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ADVANCED MICRO-REACTOR FOR SPACE AND DEEP SEA EXPLORATION: A SCIENTIFIC BRAZILIAN VISION

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ABSTRACT

Humankind is at the point to initiate a new adventure in its evolutionary journey, the colonization of other planets of our solar system and space travels. Also, there is still another frontier where the human presence is scarce, the oceans and the Earth seabed. To have success in the exploration of these new frontiers a fundamental requirement must be satisfied: secure availability of energy for life support and others processes. This work deals with the establishment of a basis for a Brazilian nuclear research and development (R&D) program to develop micro-reactor (MR) technologies that may be used in the seabed, the space or another hostile environment on Earth. The work presents a set of basic requirements that is used to define the best reactor type to be used in these environments. Also, the limits and dimensions that define the class of micro-reactors are discussed. The fast neutron spectrum was chosen as the best for the MR and the limits for the active core volume and thermal power are 30 liters and 5 MW.

1. INTRODUCTION

The Humankind is at the point to initiate a new adventure in its evolutionary journey, the colonization of other planets of our solar system and space travel. Besides, there is another frontier where the human presence is scarce so far, the oceans and seabed. To explore and dominate successfully these new frontiers a fundamental requirement must be satisfied: secure availability of energy for life support and others processes.

In the past, until the end of the 80`s, the old Soviet Union was the leader in space reactor utilization. Between the years 1970 to 1988 it launched 34 Cosmos spacecraft to place at Earth orbit a satellite powered by the 32 BUK and 2 TOPAZ reactors [1]. Today the main developer of nuclear energy for space exploration is the USA where the nuclear reactor space development initiated in the 50’s. The main milestone of the USA program was the 43 kW_{th} SNAP-10A launch in 1965 that operated during 43 days [1]. Nowadays several USA laboratories are making R&D effort in many technologies that will enable to establish a permanent base on the Moon in next decade and to launch a manned mission to Mars after

2030 [2]. Early studies were made and they designed a spacecraft to visit and explore Jupiter iced moons (JIMO - Prometheus project) [3]. In all of these missions the nuclear reactor is the main source of power supply.

An estimative of the necessary power in bases on the Moon and Mars can be made considering the current ~ 6.0 kW per capita consumption of primary energy in industrialized countries. The consumption in these bases will be much higher taking into account all the needs for life support in these hostile environments. At least a 60 kW per person would be a first guess. With this value a small base with a population of 10 people requires a power source of 600 kW. Table 1 shows some space application power needs obtained from open literature [1-3].

Table 1. Power needs in space

Mission	Power (kWe)	Comments
Space shuttle	15	In orbit
International Space Station	75	
Moon	10 to > 100	Habitats, in-situ resource utilization plants, mobility and construction equipment, science experiments.
Mars	20-60 10 - 200 (MW)	Habitat range Power engine (39 days trip to Mars)
JIMO	200	Nuclear Electric Propulsion 10-20 years operation

The Brazilian company PETROBRAS is a world leader in the deep sea oil exploration. The discovery of large oil reserves into “pré-sal” (pre-salt) layer at Brazil continental platform may stimulate the development of new technologies to explore costly e safely these reserves. Today the main infrastructure necessary to offshore exploration is located at sea surface. A platform of this type requires a number of technicians to operate and control the plant, a flexible pipe lines for transportation of the extracted oil from the seabed to the sea surface and the storage of the extracted oil for further transportation by ship. An offshore extraction platform is designed for a specific oil field and there is neither an average platform nor an average electric power source for this type of equipment. Today, pumps and some processing equipment located at seabed are supplied with energy generated at the platform. Considering the energy need of an oil platform, it seems reasonable to assume that the heat/electric power source can be in the range of 50 to 100 MWe.

An alternative to the sea surface platform can be a submerged platform operated remotely. The transport of the oil may be made by large specially designed and remotely operated tanker submarine. All transport operations can be made remotely from the dock coupling at point of charge to the point of discharge. The proximity of the platform to the points of extractions avoids long pipe lines. It may be located at the best point to supply electricity for pumps, heating oil for its transport in flexible pipe lines, heating gases (e.g. CO_2) or water for injection in the oil well, etc. The hot fluid injection improves the amount of oil recuperated from the well. If the fluid is CO_2 its sequestration will be a mitigation of a greenhouse gas. Here it is possible a synergy between the space technology development and the undersea exploration. All that has been developed in remote operation, control and coupling systems can be used, with some adaptations, from one case to another. Perhaps the exploration of these oil fields will be the effective start of the colonization of the bottom of the sea and oceans by the human being.

The construction of a system for power supply that can be used in environments cited above needs R&D in many areas. For space and seabed applications the energy sources commonly utilized today on the ground, on satellites close to the Earth and deep space missions, like: radioisotope, solar, chemical reaction, etc., are not suitable for long-term use. Solar panel has limited use due to solar illumination in deep space exploration and oceans. Radioisotope is robust and reliable energy source, for long time uses, but has low power, less than 3 kWe [4]. Chemical reactions and combustion need large fuels storage. In general, these sources are usable for periods around one month and less than 10 kWe [4]. A nuclear reactor is an alternative that combine characteristics that is well appropriated to satisfy the requirements for use in these situations: (i) the fuel energy density is high, what enable long-term (years) availability, (ii) with current nuclear technology (knowledge), and oriented R&D, it is possible to design a light and transportable power plant based on a compact reactor and suitable energy conversion system that will be able to transform the nuclear heat into electricity, and/or to dispose heat for use in other needs, (iii) with a R&D effort it is possible to design a system without maintenance for years of operation. The experience in space missions like the exploration of Mars with the rovers Spirit and Opportunity proved that successful technology for a remote control of a complex system already exist.

The objective of this work is to shown the ideas for a Brazilian fast micro-reactor (MR) that can be used in the space, seabed and terrestrial hostile areas in the future, after 2030.

2. MICRO-REACTOR REQUIREMENTS

A nuclear reactor project may be initiated with the definition of its objectives and requirements [5, 6]. These definitions create the basis for the decisions that enable the establishment of a R&D program and the planning to develop and build an actual plant. The initial considerations and requirements are not definitive, but they are dynamic rules that frequently need to be adjusted considering others relevant information’s to guarantee that the final objective is attained in the proper time. The success depends on the suitable feedback information management and from decisions made during the project life. Table 2 organizes the requirements for the MR multi-environment applications from the authors` point of view and based on references [5, 6].

Today, the GEN-IV fast reactor output temperature is 550 ^{o}C for sodium-cooled reactor, maximum of 800 ^{o}C for lead-cooled reactor and 1000 ^{o}C for the thermal Very-High-Temperature Reactor (VHTR) [7]. Fast spectrum reactor technologies are the main option for the GEN-IV. Therefore, the next fast reactor generation will have a higher output temperature than the present fast reactor technology. This increase in output temperature will enable the utilization of gas turbine, Brayton cycles, to generate electricity and to increase the system efficiency.

Table 2. Micro-reactor power plant requirements

Requirements	Comments
R1	**Portability**: utilization in different environments and conditions**.** The MR must be able to be operated remotely or autonomously in different environments, like: space, oceans and other hostile Earth regions, with little project modifications. Each one of these environments has characteristics that are very different from others. Therefore, the utilization of the same reactor project in those environments is impossible. Some adaption in a basic design must be made.
R2	**Flexibility**: use in electricity, hydrogen or heat generations. The MR must be the thermal power source of a versatile energy conversion platform that can generate electricity, heat for processes, steam, etc. To satisfy this requirement the reactor operation temperature must be the highest possible.
R3	**Transportability**. The MR platform must be able to be transported by the usual means utilized in the target environment. Dimensions and/or weight must be considered premium on this case.
R4	**Safety/Survival**: fail-safe, passive shutdown and robustness**.** The reactor plant must be protected against all events identified in the base accident scenario considered for the target environment, including transportation accidents. The MR must be able to survive or, at least, to operate partially and safely after a low level accident condition or malfunction. Safety must be based as much as possible on physics phenomena and passive systems. If the reactor fails definitely, it must fail in a condition that preserve its integrity and that does not need an external intervention for definitive passive shutdown. In all conditions the decay heat must be safely removed.
R5	**Longevity**: long-life without maintenance. The MR must be able to long-time operation, years, without periodic maintenance. Sub-systems that are critical to the reactor operation must have suitable redundancy and diversity to enable the reactor operation if one of them failed.
R6	**Extrapolation**: as much as possible adherence to the GEN-IV requirements for terrestrial high power applications. The technologies used in a MR shall be extrapolated to enable high power reactor units that can be used to supply the society energy needs.

For space or undersea applications, a higher temperature will enable the utilization of direct electricity conversion made by thermoelectric generator and heat rejection utilizing passive dispositive like heat-pipe. At deep space the heat rejection will be made by radiation transfer, the high temperature favors a small heat rejection area because the radiation heat transfer efficiency varies as the fourth power of the absolute temperature [8]. One possibility is the use of gasses: He, He-Xe, CO_2 as a reactor coolant. But, in this case the reactor primary system will need a compressor and a heavy structure to support to the gas pressure.

Considering the present reactor material technology, it seems difficulty to project a reactor that satisfies all requirements listed on Table 2, without adaptations. Compromises among core long life operation, reactor output temperature and structural radiation damage will need the relaxing of some reactor parameter like power density, to satisfy all criteria with the same basic project. Actually, the conception and the design of a basic micro-reactor that satisfies the established criteria will require a carefully choice of compatible core materials and the establishment of a R&D program in the advanced materials engineering area.

3. THERMAL VERSUS FAST MR NEUTRON SPECTRUM

The average power density in the core of a prototype fast reactor calculated in Ref. 9 is 0.308 (kW/cm^3). This value is 2.31 greater than the 0.093 (kW/cm^3) power density of the Brazilian ANGRA 2 PWR reactor [10]. Considering the same reactor power, the active core volume of a fast reactor will be lower than the one of a thermal reactor. This is possible because a liquid-metal cooled fast reactor has much better heat removal capacity and physical properties than the respective water or gas coolant thermal reactors. Therefore, a fast reactor with a small core can develop a relatively high power. To make the best choice between the thermal and the fast neutron spectrum reactor, the requirements established in Table 2 are used as a guideline in the general discussion below.

The portability (R1) and flexibility (R2) requirements are intrinsically associated to the reactor work temperature. The higher is the temperature the easier will be the adaptation of a basic design for a specific environment and needs. Both, thermal and fast spectrum reactors may be operated at high temperature. If experience must be considered, the thermal spectrum is a good choice due the operation of gas cooled reactors in the world [11]. But, this experience comes from advanced countries. Today, Japan with its HTR-10 is the leader in this technology. In the past, at a research Brazilian institution (“Instituto de Pesquisas Energética e Nucleares- IPEN”), there was a program to develop a high temperature reactor in cooperation with a USA company. This program was terminated at the end of 70´s. Therefore, Brazil lost the gained experience and all must be developed or acquired by some way if the choice is for HTGR. Experience is not a point to consider for Brazilian case. The main technologies for the GEN-IV reactors use fast spectrum with increased output temperature. If Brazil wants to develop these advanced reactors and the MR, a logical choice will be the fast neutron spectrum that satisfies both applications. Certainly, the development cost of one technology is lower than the development cost of two technologies. Fast neutron spectrum is favored by R1, R2, R3 and R6 requirements.

Thermal reactor is larger than fast reactor due to the necessity of a moderator. Graphite and yttrium hydrides are possible moderator materials for the MR [4]. Yttrium hydride is a material based on hydrogen that is an efficient moderator. It has some unknown long-term effects like the material stability in a high temperature and irradiation fields [4]. Graphite is a proven material for high temperature applications but it is much less efficient than hydrogen for moderating the neutron energy and increases the reactors dimensions. Fast reactor does not need moderator and will be more compact than thermal reactor. It can be operated at high temperature with suitable fuel and structural materials choice. An important consideration is the smaller the reactor core the smaller will be the shielding mass. For example, in reference [8], utilizing a concept of thermal or epithermal reactor of 100 kWe power, a mass penalty of 1000 kg was calculated relatively to the shielding of a fast reactor. The core and shielding are the heaviest components of the reactor. The transportability requirement (R3) will be more easily attained with fast spectrum.

Table 3 presents the ratio between one group capture cross section [12] generated with a Maxwellian spectrum integrated over the thermal energies range and with fission spectrum integrated over fast energies range. Figure 1 shows the neutron produced by absorption in ^{235}U, as function of incident neutron energy, calculated with the Janis system [13]. The capture or fission cross section of: fissile, control and structural materials in the thermal energies range are ten to thousand higher than those in fast energies range. The positive reactivity needed in the thermal spectrum to compensate the parasitic capture in structural materials, the capture in fission products and the reactivity lost due to fuel burn up is higher than in the fast spectrum. Fast spectrum is more efficient to core life from the neutron point of view. The ^{235}U one group σ_c/σ_f ratio considering the thermal and the fast energy region is 0.17 and 0.07, respectively. The ratio between these values is 2.3, an increase of 130 % in favor to fast spectrum. Also, Fig. 1 shows that the ratio between produced and absorbed neutron (η) for ^{235}U fast fissions is higher than 50% than the η for ^{235}U thermal fissions. There are more disposable neutrons for conversion from fertile to fissile nuclides. Consequently, the core conversion ratio is better and the burn up reactivity is lower than in the thermal spectrum.

Table 3 One group $\sigma_c^{thermal}/\sigma_c^{fast}$ ratio for selected elements

Element	Ratio thermal/fast	Element	Ratio thermal/fast	Element	Ratio thermal/fast
U-235	945	Ti	237	Li	574
U-238	36	Zr	20	Be	5740
Fe	631	Re	604	O	2
Cr	1083	W	349	B	817
Mo	71	Na	2049	Gd	340668
Ni	634	Pb	56	N	1917
Xe-135	2.6E+8	Sm-149	2.7E+5		

Xenon and samarium fission products capture cross sections presents a huge increase in thermal energies range and poisoning is a penalty for thermal reactor. The poisoning may restrain operational restart up after an abnormal event solution and may increase the number of core thermal cycles. The operation of a core at high temperature and the thermal cycling increase may raise the uncertainties in the operational reliability for a long life core due to the irradiation effects in the structural materials. A possible solution to overcome this problem is supply a reactivity to enable the restart up in all condition during the core life and this is a penalty for thermal spectrum. Therefore, the neutron economy is worse and reactivity control is more complicated to be implemented in thermal spectrum. Fast spectrum does not have problems with poisoning or parasitic capture by structural materials. The large mean free path of fast neutrons allows that the control can be made easily with reflectors and absorbers outside the core. The R4 and R5 requirements are better achieved with fast neutron spectrum.

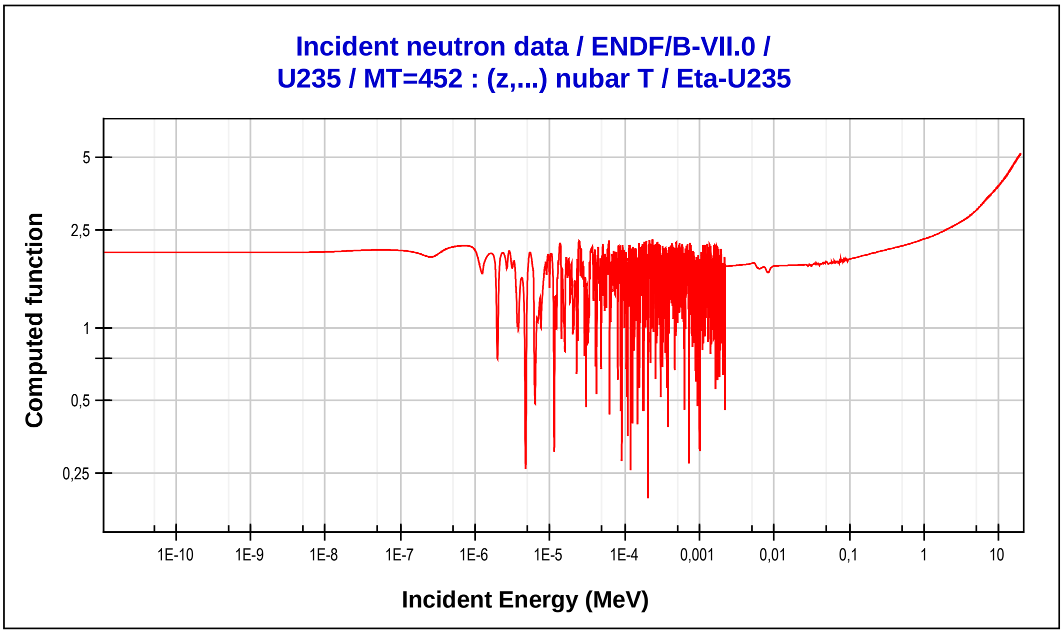

Figure 1. Eta for ^{235}U.

Three weak points of fast spectrum core are: the small prompt negative reactivity due to small Doppler effect, a possible positive reactivity insertion for core compaction and flooding in the reentry accident considered for space reactor, and average neutron energy greater than 100 keV. A high Doppler effect is desirable in transient overpower accidents (TOP) due to its prompt actuation. But considering the long time TOP passive reactor response, the higher effect is undesirable because may delay the establishment of a possible stable state condition. Here, the key is the time constants of the reactor core system feedback. A high Doppler effect introduces positive reactivity when the temperature decreases in response to core expansion. The core compaction and some thermalization of the neutron spectrum are possible in the reentry accident of a space reactor and it must be protected against these accidents. An engineering solution possibility is the disassembly of the core when it strikes land or ocean. Other possibility is to utilize structural and/or control materials that had large changes in the capture reaction with the change in the neutron spectrum. The core structures suffer damage when high energetic neutron strikes and dislocates an atom in the crystalline reticule. The amount of damage is a function of the neutron energy, flux level and time. Considering a long life core operation, fast spectrum requires a radiation resistant structural materials and/or a suitable operation power choice.

The core may be solid with metal-fuel matrix or the traditional fuel pin with cladding and coolant flow channel. The coolants may be gas or liquid–metal. For liquid-metal coolant a static electromagnetic pump can be used for fluid circulation. High conversion efficiency requires a high difference between output-input core temperatures. Liquid metal or gas coolants enable high output temperature and, consequently, a higher efficiency can be attained if heat pipe or Brayton cycle are used for electric conversion. Utilizing Brayton cycle, an intermediate heat exchanger will be necessary with liquid-metal coolant and the primary system will be more complex. If gas is used as coolant, thermal and fast spectrum can be used for high output-input temperature difference, but the primary system needs a compressor and the pump requirements will be higher than the liquid metal case. If closed Brayton cycle is used for conversion the complexity of an intermediate heat exchanger use may be avoided with inert gas coolant.

Table 4 is the synthesis of the discussions made in this section and the mark for each spectrum type points the relatively best option for Brazil, from the point of view of the authors.

Table 4. Requirements comparison for thermal and fast spectrum reactors

Spectrum / Parameter	Thermal	Fast	Related requirements	Comments
Core dimensions		●	R1, R2, R3, R6	Smaller is better
Shield mass		●	R1, R2, R3, R6	Smaller core → small shield
Reactivity excess		●	R4	Smaller is better → small control
Doppler effect	●		R4	Higher is better → quick response to accident
Neutron coupling		●	R4	Uniform burn up and core response to reactivity insertion
Fuel enrichment	●			Smaller is better → lower cost and proliferation concern
Power density		●	R1, R2, R3	Higher is better → small core
Experience	●		all	Higher is better → lesser R&D
Operational temperature	●	●	R1, R2, (R6 for fast)	Higher is better → high efficiency and small heat rejection area
Core long life: burn up reliability radiation	●	● ●	R4, R5, R6	Small reactivity and low pressure is better Swelling embrittlement

As it can be seen in Table 4, fast reactor is the system that better matches the listed requirements and is the chosen reactor type for the micro-reactor.

4. HOW SMALL IS A FAST MICRO-REACTOR?

The word micro represents an idea of very small. The micro-reactor discussed here is not the smallest critical reactor possible as presented in [14]: "a thermal spherical core fueled with $^{242m}Am(NO_3)_3$ in water with radius of 9.6 cm", that is a purely scientific curiosity. Also, it is not the small design of a particular conception like the one presented in Ref [15]. Here the search is for the limits for power and dimension that define a micro-reactor. This search was based on conceptual studies or actual projects. Certainly, the definition of micro-reactor is related to the experience in nuclear reactor area and it has a subjectivity level.

The IAEA currently classifies small reactor as the one where the generated electric power is less than 300 MW and medium sized reactor as the one that allows equivalent electric power between 300 and 700 MW [16]. By extrapolation the large power reactor is the one with electric power larger than 700 MW. And what does mean micro-reactor?

Fig. 2 shows the active core volume and Fig. 3 the reactor power density for actual and projected fast reactors considered for space and earth applications. Table 5 presents the calculated average power density for the main fuel type used in several fast reactor projects [9].

The major space reactor projects and the Russian experimental reactor BR-10 have active core volume less than 100 liters (Fig.2). With this volume it is possible to have a square shaped cylinder active core of ~50 cm. In respect to the power density parameter (kW/cm^3), the same reactors present values between 2.5 to 600 (W/cm^3) (Fig. 3). A core with 100 liters of active volume and operating with power densities in this range will generate a power from 0.25 MW to 60 MW range.

Another point to consider is the transportability requirement in the target environment. Certainly, the transportation to space will be more problematic than in Earth, logistically speaking. A complete power plant consists of reactor core, shielding, controls and all the energy conversion system. Space transportation will be limited by the space cargo limits, the higher the core power, the higher will be the rejection area and shielding weight. Utilizations in land or oceans are less restrictive. Therefore, the reactor core must be the smallest for space applications.

Today, considering electricity supply in space, Moon and Mars during 5 to 10 years (Table 1), the American SP100 concept, a 2 MWth (100 kWe) with 28.2 liters core, may be considered a superior limit. For space propulsion the reactor power may be in the range of units up to thousands of MW, and the core volume may reach units of m^3, depending on propulsion type: electric, direct, etc. A space reactor project must be conservative relatively to Earth use to guarantee the reliable operation and safety during the mission time.

The ocean is an environment where heat rejection can be easily achieved, but the transportability to seafloor may limit the dimensions. The reactor power is less restrictive in the oceanic environment and a projected reactor for space application may be operated with a higher power in oceans. The average power density for oxide fuel, Table 5, ~260 W/cm^3 is a viable value to consider in the near future for all fuel type. Considering this power density and 100 liters core, the reactor power would be 26 MW, a very high power for a micro-rector.

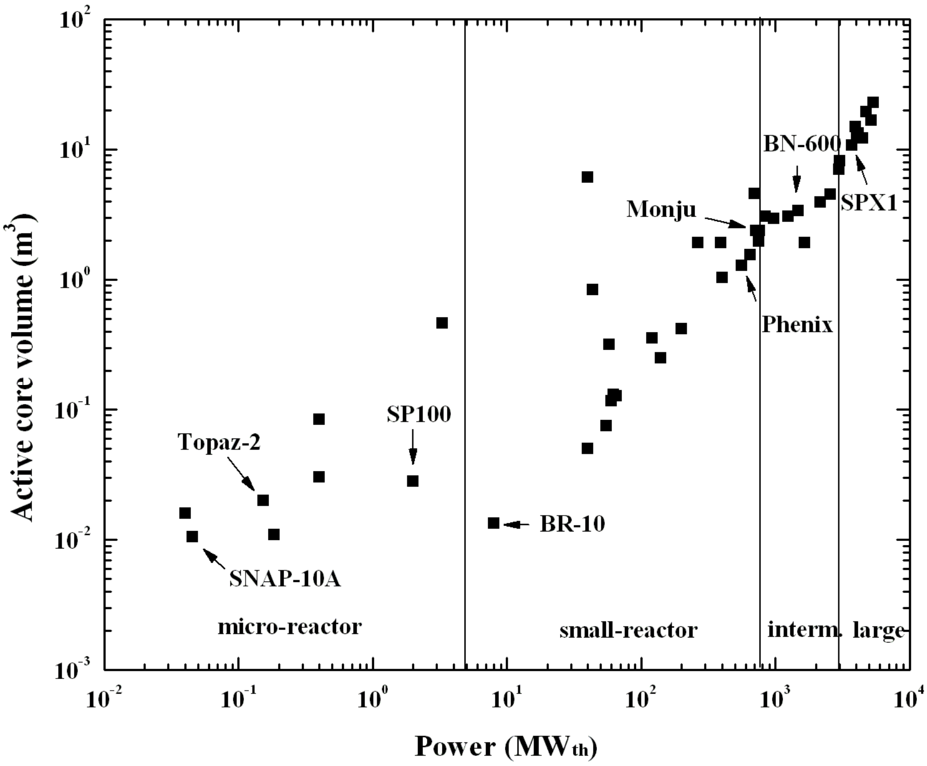

Figure 2 Active core volume versus power for fast reactors projects.

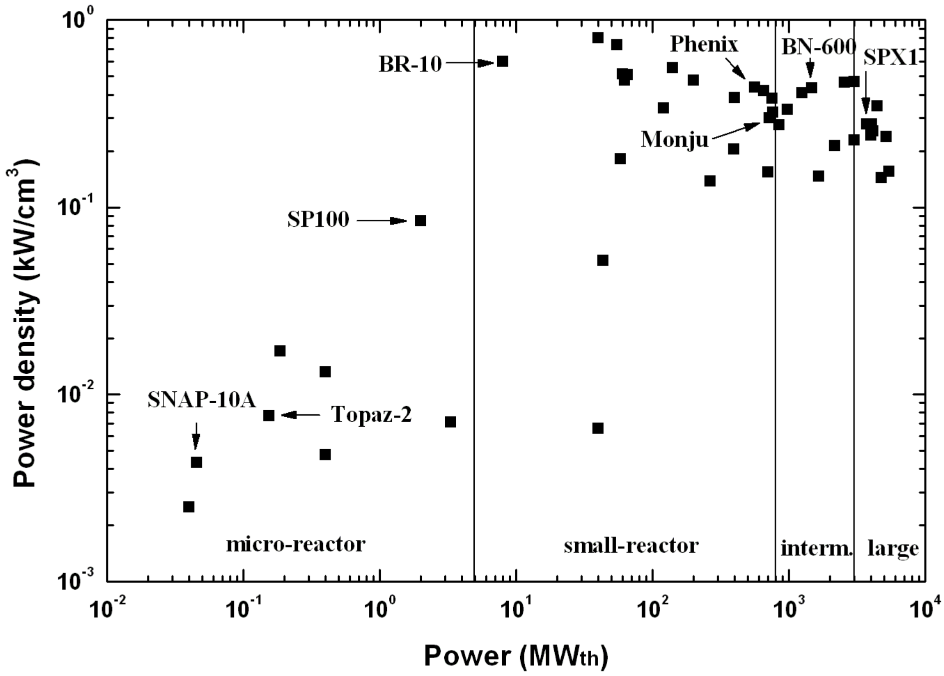

Figure 3 Power density versus power for fast reactors projects.

Table 5. Average fuel power density in fast reactor types (W/cm^3)

Reactor \ fuel	Oxide	Metal	Nitride
Experimental	123	483	600
Prototype	377	248	149
Commercial	271	213	185
Average	257	315	312

In regard to the dimensions, all the considerations above enable to establish a 30 to 50 liters range for the volume of a micro-reactor. A square cylinder core in this case has the dimension around 34 to 40 cm. Considering the power density range 2.5 to 260 W/cm^3 and the core volume range, the reactor power will be in 7.5 to 125 (kW) to 7.8 to 13 (MW) ranges.

The power increase can be obtained by simple coupling several unit cores. This approach is a good directive for the satisfaction of R1 and R3 requirements and can be used to limit the dimensions and power of a micro-reactor in such way that the R6 requirement can be satisfied. Therefore, core module fabrication can be a directive for a micro reactor.

With these considerations in mind, a micro-rector can be defined as the one that satisfy mission requirements of specific time operation at defined power with maximum active core volume and power of 30 liters and 5 MW, respectively.

Considering the definition above the early micro-reactors were the space reactors like the thermal reactor SNAP-10A (10.5 ℓ) and the fast reactor project SP-100 (28 ℓ). Today, most space reactor concepts utilize fast spectrum.

5. FINAL REMARKS

The initial ideas and definitions for a Brazilian fast micro-reactor, to be used in space, seafloor or hostile environments, were presented. First, six basic requirements were established and commented to guide the choice of the best technology. A comparison between thermal and fast spectrum based on the requirements, showed that fast spectrum is the best type. Following, considering reactor power and dimensions as basic core parameters, limits were established that define a micro-reactor type. All discussions above lead to a fast micro-reactor that has core power less than 5 MWth and active core volume less than 30 liters.

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