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FBNR BASIC DATA FOR NEUTRONICS CALCULATIONS

Fixed Bed Nuclear Reactor – FBNR (Brazil)

Fuel Element Description

The 15 mm diameter spherical fuel elements are made of compacted coated particles in a graphite matrix. The coated particles are similar to TRISO fuel with outer diameters about 2mm. They consist of 1.58 mm diameter uranium dioxide spheres coated with 3 layers. The inner layer is of 0.09 mm thick porous pyrolitic carbide (PYC) with density of 1 g/cm3 called buffer layer, providing space for gaseous fission products. The second layer is of 0.02 mm thick dense PYC (density of 1.8 g/cm3) and the outer layer is 0.1 mm thick corrosion resistant silicon carbide (SiC, density of 3.17 g/cm3). The fuel element is cladded by 1mm thick SiC. ***Fuel enrichment 5%.***

Table 1. Fuel particle (2 mm diameter)

Material	density (g/cm³)	d. inside (cm)	d.outside (cm)	volume (cm³)	mass (gr)
UO2	10.5	0	0.158	0.002065237	0.021684988
PYC (porous)	1	0.158	0.176	0.000789306	0.000789306
PYC (dense)	1.8	0.176	0.18	0.000199085	0.000358353
SiC	3.17	0.18	0.2	0.001135162	0.003598464
Average for microsphere	**6.3099629**		**0.2**	**0.00418879**	**0.026431111**

Table 2. Fuel Element (15 mm diameter)

Material	Mass (gr)	Volume (cm3)	Density (g/cm3)	Mass fraction	Volume fraction	Thermal conductivity (W/m.°C)	Specific heat (kJ/kg.°C)
UO2	3.578	0.341	10.5	0.501	0.193	5.2	
PYC porous (amorfo) 600K	0.130	0.130	1	0.0182	0.0737	2.19	1406
PYC dense (amorfo) 600K	0.887	0.493	1.8	0.124	0.279	2.19	1406
SiC	2.549	0.804	3.17	0.357	0,455	77.5	1300
fuel element	**7.145**	**1.768**	**4.041**	**1**	**1**	**30.566**	**1400**

(60% fuel particles and 40% dense graphite matrix cladded by 1 mm thick SiC)

Unit cell description

Specification of Micro Fuel Elements (MFEs) used in the design of FBNR is shown in Table 1 and Table 3. The volume fraction of fuel particles (MFE) inside the 15 mm diameter spherical fuel elements (FE) in the graphite matrix and the volume fraction of fuel elements (FE) inside the water bed of the core is set to **60%** in a realistic situation.

The 68% would be by assuming that particles are packed in graphite or water so as to form a lattice just like body-centered cubic structure of a crystal. Namely, one fuel particle contacts another only in diagonal direction.

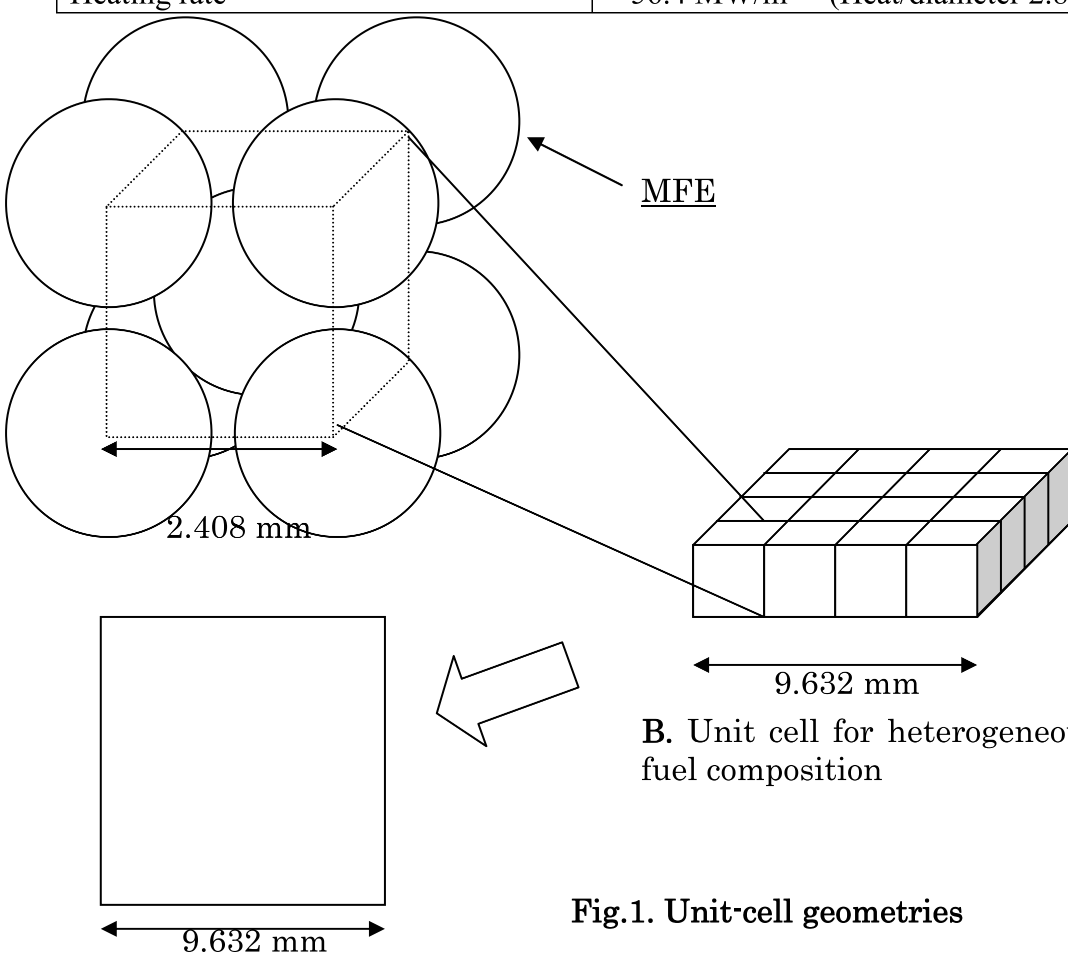
One-dimensional square lattice (**A** in Fig.1) with 9.632mm sides has been selected as a unit-cell for FBNR. It is expected to use this geometry for depletion calculations with all the materials homogenized in the cell. On the other hand, in order to consider the heterogeneity of fuel particles in the graphite matrix, it is expected to use the geometry **B** in Fig1 if possible. Boundary conditions are listed in Table 4.

Table 3. Specification of MFEs

Layer	Material	Density [g/cm^3]	Dimension [mm]
Fuel kernel	UO2	10.8	1.58 (diameter)
1st coating layer	PYC (porous)	1.0	0.09 (thickness)
2nd coating layer	PYS (dense)	1.8	0.02 (thickness)
3rd coating layer	SiC	3.17	0.1 (thickness)
TOTAL	-	-	2.0 (diameter)

Table 4. Calculation conditions

Geometry	Square	
Boundary Condition	Perfect Reflection	
Enrichment of ^{235}U	5.0wt%	
Water : MFEs	40 : 60	32 : 68
Cell length	9.632	9.237
System average temperature	308 ^oC	
System average pressure	16 MPa	
Heating rate	56.4 MW/m³ (Heat/diameter 2.8E-05 MW/cm)	



A. Unit cell for homogenized fuel composition

B. Unit cell for heterogeneous fuel composition

Fig.1. Unit-cell geometries

Comments:
Reference to the site:
http://www.sciborg.uwaterloo.ca/~cchieh/cact/applychem/metals.html
What is the fraction of the volume occupied by spheres for a bcc type structure?
Assume the radius of *spheres* be r, and the edge of the body centered unit cell to be a. There are two spheres per unit cell, thus

$$\textit{body diagonal} = 4\,r = 3^{1/2}\,a$$
$$a = 4\,r\,/\,3^{1/2}$$
$$V_{sphere} = {}^{4}/_{3}\mathrm{p}r^{3}$$
$$V_{cell} = a^3 = 64{*}r^3\,/\,3^{3/2}$$
$$\text{Fraction of volume occupied by spheres} = 2{*}V_{sphere}/V_{cell}$$
$$= 3^{1/2}\mathrm{pi}/8 \quad = 0.68 \text{ or } 68\%.$$

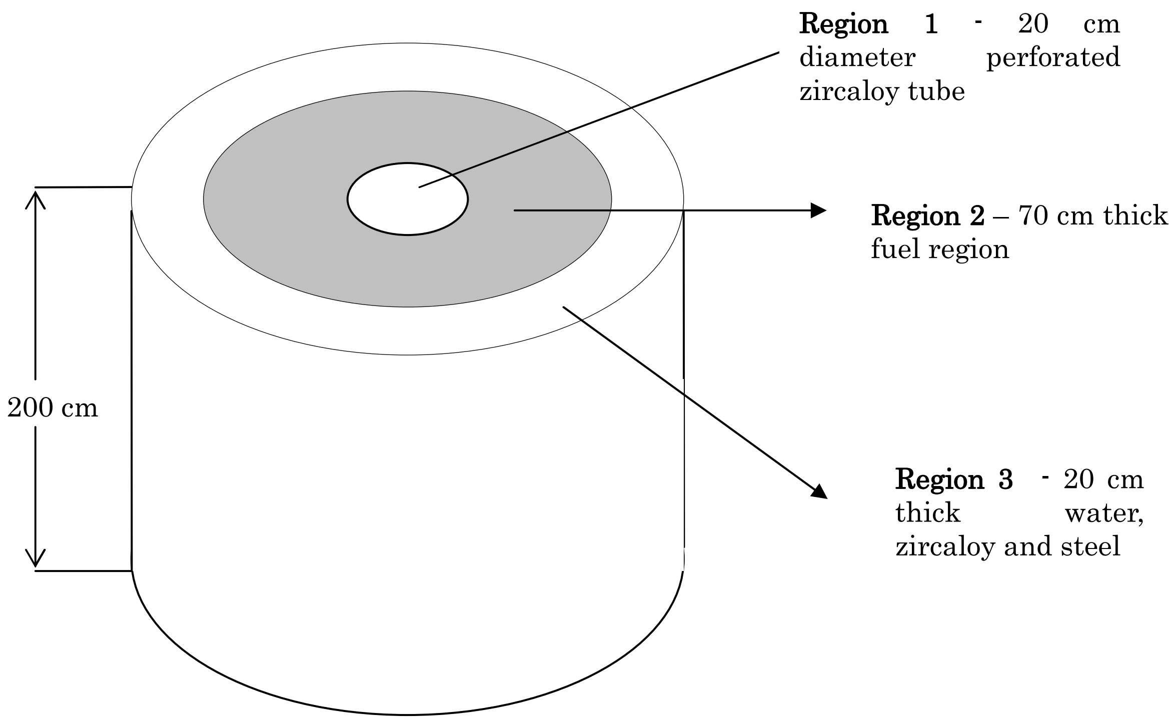
Discussion
The fraction of **0.68** is slightly less than those (**0.74**) of closest packed structures. Thus, the bcc structures are less densely packed according to the hardsphere model. The cubic unit cell contains only one sphere, and the edge length is exactly equal to the diameter of the sphere. The fraction of space occupied by spheres in such an arrangement is pi/6 (**0.52**), much less than the bcc structure type.

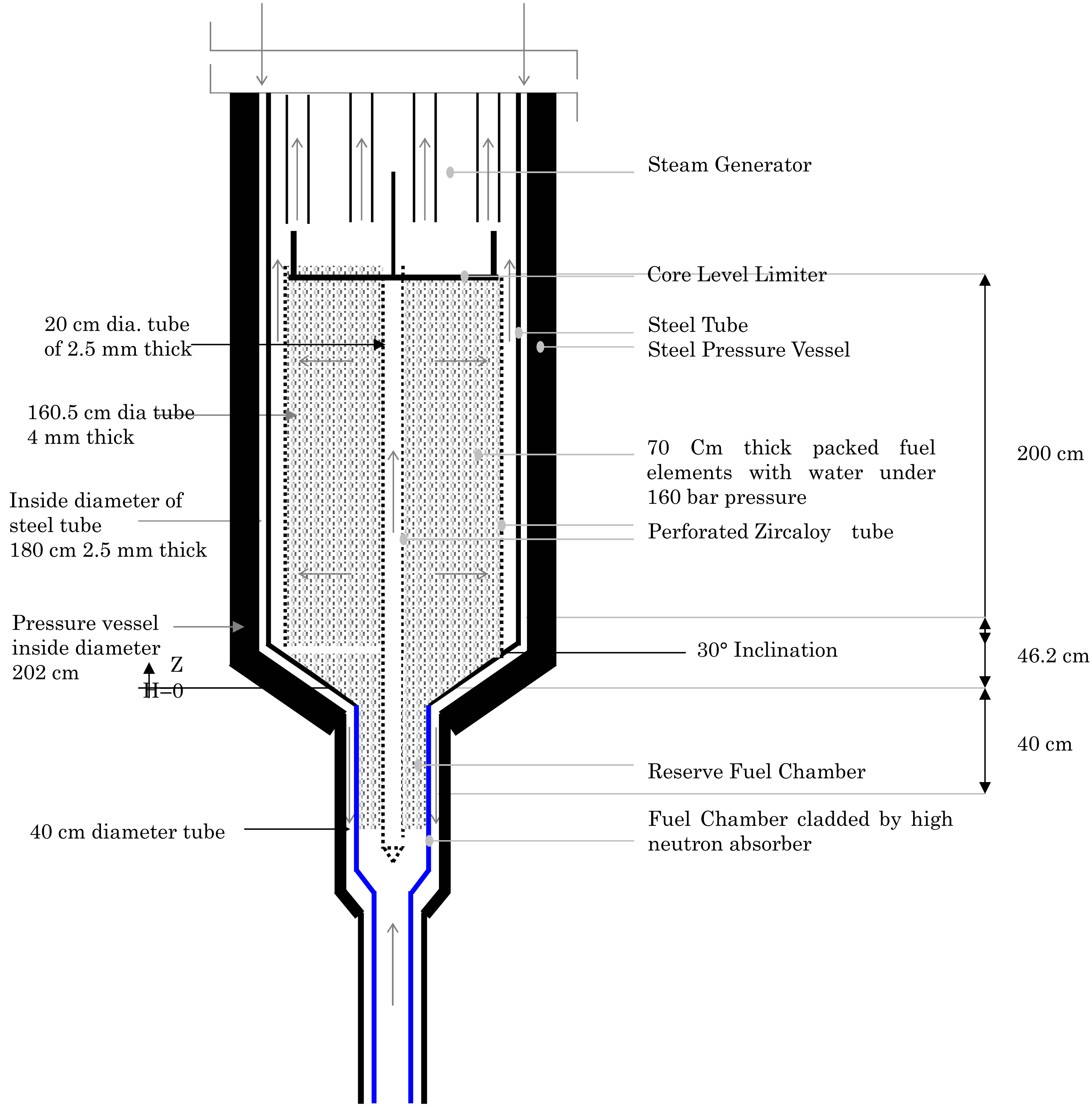
The experiments performed by pouring spherical balls into a cylindrical container, the fraction is found to be about **0.60**. Therefore, It is suggested to use the value of 0.60 that is more realistic. Thus in the FBNR fuel element, the microspheres occupy 60% of the volume and graphite the rest. The fixed bed of FBNR is made of **60%** fuel elements and **40%** water.

Table 5. Volume fraction (%) of the materials in a FBNR module.

	UO2	H2O	C	Steel	Zircaloy	SiC	Fuel	Total
Region 1	0	95	0	0	5	0	0	100%
Region 2	11.58	40	21.12	0	0	27.3	60	100%
Region 3	0	94	0	5	1	0	0	100%

- Stainless steel with a density of 7.758 g/cm3 is composed of 67.84% Fe, 10.86% Ni, 19.22% Cr, 1.88% Mn, and 0.20% Si.
- Zircaloy with a density of 5.874 g/cm3 is composed of 99.69% Zr, 0.21% Fe, and 0.10% Cr.
- Region 3 does not include pressure vessel.


Region 1 - 20 cm diameter perforated zircaloy tube
Region 2 – 70 cm thick fuel region
Region 3 - 20 cm thick water, zircaloy and steel
200 cm


Steam Generator
Core Level Limiter
20 cm dia. tube of 2.5 mm thick
Steel Tube
Steel Pressure Vessel
160.5 cm dia tube 4 mm thick
70 Cm thick packed fuel elements with water under 160 bar pressure
200 cm
Inside diameter of steel tube 180 cm 2.5 mm thick
Perforated Zircaloy tube
Pressure vessel inside diameter 202 cm
Z
H=0
30° Inclination
46.2 cm
40 cm
Reserve Fuel Chamber
Fuel Chamber cladded by high neutron absorber
40 cm diameter tube

Work Plan

Here is a preliminary proposal for neutronics calculations of FBNR. Calculate:

1. Kinf of a single spherical cell (porosity = 0.4; i.e. 40% water & 60% fuel) for cold and hot reactor.
    a. Consider a homogeneous fuel element
    b. Consider a heterogeneous fuel element. Consider micro spheres within the fuel element (double heterogeneity). This is to see the precision of homogenization process for the fuel element.
2. Ke as a function of core height (z=Hm where Ke<0.9 and z=Hc where Keff=1). The core contains burnable poison Gd. The reactor is to be critical at 250<Hc>200 cm where neutron leakage is relatively low.
3. Neutron flux distribution as a function of core radius (r) and core height (z).
4. Peaking factor (ratio of max neutron flux to average flux in the core) to see how uniform will be the fuel burn up.
5. Neutron flux at the radial centre of reactor core (r=0) in order to evaluate the effectiveness of the fine control rod that moves in the centre. Should it not be effective enough, we will need to device an alternative manner.
6. Reactor burn up calculations to determine the core life time. The desired core life is to be more than 10 years. The longer the better!
7. Compensating the long term reactivity with allowing more fresh fuel entering the core from the reserve fuel chamber; that is, by increasing the core height.
8. There may be a need to increase fuel enrichment to achieve longer core life. This will require a cost/benefit analysis of gaining longer core life at the cost of increased enrichment and neutron loss due to increased burnable poison.

IAEA Benchmark Analysis Expected Outputs

All participants in the benchmark analysis are kindly requested to:

1. Provide the following data in both tables and figures in the format specified below
2. Conduct analysis with fuel particles homogenized in specified regions as shown in the separate documents for unit-cell specifications
3. Evaluate the double heterogeneity effects of fuel particles if possible

<u>Expected Outputs</u>

1. Brief description of analysis codes and nuclear data libraries used in the analysis; methodology of solution of neutron transport equation, resonance absorption treatment, etc.

2. Neutron energy dependent parameters
   - Unit-cell averaged neutron flux per lethargy at BOC and EOC for more than 40 neutron energy groups
   - Unit-cell averaged effective multi-group macroscopic cross sections: nu*fission, fission, capture
   - Two group constants: diffusion coefficient, nu*fission, fission, capture, scattering matrix

   Note: If Monte-Carlo method is used, participants should determine the number of energy groups to be tallied considering computation time and reliability of outputs, but it is expected to use as many energy groups as possible.

   □ Format
   - Figures:
     1. Flux/lethargy[arbitrary] vs. Neutron energy [eV] Fig 1.
     2. Effective Macroscopic Cross section [/cm] vs. Neutron energy [eV] Fig 2.
   - Tables:
     1. Energy structure and Flux/lethargy Table 1
     2. Energy structure and Cross section Table 2
     3. Two group constants Table 3
     4. Scattering matrix Table 4

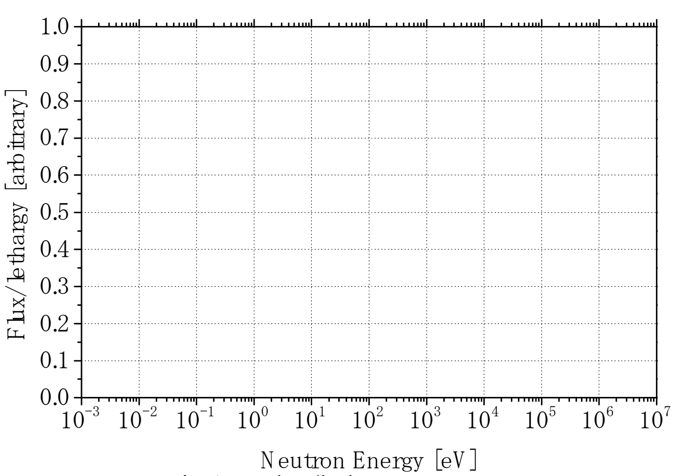


Fig 1: Flux/lethargy vs. Neutron energy

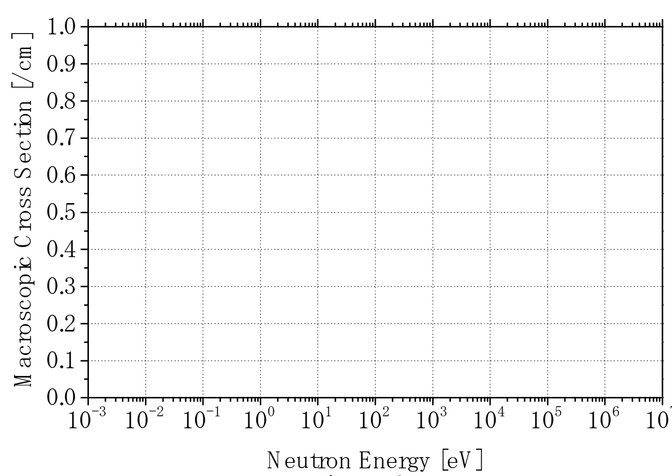


Fig 2 :

Cross section vs. Neutron energy

Table 1: Flux/lethargy and energy structure

I	E_{i-1} [eV]	E_i [eV]	Flux/lethargy
G			
g-1			
….	….	….	….
1			

Table 2: Multi-group cross sections and energy structure

I	E_{i-1} [eV]	E_i [eV]	Nu*fission	Fission	Capture
g					
g-1					
….	….	….	….	….	….
1					

Table 3: two group constants

G	D	Nu*fission	Fission	capture	Capture
1					
2					

Table 4: scattering matrix G=>g

G=>g	g = 1	g = 2
G=1		
G=2		

3. Burn-up dependent characteristics
   - Spectrum index
   - Infinite multiplication factor
   - Instantaneous conversion ratio
   - Format
     - Figure:
       1. Spectrum index vs. burnup [MWd/t] Fig. 3
       2. Infinite multiplication factor vs. burnup [MWd/t] Fig. 4
       3. Instantaneous conversion ratio vs. burnup [MWd/t] Fig. 5
     - Table:
       1. Burnup steps and spectrum index Table. 5
       2. Burnup steps and infinite multiplication factor Table. 5
       3. Burnup steps and Instantaneous conversion ratio Table. 5

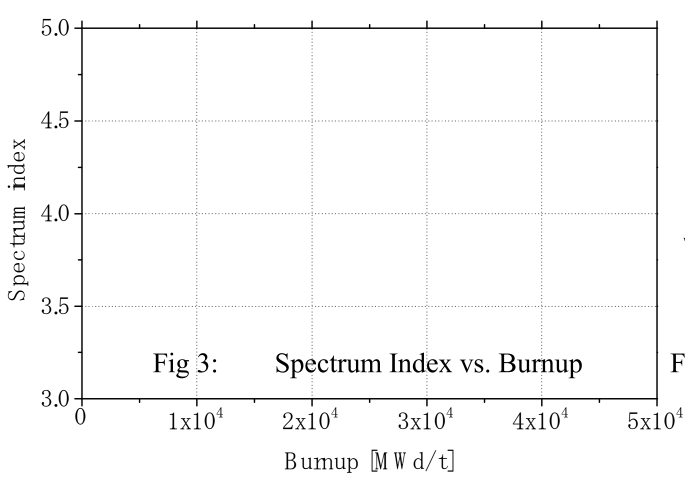


Fig 3: Spectrum Index vs. Burnup

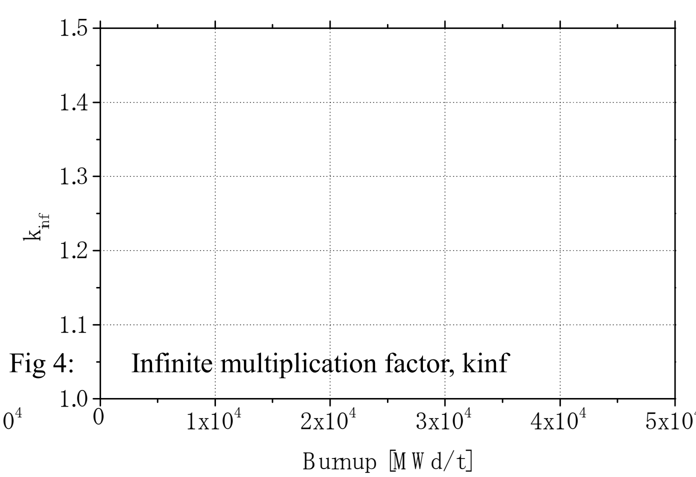


Fig 4: Infinite multiplication factor, kinf

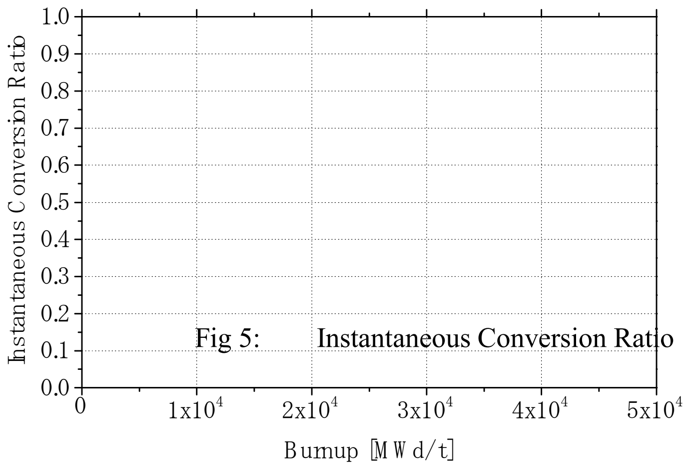


Fig 5: Instantaneous Conversion Ratio

Table 5. Burnup dependent parameters

Step	Burnup [MWd/t]	Spectrum index	Kinf	Inst. Conv. Ratio
1	0.000E+00			
2	Bu_2			
….	….			
N	Bu_N			

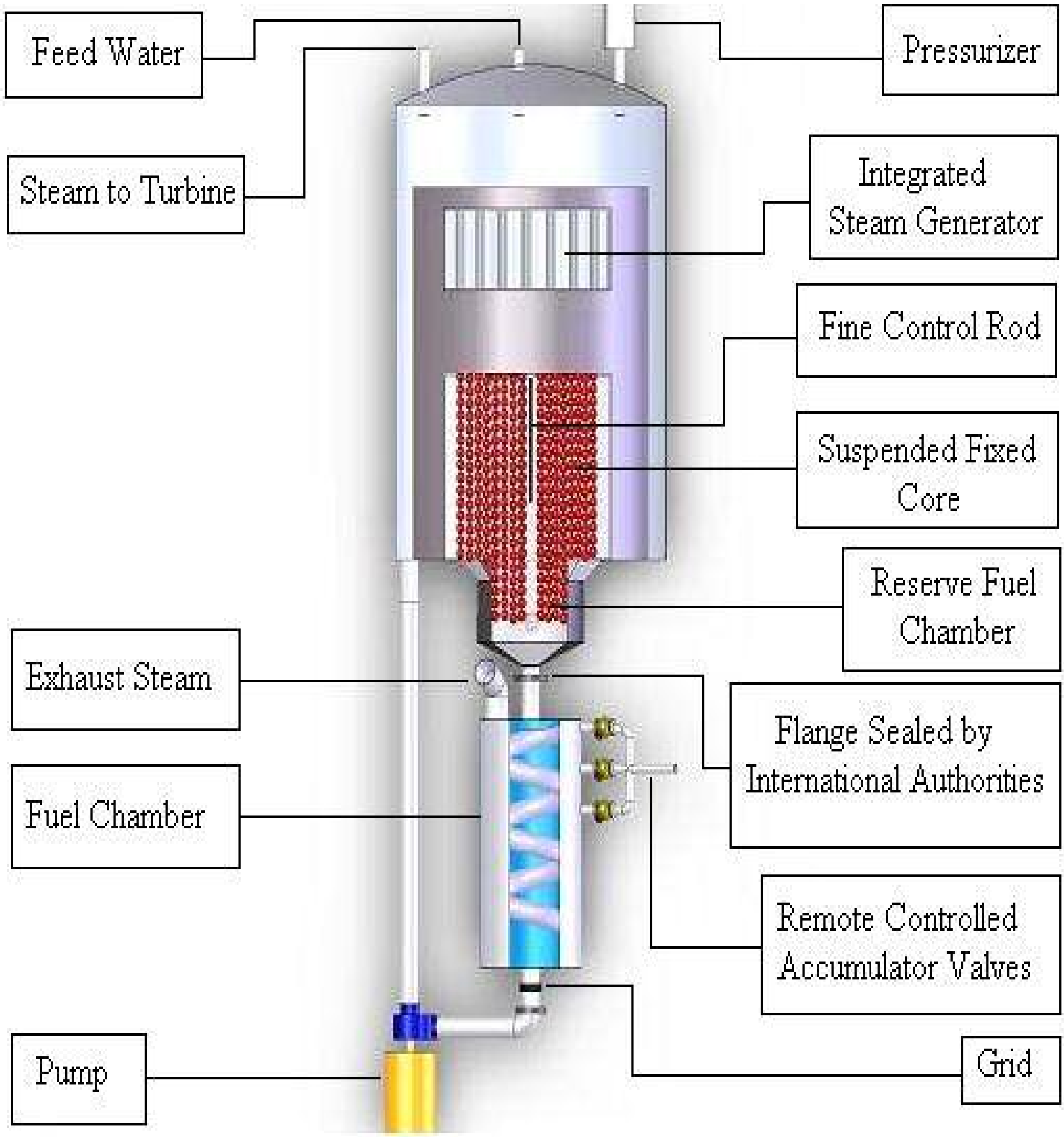
4. Fuel composition
   - Number densities of the elements listed in table 7 at BOC and EOC. Here, EOC is defined as the burnup step when infinite multiplication factor reaches unity. It is requested to provide the burnup in MWd/t at EOC.

Table 6. Number density of elements [/cm^3] at BOC and EOC

Elements	BOC	EOC
^{235}U		
^{236}U		
^{238}U		
^{237}Np		
^{238}Pu		
^{239}Pu		
^{240}Pu		
^{241}Pu		
^{242}Pu		
^{241}Am		
^{242m}Am		
^{243}Am		
^{242}Cm		
^{243}Cm		
^{244}Cm		
^{233}U		
^{234}U		
^{230}Th		
^{232}Th		
^{231}Pa		
^{233}Pa		

FIXED BED NUCLEAR REACTOR

www.rcgg.ufrgs.br/fbnr.htm



Schematic Design of FBNR