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FUEL, STRUCTURAL MATERIAL AND COOLANT FOR AN ADVANCED FAST MICRO-REACTOR

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ABSTRACT

The use of nuclear reactors in space, seabed or other Earth hostile environment in the future is a vision that some Brazilian nuclear researchers share. Currently, the USA, a leader in space exploration, has as long-term objectives the establishment of a permanent Moon base and to launch a manned mission to Mars. A nuclear micro-reactor is the power source chosen to provide energy for life support, electricity for systems, in these missions. A strategy to develop an advanced micro-reactor technologies may consider the current fast reactor technologies as back-up and the development of advanced fuel, structural and coolant materials. The next generation reactors (GEN-IV) for terrestrial applications will operate with high output temperature to allow advanced conversion cycle, such as Brayton, and hydrogen production, among others. The development of an advanced fast micro-reactor may create a synergy between the GEN-IV and space reactor technologies. Considering a set of basic requirements and materials properties this paper discusses the choice of advanced fuel, structural and coolant materials for a fast micro-reactor. The chosen candidate materials are: nitride, oxide as back-up, for fuel, lead, tin and gallium for coolant, ferritic MA-ODS and Mo alloys for core structures. The next step will be the neutronic and burnup evaluation of core concepts with this set of materials.

1. INTRODUCTION

The use a fast micro-reactor (FMR) in space, seabed or other Earth hostile environment, in the future, is a vision that some Brazilian nuclear researchers share. The fabrication of a reactor system for energy supply that can be used in these environments needs R&D in many areas. In these environments the energy sources commonly utilized today in ground or satellites close to the Earth and deep space missions, like: solar energy, chemical reaction, etc., is not suitable for long time use. The utilization of solar panel is limited to a space region close to the Sun due to solar illumination restriction in deep space exploration. Radioisotope is a robust and reliable energy source for long time (decades) uses, but develop low power, less than 3 kWe [1]. Chemical reactions and combustion needs large storage of fuel. In general, these sources are usable for periods around one month and power of less than 10 kWe [1]. A nuclear reactor is an alternative that combine characteristics that is well appropriated to satisfy the requirements for use in these extreme situations, because: (i) the fuel energy density is high and has long-time (years) availability, (ii) with current nuclear technology and oriented research and development (R&D), can be projected a light and transportable energy power plant, that is, a compact reactor with suitable energy conversion system, for electricity generation and/or to produce heat for other uses, (iii) with a R&D effort, is possible to design a systems without maintenance for years of operation. A remote operation of a small reactor power plant can be made readily in the near future. The experience in space missions like unmanned spacecraft flight and the exploration of the Martian land with the Spirit and Opportunity explorers proved that technology already exits, for a remote control of a complex system.

The fast neutron spectrum was chosen for the micro-reactor [2] due to its beneficial characteristics when compared with thermal spectrum, such as: reactor compactness, high power density, better neutron economy, etc. Disadvantages are the small Doppler effect, a possible reentry accident, compaction and/or flooding, in the case of launch failure and structural materials damage by energetic neutrons. Considering the actual fast reactor operational experience, the small Doppler effect is not a concern. The other questions can be managed with engineering solution, for example: core disassembly or poisoning for compaction or flooding accidents, flexibility of operational conditions like low power density for maintain fast fluence below the structural materials limits. Clearly, the establishment of R&D program in material engineering will be needed to develop structural materials to allow the reactor long time (years) operation without maintenance.

In this conference there is a paper [2] that discusses the requirements for a high temperature micro-reactor and establishes the FMR limits for power and dimensions. Figure 1 presents a series of information organized as a function of temperature. At the figure top, it is shown the main cycles and systems used to convert power in electricity in land and in space. At the figure intermediate part, the general reactor application possibilities for ocean, seabed, space, Mars and Moon are presented. At figure lower part, the reactor types are shown. As can be seen, in the high and very high temperature ranges occurs a superposition in the operational temperature of the next generation reactor [3] and space reactor. Therefore, the R&D made in one area may be applied to another area.

The FMR intended here is the one than can satisfy mission requirements of specific time operation at defined power with maximum active core volume and power of 30 liters and 5 MW. Examples of FMR are the American space reactor SP-100 [4] and the Russian experimental reactor BR-10 [5]. The SP-100 planned selections for fuel, core structure and coolant materials were: UN, PWC-11/Re and Li, respectively. However, the full reactor was never built. The BR-10 operated until 2003, with several fuels: PuO2, UC and UN, the coolant was sodium and the cladding material was the alloy Cr-16Ni-15Mo-3Nb.

The objective of this work is to define the candidate materials for fuel, coolant and structure for a FMR. The sequence of the paper is as follow. Section 2 presents the requirements for the FMR. Several important questions related to the materials choice for fuel, coolant and structure of the active core of the FMR are presented and discussed in Section 3. The conclusion highlights the main points and finalizes the comments.

2. REQUIREMENTS FOR A FAST MICRO-REACTOR

A nuclear reactor project is initiated with the definition of its objectives and requirements [6, 7]. These definitions create the basis for decisions that enable the planning an actual project and the establishment of a R&D program. A FMR requirements were established and commented in [2]: (i) portability, utilization in different environments and conditions; (ii) flexibility, it may be used in electricity or heat generation for several applications; (iii) transportability, it can to be transported by no special means of transportation utilized in the target environment; (iv) safety-survival to accident scenarios, fail-safe, passive shutdown and robustness; (v) longevity, long-life without maintenance; (vi) extrapolation for large reactor terrestrial application (Gen-IV technology) .

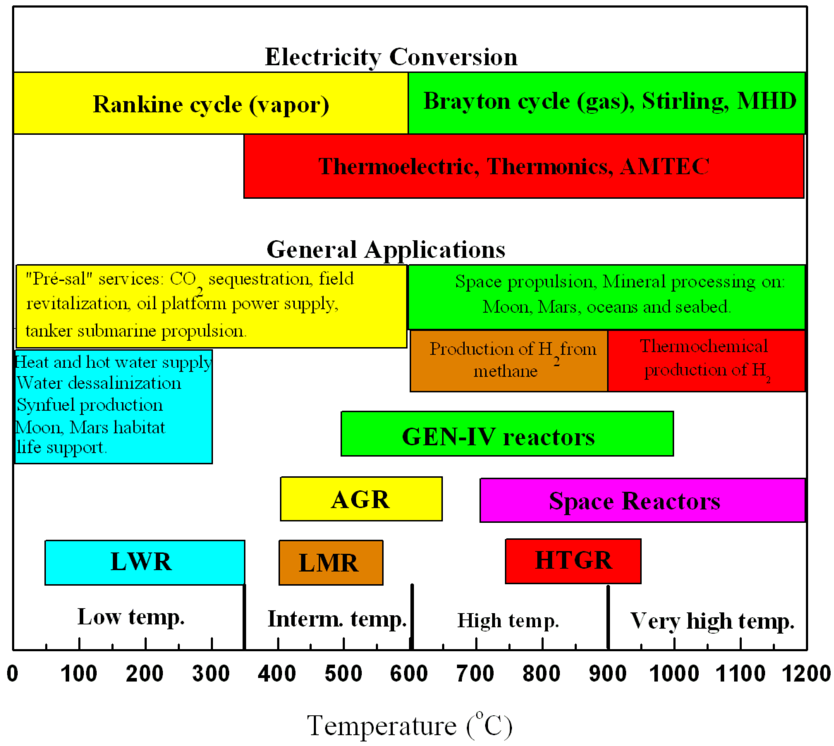

Figure 1. Electricity conversion, applications and reactors types versus temperature.

In addition to these general rules, some technical requirements can be established to limit options during an initial phase. Table 1 shows FMR technical requirements that can be classified as: essential, desirable and beneficial. In this scale the essential must be satisfied, the desirable should be satisfied and the beneficial may or may not be satisfied.

Fast spectrum reactor technologies are the main option for the Gen-IV [3]. The range of the output temperature for these reactors is 550 to 1000 ^{o}C. Today the range of temperature for space reactor is 700 to 1200 ^{o}C (Fig 1).

Considering space or undersea applications, a higher temperature allowed the use of direct electricity conversion made by thermoelectric conversion and heat rejection utilizing passive systems like heat-pipe. Liquid metal and gases are the candidate coolants for the FMR. Heated He or CO_2 can be used as work fluid in gas micro-turbine to generate electricity. In the case of undersea application, one possibility is to utilize the FMR to heat up CO_2 and pumping it into exhausted oil wells to increase the amount of oil recovered.

The limit for the fast fluence is directly related to the integrity of structural material utilized in active core and consequently to the core life. The limit shown in Table 1 is applied to the fuel cladding of fast reactor and current structural material technology, such as: CW-SS316 and HT9. Therefore the desirable long-life for the FMR core may be restricted by the fast fluence. Research in structural material may expand the present limit but the utilization in an actual FMR project will be possible only in a long-term.

Table 1. Technical requirements for a FMR

Essential	- Reactor output temperature, at least of the order of 650 ^oC or higher, target 1000 ^oC. - Neutron fast fluence $\leq 3 \times 10^{23}$ (n/cm^2) in the structural core materials.
Desirable	- Long life – minimum 5 - 10 years – without maintenance.
Beneficial	- Simple replacement of the burned core (cassete core).

3. MATERIALS FOR A FAST MICRO-REACTOR

Considering the present fast reactor material technology seems difficult to obtain an actual reactor design that satisfies all requirements listed with the same design. Compromises among core life, reactor output temperature and neutron fluence will require the relaxing of some reactor parameter, like power density, to satisfy all criteria with the same basic project and little adaptation. The conception and the design of a basic FMR that satisfy all criteria and to be used in several environments will require a carefull choice of compatible core materials: fuel, coolant and structural. Suitable neutronic properties are the first requirement for a material choice following by good physicochemical properties. The next subsections discuss the candidate materials for fuel, coolant and structural materials.

3.1. Fuel

The desired properties for a fuel material to be used in a very high temperature reactor are: good stability in operation, high melting point, high thermal conductivity, good compatibility (mechanical and chemical) with structural materials and coolant and high density. Other characteristics like, manufacturability, operational experience, behavior under accident condition, reprocessing technology and cost may be also used to define the best fuel material. The strategic requirement can override all others requirements. On the worldwide basis the most known and experienced fast reactor fuel is uranium oxide followed by U-Zr. Oxide fuel can be used as reference against a candidate fuel for comparison. Thus UO_2 is considered a back-up fuel for the FMR. Metallic fuel is not considered a candidate fuel for the FMR due its low melting point. The focus of this subsection will be on advance fuels where R&D program will be necessary to increase the data basis for steady-state and transient operations.

Several aspects of fuel performance are important to safety operation, like: material restructuring, fission gas release, swelling, etc.

Advanced nuclear fuels studied today includes: carbide, nitride and composite inert-matrix fuel (CERCER, CERMET) [8, 9, 10]. In the CERCER type the inert matrix is a ceramic material, for example SiC, ZrC, MgO, etc. The CERMET type presents a metallic inert matrix that can be: Zr, Mo, Mo-Re, etc. In both matrix types, the fuel material may be oxide, nitride, carbide, etc. The heterogeneous composite material can joint the best properties of a fuel and a matrix for a particular application.

Mixed carbide (U-Pu)C is the driver fuel of the Indian FBTR [5] that operates since 1985. The data base and experience with uranium monocarbide (MC) is higher than uranium mononitride (MN). The most data base and experience with these fuels is with the traditional pin/pellet fuel element [11, 12]. The quantity of MC and MN fuels fabricated until 2003 not exceed 1000 kg and 100 kg respectively and the number of fuel pin that have been irradiated would be less than 2000 and 200, respectively [13]. High densities fuels, relatively to the oxide type, as carbide and nitride, needs an initial free volume inside the cladding of the traditional pin design to accommodate the fuel matrix swelling during the burnup process. Thus the effective densities of these fuels are lower than its theoretical densities.

Table 2 provides a comparison of fuel properties obtained in open literature. The average power density generated in different types of fuels of actual reactor and calculated with data from Ref. [5] is showed in Table 3. As can be seen, the thermophysical properties of MC and MN are in the same range, but carbides have some disadvantage [13] relatively to nitride, such as: (i) it is more reactive and pyrophoric than MN and this requires a ultra high purity atmosphere during fabrication, irradiated carbide fuel can burn on air, (ii) $(U_y\text{-}Pu_y)C_x$ are very stable, this complicates a single phase MC fabrication (x = 1), carbides with x > 1 are undesirable in the fuel element, (iii) its higher swelling worse the conversion ratio and partially eliminate its thermal conductivity advantage over nitride in operation at high temperature. Nitride is not free from problems, its major issue is the generation of radioactive ^{14}C by parasitic capture reaction: $^{14}N(n,p)^{14}C$. A solution for this problem is the enrichment of nitrogen in its isotope ^{15}N but this is expensive. If fuel is reprocessed the enriched nitrogen can recuperated for future uses or the ^{14}C can be recuperated from the burned fuel and isolated in a solid waste and buried, what is also expensive.

CERCER and CERMET composites materials are advanced fuels materials studied since the 1960s for utilization as drive fuel of very-high-temperature space reactor and accelerator driven system (ADS) [9,17]. The composite is constituted by a matrix material and a uniformly distributed fuel particle with average diameter < 0.1 mm [9]. The fraction of each material is a parameter to be defined and qualified for each application. The differences of materials properties in the composite create safety issues in abnormal and normal operations, such as: dissociation/evaporation of one individual component, eutectic formation, etc. Several elements are studied for use as inert matrix: C, Si, Zr, Mo, Mg, etc, in compounds: formula like: SiC, ZrC, MgO, etc, or metallic form: W, Mo, Zr, Re [9, 8, 18, 17]. Nowadays oxide fuels $(U, Pu, TRU)O_2$ are the main fuel type studied for CERMET or CERCER composites due to the experience with MOX and the interest of use these advanced fuel materials for transuranic (TRU) transmutation in ADS. Research and development of Molybdenum-TRU CERMET and Magnesia-TRU CERCER are in progress for uses as ADS driver fuel [9, 10]. Zirconium carbide is a material considered for a matrix of CERCER composite to be used in a gas-cooled fast reactor [18]. Nitride and carbide fuels are alternatives to the oxide fuel considering very-high-temperature applications due to the better termophysical properties and higher densities. The fuel form consists of micro-spheres of carbide or nitride fuel dispersed in the ZrC matrix. This fuel type is expected to operate at temperature of 1400 ^{o}C that is similar to fuel temperature of HTR reactor [18].

Table 2. Properties of candidate fuel materials [1, 9, 13, 14]

Fuel	Density (g/cm^3)	Melting Temperature (^{o}C)	Compatibility with coolant	Thermal conductivity (W/mK)	Swelling [13]
UN	14.31	2630 2830	Compatible with Li [15]	15.8 (1000 K)	Higher than UO_2
UC_2	11.28	2350-2400			
UC	13.60	2400	Compatible with Na [16]	18.8 (1000 K)	Higher than UN – SD 75-81 % [11]
UO_2	10.96	2800		2.1 (1000 ^{o}C)	
U-9Mo	17.00	1135			
CERMET Mo-TRU	9,89 $^{(a)}$				
CERCER MgO-TRU	6,78 $^{(a)}$				

UN stable until 2138 K [9], $^{(a)}$ composite material/fuel fraction = 50/50 %

Table 3. Average power density for fast reactor projects (W/cm^3) [5]

Reactor \ fuel	Oxide	Metal	Nitride	Carbide
Experimental	123	483	600	657 $^{(a)}$
Prototype	377	248	149	--
Commercial	271	213	185	--
Average	257	315	312	--

$^{(a)}$ Indian FBTR

The utilization of a FMR is far in the future, after 2030 in these authors expectations. There is time to develop an advanced fuel for this reactor. All the information presented in this section indicates that the best option for the FMR fuel type is the nitride. Relatively to carbide, nitride has advantages such as: its fabrication is less complicated, the swelling is lower and the density is higher. Considering oxide fuel, the great advantage is the experience with this oxide and also it has been proven as reactor fuel for a large range on enrichment in fast reactors. Then, in a context of FMR studies the nitride fuel type is the best choice with the oxide as a backup fuel. The fuel form material is an open issue. It may be the CERMET composite or the traditional nitride pellet or vibro compacted nitride microsphere fuel in a pin element. CERCER is not considered due to its lower thermal conductivity and density in relation to CERMET with the same material fractions.

3.2. Coolant

The choice of a reactor coolant must consider the reactor module and its integration with the energy conversion system. Fast reactor may be cooled by gas (GFR) or by liquid-metal (LMR), these coolant have low neutron slowing down power. Gas-coolant has advantages over liquid metals because: it is inert, has low capture cross sections, enable run the reactor at high temperature, it works in a single phase and can be used directly through a gas-turbine without heat exchanger. The disadvantages over liquid metals are its lower density that requires high compressor power, pressurized system and low core power density. Gas fast reactor is suitable for operation with Brayton cycle. Liquid-metal reactor has flexibility and can be coupled with others dynamic or static conversion options such as: potassium rankine cycles, Stirling engines, thermoelectric devices, heat pipes, etc [19]. An important issue is the response and safety of the reactor system to an accident condition. In this last case the liquid metal coolant is superior to gas coolant because it can remove decay heat efficiently in the crucial first moments of an accident. Liquid-metal coolant eliminates high pressure in the primary system and can be circulated by electromagnetic pump, a static device.

Table 4 shows several characteristics for the reactor coolants, at 20 ^{o}C [1, 20, 21]. The nuclear properties, absorption (abs.) and moderating power (mp) were normalized with the respective sodium value. The microscopic cross section was generated utilizing a calculated neutron spectrum of a space reactor [19], with the NJOY code [22]. The heaviest coolants are Hg and Pb. From the point of view of capture and energy moderation of the neutron, the worst liquid metal coolants are Hg, Li and Ga. The alkali metals (Li, Na, K), its eutectics and Pb, presents high toxicity and requires care and proper equipment for handling. The Pb volume expansion is the largest among the liquid metal shown and this may complicate the thermal design of a reactor core, freezing is a problem.

The operational experience with fast reactor cooled by liquid-metal is restricted to sodium and at much less extent to NaK eutectic alloy. The reactor output temperature is lower than 550 ^{o}C [5]. In reality the sodium element, or NaK, is a weakness of the current fast reactor technology due its violent reaction with water needing an intermediate heat exchanger (IHX) to isolate the reactor primary system. Therefore, the utilization reactor cooled with sodium or NaK in oceans and seabed raises a major safety concern.

In the 1990s two facts renewed the interest in lead as coolant of fast reactor: (a) the experience with the utilization of the lead-bismuth eutectic (LBE) alloy in nuclear submarines of the old Soviet-Union motivated the Russians to propose the lead-fast reactor, (b) the renascence of a subcritical reactor system constituted by a fission reactor driven by high-energy accelerated proton (Accelerator Driven System - ADS) as a alternative to critical reactors. The ADS concept uses high energetic proton and the spallation nuclear reaction in a target to generate tens o fast neutrons that cause fissions in the fuel. One of the most efficient target to be used in ADS is lead. So, there is some experience with LBE coolant due to the operation of nuclear submarines. Lithium was the coolant of the SP-100 space reactor and it is the lightest among the liquid metal candidates. It also reacts with water, so it presents the same problem of sodium.

Table 4. Fast reactor candidate coolants properties [20, 21]

Coolant	Temperature (melt.) (boil.) (^oC)	Density (g/cm^3)	Normalized (abs.) (mp)	Compat. structural material	Volume change melt. (%)	Reactiv. with air, water
He	gas	0.125	(-) (1.25)	inert	--	inert
Na	(97.7) (883)	0.97	(1) (1)	corrosive	+2.65	high
K	(63.4) (759)	0.89	(3.78) (0.38)	corrosive		high
NaK	(-12) (785)	0.908	(2.84) (0.56)	corrosive		high
Li	(180.5) (1342)	0.534	(80.1) (0.96)			high
Ga	(29.8) (2204)	5.91	(5.45) (0.71)			
Pb	(327.5) (1749)	11.34	(0.35) (0.38)	corrosive	+3.6	low
Bi	(271.4) (1564)	9.80	(0.08) (0.32)	corrosive	-3.3	low
PbBi	(125) (1670)	10.47	(0.21) (0.35)	corrosive	~+0.5	low
Hg	(-38.8) (356.7)	13.53	(227) (0.47)		--	
Sn	(231.9) (2602)	7.29	(1.11) (0.31)			

Lead has many attractive characteristics to be used in nuclear reactor. It shield and reflect effectively γ rays and neutrons which escape from the core. Its low moderating power and capture cross section allows the increase of the flow coolant channels. Consequently, the natural circulating characteristics are better than sodium cooled reactors. The weak reaction with water/steam and CO_2 [20] open the possibility of the elimination of the IHX which simplifies the primary system. In principle, there is enough temperature margin until the boiling temperature and it seems feasible its utilization in very high temperature (~1000 ^oC). The system temperatures will be not limited by coolant boiling, but by the structural temperature limits or other issues like corrosion or erosion. However, lead has some drawbacks, such as: high fusion temperature and the possibility of freezing during shutdown, and a high mass density which may impact on weight limits, in the case of space reactor. The corrosion/erosion issues are technological challenges for very high temperature applications. The early issue of ^{210}Po formation, which is a problem for LBE, is not a concern for Pb [20]. The Pb higher toxicity for humans and environment can be a problem for public acceptation. In the Generation IV International Forum these issues did not excluded lead as coolant for fast reactor. Its merits directed the choice of the Lead Reactor as the one of the systems to be considered for the next generation reactor [3]. The American SSTAR and the European ELSY reactor concepts use lead as coolant [20].

The experience with gas as a coolant (He) is restricted to thermal reactors. Although gas-fast reactor (GFR) cooled by He or CO_2 was studied extensively in the past, no unit was built.

With the GIF work the interest in GFR was renewed. In 2006, the Euratom, France, Japan and Switzerland signed an agreement for R&D of a modern GFR nuclear energy system [3].

Heat pipe is a device used in several space reactor projects to remove heat generated in the core. This system is constituted by a working fluid and a suitable wick inside an evacuated pin cladding. The drive force for the operation of this passive device is provided by capillarity pressure in the wick obtained with the evaporation of the fluid in the hot side and condensation in the cold side. For high temperature uses the liquid metal are the naturally choice for the work fluid. Heat pipe with K or Na-K eutectic has been used in space reactor projects.

Gallium is a metal that presents low melting point (29.8 ^{o}C) and high boiling point (2204 ^{o}C). Among the candidate liquid metal coolants it has the second large temperature interval between melting and boiling points. This element has been proposed as the coolant for a fast reactor and the blanket of tokamak fusion reactor [23, 24]. The relevant characteristics for gallium are: low melting point and high boiling point, and compatibility with tungsten, a candidate structural material for very-high temperature reactors. Gallium does not react with water and air and can be circulated utilizing electromagnetic pump. It has been studied for uses in thermo-ionic and magneto-hidrodynamic electricity conversion systems [23].

The aim here is to consider the use the micro rector in space, seabed and other hostile environments. Although sodium is the most experienced liquid metal coolant its characteristics, reaction with water and low boiling point, eliminates its utilization in oceans and very-high temperature reactors. Lead is a new coolant in the fast reactor scenario and its utilization in oceans or land, in a very-high temperature rector, has technological questions, e.c. corrosion, that must be solved. Considering a space reactor, the lead weight is a problem to be considered. Lithium is an alternative coolant for space reactor but presents the same problems of sodium and has high neutron capture. It seems that gallium and tin are attractive alternatives to lead and sodium. From the point of view of the micro-reactor the lead, tin and gallium liquid metal can be the choices to be evaluated in more details. The sodium, potassium and its eutectics alloy can be studied for use in a heat pipe device. Cost was not considered here, but it seems that lead is the cheapest among the liquid metal candidates.

3.3. Structural Material

The choice of structural materials for the FMR operating under very high temperature and to be utilized in several environments must consider all the applications were its energy will be used. Particularly for electricity generation, the working reactor temperatures must be well established for the high efficiency of the conversion system. In the Carnot cycle the efficiency is calculated as: $\eta = \Delta T / T_{hot}$, where ΔT is the temperature difference between T_{hot} and. T_{cold}. Space and oceans are environments that provide very different temperatures and means for heat rejection. From the point of view of thermal cycle the higher the ΔT, the higher the efficiency will be, the contrary is applied for a high temperature and same ΔT. A very high temperature output for the FMR, around 1000 ^{o}C, is desirable considering space and seabed applications.

The requirements for structural materials of a long-life FMR uses include: (1) resistance to neutron irradiation embrittlement, (2) dimensional stability under irradiation (low swelling),

(3) corrosion resistance, (4) low susceptibility to hydrogen and/or helium embrittlement, (5) high-temperature strength, (6) thermal and irradiation creep resistance. From the nuclear point of view the neutron capture is not a concern considering that the reactor use fast spectrum. But a neutron absorption reaction shift (fast (low) → thermal (high)) may be considered a good property in the case of reactor flooding accident. For practical applications other technological considerations need to be established such as: mechanical and chemical interactions with fuel and coolant, weldability, workability and special heat treatment.

A structural material is developed for specific application considering: temperature, system life and the working environment. All structural materials must have a working temperature window where it can be used with relative safety during the projected system life. A way to organize the structural materials in order to facilitate choices among candidates is to use their operating temperature window.

The final choice needs a detailed thermal-hydraulic calculation, considering complete system model, reactor and conversion system, to generate a detailed temperature and pressure map. With this map in hand, the materials candidate can be chosen. This approach is an interactive process that finalize with the materials definitions and, frequently, the establishment of a R&D program to qualify these materials.

Good high-temperature properties are essential for the candidate structural core materials for the FMR like swelling, creep and corrosion resistances. Phase changes increase the susceptibility to neutron irradiation and, also, H/He embrittlement, swelling and corrosion [26] must be considered. Phase stability is crucial to high temperature applications.

In Ref. [25] Zinkle and Ref [15] El-Genk presents excellent discussions over operating temperature windows for candidate structural materials applied to fusion and space reactors. According to Zinkle the lower operating temperature limit for the most structural core materials is the radiation embrittlement and this effect will limit the lower window temperature for the FMR. This phenomenon increases with irradiation temperature below ~ 0.3 T_{melt}. - the ductile-to-brittle transition temperature (DBTT). Operating temperatures higher than 0.3 T_{melt} is acceptable. The upper operating temperature limit is determined by one of the four factors linked to the operation time: thermal creep, high temperature He embrittlement, swelling or anisotropic grow, or coolant/structural material compatibility/corrosion issues. Another superior limit to consider is the re-crystallization temperature. If the temperature rises to values higher than this point, materials characteristics, like tensile strength and ductility characteristics can be lost [15]. In general the window upper temperature limit will be determined by coolant/material compatibility/corrosion issues.

Zinkle evaluated nine materials: four reduced-activation materials (oxide dispersion strengthening (ODS) and ferritic/martensitic steels, and composites SiC/SiC, copper, tantalum, niobium, molybdenum and tungsten alloys. Fusion reactor presents the same problems that fast reactor in respect of temperature and radiation effects. For the candidate SiC/SiC composites, nowaday, the limit will be defined by radiation-induced thermal conductivity degradation due to its high swelling.

El-Genk made a similar Zinkle study, but with the focus on space nuclear power systems. The reviewed structural materials were: MA-ODS steels, Nb-1Zr, PWC11 (Nb-1Zr-0.1C), Mo-TZM, Mo-Re, T111 and ASTAR-811C. The temperature of interest spam from 1000 K to 1500 K in liquid metal, heat pipe-cooled and gas-cooled nuclear reactors. According to El-Genk for applications temperatures in 1200 - 1450 K range, niobium and molybdenum alloys are good candidates. An issue for niobium alloys is the embrittlement due to low (ppm) contamination of oxygen requiring controlled environment in fabrication and assembly and surface protection must be provided if the fuel is of oxide type. Molybdenum alloys TZM and Mo-xRe (x = 7 - 47 wt %) are more resistant to oxygen embrittlement but are heavier and has workability difficulties. Candidate alloys for space reactors structural material are shown in Table 5 with some properties obtained from Refs [15, 25].

Table 5. Candidate structural materials for a micro-reactor

Alloy	Composition (wt%)	Dens. (g/cm^3)	Norm. neutron capture	Temperature. (K)	
				Melting DBTT	Recryst.
Hastelloy	Fe-Ni-Cr-Mo-Co-W 18-49-22-9-1.5-0.5	8.22	4.39	1530 510	--
ODS MA754	Fe-Ni-Cr-Ti-Al-C-Y_2O_3 1-77.55-20-0.5-0.3-0.05-0.6	8.34	5.10	1673 496	1570
ODS MA956	Fe-Cr-Ti-Al-C-Y_2O_3 74.45-20-0.5-4.5-0.05-05	7.25	2.98	1755 526	1525
ODS MA957	Fe-Cr-Ti-Mo-Y_2O_3 84.55-14-0.9-0.3-0.25	7.69	3.23	~1800 600	1620
Nb-1Zr	Nb-Zr 99-1	8.58	1	2680 804	1253
PWC-11	Nb-Zr-C 98.9-1-0.1	8.60	1.00	2680 804	~1253
Mo-TZM	Mo-Zr-Ti-C 99.37-0.1-0.5-0.03	10.16	2.40	2893 868	1698
Mo-14Re	Mo-Re 86-14	11.9	2.37	2800 840	1645
T-111	Ta-Hf-W 90-2-8	16.7	20.6	3250 975	1923
ASTAR-811C	Ta-Hf-Re-W 90.27-0.7-1-8	16.6	19.9	--	--
W-4Re	W-Re 96-4	18.35	18.2	--	--

An important nuclear characteristic for structural materials is the capture cross section. A high capture needs a high fuel enrichment to compensate the parasitic capture of neutrons. Table 5 presents normalized macroscopic neutron capture for the candidate structural materials. The reference for normalization was the Nb-1Zr macroscopic cross section. The one group macroscopic capture was calculated with nuclear data from ENDF/B-7.0, at 300 K. The microscopic cross section was generated with the NJOY code [22] and calculated neutron spectrum of a space reactor concept [19]. As can be seen, T-111, ASTAR-811C and

W-Re presents the highest values and this is due to the higher capture micro cross sections for Hf/Re/Ta/W elements: ~58/27/7/5 (barns). For comparison, the same values for the Nb/Mo/Fe/Cr elements are: ~ 0.4/0.8/0.7/0.9 (barns). The Nb alloys presents the lowest neutron capture among the alloys in Table 5.

Mechanically alloyed oxide dispersion strengthening (MA-ODS) steels are alloys with small amount (1%) of Y_2O_3 ultrafine powder oxide dispersed in metal matrix. The inter-particle spacing must be in the order of 100 nm or smaller for effective long-term creep resistance at elevated temperature [27, 15].

The advantages of MA-ODS over Nb and Mo refractory metals are [15]: (i) their lower strength decrease at high temperature (>1000 K), (ii) lightweight and cost, (iii) low swelling and embrittlement under high fluence (10^{23} n/cm^2), and (iv) may be compatible with alkali liquid metal up to 1100 K. An issue is the anisotropy swelling that can be managed with cold work.

Studies of ODS ferritics steel made in Japan [26] show that the corrosion resistance increases with the chromium concentration in the range 13-22 %. These steels are candidates for use with lead coolant in high temperature reactor. Austenitic steels are not compatible with lead due to the solubility of Ni in lead [26]. Ferritic ODS with Y_2O_3 particles in the nano-scale (1-5 nm) range are considered as promising structural material for high burnup (100 GWd/tHM) and high temperatures (700 ^oC) core [26].

With operations conditions of 10 years and temperature approaching 800-1000 ^oC the Ni-based superalloys are not suitable, as well as ODS and refractory alloys, considering the creep performance [27]. An issue with ODS alloys for high temperature use is the weldability, the joining processes must maintain the microstructure intact to prevent weakness in its creep resistance.

If the primary reactor system works with intermediate heat exchanger (IHX) the reactor outlet temperature will be around 100 ^oC higher than the IHXr tubes temperature [27]. In a typical space reactor design the temperature may be as higher as 1000 ^oC to increase the heat rejection capacity and diminish the mass of heat rejection system.

The utilization Nb-1Zr alloy must be restricted to space and temperature above 700 K, below this temperature occur irradiation embrittlement. Niobium alloy in presence of oxygen pressures and cooled in hydrogen environment suffer oxidation and can be disintegrated into powder [27]. The oxidation concern requires that all the alloy fabrication phases, until its utilization in space, will be made under controlled atmosphere.

Molybdenum-Rhenium alloys are materials used in many industries including defense, medicine, energy and aerospace [28]. This alloy presents attractive properties for use in the space reactors [19]: high temperature strength, corrosion resistance, high thermal conductivity, good ductility and fabricability [28], excellent compatibility with lithium and sodium coolants and UO_2 fuel [15]. Rhenium is compatible with UN fuel and its capture cross section in thermal spectrum is much higher than in fast spectrum. This spectral shift characteristic is desirable in a possible space reactor reentry accident with submersion and flooding of the core. A week point of Mo alloys is the fabrication difficulties and the high uncertainty in the preservation of strength and ductility characteristics in the post-welded form [15].

For very high temperature applications, up to ~2200 K, the tantalum and tungsten alloys are good candidates [15]. The tantalum alloys T-111 and ASTAR-811C had high yield and creep strengths and good weldability and compatibility with liquid alkali metals [15]. In the El-Genk review ASTAR-811C is considered the strongest among the studied refractory alloys.

Figure 2 shows the work window temperature for several structural materials, obtained from Refs [15, 25]. The green bar indicate the possible operating temperature range and the superimposed blue bar is the temperature window recommended for the material. Only the most promising materials are presented. Superalloys are not considered for FRM structure material due to its: low melting temperature ~1600 K, matrix swelling and low creep resistance with low fast neutron fluence. The SiC/SiC [25] composite suffers a high change in thermal properties due to irradiation swelling and is discarded. The conventional stainless steel SS-316, which is used in fast reactor projects today, is not suitable due to the low limit for operating temperature (< 650 ^{o}C). But the SS316 window temperature is high (510 ^{o}C) [25].

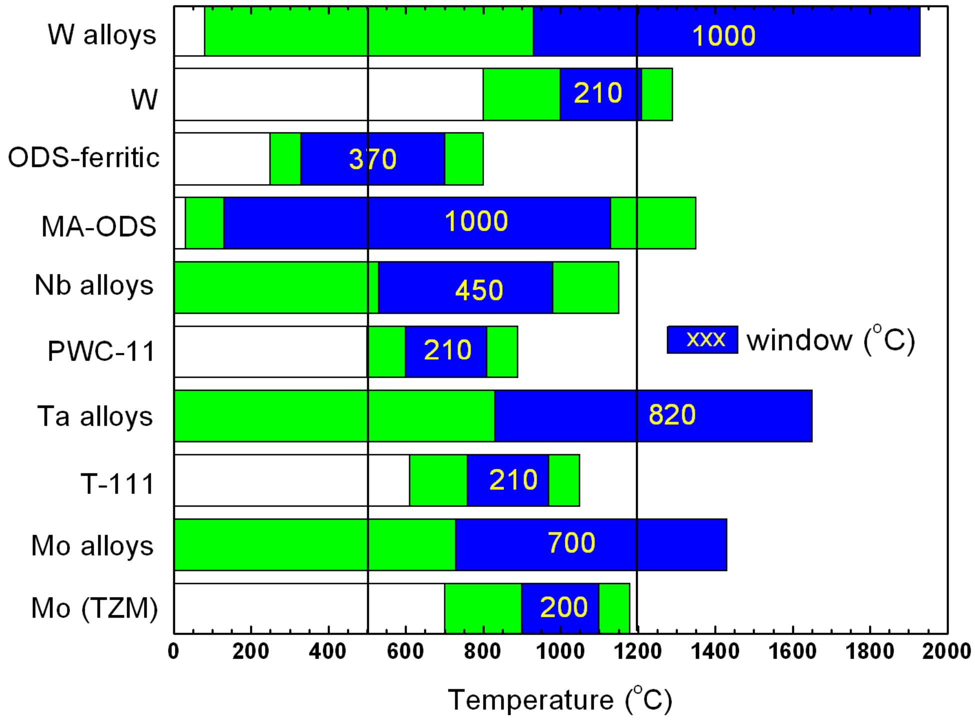

Figure 2. Operational window temperature for structural materials [15, 25]

In Fig 2 the operating temperature range, 500 – 1200 ^{o}C, for GEN-IV and space reactors is delimited by the vertical lines. As can be seen, the ranking for the candidate structural materials for the active core, considering the temperature window and the delimited range are: MA-ODS, Mo, Ta, Nb and W, alloys.

Fast fluence (>0.1 MeV) limit for MA-ODS is 10^{27} (n/m^2) [15]. An estimative for the reactor life for this fluence can be made considering the actual peak fast flux of the Russian micro-reactor BR-10 of 0.86×10^{15} (n/s.cm^2) [5]. In this case the micro-reactor structural life will be 3.7 years. If a ten years life is an objective for the micro-reactor this time can be obtained by lowering the power density by a factor higher than two. Therefore, the set of information about MA-ODS indicate that it is the most promising structural material for the active micro-reactor core today.

Refractory alloy have high creep strength at high temperatures if oxygen nitrogen and carbon elements are below 10 ppm in all phase of its life, including fabrication [15].

A tentative simple ranking for the discussed structural alloys is presented in Table 6. The materials were compared using the six criteria listed in the table. The several requirements, discussed in the previous sections were considered. The ranking was based on the authors judgments and knowledge. The best option presents the lower total score.

Table 6. Structural materials ranking

Alloys / Criteria	MA-ODS	Niobium	Molibdenum	Tantalum	Tungsten
Fuel/Coolant compatibility	1	2	1	1	1
Fabricability and handling	3	5	3	1	5
Neutron capture	3	1	2	5	4
Window temperature	1	5	4	3	2
Experience	2	4	1	3	5
Weight	1	2	3	4	5
Total score	11	19	14	17	22

Considering all information of this section and the ranking in Table 6, the best candidates to be the structural material of a high temperature fast micro-reactor core are: MA-ODS, Mo-Re alloys and Ta alloys.

4. FINAL COMMENTS

The definition of a set of compatible materials for a very high temperature, long-life operation, fast micro-rector core, to be used in several hostile environments, is a challenge. Actually, there is no one set of approved materials: fuel, coolant and structural materials that can be used with confidence and safety in these conditions. This work deals with this challenge. Based on open literature a brief review of candidate materials for fuel, coolant and structural materials were made. Utilizing several requirements and materials properties a set o materials for a fast micro-reactor were suggested, for further neutronic analysis. The set o materials to be evaluated are: nitride fuel in form of pellet, micro sphere or CERMET, lead, tin and gallium for primary coolant, and potassium and sodium potassium eutectic as working fluid for a heat pipe device, ferritic MA-ODS and Mo alloys is actually the best option for the core structural materials. The next step will be the definition of micro-reactor core concepts to perform a series of neutronic and burnup calculations to evaluate the best possible associations among the selected materials.

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