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A LOW-POWER HTGR FOR INTERPLANETARY SPACE MISSIONS: PRE DESIGN PHASE

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ABSTRACT

Nuclear power systems, thanks to their features of safety, efficiency and reliability are well suited to provide electric power within the range demanded from the near future space exploration programs (10-100 KW). Space applications of a nuclear fission reactor refer to electric power production both during deep space transfers, when electric power feed electric engines (NEP: Nuclear Electric Propulsion) and during stationary phases on some planet or natural satellite, producing electrical power for manned or unmanned settlements. In this study a low-power, fission reactor is undertaken. 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. This paper focuses on the optimization of a small, innovative, low-power high temperature gas cooled reactor. A Thermoelectric device and a Brayton cycle have been evaluated as power conversion system. To define the main aspects of the system and the reactor geometry, a conspicuous number of neutronic calculations, based on WIMS code benchmarked with MCNP code, were carried out. An evaluation of materials high temperature behavior, a preliminary design of the core supports and very preliminary launch vibration analysis have been carried out. On the basis of this preliminary analysis no item seems to be unsolvable. Even if only an R&D program of reasonable extent may guarantee the effective feasibility. As some demanding researches could be also of interest for the new terrestrial High Temperature Gas Reactor.

INRODUCTION

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, this is a continuation of a previous study. In fact after a first search and definition of the systems many were the open problem, so a more detailed analysis has been necessary to investigate this concept. 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.
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 idea is to extend as much as possible the HTGR technology adopted for producing high powers in terrestrial applications[4] to the design of a reactor suited for space conditions.
However a number of modifications are needed. Let us summarize them. Fuel: conventional powder of 93% enriched uranium oxide, sintered in micro spheres of 350 μm diameter. Cladding material and thickness: the fuel micro spheres are protected by four carbon based layers of overall thickness equal to 400 μm and then the outer diameter turns out to be 750 μm . Fuel "rod", said compact: the micro spheres are mixed with a graphite powder and then compacted to form an hexagonal rod or compact, while the length is that of the reactor height and thus it is the result of the neutronic calculations to define the core size.
Fuel-moderator-coolant channels: the moderator is graphite under the form of hexagonal blocks having the same length of the reactor height. The blocks have an apothem which depends on the moderation ratio. The blocks are drilled by hexagonal holes: every coolant hole is surrounded by six for the compacts, see figure 1.

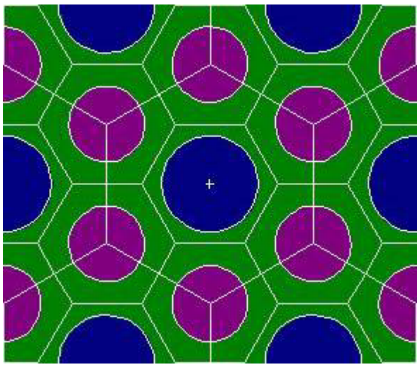


Figure 1. Fuel channels (pink) and coolant channels (blue).

Fuel burnup: an average value of 100 MWd/kgU is assumed, which is about the same value presently adopted in HTGRs. Fuel quantity: Present calculations show that the minimum mass for both conversion cycles does not minimize the overall reactor mass and it is to be set to 150 kg UO_2 for the Brayton reactor and 200 kg for the thermoelectric one. Core geometry and reflector: the core geometry is based on the assumption to have a cylinder with the diameter equal to the height. The reflector, composed mainly by Beryllium oxide, is located partially inside the vessel, holed by rotating bars composed by BeO and B_4C and partially outside. The outside cylinder can slide so that neutronic start-up of the reactor is assured. The reactivity control: two main reactivity excursions have to be faced, the start-up gradient, faced by the sliding reflector and the during-life reactivity gradient faced by rotating bars.
Temperatures and pressures: the maximum and the minimum temperatures are in both case 900/735 °C respectively. The minimum pressure is the usual value of 3 MPa, 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: in this case the choice depends on the generator type adopted. Electrical generator: two alternate designs are possible i.e.: thermoelectric generator, the Brayton gas cycle. The thermoelectric generator is a possible and interesting solution in this case, thanks to the relatively high temperatures. In fact a net efficiency of 4.67% has been calculated, obtaining a reactor thermal power of 2137 kWth. The direct Brayton gas cycle is characterized by a much higher net efficiency equal to 24 %. This leads to a value of thermal power equal to 417 KW.

Core analysis

The core analysis has been performed using two codes largely used for reactor design: the MCNP-4C Monte Carlo code[5] and the WIMSD[6,7] deterministic code. A procedure has been implemented using the two codes to obtain all the neutronic data required.
The first gives the reactivity in an infinite mean: to obtain the reactivity of a finite reactor, the values of axial and radial buckling, which are crucial parameters in this small size reactor, are required[8]. Because of the strong dependence of the effective multiplication from the buckling values, the use of the Monte Carlo program, MCNP-4C, was requested. Using the burning of the WIMS solution and the multiplication factor at the beginning of life given by MCNP a procedure has been implemented to determine Montecarlo reactivity at end of life, EOL.

The procedure to calculate the exact multiplication factor is represented by the flow chart in figure 2. The main point of the procedure are:

1. Calculating both Montecarlo, k^M_{BOL} and WIMS k^W_{BOL} and k^W_{EOL},
2. Defining $\Delta_e k^W$, the multiplication factor variation over the lifem'purified' of the WIMS buckling definition
3. Defining a new a multiplication factor variation over the life weighted on the 'exact' Montecarlo solution ΔK:
4. Finally calculating the k value at the end of life.

This procedure assures to correct the uncertainties related to the buckling definition in the WIMS code, relying totally on the possibilities given by the Montecarlo code, figure 2.

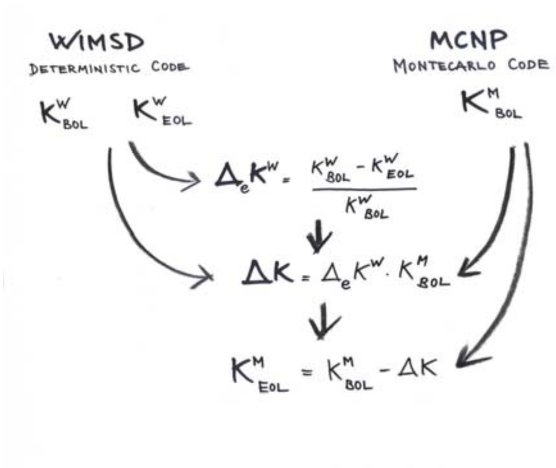


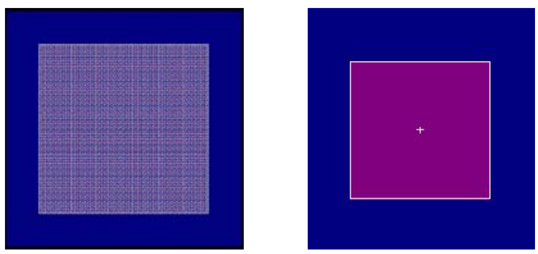
Figure 2. Strategy implemented.

A more detailed fuel neutronic analysis has been necessary for these reactors in order to define a good neutronic model to describe the fuel.
In fact a first analysis has been required to define the limits of the homogeneous approximation of the heterogeneous microsphere: the homogeneous sphere, figure 3.a, reactivity has been compared to the heterogeneous one, figure 3.b. The distance between these solutions once sets the limit of this first approximation.

(a) (b)

Figure 3. Particles simulated.

A second analysis has been necessary to define the limits of the second heterogeneity fuel-compact: the homogeneous compact, figure 4.a, reactivity has been compared to the heterogeneous one, figure 4.b.



(a) (b)

Figure 4. Elements simulated.

The distance between these solutions once sets the limit of this second approximation

and the tolerance definition of all the neutronic calculations.
Once set the tolerance the neutronic calculations for the two reactors are defined and the reactors definition possible.

Control strategy

Once defined the geometry a control strategy has to be defined as the reactor dimensions and features will depend strongly on this item. The reflector positioning is a key issue, in fact it could allow the start-up together with the life control of the reactor.

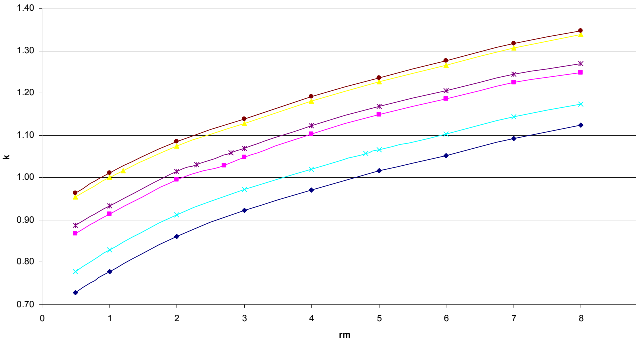


Figure 5. Inside reflector configuration for 100 (bleu), 150 (pink) and 200 (yellow) kg of uranium, partially outside reflector configuration for 100 (cyan), 150 (violet) and 200 (red) kg uranium reactors.

A comparison between two configuration has been done, reflector fully inside the vessel, and reflector partially outside the vessel both for 100, 150 and 200 kg of uranium loaded, the results are in figure 5. As visible the partially outside configuration allows a higher reactivity and so a reduction of the uranium loaded. Moreover sliding this BeO cylinder up allows the start up of the reactor and a very secure launch.
In order to manage the reactivity excess during the reactor life and the reactivity gap between the BOL at cold and hot zero power condition, BOLC, BOLH, the some parts of the core have to be movable. The control of the reactor should have been done using several control rods[10]. As the use of these many rods would have implied a very complex, heavy and voluminous system, rotating bars have been selected inside the vessel.

Defined the design tolerances, the control strategy and the reflector configuration the design of the cores could be completed.

The Brayton reactor

The features of the Brayton reactor are in table 1, as visible the uranium mass required 150 kg. The layout of the core is in figure 6, while the effect of the control strategy on this configuration is in figure 7.

Power [KWth]	417
Conversion Cycle	Brayton
Efficiency	24%
Hot well temperature [°C] Cold well temperature	800 200
Load of Uranium [kg]	150
Vessel Radius [cm]	60
Holes Diameter [cm]	1
Power Density [kW/kg]	2.78

Table 1. Brayton reactor features.

This reactor adopt a 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.

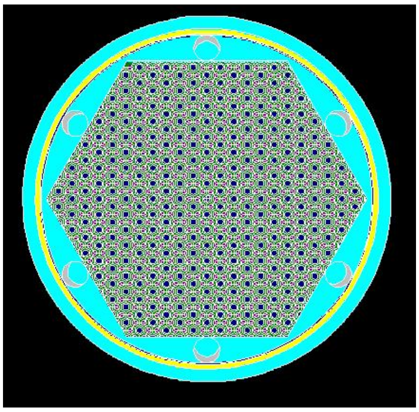


Figure 6 Horizontal cross section

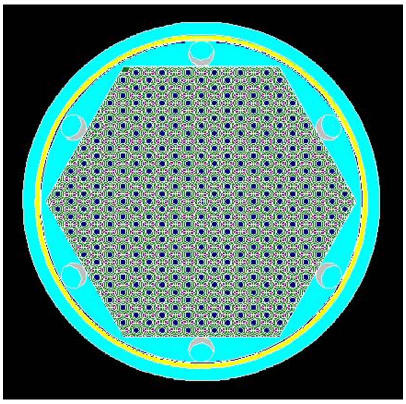


Figure 7 Horizontal cross section, rotated bars

The design pressure of the primary system is equal to the operating pressure multiplied a

factor of 1.10, which takes into account the value of the safety valve setting. On this basis the pressure vessel thickness have been determined using the same steel adopted in PWR. The regenerator is a crucial component both for the size, transferring a power of 2.75 times that of the reactor and the high temperatures and pressures involved (maximum values 750°C and 4.8 MPa).
The cold well must dissipate in the case of Brayton cycle 317 kW[9]. By integrating the radiation equation and considering a view factor of 0.6 and an emissivity of 0.90.
By assuming titanium tubes the condenser can be imagined to be a cylinder of 2 m radius and 3 m height.
A sketch of the system is in figure 8 and its mass budget is in table 2.

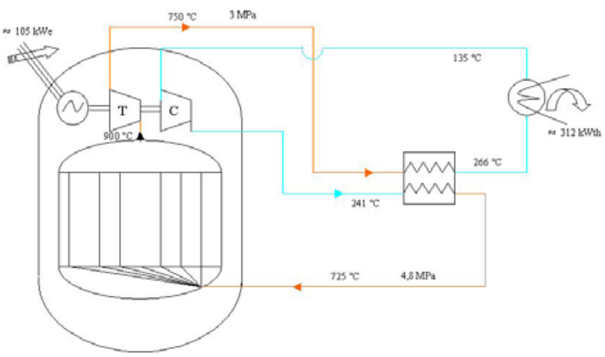


Figure 8 - Conceptual Layout for the Brayton reactor

Core + vessel [kg]	2085
Cold Well [kg]	834
Compressor + Turbine [kg]	300
Other Components [kg]	200
Total [kg]	3419
Overall system Mass [kg]	4512

Table 2. Brayton reactor mass.

The Thermoelectric reactor

The features of the thermoelectric reactor are in table 3, as visible the uranium mass required 150 kg.
The layout of the core is in figure 9 while the effect of the control strategy on this configuration is in figure 10.
As for the Brayton reactor this HTGR is a semi integrated solution, where the rotating machines are put inside the pressure vessel: the compressor and its own motor are integrated inside the vessel.
The design of the pressure vessel has been performed with the same materials and temperature conditions of the Brayton reactor.

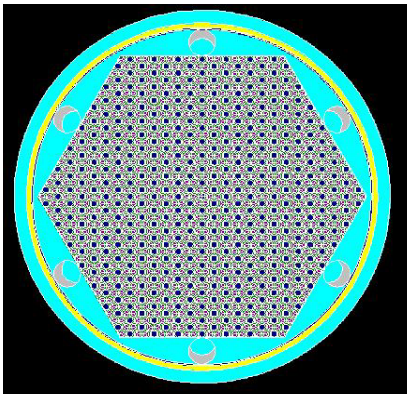


Figure 9 Horizontal cross section.

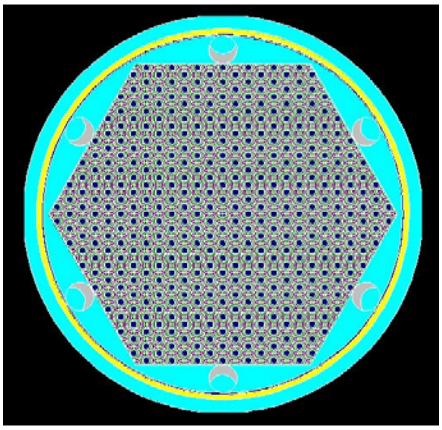


Figure 10. Horizontal cross section, rotated bars.

The electrical power generation system is the thermoelectric device[10,11]. Over the temperature range typical of HTGR (700 - 1000°C), the best thermoelectric material is SiGe.
An optimization process has been developed in order to maximize the efficiency, minimizing the area of the radiators and the thermal power to be produced.

Power [KWth]	2144
Efficiency	4.66%
Hot well temperature [°C] Cold well temperature	800 473
Load of Uranium [kg]	200
Vessel Radius [cm]	56
Holes Diameter [cm]	1
Power Density [kW/kg]	10.5

Table 3. Thermoelectric reactor features.

The data obtained are:
Thot = 1085 K,
Tcold = 729 K,
ZT = 0.6442,

efficiency= 4.8%.
The net efficiency, calculated in order to take into account the system absorbed power is 4.67%.

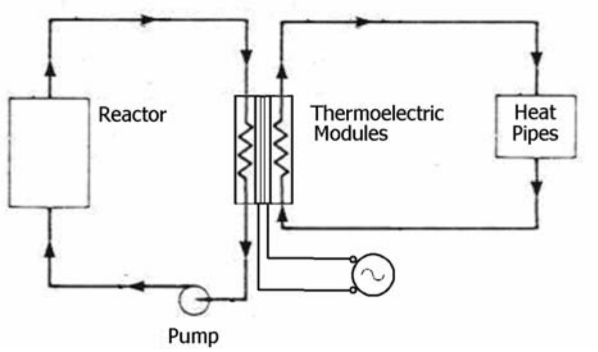


Figure 11 – Conceptual Layout for the thermoelectric reactor

Anyhow the absorbed power may be more significant in this case, due to the rather high pressure drops of the helium circuit. A detailed design should be carried out to this regard. In this case, for the cold well a heat pipe solution has been adopted.

Core + vessel [kg]	2387
Cold Well [kg]	668
Termoelectric device [kg]	200
Other Components [kg]	200
Total [kg]	3628
Overall system Mass [kg]	4789

Table 4. Thermoelectric reactor mass.

The chosen heat pipe consists of a sealed aluminium container, a working fluid compatible with the container, Freon and a porous structure in aluminium. The dimensioning has been realized considering: the sun irradiation is present, each thermoelectric module produces 10 W, the view factor of each heat pipe is 0.5. The radiator obtained in order to dissipate 2037 kW is a cylinder 4 m high and 2.5 meter radius.
A sketch of the system is in figure 11 and its mass budget is in table 4.

Conclusion

This feasibility study has allowed us to find a first list of open issues to be solved for going on this route, which need a R&D program. The fuel is identical to that foreseen in terrestrial reactors, and then it can be assumed that it is or will be developed by already existing R&D programs. The R&D about thermoelectricity at high temperature is of paramount importance for this reactor, because if present efficiency can be improved and assure the long term reliability by a suitable choice of materials, a thermoelectric apparatus might became the right solution for this nuclear system, instead of the much more complex Brayton cycle. Even if this list is incomplete, no item seems to be unsolvable, and the lack of fuel development activity is greatly advantageous. On the other hand, some high temperature design issues appear demanding especially for long term operation. An R&D program of reasonable extent may yield the needed answers, but what is important that the most demanding researches also are of interest for the new generation High Temperature Gas Reactors.
A detailed safety analysis is outside the scope of this feasibility study, for its complexity and need to define the detailed requirements. In fact this reactor from one side is not subjected to the licensing procedure of terrestrial reactors imposed by the safety authorities, from the other it must satisfy specific safety issues connected to its launch and possibility to fall down to the earth. These reactors have the inherent feature to resist to the consequences of a LOCA, without provoking the fuel melting.
At the end of this very preliminary feasibility study about the use of HTGR system for space reactors, it can be concluded that no insoluble issues have been evidenced, which would prevent of going on along this route in order to execute a more detailed design.

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