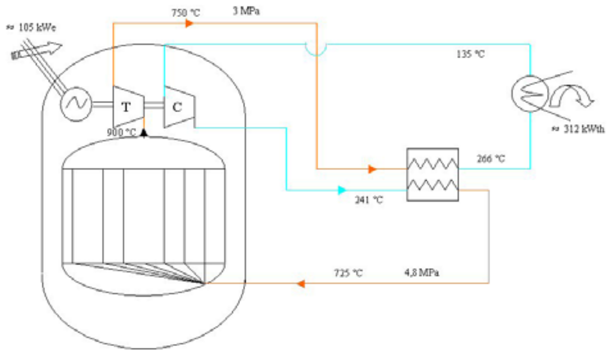
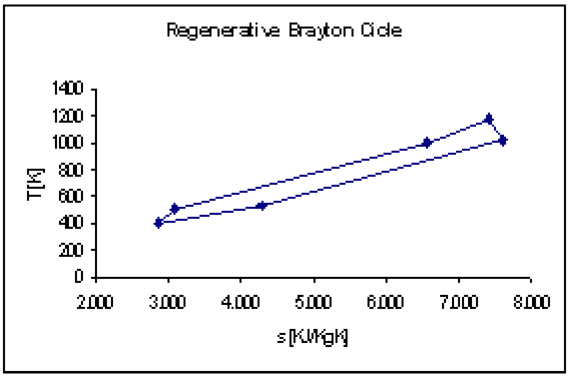


Figure 7 - Conceptual Layout for the Brayton reactor

The gross efficiency is 25.36 %, which, for auxiliary systems absorption of about 5 KW, gives a net value of 24.1 % rounded to 24 %. Then the thermal power of the reactor is 417 KW.
The cold well with the above efficiency must dissipate (417- 100) = 317 KW.
The primary system adopts semi-integrated solution, where the rotating machines are put inside the pressure vessel. The turbine, the compressor and the alternator are integrated inside the pressure vessel in order to recuperate the small gas leakage from the turbomachines and to cool the pressure vessel walls by a relatively cold gas.



FFigure 8 - Brayton cycle

Thermoelectric reactor

The core of the 2114 KWth reactor is composed by 265 hexagonal graphite blocks. Each block is drilled with a central hole of 4 mm radius surrounded by six holes for the fuel compacts. The core is surrounded by a 120 mm thick reflector.
Figure 9 shows that the constrain to have a reactivity of 1.00 at the End of Life is satisfied choosing a moderation ratio of 9 for the 2144 KWth reactor. Regulation of the neutron flux during the 10 years reactor life is performed also in this case with control drums made of a neutron absorber in a portion of the drum and of a neutron reflecting material in the other portion They will be placed into the radial reflector region to limit their high temperature exposure; a first attempt to develop this control strategy shows that a large number of drums are needed and

that an optimization of the core is required to perform the reactivity control with a reasonable margin.

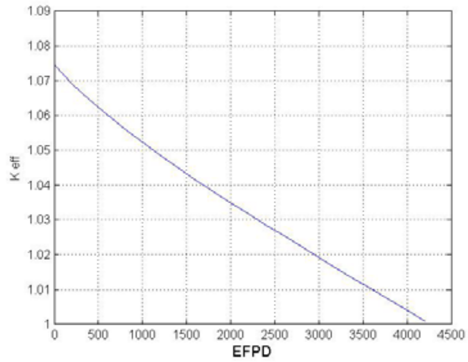


Figure 9 - K-effective 2144 KWth Reactor

The reactor vessel is a cylinder with hemispherical domes.
The reactor dimensions are shown in table 1.
The conceptual layout of this reactor is shown in figure 10.
The primary circuit of Thermoelectric reactor is semi-integral: the reactor vessel contains the reactor core, the compressor, the motor, the reactivity control mechanism and the instrumentation the Thermoelectric cells are bonded to hot pipes linked to the core.
The materials chosen for the vessel are the same that Brayton reactor.

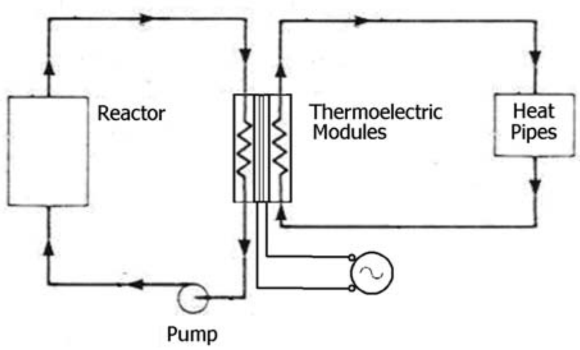


Figure 10 – Conceptual Layout for the thermoelectric reactor

Thermoelectric devices were considered as converters because of their extreme reliability, high portability and small size[10]. They are static elements, generally composed by semiconductors that using the Seebeck effect, due to the material properties and the temperature gradient, produce electric power. In order to produce 100 KWe, 10000 thermoelectric cells are needed.
The dimensionless thermoelectric figure of merit, ZT, determines the dependence of device efficiency upon material properties, and is defined as follows,

$$ZT = TS^2 \sigma / \kappa$$

Where T is the absolute temperature, S the Seebeck coefficient, σ and κ the electrical and thermal conductivity, respectively, and the latter is the sum of the electronic κ_e and lattice κ_L components at the temperature T. The electrical properties of the semiconductors materials employed can change dramatically with temperature[11]. Over the temperature range 100 – 1000°C, two different couples are the best for the space reactor application:

- PbTe is the best (maximum factor of merit) for medium temperature below 700°C
- SiGe is adapted to higher temperature (700 – 1000°C).

The efficiency of the entire system is defined: $\eta = \eta_{carnot}\, \eta_{thermo}$.
Where η_{carnot} is the Carnot (ideal thermodynamic) cycle efficiency and η_{thermo} is the thermoelectric junction efficiency.
The total thermoelectric power conversion system efficiency as:

$$\eta = \frac{\Delta T}{T_{hot}} \times \frac{\sqrt{(1+ZT)} - 1}{\sqrt{(1+ZT)} + \frac{T_{cold}}{T_{hot}}}$$

Where: ΔT is the temperature difference between hot and cold junctions; T_{hot} is the temperature of the hot junction (K) and T_{cold} is the temperature of the cold junction (K)
The hot well temperature is imposed by the core design, the average of the inlet and outlet reactor temperatures is T_{hot} = 1085 K.
The highest efficiency is obtained as the cold well temperature is as low as possible.

As the temperature of the cold well decreases, the efficiency increases and the thermal power of the space reactor decreases. At the same time as the cold well temperature decreases, the area of the radiators increases, in fact this area is proportional to the ratio of the power to be wasted to the fourth power of the cold well temperature:

$$P = A(\varepsilon\sigma T_{cold}^4 - P_{sun}) .$$

Where P_{sun} is the specific power irradiated by the Sun on Mars, approximately equal to 0.25 KW/m^2

An optimization process has been developed in order to maximize the efficiency, minimizing the area of the radiator and the thermal power. This optimization has been developed finding a minimum of a constrained nonlinear multivariable function F = f(x) chosen as the ratio between the area of the radiator A_{rad} and the overall efficiency η; this function depends on the cold well and the hot well temperatures, T_{cold} and T_{hot}, respectively.

At the end only boundary constraints have been set up:

- limitation of the highest and lowest temperature for the hot well
- limitation of the highest and lowest temperature for the cold well.

The function F is shown in figure 11.

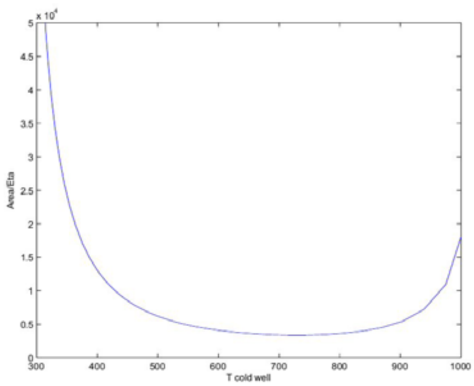


Figure 11 - Optimization function

The results of this optimization procedure are:

T_{hot} = 1085 K
T_{cold} = 729 K
ZT = 0.6442
η = 0.0473

The net efficiency, calculated in order to take into account the system energy requirements with the same hypotheses adopted for the PWR is: η_{net}= 0.0466.

However, the overall pumping power might be significant, because of the relatively high-pressure drops in the circuit, which must be carefully optimized.

The Cold Well

In this preliminary study a heat pipe solution for both cases has been adopted because heat pipes are simple devices that have a high thermal conductivity and they have been already extensively adopted in space applications, as their operation is independent of gravity. A feature of the heat pipe is that it can be designed to transfer heat from the heat source to the heat sink without significant temperature drops. The chosen heat pipe has Freon as working fluid and the container material is aluminium. The final design has been obtained making several hypothesis:

the operating temperature is 729 K for the 2144 KWth reactor and the interval 408-533 K for the 417 KWth one;

– the sun irradiation is present (0.25 KW/m^2);

– the view factor of each heat pipe is 0.5.

The power to dissipate is directly proportional to the fourth power of the temperature and to the cold well surface. Thus, the theoretical surface is:

$$A = \frac{P_{diss}}{\varepsilon \cdot \sigma \cdot T^4 - P_{sun}}$$

and therefore the real area to consider is:

$$A_{real} = \frac{A}{V_{iewfactor}}$$

For the thermoelectric solution two other hypothesis have been considered:

– each thermoelectric module produces 10 W electrical power;

– each heat pipe is mounted on one thermoelectric cell;

– the thermoelectric cell diameter is 75 mm.

The radiator obtained in order to dissipate 2144 KWth has a theoretical surface of 165 m^2. There are 10000 heat pipes total. The containers are 123 mm long and they have a thickness assumed equal to 0.75 mm because of structural reasons. Therefore, the cold well total mass is 842 kg.

To design the 417 KWth reactor cold well a suitably weighted average temperature in the interval 408-533 K has been considered: the theoretical surface needed to dissipate 317 KWth at the average temperature of 463 K is 207 m^2. The helium outgoing from the turbine flows through the main heat line and then flows back in the compressor. Each one of the 10000 heat pipes is attached on this heat line The thickness of the aluminium containers is 0.75 mm and their length is equal to 128 mm. Thus the overall radiator mass is about 834 kg.

Overall Masses And Volumes

The mass budget for both reactors is detailed in table 2. Some further components of the reactor have not been considered yet. The mass of these not considered parts has been assumed to be about 200 kg for both reactors.

A 5% of the mass of any single component has been considered as subsystem mass margin and the final sum has then been increased by a further 10% as total mass margin.

The total mass has been increased by 20% in order to consider the mass of the shielding.

Thermal Power [KW]	**2144**	**417**
fuel diameter [mm]	4.3	4.3
Compact apothem [mm]	3.21	2.96
Core+reflector diameter [cm]	59.85	57.33
External vessel Diameter [cm]	62.16	59.57
Cylindrical vessel thickness [mm]	13.00	12.00
Reactor height [cm]	173.91	172.00
Radiative area [m^2]	165	207

Table 1 – Reactors dimensions

Thermal Power [KW]	**2144**			**417**		
Core Mass [kg]	1384			1198		
Core+Reflector Mass+plates [kg]	1741			1528		
Vessel Mass [kg]	647			556		
Overall Reactor Mass [kg]	2387	5%	2507	2085	5%	2189
Cold Well [kg]	668	5%	701	834	5%	876
Compressor [kg]	0	5%	0	100	5%	105
Turbine/Thermoelectric Device [kg]	200	5%	210	200	5%	210
Other Components [kg]	200	5%	210	200	5%	210
Total Mass without shielding [kg]	3628	10%	3991	3419	10%	3760
Overall System mass [kg]		20%	**4789**		20%	**4512**

Table 2- Mass budgets

The 2144 KWth reactor has a mass of 4789 kg and the 417 KWth has an overall mass of 4373 kg.
It can be noticed that the mass difference between the two solutions is really small considering that the ratio of the powers is 5.14.

Preliminary safety consideration

This nuclear system must satisfy the usual safety requirements of terrestrial, besides this system has to assure that:
- no irradiated fuel is present at launch; as the reactor would not reach its first criticality before being outside terrestrial space this is inherently assured.
- the core sub criticality in the case of possible launch accidents (flooding);
- the radiation protection without impairing weight requirements; for surface reactor, the shield cannot be transported from the earth and it is to be provided by a suitable system layout on the Mars surface; For propulsion reactor an intermediate solution is to be found by balancing the addition of a small shield around the core with the reduction of the radiation danger by locating the reactor far away from the sensible zone - an easy decommissioning in space;

A detailed safety analysis is outside the scope of this feasibility study, for its complexity and need to define the detailed requirements: this reactor is nor subjected to the licensing procedure of terrestrial reactors imposed by the safety authorities, but it must satisfy specific safety issues connected to its launch and possibility to fall down to the earth.

Conclusions and Open Issues

At the end of this very preliminary feasibility study about the utilisation of HTGR for space applications it can be concluded that no insoluble issues have been evidenced, which would prevent of going on along this route in order to develop a more detailed design. At that point only it will be possible to draw a more justified conclusion The two reactors here presented have been designed for a surface solution, however they both suits to a deep space utilization for the NEP with small variances.

In the short range, future design activities should address the detailing of many elements here presented and also of some new ones. In fact the conservative assumptions done affect the reactor size, dramatically influencing the overall mass. A better definition of radiation shielding, vessel fluence, vessel material, ancillary circuits for start up, as well as safety criteria, overall layout, containment, leakage and control coolant purification will allow a better definition of entire systems and a preliminary R & D program. An optimization of these two reactors could lead to a lighter and more reliable reactor, as previousely demnstrated, there is no real difference between the bryton reactor and the thermoelectric one in terms of masses, but there is a real gap in terms of reliability. Because of this a future developement could be the optimization of the thermoelectric HTGR detailing the analysis of others of its subsystems.

In any case both these reactors seem feasible and their realization would permit a human mission to Mars or a robotic mission to outer solar system planets, allowing mankind to realise the most ancient of its dreams: to reach other worlds and to live on it in a safe and durable way.

Acknowledgments

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References

[1] Friedensen, V.P., “Space Nuclear Power: Technology, Policy, and Risk Considerations in Human Mission to Mars”, *Acta Astronautica*, **42**, *1-8*, 395-409 (1998).

[2] Summerer, L., “Nuclear Power Sources Basic Considerations”,in

Proceedings of CNES Workshop on "Nuclear Space Propulsion", Jouy-en-Josas, France (2002).

[3] Powell, J., et al, "Compact MITEEE-B: Bimodal Nuclear engine for Unique New Planetary Science Missions", *AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, July 2002, Indianapolis, Indiana, USA

[4] Lombardi, C., *Impianti nucleari*, Città Studi, Milano,2004

[5] WIMSD, A Neutronics Code for Standard Lattice Physics Analysis, AEA Technology, distributed by the NEA Databank

[6] Hutton, J.L., *New capabilities of the WIMS code*, USA, May 2000

[7] Lamarsh, J.R., *Introduction to nuclear reactor theory*, Addison-Wesley, New York,1972

[8] Briesmeister, J.F., *MCNP - A General Monte Carlo N-Particle Transport Code, Version 4C*, LA-13709-M, Los Alamos National Laboratory, April 2000.

[9] El-Wakil, M.M., *Nuclear Energy Conversion*, Intext educational publishers, 1971

[10] Goldsmid, H.J. and Nolas, G.S., "A Review of the New Thermoelectric Materials", *20th International Conference on Thermoelectrics*, 2001.

[11] NASA tech brief, *New High Performance p-type Thermoelectric Materials Based on B-Zn_4Sb_3*, vol.23, No.2, Item #, JPL new technology report NPO-19851, February 1999