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# A Feasibility Study of an Integral PWR for Space Applications

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**Abstract –** *Fission space power systems are well suited to provide safe, reliable, economic and robust energy sources, in the order of 100 KWe. A preliminary feasibility study of a nuclear fission reactor is here presented with the following requirements: i) high 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 human intervention, v) possibly to be also used as a byproduct for some particular terrestrial application (or at least to share common technologies), vi) to start with stationary application. The driving idea is to extend as much as possible the PWR technology, by recurring to an integral type reactor. Two options are evaluated for the electricity production: a Rankine steam cycle and a Rankine organic fluid cycle. The neutronics calculation is based on WIMS code benchmarked with MCNP code. The reactivity control is envisaged by changing the core geometry. 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: cold well, small steam turbines, fluid leakage control, pumps, shielding, steam generator in low-gravity conditions, self pressurizer, control system. A R&D program of reasonable extent may yield the needed answers, and some demanding researches are of interest for the new generation Light Water Reactors.*

## I. INTRODUCTION

Ambitious solar system exploration missions in the near future will require robust space power sources in the order of 100 KWe.[1,2] Fission power systems are well suited to provide safe, reliable, and economic power within this range.[1] Therefore, the goal of this research program is to carry out a preliminary feasibility study of a nuclear fission reactor suited for space applications. These refer either to rocket propulsion by electricity (NEP: Nuclear Electric Propulsion) or to electrical power production for stationary settlements (manned or unmanned) on some planet (Mars), or deep space planetary surfaces, or satellites (Moon).

Such an application of nuclear energy is technically highly demanding and it should be addressed in a gradual way, because numerous space fission power programs failed having tried to do too much too soon.[3] Thus a good option is to start by developing and utilising a low-power surface fission power integrated system, because it generally places less demanding requirements in comparison with the propulsion system. Then, even if this study concerns both applications, the solutions envisaged apply better to surface applications.

This very preliminary study cannot have the ambition to give by now a proposal for a specific R&D program, but to show that the low-power nuclear reactor concept is viable for space applications.

In addition to the appropriate 100 KWe power level, the reactor was designed according to the following specifications:

1. high reliability;
2. R&D program of moderate cost;
3. development within a reasonable period of time;
4. operation and control for a long time without human intervention;
5. as a by-product for potential use in some particular terrestrial application (or at least to share common technologies).

The first three items mean that the chosen reactor type must be already extensively and positively used or tested interrestrial applications; therefore too innovative designs are a priori excluded in this study. Item 4) is important and again in favour of simple and reliable solutions. Item 5) is motivated by the usefulness to have an economic return of the R&D costs from other non space applications of the same reactor concept; in fact it seems possible and likely that some technologies needed for space reactors can have a terrestrial application in nuclear and non nuclear systems.

All the above considerations taken into account, it can be concluded that such a reactor type should be:

- based on the well proven technologies of present terrestrial reactors, allowing an easier development of different components and systems needed to accomplish the specific mission of a space reactor;
- suitable both for propulsion and stationary applications, apart from motivated and moderate differences.

This basis assumed, the first result is that the propulsion reactor has to produce electricity, in the same way as the stationary one, and its electricity will be used for propulsive scopes, by adopting suitable converting apparatus downstream the reactor.

Other requirements have been considered in the study, due to the main features of the space mission, identified by ESA, and by technological considerations on the nuclear system and its non conventional use. In particular the nuclear system has to:

- produce an electrical power around 100 KW;
- last a long period of time (around 4000 days) without any human intervention and fuel supply;
- minimise the overall mass and volume for rocket payload constraints;
- allow the use of high enriched uranium;
- accept a core power density substantially lower than that of current reactors;
- satisfy the usual safety requirements of terrestrial reactors, as well as those discussed in par. II.F;
- get a simple control of the reactor and the overall plant;
- get a substantial reduction and simplification of maintenance and repairs activities;
- avoid any leakage of the contained fluids or implement systems to recuperate them.

The first reactor type considered in this study is the PWR. In a follow up of the work, the HTGR type will be analysed as well. The PWR is the most common reactor type and in particular widely used for submarines propulsion, which relatively speaking have features similar to those required for space reactors. The idea to use such a reactor type for space application has already been put forward by Technicatome.[4]

The present feasibility study is articulated in the following steps:

- assume as a first choice the PWR solution as the reference system, with a power output of 100 KWe;
- adopt an integral layout, in which all primary components are located inside the pressure vessel;
- perform an adequate neutronic study for the core, since the rated thermal power hence the core dimensions are not usual;
- define the preliminary scheme of the plant, by adopting alternative solutions for electricity production;
- put in evidence the differences between propulsion and stationary reactor specifications and the way to fulfil them;
- identify a research and development program including the aspects of interest for civilian (industrial) purposes in Europe.

## II. THE STUDY

The underlying idea is to extend as much as possible the PWR technology adopted for producing power in terrestrial applications to the design of a reactor suited for space conditions. Obviously a number of modifications are needed. A first important difference concerns enrichment. The higher the enrichment the lower the size and the weight of the reactor. However, the proliferation problem plays a role in the sense that uranium up to 20% enrichment is considered as proliferation safe, while uranium with 93% enrichment has to be classified as military use. It is well known that the Nuclear Powers are against any action facilitating the nuclear proliferation. However, this political constrain appears to be too heavy to be maintained, because of its penalty on the masses, and the 20% enriched fuel solution has been dropped in favor of the 93% one.

Preliminary technological considerations led to the selection of the following main features for the basic nuclear system configuration:

*Fuel composition*: conventional powder of 93% enriched uranium oxide, sintered in very small pellets. *Pellet diameter***:** this is substantially different from that of current PWRs: the high enrichment imposes a small diameter and the chosen value is 1.8 mm, four times lower than the smallest current pellet. Fabrication processes need to be defined. *Cladding material*: Stainless steel; this choice is a conservative solution with respect to Zircaloy, but not so penalizing in high enriched cores. *Cladding thickness*: 0.2 mm. *Fuel rod size*: the outer diameter is 2.2 mm, while the length is a design parameter, because it results from the core size, which has the form of a cylinder with the diameter equal to the height. *Fuel bundle*: 19 rods are assembled in a hexagonal geometry, and inserted in a hexagonal stainless steel shroud with a thickness of 0.3 mm, which is required for the main reason to adapt the channel flowrate to fuel bundle power, in order to maximize the outlet temperature, set equal to the saturation value. *Fuel burnup*: an average core value of 60 MWd/kg is assumed.

*Temperatures and pressures*: the maximum operating pressure is assumed identical to PWRs, i.e. 15.5 MPa. Regarding the maximum temperature, there are two requirements going in the same direction: i) to maximize it in order to improve the efficiency and ii) to have saturation temperature at the core exit, in order to use a self-pressurizer. The latter is possible only for surface application, because gravity is needed to separate liquid and steam. For propulsion application a different type of pressurizer must be envisaged; some possible solutions are under consideration, but they will not be detailed here. The maximum temperature is set equal to 345 °C, which is about 15 °C higher than that of current PWRs, while minimum temperature at the inlet is assumed equal to 335 °C, which is about 45 °C higher than that of PWRs.

*Cold well temperature*: the lower the cycle cold temperature, the higher the cycle efficiency, but this imply also a larger cold well size and mass. A preliminary optimization in order to minimize the overall mass of the system has shown that a temperature of 165 °C is a reasonable trade off between these opposite requirements. However, this thermal power might be used to heat directly the living zones on the planet surface, thus eliminating the cold well: this will be considered in the future.

*Electrical generator*: three alternative designs have been considered i.e. a thermoelectric generator, a Rankine steam cycle and a Rankine organic fluid cycle. The thermoelectric generator has been discarded in the PWR case, because the relatively small temperature difference between the primary fluid and the heat sink gives too low efficiencies, around 2-3%; this means a too high penalty in the overall system size, even if this generator is highly reliable and experienced. The other two cycles are characterized by a calculated net efficiency equal to 12.5% and 18%, respectively. This leads to two values of thermal power equal to 800 KW and 555 KW.

*Primary pumps*: the industry has in advanced stage of development the technology of *spool pumps*, which, opposite to canned pumps, can be fully inserted into the primary circuit without any barrier, because the motor can operate at high temperature inside the coolant.

*Minimum fuel quantity*: being the thermal power, the burnup and the full power duration (4000 days) be set, the following minimum fuel masses are straightforwardly calculated: 53.3 kg for the 800 $KW_{th}$ and 37.0 kg for the 555 $KW_{th}$. This is equivalent to an average fuel power density of 15 KW/kg, which is lower than that of conventional PWRs (38 KW/kg), while the average linear power rate is much lower (0.39 against 17.8 KW/m). *Core geometry* is based on the assumption of a cylinder with the diameter equal to the height, a value very close to the minimum neutron leakage configuration and an optimum compromise for vessel volume exploitation and mass limitation. *The reflector* in these calculations is a layer of 10 cm of water all around the core.

*II.A. The Neutronic Design*

The WIMS[2] code has been adopted for the neutronic calculation. It is a deterministic code, which uses a wide variety of calculation methods to solve reactor physics problems. It is suitable to study any kind of thermal reactors. WIMS evaluates the $k_\infty$ multiplication factor in an infinite mean, then, to obtain the reactivity of a finite reactor, it requires as input the values of axial and radial buckling, which is a crucial parameter in this small size reactor. Since this effective multiplication factor strongly depends on the buckling values introduced in input, the results have been compared with those obtained via a Monte Carlo code. The comparison was made in four specific conditions for the core: i) infinite lattice and ii) actual reflected reactor at beginning of life, iii) cold and iv) hot conditions, by varying the moderation ratio. The Monte Carlo code here used is the well known MCNP-4C[3], as distributed by NEA Data Bank. The comparison was positive (Fig. 1), the result being that WIMS calculation should converge at the End Of Life to a reactivity of 1.025, including a safety margin.

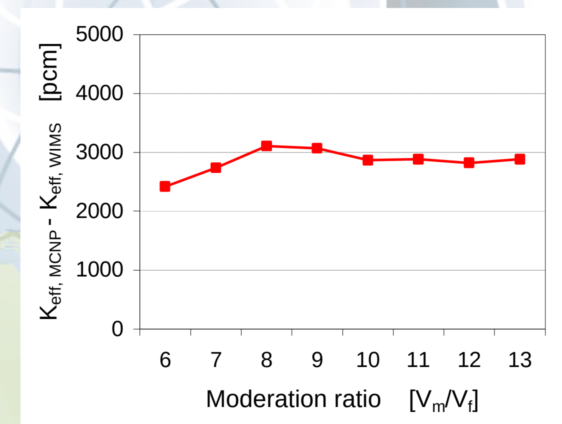


*Fig 1: Differences between MCNP and WIMS $k_{eff}$ results vs. moderation ratio in operating conditions.*

The neutronic calculation confirmed the possibility to use the above determined minimum fuel masses by choosing the moderation ratio of 6.5 and 10 for the 800 $KW_{th}$ and 555 $KW_{th}$ case, respectively (Fig. 2).

Figs. 3 and 4 show the reactor horizontal and vertical cross sections in the 800 $KW_{th}$ core. It is interesting to note that the core and the reactor size is the same for the two required powers: the lower fuel content required by the 555 $KW_{th}$ core is compensated by the need to increase the moderation ratio.

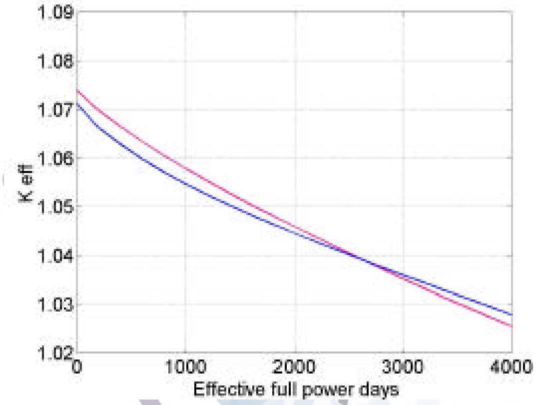


*Fig 2. $k_{eff}$ vs. burning time for 800 $KW_{th}$ (red line) and 555 $KW_{th}$ (blu line) cores.*

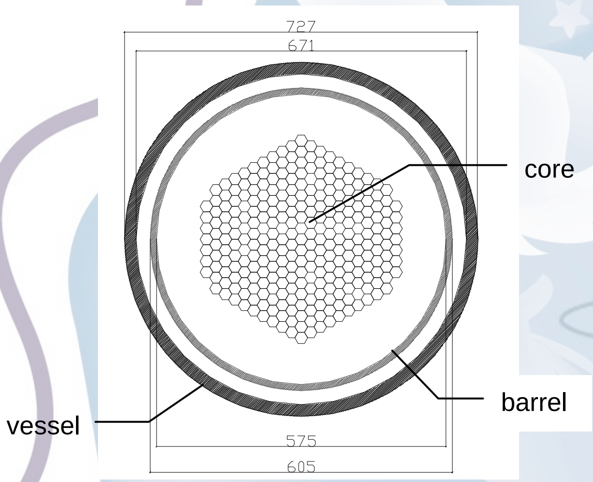


*Fig 3. Horizontal cross section and fuel channel disposition for the 800 KW reactor.*

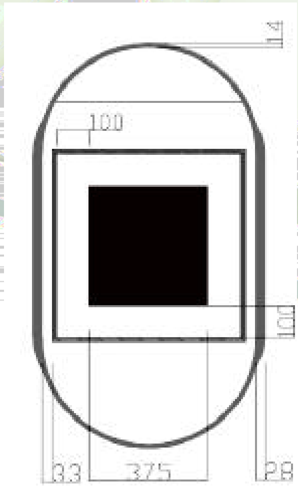


*Fig. 4. 800 KW reactor vertical cross section.*

*II.B. The Primary System*

The primary system is made by the reactor vessel which contains the reactor core, the barrel, the steam generator, the pressurizer, the circulating pump, the safety valve, the reactivity control mechanism and the instrumentation. All these components are inside the reactor vessel, thus adopting an integrated layout. This solution, suggested by the small size of the reactor, is well suited to compact the primary system to a minimum in terms of size and mass, together with a reduction of the escaping radiation and of the fast neutrons fluence on the vessel. Water flows upward through the core and then through the lower part of the upper plenum (the remaining part is filled with steam for the pressurizer), where the flow direction is reversed and the coolant is directed downward through the annular downcomer region, between the core barrel and the vessel. The steam generator is placed into this annular space; the primary water flows on the outer surface of the steam generator tube, transferring heat to the secondary fluid (water or organic fluid) down to the lower plenum, where the suction of the circulating pump is located; then the pumped coolant enters the reactor core to close the primary fluid path (Fig.5).

The vessel shape is a cylinder with hemispheric domes (Fig.4), made of steel. Evaluation is under way to select a fully stainless steel vessel or a carbon steel vessel with a stainless steel liner. This is a conservative choice, anyway motivated by the fact that the only possible alternate material is Titanium. This material has lower density (4500 $kg/m^3$) than steel (7800 $kg/m^3$), but its features both in terms of strength and corrosion resistance at high temperature are to be verified. The carbon steel recently adopted for PWR vessels has an yield stress of 205 MPa, resulting in a thickness equal to 28 mm and 14 mm for the cylindrical portion and the spherical domes respectively, for both reactors.

The barrel is a simple steel cylinder wit no pressure load, thus its thickness is determined by the requirement to have a good stiffness and to reduce fast neutronic fluence on the vessel if needed: a value of 15 mm has been assumed.

The steam generator design here proposed is different from the usual one, the main difference being that all the components – i.e. tubes and headers – are inside the pressure vessel and are compressed instead of being stretched, because the higher primary pressure is acting on the outer surfaces, hence primary stresses are compressive. As far as the tubes are concerned, stability requirements to avoid their collapse imply the adoption of a tube thickness that is about twice as much the value needed to resist to the pressure compressive stress, based on full (primary) outer pressure. This means that deterioration mechanisms due to high stresses, such as fatigue, should inherently be eliminated; those ones connected to Stress Corrosion

Cracking on both surfaces are not possible from a mechanical point of view, i.e. considering only the compressive primary stresses. Magnetite and copper impurities, or others such as lead, on the tube inner surface in contact with the secondary fluid can be an issue for long term operation, which should be thoroughly addressed when choosing the materials of the turbine system. Taking into account the limited thermal power to be transferred in this case, it has been decided to design a single helical tube in order to eliminate any thermalhydraulic instability phenomena due to parallel channels. This would imply to choose a relatively high diameter and length of the tube. The thermalhydraulic behavior of helix was not well studied in the past, thus an experimental campaign is needed for its development, also for the effect of lack or reduced gravity.

If organic fluid is adopted instead of water, three main differences occur: i) the power to be transferred is 555 $KW_{th}$ instead of 800 $KW_{th}$, ii) the heat transfer properties of complex organic fluids are worse than the water ones, iii) the organic cycle uses only saturated fluid, then inside the SG there is no superheated zone. Probably these differences are self compensating, so that the overall SG surface for the organic fluid option may result almost equal to the water one. If this is the case, also the overall layout will be similar, being the core size practically equal.

The pressurizer is a rather complex system, which can be simplified by putting the pressurizer in direct connection with the vessel (in the upper dome in our case) and bringing the outlet temperature to the saturation value. An abundant free steam volume, about 30 liters per MW, which is several times the value used in conventional PWRs, is adopted. This means 24 liters and 17 liters for 800 $KW_{th}$ and 555 $KW_{th}$ reactors, respectively. The water sprayers have been eliminated, since the large steam volume dampens the pressure variation due to the volume expansion of the primary water. These volumes are only a fraction of the upper sphere volume, which is equal to about 80 liters. The water expansion between cold and hot conditions must be accommodate as well: the specific volume increases by a factor 1.64, going from ambient temperature (on the earth) to the average reactor temperature of 340 °C. Two alternatives can be pursued: to discharge the excess of water to an ad hoc vessel or to leave an initial void inside the cold vessel exactly equal to the above volume difference. The first solution seems to penalize the system in terms of mass and volume, because this excess of water is to be discharged during the start up operation in an external reservoir; however, a given amount of water is probably needed to cope with possible water leakage during such a long period of operation. Obviously this pressurizer, integrated inside the vessel, is viable only in presence of a suitable value of the gravity to separate steam and water. This is the case for surface reactor, but not for propulsion. Some pressurization alternatives can be imagined, but each of them is to be carefully studied and experienced. Future R&D activities will be devoted to explore them.

The primary coolant pump is of the spool type[4], which has been used in marine applications and designed for chemical plant applications requiring high flow rates and low developed head. The motor and pump consist of two concentric cylinders, where the outer ring is the stationary stator and the inner ring is the rotor, that carries high specific speed pump impellers (Fig.5). The spool pump is located entirely within the reactor vessel; only small penetrations for the electrical cables are required. High temperature windings and bearing materials are currently being developed by the industry, to eliminate the need of cooling water and the associated piping penetrations through the reactor vessel. Moreover, the demonstration of long lasting operation capability, without maintenance and inspection, is part of this development program. The achievement of these goals is mandatory for this application.

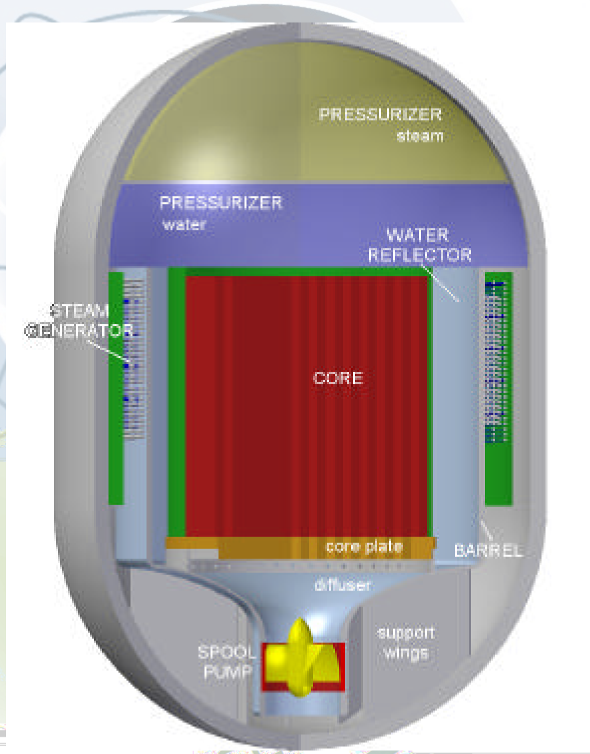


*Fig 5. 3-D conceptual view of the reactor.*

*II.C. Reactivity Control*

The PWR has inherently favorable features for control requirements, since it is characterized by a negative reactivity coefficient of temperature, which gives the reactor a load follower capability. The temperature coefficient around operating conditions in this space reactor configuration is much higher than in current PWRs: approximately 270 pcm/°C against 30 pcm/°C. The overall reactivity to be controlled is about 30000 pcm against 6000 pcm of current PWRs. The differences are due to the high enrichment and to a reduced extent to the low power density. The control of this reactivity excursion is not an easy task. Many designs foresee the use of rods inside the reflector instead of in the moderator. In small size reactors the leakage of neutrons is so high, that a reflector poisoning may be enough to reduce the reactivity, but this is to be thoroughly verified. If this is the case, the control rods can be placed in the reflector region without vertical movement, but by a rotating hollow cylinder, having on its diameter a poison plate.

Here a different proposal is put forward, based on the fact that the core is very small and its portions can be moved apart rather easily. The principle is shown in Fig.6: the core is divided in six moving slices each of a mass of roughly 20 kg, operated by a single mechanism. The requirement is that by moving apart the slices in outside direction up to a maximum radial position equal to the thickness of the reflector, the reactivity decreases continuously to a minimum equal to that required for the overall control. The neutronic calculation in such an articulated structure is rather complex.

However, preliminary WIMS and Monte Carlo calculations show that the reactivity first rises, because the core is under moderated, then reaches a maximum and afterwards goes down rapidly: at 12 cm of distance the reactor is no longer critical (this distance is higher than the reflector thickness of 10 cm, which in case should be slightly increased).

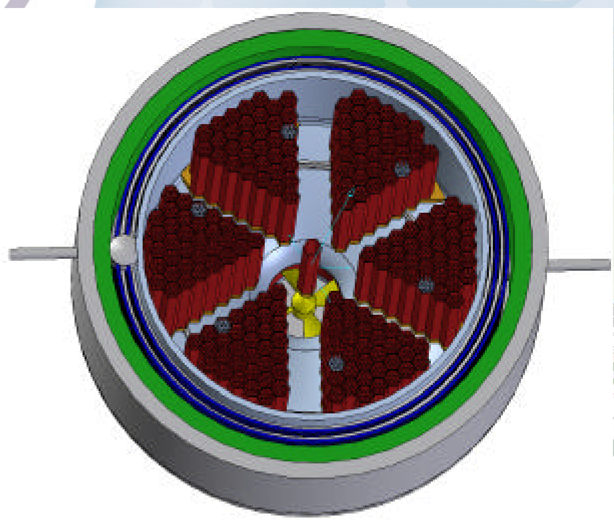

*Fig 6. Operating principle of the reactivity control system by six moving slices.*

In conclusion, the following sequence is imagined: i) the reactor starts in cold conditions at the maximum outside displacement, where the reactivity reaches $k_{eff} = 1$; ii) by approaching smoothly the slices, the reactivity rises yielding an increase of the nuclear power; the consequent temperature increase produces a negative feedback on the reactivity and then the slices need to be further approached in order to maintain a constant $k_{eff} = 1$; iii) as soon as the temperature reaches the operating one, the full power is produced and the fuel starts burning; iv) to compensate the reactivity reduction due to fuel burning, the slices are progressively approached one another along the fuel life till the point of maximum reactivity. In any condition the temperature reactivity coefficient results negative. If this proposed procedure is confirmed by further analyses, this control procedure can in principle be adopted. The demanding issues is the design of the slice command mechanism and how to avoid that the water trapped between the slices mixes with the outlet coolant, to avoid the lowering of its temperature below the saturation.

### *II.D. The Cold Well*

The cold well is one of the most crucial component of any thermodynamic cycle for space application. Referring to the solution adopting the steam Rankine cycle with power of 800 KW and a net efficiency of 12.5 %, the thermal power to be dissipated in the condenser is 700 KW. The Mars atmosphere is practically made of carbon dioxide at a pressure of 500 Pa, 200 times less than the atmospheric terrestrial pressure. This gas mixture has very low heat transfer capability, even if it cannot be discarded for this cooling action. For the time being, only radiation has been considered. In a preliminary optimisation study the conclusion was reached that the optimum condenser temperature for minimising the overall weight is around 165 °C. By assuming a tentative view factor equal to 0.6 and a back radiation of an average temperature of 300 K, the specific surface results to 1.14 $m^2$/KW, thus a total surface of 796 $m^2$. The condenser geometry is made by a bundle of 464 titanium tubes of ID/OD = 6/6.84 mm connected in parallel. The condenser can be imagined as a cylinder of 8 m diameter and 10 m height. The final design would take into account the real pay load size of the launch. In particular, if necessary the condenser can be divided in several identical pieces to be assembled on the site.

In the case of organic Rankine cycle the power to be dissipated is 455 KW. Even if in this case the thermodynamic properties of the organic fluid are not defined, on the basis of the above results the radiation is the controlling mechanism, so that the overall surface is about proportional to the power to be dissipated. Thus, adopting the same tubes, the condenser would be a cylinder of 5.3 m diameter and 10 m height.

*II.E Masses*

The overall masses are equal to about 3570 kg and 2900 kg for the 800 $KW_{th}$ and 555 $KW_{th}$ reactors, respectively. These values includes the overall reactor filled with cold water, the cold well the steam generator and the turbine, and account for a contingency of 500 kg for auxiliary systems and safety margin. These values are reasonably within the expected transportation capabilities of the launching system. Moreover, the resulting specific datum of 36 kg/KW and 29 kg/KW appears in line with alternative designs.

*II.F. Preliminary Safety Considerations.*

A detailed safety analysis is outside the scope of this feasibility study, for its complexity and the need to define the detailed requirements. In fact, this reactor would probably not be subjected to the same licensing procedure for the terrestrial reactors, anyway it should satisfy the following specific safety issues:

a) no irradiated fuel should be present at launch;
b) core subcriticality in the case of possible launch accidents (flooding);
c) radiation protection without impairing mass requirements;
d) an easy decommissioning in space.

Item a) is inherently satisfied, because the reactor would undergo only zero-power level testing before launch. Item b) seems inherently satisfied because a water reactor cannot be flooded. Item c) is a an important issue, which can be addressed only after having defined some conditions, especially for the propulsion solution. The last one is too indefinite at this stage of the design for specific consideration.

In this study, calculations have been done to verify whether in the case of severe accidents, fuel melting is avoided. If the fuel is no longer cooled by the water, the fuel heats up adiabatically till it reaches its melting point. However, as soon as the fuel temperature rises, the thermal radiation process takes place, the importance of which increases rapidly with the temperature. This radiation power is exchanged among the rods inside the core and from the outer rods ring toward the vessel and then from the latter toward the outside environment. Besides the radiation, there is also the convection of steam or air, which flowing inside the hot core brings its heat to the vessel walls and from them to the outside world. A rather simplified but sufficiently realistic model has been prepared, limiting conservatively the study only to the radiation process (based on Ref.5). The results show that the maximum temperature is far from the melting point of stainless steel (1700 K) and even more from that of uranium oxide (3000 K). However, this analysis should be improved in the future, to take into account the shrouds, the radial and axial flux distribution and the effect of rod pitch.

## III. OPEN ISSUES AND R&D NEEDS

This feasibility study led to find a first list of open issues to be solved for going on this route, which need a R&D program. The issues here below indicated are listed according to three different goals: a) those specific for space reactor, b) those interesting for terrestrial reactors as well, c) those interesting for generic terrestrial applications as well.

- fuel (a);
- internals: mechanical design (a);
- increase of operating pressure: fuel implications, primary circuit materials (b);
- saturation temperature at the reactor outlet: effect of small boiling inside the core (b);
- cold well as a condenser (a);
- small steam turbines (c);
- organic fluids: type, stability, thermal transport capabilities; small organic fluid turbine (c);
- fluid leakage: how much, how to cope with (b);
- maintenance requirements of the whole system (b);
- optimum reflector: technological aspects (b);
- pumps: development of spool pumps, reliability for long periods (b);
- neutronic fluence effects on vessel in these particular conditions (a);
- shielding (a);
- safety valves: reliability, how to cope their intervention (a);
- vessel material different from stainless steel (c);
- Steam Generator thermalhydraulic behavior in helical geometry (b) also in presence of low or no gravity (a);
- corrosion deposits inside the SG tube (b);
- pressurizer: self pressurization, different concepts for propulsion reactor as feed and bleed, cold pressurizer (b), centrifugal action (a);
- control of the system and of the reactor and its constructive implications (a).

Even if this list is incomplete, no item seems to be unsolvable. An R&D program of reasonable extent may yield the needed answers. It is important to note that the most demanding research is also of interest for the new generation Light Water Reactors. A cost sharing action could be proposed and duly programmed, according to the time schedule of the commercial exploitations of these terrestrial reactors.

## IV. CONCLUSIONS

At the end of this very preliminary feasibility study about the use of PWR system for space reactors, it can be concluded that no insoluble issues have been found, which would prevent of pursuing this route in order to execute a more detailed design. Then it will be possible to draw a more justified conclusion about the usefulness to follow this solution. At the beginning of the study it was supposed that the solutions for propulsion and surface application might be the same.

*Table I – Main data for the 800 $KW_{th}$ and 555 $KW_{th}$ reactors.*

| REACTOR TYPE: | 800 | 555 |
|---|---|---|
| Thermal/Electrical power [KW] | 800 / 100 | 555 / 100 |
| **Primary circuit** | | |
| Fuel channel | | |
| Fuel | $UO_2$ – 93% | |
| Cladding / Shroud material | Stainless steel | |
| Shroud geometry | Hexagonal | |
| # of rod per bundle | 19 | |
| Fuel rod OD [mm] | 2.2 | |
| Height [mm] | 374 | |
| Moderation ratio | 6.5 | 10 |
| # of fuel bundle | 285 | 199 |
| Fuel quantity [kg] | 53 | 37 |
| Pressure [MPa] (assumed) | 15.5 | |
| Tmax / T min [°C] (assumed) | 345 / 335 | |
| **Secondary circuit** | | |
| Cold well temperature [°C] | 165 | |
| Rankine cycle | Steam | Organic |
| Net efficiency [%] | 12.5 | 18 |
| **Vessel dimension [mm]** | | |
| Outer diameter | 726 | |
| Overall height | 1273 | |
| Spherical / Cylindrical thickn. | 14 / 28 | |
| **Steam generator** | | |
| Geometry | Helical single tube | |
| ID / OD / t [mm] | 20 / 24.4 / 2.2 | |
| Tube length [m] | 50 | |
| Inlet / Outlet sec. temp. [°C] | 165 / 335 | |
| Secondary pressure [MPa] | 5.7 | N.A. |
| **Cold well** | | |
| Type | Bundle of tubes | |
| Surface area [$m^2$] | 796 | 517 |
| Cylinder height/diameter [m] | 10 / 8 | 10 / 5.3 |
| ID / OD / t [mm] | 6 / 6.84 / 0.42 | |
| **Masses [kg]** | | |
| Overall vessel with cold water | 968 | 949 |
| Cold well | 1840 | 1196 |
| Others and contingency | 760 | |
| Total | 3568 | 2905 |

However, this hypothesis holds only partially, because the lack of gravity and of a soil render the propulsion solution rather different and more demanding than the surface one. In particular, two aspects have been outlined for propulsion reactors: the lack of steam water separation in case of no gravity (pressurizer, steam moisture separation), and the need of an autonomous radiation shield, which could be provided by local regolith in the case of surface reactors. On the other side, it was anticipated in the foreword that the use of space nuclear reactors should be approached gradually starting from the easiest application, which is that for surface use: this study is a confirmation of the statement.

In the short range, future design activities should address the detailing of many aspects of the analysis presented in this paper and add new ones. Among the first ones, fuel, cold well (in forced convection as well), reactivity and plant control. New research activities should be radiation shielding, vessel fluence, safety aspects, choice of vessel material, overall layout, containment (?), leakage control, auxiliary circuits for start up, coolant purification, radiolysis and other exigencies. Moreover, at the end of this further activity a preliminary R.& D. program should be detailed.

A list of the obtained data for the PWR reactor is detailed in Table I.

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