Proceedings of ICAPP 2007
Nice, France, May 13-18, 2007
Paper 7012

An Integrated PWR for planetary exploration

Elvina Finzi1, Carlo V. Lombardi1, Leopold Summerer2
1Department of Nuclear Engineering, Politecnico di milano, Milano, Italy
2ESA Advanced Concepts Team, ESTEC, Noordwijk, The Netherlands
tel: +39022665866; email: elvina.finzi@polimi.it

Abstract – *Ambitious solar system exploration missions in the near future will require robust space power sources, in the order of 100 KWe. Fission power systems are well suited to provide safe, reliable, and economic power within this range. Therefore the goal of this research program is to carry out a feasibility study of a nuclear fission reactor suited for space applications. These refer either to electrical power production for stationary settlements (manned or unmanned) on some planet, or deep space planetary surfaces, or satellites (Mars, Moon).*
This application of nuclear energy is very demanding, in general, and the following requirements for the space nuclear reactor have been assumed: i) extreme reliability, ii) R&D program of moderate cost, iii) to be deployed within a reasonable period of time (e.g. 2015), iv) to be operated and controlled for a long time (10 years) without intervention, v) possibly to be also used as a byproduct for some particular terrestrial application (or at least to share common technologies). In this study a low-power, surface, fission power system is undertaken. The driving idea is to extend as much as possible the PWR technology adopted for producing high powers in terrestrial applications to the design of a reactor suited for space conditions. Taking into account the small size, an integral type reactor is investigated. A Rankine steam cycle is evaluated for the electricity production. The neutronics calculation is based on WIMS code benchmarked with MCNP code. The reactivity control is envisaged by changing the core geometry. A mass estimation is then given, the resulting system appears viable and of reasonable size, well fit to the present space vector capabilities. Finally, a set of R&D needs has been identified and some demanding researches are of interest also for the new generation Light Water Reactors. Even if a water Rankine system still presents challenging tasks for space applications no item seems to be unsolvable so that the system could be developed at a low cost and on an acceptable schedule.

I. 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 a continuation of an ESA research contract, is to detail the 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. The solutions envisaged in this work better apply to the surface applications.

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 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 well proven technology of present 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 the PWR and in particular the Integrated Pressurized Water Reactor. As known the Pressurized Water Reactors, PWR, is the most common reactor type for terrestrial power stations but widely used also for submarines propulsion [3]. Of the preliminary studies accomplished [4] a classical Rankine cycle has been confirmed as the best solution in terms of masses and efficiency, and on this range of power also in terms of reliability [5].

II. THE PWR DESIGN

The most significant modifications to be drawn to a terrestrial PWR to make it fit to space applications are listed in the following. Fuel composition adopted is matrix fuel composed by 45% of 93% enriched Uranium and 55% of ZrH1.7. Cladding material is stainless steel, a conservative solution. Cladding thickness is 0.3 mm. Temperatures and pressures: the maximum operating pressure assumed is identical to PWRs, i.e. 15.5 MPa. Maximum temperature has been chosen in order to improve the efficiency and to experiment the saturation temperature at the core exit, in order to use a self-pressurizer. The latter one asking for a gravitational environment. The maximum temperature is set equal to 345 °C, about 15 °C higher than that of PWRs, while minimum temperature at the inlet is assumed equal to 335 °C, 45 °C higher than PWRs. Cold well temperature definition imply a preliminary optimization in order to minimize the overall mass as lower temperature means higher efficiencies, but higher cold well size. Electrical generator selected is a Rankine steam cycle. Core geometry and reflector: the core is assumed to be a cylinder having the diameter equal to the height. Rounded by a 12 cm thick reflector. Primary pumps: spool pumps, fully inserted in the primary circuit without any seal, have been considered, being their technology under development.

As the electric power depends on the efficiency of the conversion circuit a classical Rankine steam cycle is considered in order to define its efficiency. The net efficiency of the Rankine steam cycle in Martian conditions turns out to be 12.5% asking for a 800 kWth.

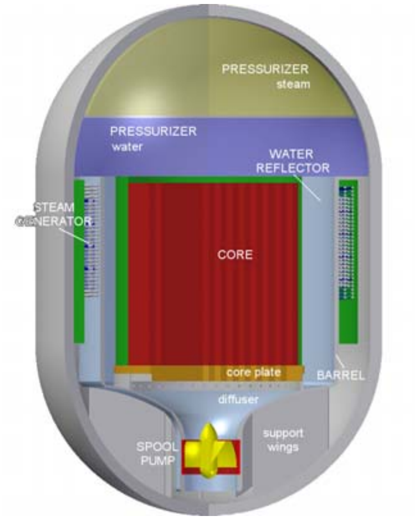


Fig. 1. Primary circuit sketch vertical cross section

The integrated layout of Rankine reactor places within its vessel almost all the components of the primary system: the reactor core, the barrel, the steam generator, the pressurizer, the circulating pump, the safety valve, the reactivity control mechanism and the instrumentation, in order to guarantee minimum size and mass, together with escaping radiation and fast neutrons fluence reduction on the vessel. A sketch of the primary circuit, totally inserted in the pressure vessel, is represented in Fig. 1. As visible the fuel-core is surrounded by the reflector, this is surrounded by a stainless steel barrel and this is surrounded by the steam generator, contained in the vessel.

III. NEUTRONIC DESIGN

The neutronic design has been accomplished using two different codes: the deterministic code Winfrith Improved Multi group Scheme, WIMS [6]. WIMS and the Montecarlo code MCNP4C [7]. 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. Because of the strong dependence of the effective multiplication from the buckling values, the use of the Monte Carlo program, MCNP-4C [8], 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.

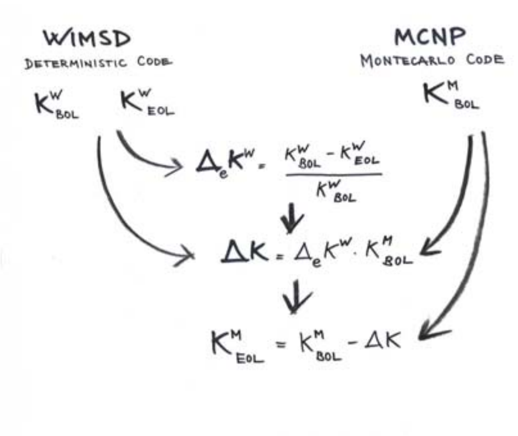


Fig. 2. Procedure implemented to define the core

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

- Calculating both Montecarlo, k_{MBOL} and WIMS k_{WBOL} and k_{WEOL},
- Defining DekW, the multiplication factor variation over the life 'purified' of the WIMS buckling definition,
- Defining a new a multiplication factor variation over the life weighted on the 'exact' Montecarlo solution ΔK,
- 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.

TABLE 1
Features of SURE reactor.

	SURE U-ZrH
Power [kWe]	100
Lifetime[d]	4000
Power [kWth]	800
Fuel	U-$ZrH_{1.7}$
Power conversion	Rankine H_2O
Coolant	H_2O

To define the core it is necessary to recall the general features of the reactor, summarized in table 1. These parameters values are derived from the ESA requirements for a Mars manned mission [9].

Considering a thermal power of 800 kWth, 4000 burning days and an average burn-up of 60 MWd/kg the uranium necessary mass turn out to be 41.4 kg, but having the most effective reflector a first layer of 8 cm of BeO followed by a second water layer of 4 cm, the value of 41.4 kg of uranium results to give a too high reactivity. A mass optimization process is then required, considering the geometries and the control strategy defined for the reactor considered.

III.A. Geometry definition

Two geometries have been considered for what concern the fuel positioning:

- The 'classical' configuration, Fig. 3, consisting in clusters of seven fuel rods surrounded by a stainless steel cladding and water, the rods clusters being by a metallic hexagonal shroud.
- The 'matrix' configuration, Fig. 3, consisting in the dual geometry of the classical one, presenting an hexagonal based prism of U-ZrH holed and crossed by water. The cladding in this case is a folder for the fuel matrix.

Both these reactors are surrounded by an identical reflector, as it has been demonstrated to be the optimum one and because the same control strategy has been used in both reactors using the reflector effect.

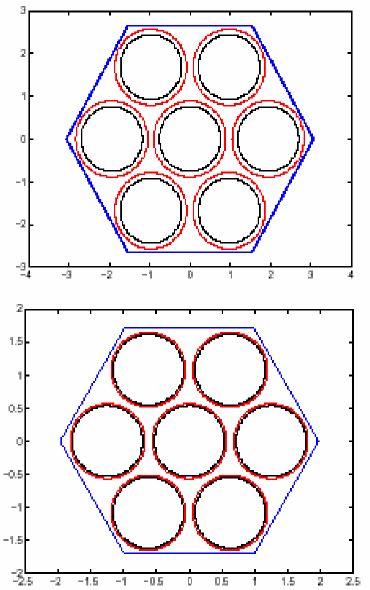


Fig. 3. Classical configuration and Matrix configuration

IV. 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. In order to guarantee a total reactivity management any control procedure should guarantee:

- The subcriticality in an open cold zero power condition, koc < 1;

- A reactivity variation between a closed BOLH condition and an open reflector BOLC condition greater then the reactivity variation given by the fuel burning, in order to guarantee an adequate Shut Down Margin.

The issues of this process are the reactivity behaviour versus distance and the overall reactivity needed value to be controlled. 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 withdrawn. 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, a new control strategy have been developed. This proposal is based on the fact that the core is very small and its portions can be probably moved apart rather easily.

This can be obtained in three different ways:

1. withdrawing radially the reflector,
2. withdrawing it vertically,
3. splitting the core plus the solid reflector in slices to be withdrawn.

In order to manage the reactivity excess during the reactor life and the reactivity difference between the BOL at cold, BOLC, and hot zero power condition, BOLH, some parts of the core have to be withdrawn.

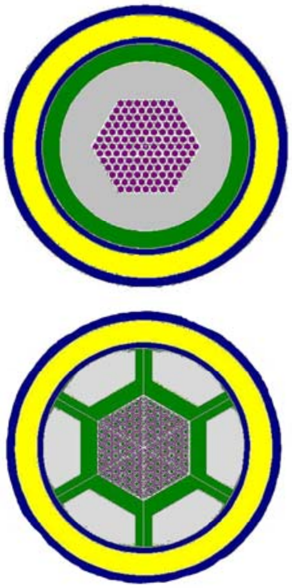


Fig. 4. Matrix configuration: Radial withdrawal of the reflector.

The Radial Withdrawal

A first solution can be the radial withdraw, to this aim the reflector is divided in six moving sectors, operated by a single mechanism, to be defined during the realization phase. These sections can be withdrawn from the closest position to the core, called 'close', to the most distant position from the core, called 'open', Fig. 4.

The effect of this withdrawal on the reactivity has been simulated and the reactivity decreases from k_{cr} to a minimum k_{or}.

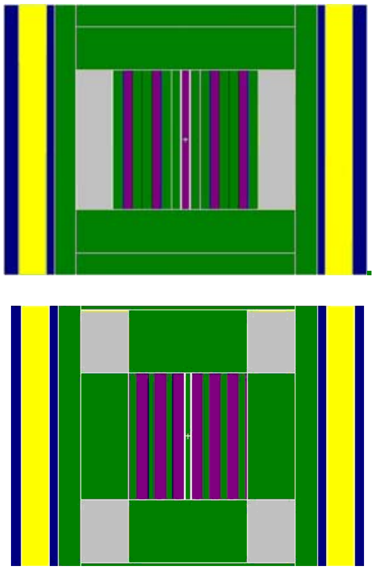


Fig. 5. Matrix configuration: Axial withdrawal of the reflector.

The Axial Withdrawal

A second possible solution is the axial withdraw, to this aim the reflector is divided in two moving sectors, operated by a single mechanism, to be defined during the realization phase, able to move vertically the reflector parts from the closest position to the core, called 'closev' to the most distant position from the core, called 'openv', Fig. 5.

The effect of this withdrawal on the reactivity has been simulated: the reactivity decreases from k_{cv} to a minimum k_{ov}.

The Core Withdrawal

A third solution can be the all core withdrawal, to this aim the core: fuel, moderator, cladding and reflector is divided in six moving sectors, operated by a single mechanism able to withdraw the core parts from the closest position to the core, called 'close' to the most distant position from the core, called 'open', Fig. 6.

The effect of this withdrawal on the reactivity has been simulated: the reactivity decreases from k_{cc} to a minimum k_{oc}.

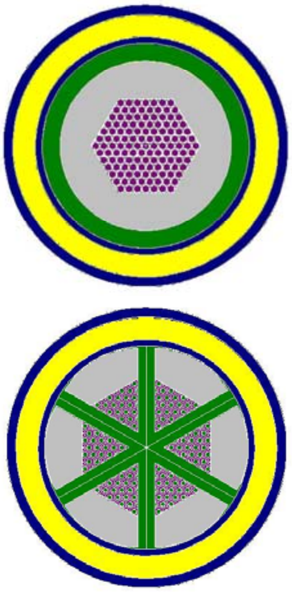


Fig. 6. Matrix configuration: Radial withdrawal of the core.

IV. A. INNOVATIVE CONTROL STRATEGY

Any of these techniques, together with the mass optimization, are not effective enough to define a controllable core, for this two other options have been considered as:

- the withdrawn of the barrel
- the neutron poison

The withdrawn of the barrel allows the extension of the radial dimension of the reactor, this can allow the decrease of the the reactivity in cold zero power conditions. At the same time as the barrel is withdrawn the system total mass increases. In fact the most important mass increase factor, using this technique, is not due to the reflector but to the all system. The low reactivity gain obtained by the reflector expansion does not justify such a mass increase.

The second technique is the use of neutron poison, the effect of gadolinium in the fuel burning is very important: the burning slope becomes less linear as the gadolinium quantity increases, and at BOL and EOL the reactivity decreases. As the design of burnable poison solution is complex for any reactor, it would be better not to insert them in the fuel, but considering the high enrichment and the different configuration, no other choice is possible.

Three final control strategies have been selected: the radial, axial and core withdrawn, all three poisoned in gadolinium. All the three are applied both to the classical and the matrix configuration. The three possibilities given by the reflector/core moving coupled with the poison could work in a sequence as:

1. The reactor starts in cold conditions at the open position, where the reactivity reaches the minimum below criticality;
2. As soon as the temperature rises, the
3. reflector/core slices are approached one another in order to operate
4. at k=1;
5. As soon as the temperature reaches the operating value, the full power is produced and the fuel burning starts;
6. The slices are progressively approached one another until the maximum reactivity point, to compensate the reactivity reduction due to fuel burning.

IV.B. The Homogeneous Equivalence

The choice of a fuel composed of highly enriched uranium and zirconium hydride is a key point for the management of the reactivity of the system. A full water moderated system presents on one side a too high hot-cold reactivity gap, high temperature coefficient together with a very low Doppler coefficient. Reducing all these problems, as explained previously and as shown in the summarizing tables 2 and 3, a partially solid moderator mixed with the fuel has also another important key aspect: the neutronic behaviour of a reactor with this kind of fuel is close to the one of an homogeneous reactor.

TABLE II

Comparison between reactivity coefficients of different cores, for the only water configuration the data are obtained from (Mandelli, 2004).

	only water	classical	matrix
α_C	-270	-61.6	-47.75
α_R	-55	-39.7	-33.6
α	-325	-101.3	-81.35
α_f	-0.2	-0.67	-0.6

TABLE III

Comparison between reactivity gaps of different cores, for the only water configuration the data are obtained from (Mandelli, 2004), *= non poisoned fuel.

	only water	classical	matrix
Δ Cold Hot [pcm]	23000	6900	7520
Δ Bol- Eol [pcm]	6500	10760	13280

Both the classical configuration and the matrix one have been compared to their equivalent dual reactor, in order to compare the two configurations in the same conditions, and homogeneous reactor. In fact the two configurations explained are not totally equivalent, to allow the comparison the dual reactor has been created from the data of the original one, even if from the system point of view the result could be unfeasible.

As visible from table 4 the keff is similar among the three reactors, the matrix reactor configuration is closer to the homogeneous configuration, but clearly also the classical configuration is not distant to its equivalent homogeneous reactor.

This implies that these kind of reactors could be simulated directly by the homogeneous configuration reducing drastically the problems of reactor neutronic design. Moreover the burning of the fuel at the same time is simplified, in fact a deterministic code, like WIMSD, could simulate in a realistic way the core without using the buckling definition, but the reactor equivalent sphere.

TABLE IV

Comparison between the multiplication coefficient of three different fuel configuration for the two reactors;
*= non poisoned fuel.

Configuration	Classical* **k_{eff}**	**Δ [pcm]**
Classic	1.11402	
Dual Matrix	1.11795	393
Homogeneous	1.12224	428
Configuration	Matrix* **k_{eff}**	**Δ [pcm]**
Dual Classic	1.13443	
Matrix	1.13841	397
Homogeneous	1.14273	432

V. CLASSICAL POISONED REACTOR CONFIGURATION

Being the fuel, the control strategy and the geometry of the reactor defined it is possible to define the reactor itself thanks to calculations and simulations. The features of the reactor are in table 5 as visible the uranium mass required 24.77 kg, having a poisoning percentage of 0.41%. The effect of the three control strategy is in table 6. As visible the three withdrawn are effective, Fig. 7 shows the reactivity reduction in cold and hot condition using the three strategies.

TABLE V

Classical poisoned reactor features

	Classical Reactor features
Uranium Mass [kg]	24.77
Percentage of Gd %	0.41%
Fuel Mass [kg]	55.05
Fuel Radius [cm]	0.76
Rods height [cm]	25.76
Equivalent Radius [cm]	12.196
Fuel Power Density [MW/m^3]	118.8

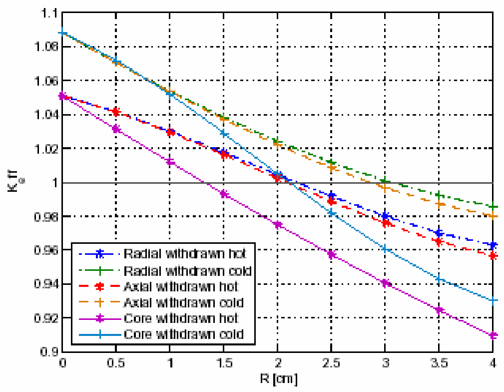


Fig. 7. Effect of the three control strategies.

TABLE VI

Effect of the three control strategies.

	Hot Condition	Cold Condition
Closed configuration	1.05227	1.08815
Reflector Radially Open	0.96276	0.98566
Reflector Vertically Open	0.95663	0.98002
Core Radially Open	0.90950	0.93013

In a typical PWR the total reactivity difference between BOLC and EOL is approximately equal to 24500 pcm [10], while in the reactor here designed is 6600 pcm, this being due to the partially solid moderator. This reactivity variation can be subdivided according to the following analysis, where in brackets, the typical values of PWRs are compared to the space reactor ones in pcm:

- From cold condition to operating temperature the reactivity decreases (6000 pcm vs 3600 pcm) ;
- From zero power to full power conditions reactivity decrease, foreseing the absorptions by Xe and Sm, which reach their equilibrium value in tenths hours. (4000 -1200 for Doppler + 2800 for Xe and Sm- vs 200 pcm);
- Along the fuel life the reactivity decrease to cope with the reduction of fissile material and the accumulation of poisoning fission products (14000 vs 4500 pcm);

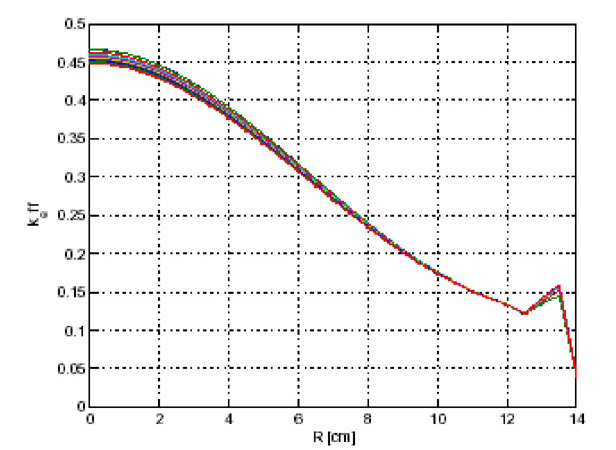


Fig. 8. Radial power distribution of the classical poisoned configuration.

The radial power distribution is presented in Fig. 8, as visible there is a peak in the peripherical region. This peak is probably due to the poison together with the thermalization of the reflector, the thermalized neutrons have a higher probability to be captured by the poison, increasing a peak already present. The features of this reactor, together with its mass estimation are summarized in table 9.

V. MATRIX POISONED REACTOR CONFIGURATION

Being the fuel, the control strategy and the geometry of the reactor defined also for this second configuration it is possible to define the reactor itself thanks to calculations and simulations.

TABLE VII

Matrix poisoned reactor features

	Classical Reactor features
Uranium Mass [kg]	21.7
Percentage of Gd %	0.58%
Fuel Mass [kg]	46.7
Holes Diameter [cm]	1.072
Fuel height [cm]	22.2
Core Apothem [cm]	10.55
Fuel Power Density [MW/m^3]	103.3

The features of the reactor are in table 7 as visible the uranium mass required 21.7 kg, having a poisoning percentage of 0.58%. The effect of the three control strategy on this configuration is in table 8.

As visible the three withdrawn are all effective also for this configuration, Fig. 9 shows the reactivity reduction in cold and hot condition using the three strategies.

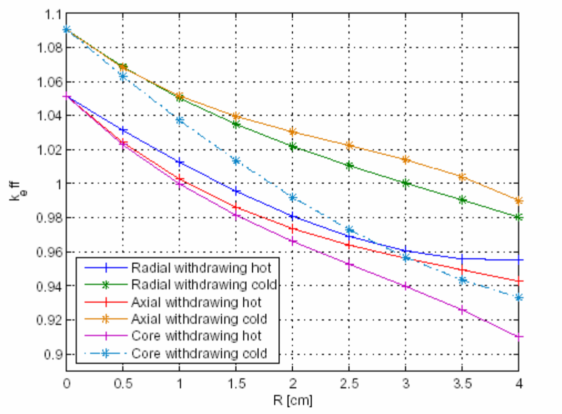


Fig. 9. Effect of the three control strategies.

TABLE VIII

Effect of the three control strategies.

	Hot Condition	Cold Condition
Closed configuration	1.05458	1.09064
Reflector Radially Open	0.95534	0.98036
Reflector Vertically Open	0.94271	0.99000
Core Radially Open	0.91060	0.93324

In the reactor here designed the total reactivity difference between BOLC and EOL is approximately equal to is 8400 pcm, this being due to the partially solid moderator.

This reactivity variation can be subdivided according to the following analysis, where in brackets, the typical values of PWRs are compared to the space reactor ones in pcm:

- From cold condition to operating temperature the reactivity decreases (6000 pcm vs 42000 pcm) ;
- From zero power to full power conditions reactivity decrease, foreseeing the absorptions by Xe and Sm, which reach their equilibrium value in tenths hours. (4000 -1200 for Doppler + 2800 for Xe and Sm- vs 200 pcm);
- Along the fuel life the reactivity decrease to cope with the reduction of fissile material and the accumulation of poisoning fission products (14000 vs 4000 pcm);

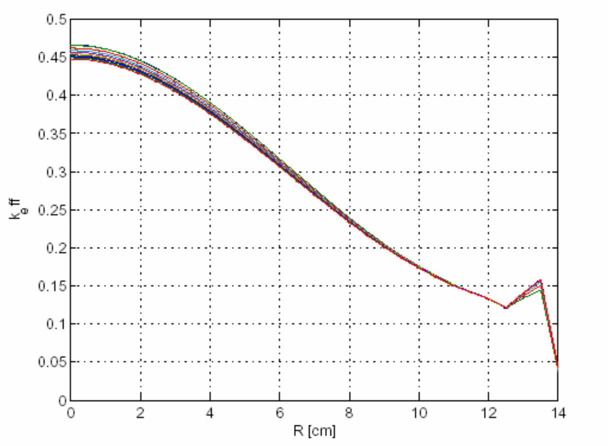


Fig. 10. Radial power distribution of the classical poisoned configuration

As clear, the reactor is smaller ad so the power distribution is higher, the radial power distribution is presented in Fig. 10, as visible also here there is a peak in the peripheral region. This peak is probably due to the poison together with the thermalization of the reflector, the thermalized neutrons have a higher probability to be captured by the poison, increasing a peak already present. The features of this reactor, together with its mass estimation are summarized in table 9.

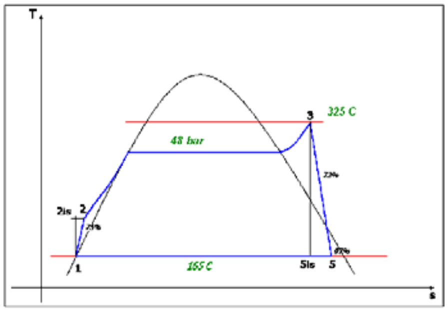
VI. POWER CONVERSION CYCLE

As already described the power conversion cycle selected is a 12% efficiency Rankine cycle. A preliminary optimization study has been performed[4] to determine the heat sink temperature and the temperature obtained is 165 °C. The cycle details its conceptual design are in Fig. 10. The heat sink is represented by a minimum tubes bundle cylinder [11] hexagonal based with six wing, represented in Fig. 12. The total masses and the relative alpha coefficient are in table 10.

TABLE IX

Summary of the data of the the classical poisoned and of the matrix poisoned configuration

	Classic Reactor	Matrix Reactor
Fuel Composition	U-$ZrH_{1.7}$	U-$ZrH_{1.7}$
Uranium Percentage	45%	45%
Fuel Mass [kg]	24.77	19.7
Fuel Density [kg/m3]	8178	8178
Enrichment BOL	93%	93%
Enrichment EOL	69%	74%
Poisoning BOL	0.41 %	0.60%
Poisoning EOL	0.30%	0.25%
Cladding Material	AISI 316L	AISI 316L
Fuel Channel Geometry	Hexagonal	Hexagonal
Fuel/Channels Radius [cm]	0.76	0.54
Core E. Radius/Apothem [cm]	13.6	10.45
Core Height [cm]	25.27	23
Specific Power [kW/kg]	32.3	40.6
Linear Power [kW/m]	23.3	34.78
Coolant Temperature		
Outlet [K]	618	618
Inlet [K]	608	608
Fuel Temperature		
Maximum [K]	814	666
Minimum [K]	700	656
Reflector Material	BeO + H2O	BeO + H2O
Reflector Thickness [cm]	8 + 4	8 + 4
Core Mass	78.4	64.8
Reflector Mass	91	78.3
Total Mass	186	157.5



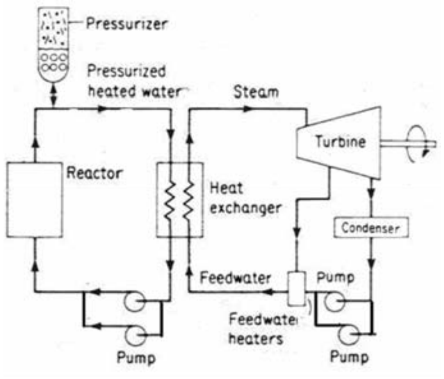


Fig. 11. Rankine cycle for the SURE reactors and conceptual Layout for the Rankine-Cycle-based reactor.

TABLE X

Final masses of the classical and matrix configurations

MASSES	Classic Reactor	Matrix Reactor
Overall vessel (filled with cold water)	862	740
Heat Sink	2500	2500
Steam Generator	67	66
Turbine	200	200
Overall System Mass	3829	3707
Contingencies [10%]		
TOTAL	4356	4210
α [kg/kW]	43.56	42.1

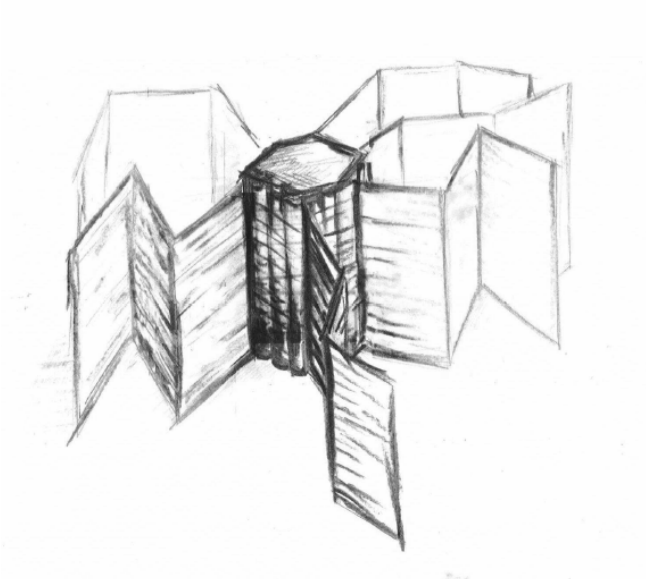


Fig. 12. Reactor unfolded on mars surface.

CONCLUSIONS

At the end of this preliminary feasibility reliability study about the utilisation of PWR 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 Of the two reactors here presented no possible choice is feasible by now.

Even if the matrix configuration reactor is slightly lighter, some important questions about the realizations of its fuel have to be answered.

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 that have been 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, control coolant purification and radiolysis will allow a better definition of entire systems and a preliminary R & D program.

In any case both these reactors seem feasible and their realization would permit a human outpost on Mars, allowing mankind to realise the most ancient of its dreams: to reach another world and to live on it in a safe and durable way.

ACKNOWLEDGMENTS

This work has been carried out within the research activities for the ESA-ESTEC contract # 17301/22/NL7LvH-CCN001.

REFERENCES

1. V.P. FRIEDENSEN, "Space Nuclear Power: Technology, Policy, and Risk Considerations in Human Mission to Mars", *Acta Astronautica*, **42**, *1-8*, 395-409 (1998).
2. L. SUMMERER, "Nuclear Power Sources Basic Considerations", *Proceedings of CNES Workshop on "Nuclear Space Propulsion"*, Jouy-en-Josas, France (2002).
3. Ch. FRIBOURG, JP. ROUX, *"Nuclear power generation for planetary exploration: why not aPWR?"; IAF-99-R.3.09, 1999.*
4. E. Finzi, S. De Grandis, C. Lombardi, D. Mandelli, E. Padovani, M. Passoni, M. E. Ricotti, L. Santini, STUDY ON SPACE NUCLEAR REACTOR DEVELOPMENT (SURE), Estec Contract Nr. 1730/03/NL/Lvh, Scientific Report Cesnef-in-03-12/01, 2003.
5. E. Finzi, S. De Grandis, C.V. Lombardi, A. Maioli, L. Summerer, "A PWR for a Mars Human base", Proceedings of IYNC 2004,Toronto-Canada, May 9-13, 2004, IYNC2004-185.
6. J.M. KUJAWSKI, D.M. KITCH, L.E. CONWAY, "The IRIS Spool-Type Reactor Coolant Pump", *Proc. of ICONE10, 10th International Conference on Nuclear Engineering,* paper #22572, CD-ROM, Arlington, VA, (2002)..
7. "WIMSD, A Neutronics Code for Standard Lattice Physics Analysis", AEA Technology, distributed by the NEA Databank 2000.
8. J.F. BRIESMEISTER, "MCNP - A General Monte Carlo N-Particle Transport Code, Version 4C", LA-13709-M, Los Alamos National Laboratory (2000).
9. 'S51 Architecture study' Esa, 2001.
10. C.V.Lombardi, *Impianti Nucleari*, CLUP MI (1991)
11. E. Finzi, S. De Grandis, C.V. Lombardi, D. Mandelli, E. Padovani, M. Passoni, M.E. Ricotti, L. Santini, L. Summerer, "A Feasibility Study of an Integral PWR for Space Applications", Proceedings of ICAPP '04, Pittsburgh, PA USA, June 13-17, 2003
12. D. Mandelli 'Studio di noccioli di reattori ad acqua in pressione per applicazioni spaziali', Politecnico di Milano, Dipartimento di Ingegneria Nucleare, 2004.