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Reactor Design Strategies for Martian Research Base

E. Shwageraus[1], L. Droizman[1], V. Dostal [2]
[1]Department of Nuclear Engineering,
Ben-Gurion University of the Negev, Beer-Sheva, Israel
eush@bgu.ac.il, droizman@bgu.ac.il
[2] Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology,
2-12-1 O-okayama, Meguro-ku, Tokyo 152-8550, Japan
vdostal@nr.titech.ac.jp

ABSTRACT

The recent interest in human exploration of Mars requires a reliable, high power density energy source. A nuclear power system is, clearly, the only technologically mature option for the near term deployment. A design strategy for such reactor is developed and preliminary design choices are made in this paper. The proposed reactor is a gas-cooled reactor using spherical fuel particles and compressed Martian atmosphere as a coolant.

1 INTRODUCTION

For the successful manned exploration of the Solar system the use of nuclear power is inevitable. Nuclear powered propulsion systems can provide high propellant efficiency and short transfer times to other planets, while long-life and compact nuclear reactors can provide power-rich environment for the research activities on the planet surface.

For example, Reference Mission of the Mars Exploration [1] developed at NASA relies on the Nuclear Thermal Rocket (NTR) concept for the men and equipment transfers from Earth to Mars. According to the same mission plan, the nuclear powered In-situ Resource Utilization (ISRU) unit should be set up on the Mars surface and produce methane fuel from the Martian atmosphere for the crew return trip.

The members of Mars Homestead Project™ team are taking the challenge of space exploration one step further and aiming ultimately at establishing a permanent colony on Mars. The success of such enterprise would depend to a large extent on the availability of abundant and reliable energy source capable to satisfy the colony power needs. Considering the solar energy density at the Mars surface and the availability of other local resources, a nuclear power system is, clearly, the only technologically mature option for the near term deployment. The first estimate of the Mars colony energy needs has been recently reported by the Mars Homestead Project™ team at the 8th International Mars Society Conference [2]. The main bulk of the energy is assumed to be supplied by three nuclear reactors 2 MW_{th} each.

This paper outlines the fundamental considerations of such nuclear reactor design.

2 REACTOR DESIGN CONSIDERATIONS

The major requirements for Mars base power system can be summarized as follows.

1. highest possible power density
2. high reliability (low probability of failure)
3. long service life
4. maximum use of local (Martian) resources
5. excellent safety

6. easy operation and maintenance
7. avoid using technological features, which may impede the mission progress due to political or environmental concerns.

All these considerations affected the choice of reactor concept presented here.

2.1 Power Density

Because the costs of transportation from Earth are very significant the reactor should have the smallest possible mass and volume for a given electric or thermal energy output.

2.2 Reliability

The total loss of power supply would ultimately lead to the mission failure. Therefore, the design should take maximum advantage of readily available proven technologies to assure high reliability. As was already pointed out, the Mars Homestead Project™ team, for which this power system is being developed, proposes the use of three reactors for the heat, process heat and electricity production. Three reactors, each with higher than one third of total required power, should provide for the possible reactor downtime due to maintenance or other reasons. The amount of the overcapacity of each reactor remains an open question at this point mainly because the detail power requirements are not finalized. There is even a possibility of having zero overcapacity and during the time of the reactor downtime certain activities will be halted to reduce the power consumption. It is recognized that high reliability of power supply is a beneficial factor, however, due to the large Earth – Mars transportation costs the amount of overcapacity should be optimized.

Another aspect important for the reliability of the whole power supply system is that ideally the reactors should be of different type in order to minimize the possibility of the common cause failure that could bring down all three reactors. This approach, however, increases the cost associated with the development of the reactors and may decrease the reliability of a single reactor. Since mission success is of main importance these negative effects may be justified but have to be carefully evaluated.

The last aspect that should be pointed out is that the reactor has to be able to start up after it has been launched, travelled through space and landed on Mars. After the landing any adjustments to reactor should be avoided. The reactor should be able to start-up even if slightly damaged. For this reasons the reactor core geometry should not be fixed, but variable.

2.3 Long Service Life

At the early stage of Mars settlement, the nuclear reactors could not be manufactured locally, so a new one will have to be transported from the Earth once the reactor reaches the end of its service life. The numbers ranging from 15 to 25 years reactor lifetime have been quoted in various manned mission designs. However, if well designed and maintained it can be expected to achieve a prolonged reactor lifetime so only new fuel would have to be transported from the Earth. Given the terrestrial experience reactor lifetime of 40 and more years may potentially be possible. This will, however, have to be proven by the operation on Mars.

2.4 Use of Local Resources

The use of the local Mars resources is important for two reasons. As already mentioned, the transportation costs from the Earth to Mars are significant and has to be minimized. The transportation costs are proportional to the weight at launch. Therefore, the reduction of the system weight due to omitting certain parts of the reactor system is beneficial. The second reason is that the use of local Martian resources improves the reliability of the system, since they are readily available and do not have to be transported from the Earth.

2.5 Safety

The safety of the reactor is ensured already by the requirement on the system reliability. Safe shutdown and decay heat removal and inherently safe response to the possible initiating events are sought. Minimizing the reactor weight drives the selection of the safety systems. Therefore, passive safety feature routinely applied in the terrestrial applications are not suitable as they are usually bulky and heavy. Highly reliable compact and light weighted active safety systems are more suitable. Nevertheless, the reactor design should be inherently safe and thus minimize the amount of required safety systems. Selection of the operating conditions is important as well and should ensure that fuel will not melt at any conceivable situation.

2.6 Operation and Maintenance

The reactor operation will be fully automatic at all situations. If human action will be required it will only be in the situations that were not foreseen. The system maintenance activities should be infrequent and as simple as possible. This requirement leads toward the ex-core control and minimum reactor internals.

2.7 Political and Environmental Issues

The use of potentially weapons usable nuclear materials as reactor fuel may incite public opposition to launch of such materials into space. Moreover, in the case of an accident during the launch, the system criticality upon water submersion may result in some environmental contamination. Both issues have been considered in the past as significant “showstoppers” and therefore should be avoided.

2.8 Simplicity

This section should be concluded by pointing out that several of the design considerations require a very simple design. Thus, even though simplicity is not included among the design consideration it is a result of applying the others.

3 REACTOR CONCEPT DESCRIPTION

3.1 Selection of the Core Geometry and Fuel Type

The reliability requirements call for the reactor core with variable geometry. Therefore, the suggested reactor concept is based on Pebble Bed Modular Reactor (PBMR) technology currently under development in South Africa [3] and the particle (packed-bed or fluidized-bed) reactor concepts. The TRISO particle fuel technology planned to be employed in PBMR is remarkably robust with respect to fission product containment at high temperatures and burn up levels of up to 700MWd/kg.

The core cavity is filled with fuel pebbles or particles and their packing determines the geometry of the coolant channels. The fuel pebbles or particles are added to the core cavity after the landing just before the start-up of the reactor. To avoid the criticality accident at launch, the fuel can be transported in separate packages or even separate space flights, which ensures that it will not become critical under any circumstances.

3.2 Selection of Coolant

Coolant is the basic necessity for having operational reactor. Coolant leaks occur, therefore the selected coolant should be either readily available on Mars or its required amount should be very small. The authors feel that the first choice is more favourable as coolant availability on Mars can solve potential operational difficulties. There are two possibilities: either use Martian atmosphere or

Martian water. As surface liquid water is not readily available the choice of Martian atmosphere seems more reasonable. In addition, this selection does not affect the selection of the neutron spectrum. Therefore, the reactor is cooled by Martian atmosphere or by pure CO_2, which is the primary component (95%) of the Martian atmosphere. In this case, the coolant reserves are abundant.

3.3 Selection of Operating Conditions and Power Conversion System

Use of CO_2 limits the operating temperature to at most 700^oC, due to the corrosion and CO_2 molecule stability requirements. The selection of operating conditions is largely driven by the power conversion system considerations. Clearly, the CO_2 Brayton cycle seems to be the primary option. The CO2, if brought above its supercritical pressure, can provide power conversion efficiency of up to 50% for the core outlet temperatures of about 650°C [4]. The optimum pressure required by the supercritical CO_2 (SCO_2) power conversion system is 20 MPa or more. Higher pressure than 20 MPa does not significantly increase the efficiency, but reduces the component dimensions and pressure drop. On the other hand, selection of high pressure may cause problems during the operation [4]. Therefore, there is always a possibility of using an indirect cycle, in which case the reactor could operate at low pressure. The decoupling of the power conversion system from the reactor is beneficial for the maintenance, since in the direct cycle, the turbine gets slightly activated. However, given the higher radiation background on Mars, this may not be of significant importance, as the colony inhabitants will routinely use radiation protected suits. Both direct and indirect concepts should be investigated.

3.4 Selection of Other Reactor Materials

At the early stages of settlement construction, the reactor is shielded with local materials e.g. Martian rocks and soil or operates without the shield at all. In the more advanced stages, once water becomes available, it serves as neutron moderator and reflector. This way the launch mass of the reactor can be significantly reduced.

3.5 Selection of neutron spectrum

The choice of the neutron energy spectrum for the reactor operation is not obvious. Thermal spectrum reactors tend to have more favourable safety characteristics, proven technologies, and put considerably less strain on the reactor materials. However, the reactivity-limited life of such reactors is relatively short and the presence of moderator increases the mass of the system. The fast spectrum reactors, on the other hand, are more compact, have longer life, but more challenging to control and maintain.

The proposed reactor concept offers a large degree of the design flexibility allowing taking advantage of the favourable features of both – fast and thermal reactors. Initially, the fast spectrum can be employed providing compactness and fissile material breeding with uranium enrichment satisfying the proliferation resistance limit of 20%. At this stage, the reactor can operate with lower efficiency but larger safety margins and therefore higher operational flexibility. Martian soil can be used as reflector or the reactor can operate without reflector at all achieving criticality through higher fuel loading. Later on, the water reflector can be used to switch the neutron spectrum to thermal energy range where the bred fissile material can be utilized more efficiently. In addition, the improved safety characteristic can allow up rating of the reactor operating conditions and increase its power conversion efficiency.

The reactor consists of a core pressure vessel gradually filled with fuel pebbles or particles. The fuel is added as necessary to maintain criticality and never removed. Once water becomes available, or by the time the core barrel is completely filled with the fuel spheres, the empty volume surrounding the reactor is gradually filled with water. It serves as neutron moderator and reflector. In such a design, the long-term reactivity control is achieved through the addition of fuel, or water level in the reflector, or both. The schematic view of the reactor is presented in Figure 1. The possibility of reactivity control by variation of the reflector height is illustrated in Figure 2.

In order for the reactor to have an option to switch from fast to thermal spectrum by simply filling the reflector with water, the core dimensions should be such that the presence of the reflector will be perceptible throughout most of the core volume. This is because of the fact that the thermalized neutrons will penetrate back into the core on the order of one migration length deep. Namely, the core should be thin and tall with the diameter ranging from 2 to 4 migration lengths in order for moderator in the reflector region to be effective.

The possibility of reactivity control by changing the water level in the reflector is illustrated in Figure 2 for both initially fast (UC fuel in SiC matrix) and thermal (UC fuel in ZrH2 matrix) reactor cores. The percent change in criticality due to the presence of the reflector is larger for cores with larger height to diameter ratio. The effect of the reflector is also more pronounced for the cores with high H/D ratio because for such cores the leakage is larger therefore leading to higher reflector importance.

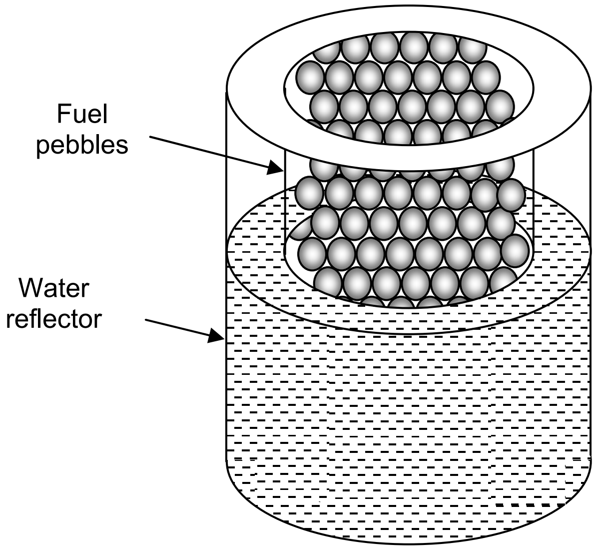

Figure 1: Schematic view of the reactor

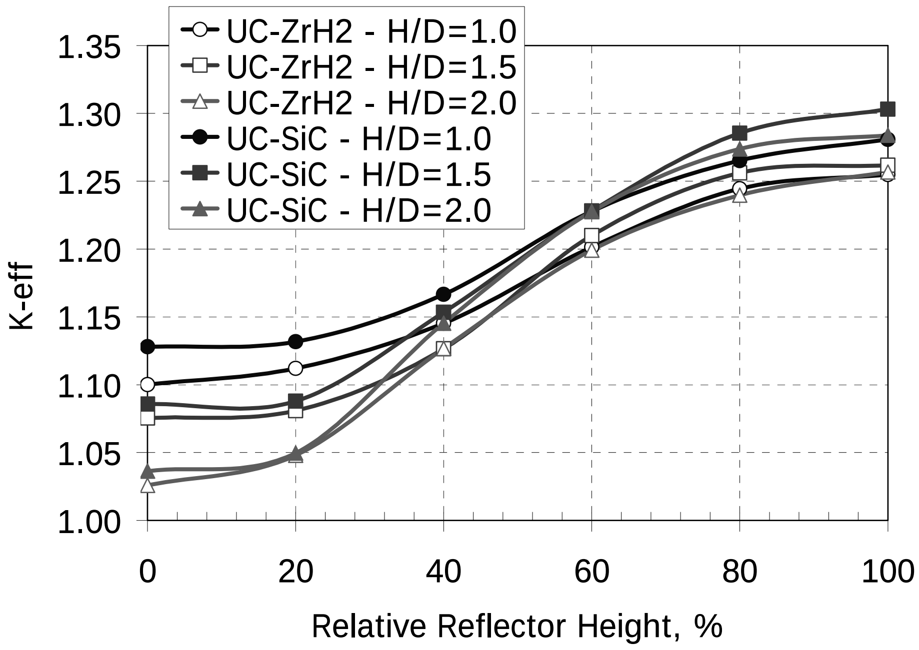

Figure 2: Criticality vs. reflector height

3.6 Selection of Pebble or Particle Diameter and Coolant Flow Orientation

Design Options

Based on the pebble or particle diameter, coolant velocity and flow orientation with respect to the gravity force, there are four basic design options:

Option 1. Packed-bed reactor – in this type of the reactor the coolant velocity is kept below the minimum fluidizing velocity. The particles or pebbles rest on the core bottom (or distribution) plate. The porosity of this bed can be approximated by the porosity of closed packed spheres.

Option 2. Fluidized-bed reactor – in this type of reactor the velocity of the coolant is above the minimum fluidizing velocity (umf). The particles (or pebbles) are fluidized due to the drag force and form a fluid-bed. The porosity varies based on the coolant velocity.

Option 3. Top pressed packed-bed bed reactor – in this type of reactor the coolant velocity is above the terminal velocity u_T of the particles. Particles are pressed by the coolant on the top reactor plate, and form the packed-bed. The porosity of this bed can be approximated by the porosity of closed packed spheres.

Option 4. Bottom pressed packed-bed reactor – in this type the coolant flows downwards, like in the PBMR. The drag force acts together with the gravity force and presses the particles or pebbles to the core bottom plate.

Advantages

Option 1. The fuel particles cannot be entrained to the power conversion system

Option 2. Fluidized-bed reactors feature an excellent heat transfer rate. The particle surface temperature is almost equal to the coolant temperature. Due to good mixing the uniform burn up can be achieved. In the accident situation the fuel particles can fall down from the core. At early stage of fuel melt a particle fuse will occur and the newly formed shape is not able to fluidize and falls down from the core preventing significant amount of fuel to be melted.

Option 3. The particle diameter and coolant velocity can be chosen independently of each other; therefore they can be optimized for the maximum heat transfer rate. In the accident situation, the fuel particles can fall down from the core. Particle abrasion is not very important.

Option 4. The particle diameter and coolant velocity can be chosen independently of each other; therefore they can be optimized for the maximum heat transfer rate.

Disadvantages

Option 1. The balance between the drag force and the gravity force has to be maintained. Which results either in larger particles or lower coolant velocities, which reduces the heat transfer rate.

Option 2. Simulations show that due to the random motion of particles the power of the reactor significantly fluctuates. Particle abrasion has not been addressed.

Option 3. In the case of upper plate failure, the particles may leave the core and, in the case of direct cycle, enter the power conversion system. This could lead to the turbine failure.

Option 4. If the fuel particles are small, they can be carried out from the core in the case of bottom plate failure.

The current design is option 4 reactor type. However, the future work will focus on the design option 2 and 3, since they offer potential for further reduction of reactor mass and improved safety.

From the thermal hydraulics point of view the core pressure drop and core heat transfer rate are the two most important parameters. From the analysis of pebble heat transfer mechanisms it is found that the most limiting heat transfer mechanism is the heat transfer from the pebbles or particles into the coolant. The reduction of the pebble or particle diameter increases the heat transfer surface area, thus improving the core heat transfer rate. With higher heat transfer rate the higher power densities are available, which reduces the total mass of the reactor. This is particularly important if the fuel kernels are used without matrix. In such case the criticality constraint may not be the most stringent one.

On the other reducing the pebble diameter increases the core pressure drop, therefore these to effects has to be carefully balanced and optimized for the particular designs.

For the particle bed the pressure drop can be calculated from Eqs. (1,2 and 3):

$$\Delta \mathrm{p} = \mathrm{f}\,\frac{\mathrm{H}}{\mathrm{d}_\mathrm{p}}\,\rho \mathrm{v}_0^2\,\frac{(1-\varepsilon)^2}{\varepsilon^3} \tag{1}$$

Where H si the core height, d_p is the pebble diameter, ρ – density of the coolant, v_0 – its velocity, ε - pebble surface roughness, and f is the friction factor defined as:

$$\mathrm{f} = 1.75 + \frac{150}{Re_\mathrm{p}} \tag{2}$$

where Reynolds number (Re) is defined as

$$Re_\mathrm{p} = \frac{\mathrm{v}_0 \mathrm{d}_\mathrm{p}}{\nu(1-\varepsilon)} \tag{3}$$

with ν - kinematic viscosity of the coolant

The heat transfer rate can be estimated from Eqs. (4-8):

$$\mathrm{hA} = \frac{4\varepsilon_{\mathrm{p}}\mathrm{kNu}}{\mathrm{d}_{\mathrm{p}}^{2}} \qquad (4)$$

$$\mathrm{Nu} = \left(1 + 1.5\left(1 - \varepsilon_{\mathrm{p}}\right)\right)\mathrm{Nu}_{\mathrm{PEB}} \qquad (5)$$

$$\mathrm{Nu}_{\mathrm{PEB}} = 2 + \sqrt{\mathrm{Nu}_{\mathrm{LAM}}^{2} + \mathrm{Nu}_{\mathrm{TUR}}^{2}} \qquad (6)$$

$$\mathrm{Nu}_{\mathrm{LAM}} = 0.644\sqrt{\frac{Re}{\varepsilon_{\mathrm{p}}}}\,Pr^{1/3} \qquad (7)$$

$$\mathrm{Nu}_{\mathrm{TUR}} = \frac{0.037\,Pr\left(\dfrac{Re}{\varepsilon_{\mathrm{p}}}\right)^{0.8}}{1 + 2.443\left(\dfrac{Re}{\varepsilon_{\mathrm{p}}}\right)^{-0.1}\left(Pr^{2/3} - 1\right)} \qquad (8)$$

where h is the heat transfer coefficient, Nu is the Nusselt number, Pr – Prandtl number of the coolant and, and k – thermal conductivity of the coolant.

As shown in Figure 3, reducing the pebble diameter to about 2 cm does not provide a significant advantage as far as both pressure drop and heat transfer rate are concerned. It is at lower fuel particle diameters, where the heat transfer rate increases much faster than the pressure drop. This indicates that in the future work the focus should be on the particle beds, rather than the pebble bed. In such cases, the fuel without matrix, i.e. only the fuel kernels, have to be used in order to overcome the criticality constraint (see section 4)

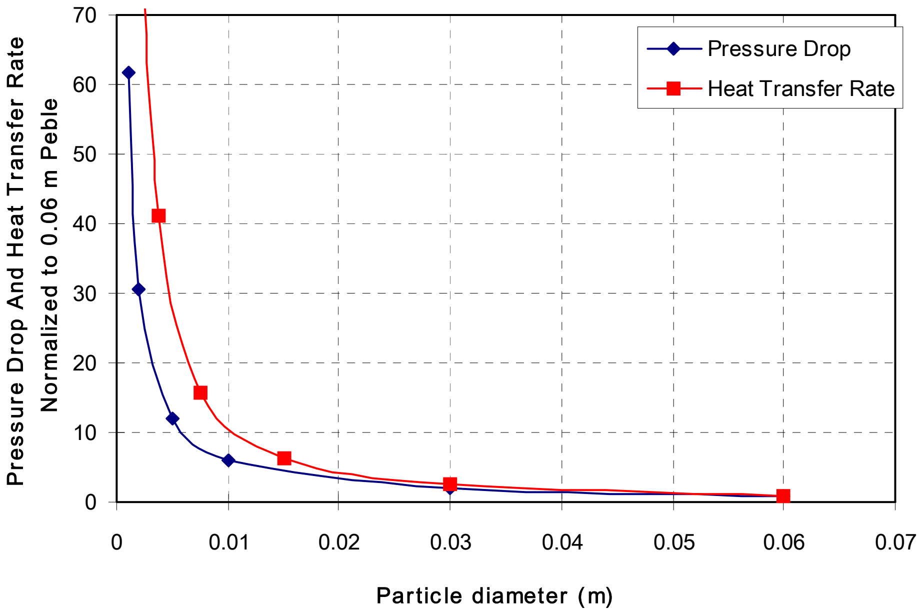

Figure 3: Effect of particle diameter on core pressure drop and core heat transfer rate (fixed height)

4 REACTOR DESIGN STRATEGY

The described approach provides high reliability of the power system. The reduced performance of individual component can be compensated by other components or more relaxed operating conditions while still being able to produce power. For example, the unexpected damage to the core barrel upon landing, damage to some fuel elements prior to loading to the reactor, or other geometry distortions can be compensated by larger fuel loading or higher water level in the reflector assuring the reactor criticality.

The reactor design for maximum power density is approached from three different directions:

- the reactor should sustain criticality for the target service life,
- operating temperatures should assure safe operation with sufficient safety margin,
- reactor materials' integrity under irradiation should be maintained.

We considered the most obvious choices for the fuel form and fuel matrix materials, which include conventional Uranium oxide and uranium carbide as fuel forms and SiC, Be, BeO, and Graphite as fuel matrices. Zirconium Hydride was also considered as neutron moderator material. These choices are based on the relevant physical properties, existing experience, as well as the research and development efforts currently ongoing or planned for the future in the adjacent reactor technology fields.

Figures 4 and 5 illustrate sensitivity of the reactor core mass to the thermal and burnup constraints assuming 25 years lifetime of the reactor and 1000°C fuel pebble surface temperature respectively and total reactor power of 2 MWth.

An increase in the designed fuel burnup allows reduction of the fuel mass with relatively small sensitivity to the fuel form and the fuel matrix.

Approximately 200 to 300 kg of the core materials' mass would be required to achieve the burnup levels on the order of 100 MWd/kg over the 25 years life. Such burnup level, although almost twice as high as that attained in the current generation of LWRs, represents a reasonable assumption because of the use of highly robust TRISO fuel particles. Most of the Generation VI reactor concepts aim at achieving similar or even higher burnup levels.

Similar to the burnup constraint, the thermal constraint puts roughly the same limits on the total mass of the core materials. The core heat removal capabilities are determined primarily by the fuel pebbles/particles size (or rather surface area exposed to the coolant) for the fixed coolant flow rate, pebble surface temperature, and the core total power (2 MWth). That is, higher power density is achievable for smaller pebbles sizes. As can be observed from the Figure 5, low mass density materials (UO2 + Graphite) are preferable from the heat removal point of view. On the other hand, high density materials (UC + ZrH2) are required to assure the core criticality. In any case, the thermal constraint limits the core materials mass to less than 350 kg even for the conventional (6cm) pebbles containing the highest density materials considered.

The calculations performed with MCNP-4C [5] computer code showed that critical system with the core mass below 1 MT can be designed having either fast or thermal spectrum depending on the fuel matrix choice (Figures 6 and 7). The uranium with hypothetical 100% enrichment was used for the analysis presented here to estimate the upper limit for the power density from the criticality constraint point of view.

Figures 6 and 7 present criticality of the UO2 and UC fuel cores respectively, as a function of total core mass. Sensitivity of the core criticality to its height to diameter ratio is also presented for every fuel + matrix combination. The core with high H/D ratio would benefit the most from the presence of the radial reflector filled gradually with water. The bare reactor however, would require higher fuel loading to achieve criticality for the high H/D ratios because of the higher neutron leakage. Since the reactor is assumed to operate in both modes (with and without the reflector), the H/D ratio would have to be optimized.

The choice of the fuel matrix material together with the reactor coolant generally dictates the neutron spectrum.

High power density can be achieved either by choosing thermal spectrum with very effective (high slowing down power - $\xi\Sigma s$) moderator or by choosing the fast spectrum through minimal use of neutron slowing down materials in the core.

Excluding the light water, Zr hydride appears to be the most effective moderator due to the high hydrogen density (greater than in light water). Yttrium hydride, however, might be the preferable choice because of its better stability at elevated temperatures despite about 20% lower hydrogen density than in ZrH2. In general, the use of metal hydrides inside reactor core is problematic because their decomposition and hydrogen leakage limit the core operating temperatures. The hydrogen containing materials can be physically separated from the fuel and introduced into the core either as separate moderator pebbles or stationary solid blocks. This would reduce the hydrides temperature and slow down the hydrogen release and leakage rate.

Somewhat more compact cores can be obtained with UC fuel than with UO2 fuel because of the higher heavy metal density in the former. The UC has also higher thermal conductivity than UO2 which would result in the lower fuel temperature. The use of Nitride (UN) fuel is also possible since UN also has higher HM density and thermal conductivity than UO2. However, the UN fuel option would likely require nitrogen enrichment in N15 isotope in order to reduce the large parasitic neutron absorption by the natural nitrogen. The UN fuel option still worth consideration since fuel manufacturing costs including nitrogen enrichment may prove to be negligible as compared with the costs of the reactor transfer from Earth to Mars.

SiC was assumed as a fuel matrix for fast spectrum core because it is currently being considered as the most promising fuel matrix choice for the next generation Gas-Cooled Fast Reactors [6]. In the current Gas-Cooled Fast Reactors studies, the matrix to fuel volume ratio is estimated to be on the order 1:1 in order to assure reliable fuel performance from the mechanical and radiation damage resistance perspectives. This ratio was used in the calculations presented in Figures 5 through 7. In the fluidized bed core option (not considered currently in the neutronic analysis), the use of the fuel matrix can be eliminated completely further reducing the core mass and increasing its specific power.

The performed calculations showed that even with 100% Uranium enrichment, the criticality constraint is the one that limits the reactor power density. Nevertheless, if political and fuel costs constraints can be overcome or turn out to be insignificant in comparison with other considerations, typical Reactor Grade (RG) Pu can be the best choice as a fuel for the fast spectrum reactor. Whereas, Am-242m is the best fissile material choice for the thermal spectrum reactor.

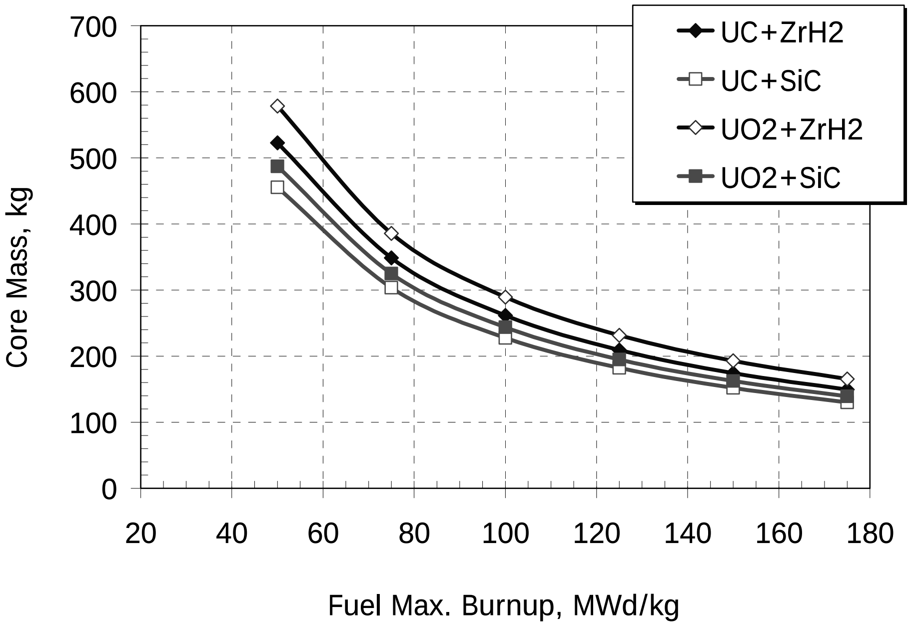

Figure 4: Core mass: burnup constraint

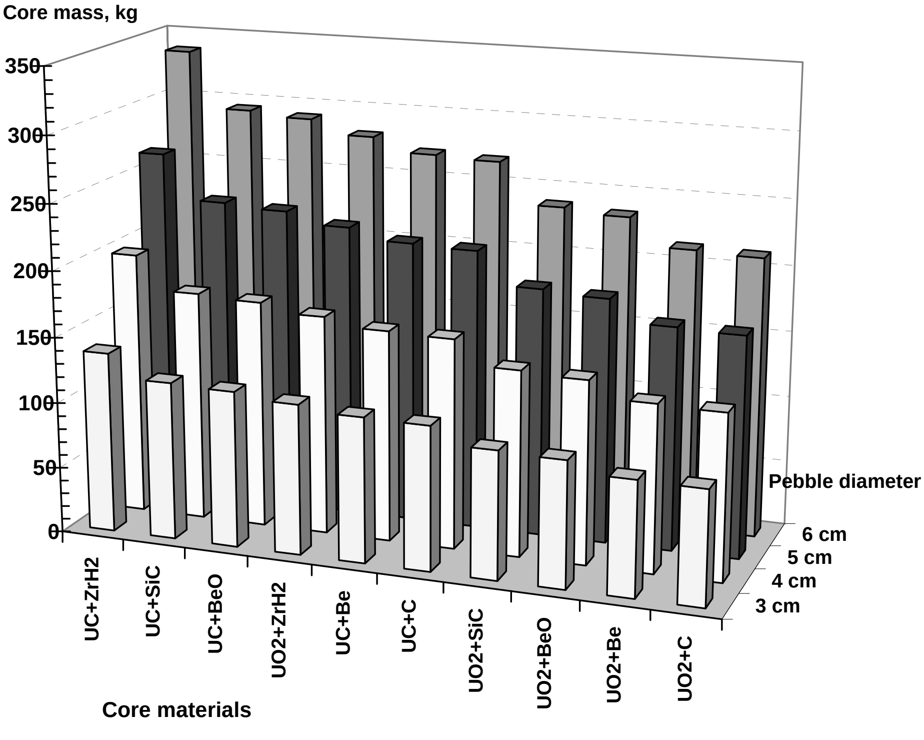

Figure 5: Core mass: thermal constraint

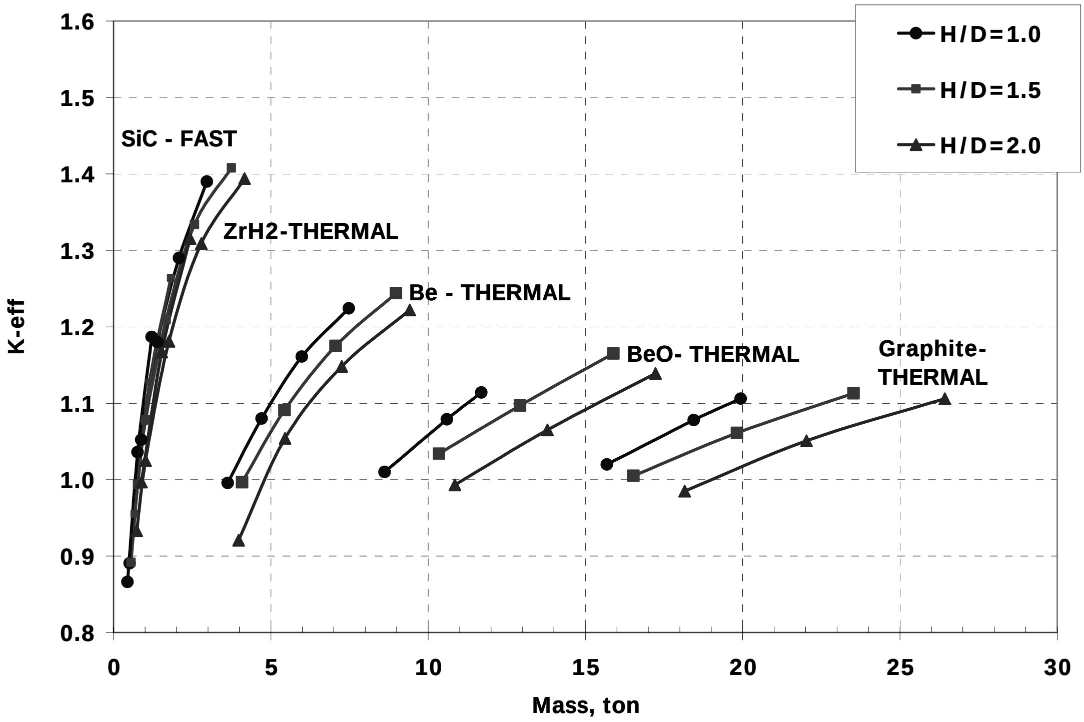

Figure 6: Bare Pebble-Bed Core Criticality for UO2 Fuel in Various Matrices

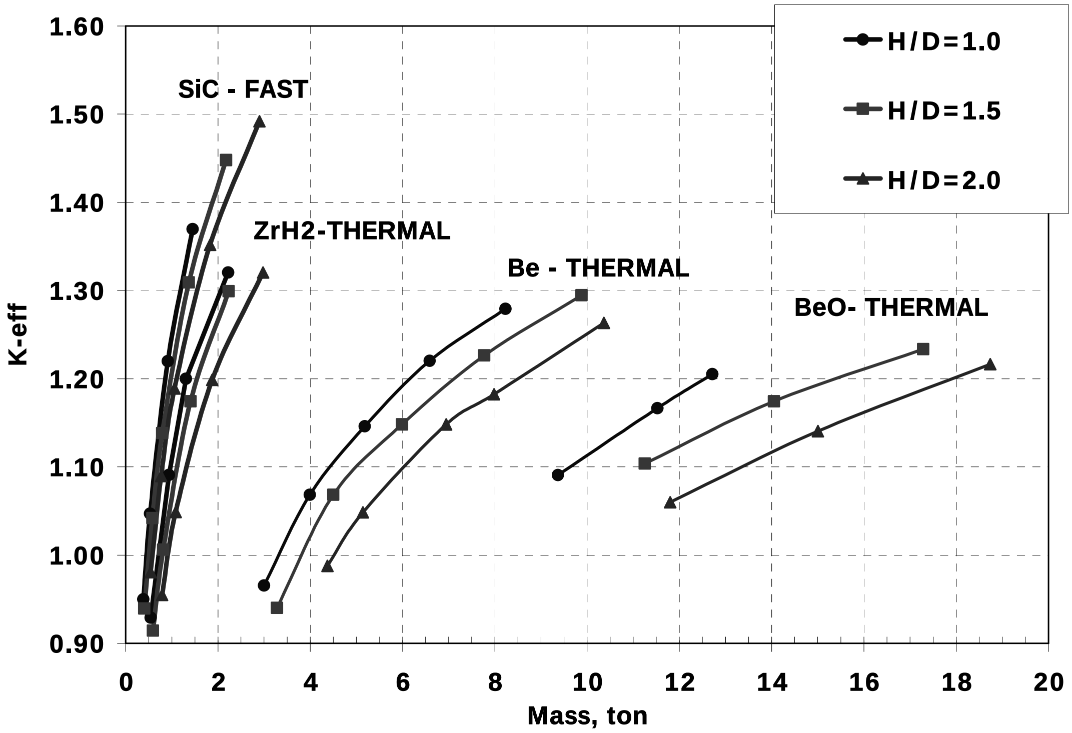

Figure 7: Bare Pebble-Bed Core Criticality for UC Fuel in Various Matrices

5 CONCLUSIONS

In this work, we propose and discuss the basic strategies for the design of nuclear power system for the permanent human settlement on Mars.

The design of such a system is fundamentally different from any terrestrial reactor. The major differences are:

- High transportation costs from Earth to Mars, which makes the system mass minimization the primary design objective to be achieved virtually by any means.
- Long service time with minimum or non maintenance activities.
- Large number of uncertainties in the reactor deployment and operation processes, which also, have to be autonomous most of the time.
- The system reliability requirements are paramount because the power system failure would likely to cause the failure of the whole mission. The consideration of these uncertainties and reliability requirements leads to a design with high redundancy and large safety margins.

The possible ways to address these issues is to take maximum advantage of the existing reactor technologies and make maximum use of the local resources on Mars.

In light of these considerations, we propose a nuclear power system based on the Pebble-Bed gas cooled reactor technology offering vast experience and highly robust fuel form. The reactor is cooled by CO2 gas from the Martian atmosphere and uses water reflector also obtained locally. Fuel pebbles loading and water level in the reflector provide the long term reactivity control of the reactor. Such strategy offers additional flexibility and redundancy in the reactor operation.

Packed or fluidized pebble (or fuel particle) bed concepts can be employed to enhance the reactor safety features and heat removal capabilities. Reduction in the fuel pebbles/particles size may significantly increase the reactor power density without compromising its safety.

Preliminary scoping calculations showed however that for the 2 MWth reactor, the system criticality is the main parameter limiting the system power density. Conversely, for the minimal critical core dimensions, the power higher than 2 MWth can be extracted.

In summary, the authors believe that the current status of the nuclear technologies is sufficient to achieve the goal of designing and operating safely and reliably a power system that will satisfy the needs of the first human settlement on Mars. The design issues outlined in the present work are planned to be addressed in the future studies.

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