CORE DESIGN FOR NEUTRON FLUX MAXIMIZATION IN RESEARCH REACTORS

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ABSTRACT

We present a core design for a new research reactor. The desired characteristics in this pool type research reactor of 10 MW power are: high thermal neutron fluxes, plenty of space to locate facilities in the reflector and an acceptable life cycle. In addition, the design is limited to standard fuel material of low enrichment uranium. The goal is to maximize the maximum thermal flux to power ratio, to obtain a design concept that operating at moderate power allows running successfully applications found in existing multipurpose research reactor. Following the design of the German research reactor, FRM-II, which delivers high thermal neutron fluxes, an asymmetric cylindrical core with an inner and outer reflector is developed. More specifically, considering the angular coordinate of the cylindrical core, the design is asymmetric in the sense that one half of the core is thicker than the other half. This design concept analyzed using MCNP, ORIGEN2 and MONTEBURNS codes, achieves the desired features and allows further improvement. The first design produces a life cycle of 41 days and a high thermal neutron flux zone (3.9E14 $n \cdot cm^{-2}s^{-1}$), a moderate thermal neutron flux zone (2.4E14 $n \cdot cm^{-2}s^{-1}$), and a low thermal flux zone (1.0E14 $n \cdot cm^{-2}s^{-1}$) in the outer reflector. Moreover, an inner-irradiation area of at least 154 cm^2 is provided. The second design consists in a more compact version of the first one, with less space to irradiate materials in the inner core region but with a maximum unperturbed thermal flux of 4.9E14 $n \cdot cm^{-2}s^{-1}$. The low thermal flux region in this second design still achieves an attractive maximum thermal flux of 3.20E14 $n \cdot cm^{-2}s^{-1}$. The life cycle is estimated to be 25 days.

1. INTRODUCTION

Neutrons are a powerful research tool, and are also useful in industrial and medical applications. Sources capable of producing high neutron fluxes are needed to perform material research, radiography and cancer therapy among other important uses. Research reactors are used to produce neutrons and to carry out related experiments. The flux and spectrum of these neutron sources and availability of irradiation facilities determine types of applications, and therefore, competitiveness of the reactor.

The simplest RR requires a core with a powerful and stable neutron source to be competitive. High neutron flux levels are associated with high thermal power levels (several MWs). This requirement adds to the complexity of the cooling system and the complexity of the reactor in general. Table I shows Maximum Thermal neutron Fluxes in the reflector (MTF in units of $n \cdot cm^{-2}sec^{-1}$) with other characteristics of some RRs that are operating, under construction or projected. As the level achieved in the MTF peak is proportional to the power of the reactor, the MTF normalized with power (MTF per Megawatt, MTF/MW) is a parameter that allows comparing maximum fluxes for reactors with different power levels. As can be seen from Table I, the FRM-II German reactor [1] has the highest MTF/MW. Despite the fact that it was designed to operate with 93% enrichment, the compact construction of its fuel element is an attractive feature.

Table I. Maximum thermal fluxes, power and fuel material of some RRs around the world.

Research Reactors	MTF $*10^{14}$	Fuel	Enrichment	Power (MW)	MTF/MW $*10^{13}$
HFIR (USA)	25.5	U_3O_8-Al	N/A	85	3.0
FRM-II (Germany)	8.0	U_3Si_2-Al	93%	20	4.0
HANARO (Korea)	5.0	U_3SiAl	20%	30	1.7
JRR-3M (Japan)	3.0	U_3Si_2	20%	10	3.0
JHR[a] (France)	7.4	UMo_7	<20%	100	0.7
RRR[b] (Australia)	3.2	U_3Si_2-Al	20%	20	1.6

[a]Projected
[b]Under construction

The objective of this work is to study different core configurations in a multipurpose pool type RR to maximize the intensity of the neutron sources or, in other words, the neutron fluxes delivered to the reflector. Specifically, our goal is a RR design with the following general features:

- Pool type reactor with a central core and heavy water as reflector (plenty of free space in the reflector),
- Annular core allowing irradiation positions with harder spectrum than in the reflector,
- Thermal power of 10 MW,
- Enrichment lower than 20%.

Setting the highest MTF/MW (FRM-II) to be our goal, we start our optimization studies from the core shape of the FRM-II (cylindrical fuel element). The following characteristics are sought in the optimized core-shape of our design:

- Unperturbed thermal neutron flux peak greater than $4x10^{13}$ $n{\cdot}cm^{-2}s^{-1}MW^{-1}$,
- Life cycle greater than 40 days,
- Free space to irradiate materials in the inner part of the annular core.

2. STARTING POINT: ELEMENTARY MODEL OF THE FRM-II

The goal of this part of the study is to explore the basic core and reflector design concepts that accomplish the characteristics mentioned above. The first step is to consider a simplified model of the FRM-II to evaluate whether this simplified model retains the characteristics in the neutron flux delivered by the actual reactor.

Core geometry of the FRM-II is complex. However, a very accurate modeling of the core is considered to be not essential for the goals of this study. Hence, a simplified model was simulated using MCNP, Monte Carlo multi-particle transport code [3]. This model is an annular cylindrical core (homogeneous mixture 17 v% fresh U_3Si_2, 21 v% cladding (aluminum) and 62 v% light water) with heavy water as external reflector and beryllium as internal one. The height of the active core region is 70 cm and a layer of 35 cm of light water was modeled over and below the core. The model is symmetric with respect to the $z = 0$ plane (z is the axial direction) and is azimuthally symmetric. Two different uranium densities were modeled in the core, 3.0 gr/cm^3 from 6.75 to 10.5 cm and 1.5 gr/cm^3 from 10.5 to 11.2 cm in the radial direction. The outer radius of the model was 250 cm and vacuum-boundary conditions were considered over all external surfaces. No facilities were modeled in the reflector. In this particular case, FRM-II simplified model simulation, 500 cycles of 1000 particles per cycle were simulated (standard deviation in k_{eff} is less than 0.0015).

Fast and thermal (<0.625 eV) neutron flux distributions were calculated for the simplified model. Two cases were considered. The first one is a non critical configuration and the second one corresponds to a critical configuration at the BOC. The criticality condition was achieved by replacing the inner reflector (beryllium) by a control rod (CR) composed of aluminum (0.75-5.35 cm) and hafnium (5.35-5.6 cm). This second condition was simulated to evaluate possible variations in the radial profile of the neutron flux due to criticality. Figure 1 shows the radial profiles for fast and thermal fluxes ($k_{eff} \cdot \phi$) calculated at the central horizontal plane of the reactor (between $z = \pm 1$ cm) and rings of $\Delta r = 1$ cm for both cases mentioned above (crit in Fig. 1 refers to the critical case). The multiplication factor for the non critical case is $k_{eff} = 1.202$. Dots in Fig. 1 show non-perturbed thermal fluxes in the reflector for the FRM-II reactor as reported in Ref. 1. The purpose of this comparison is not to show quantitative agreement between fluxes reported in Ref. 1 and the simplified model. It is presented to justify that a model based on a homogeneous description of the core yields enough details to allow parametric studies to maximize the thermal flux in the reflector for different "FRM-II core type" configurations.

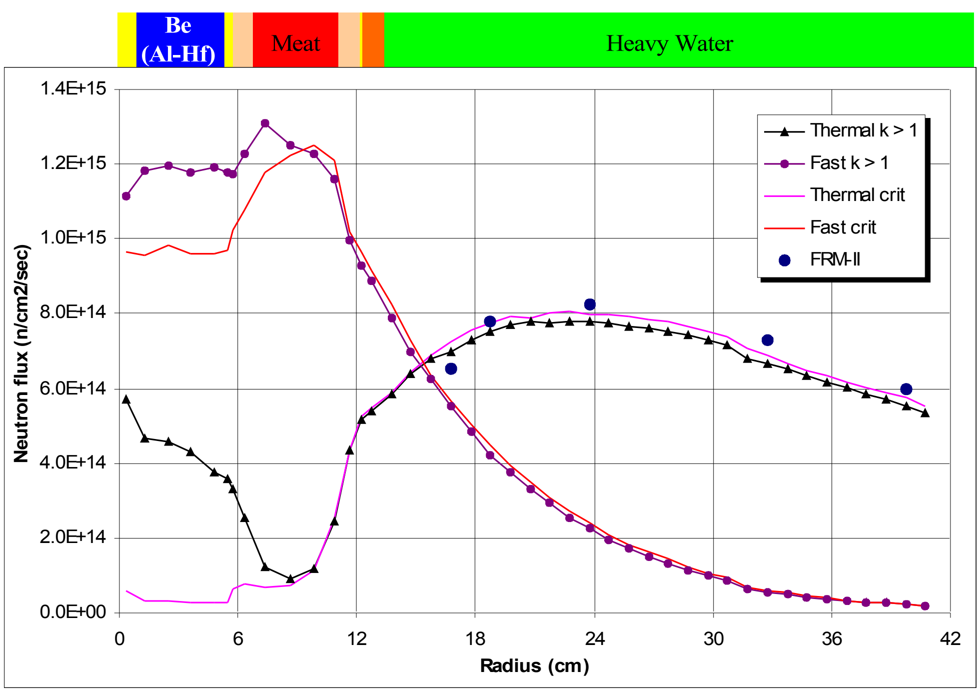

Figure 1. Radial profile of thermal and fast neutron fluxes in the simplified model of the FRM-II. Case 1: BOC, k > 1; Case 2: BOC, k=1 (by replacing Be by a CR).

With some assurance that homogeneous core mixtures yield enough detail in flux distribution for such a core, the next step is to investigate the effect on the thermal peak or MTF of core configurations that satisfy the design features mentioned above.

3. BASIC VARIATIONS OF FRM-II MODEL

Comparing the features of the FRM-II reactor and the characteristics sought in our design, the first set of modifications introduced are to obtain an inner irradiation zone and enrichment lower than 20%. The modified MCNP model has the following features:

- Core: homogeneous, 17% volume meat (U_3Si_2 of 4.8 gr/cm^3, 20% U5), 21.3% cladding (Al) and 61.7% light water. 70 cm height,
- Inner reflector: beryllium, 70 cm height,
- Inner irradiation zone: light water, 70 cm height. Radius equal to 10 cm (equivalent to an irradiation zone of 314 cm^2).

All other dimensions are the same as in the simplified FRM-II model. Figure 2 shows r-θ and r-z views of the MCNP model for this case.

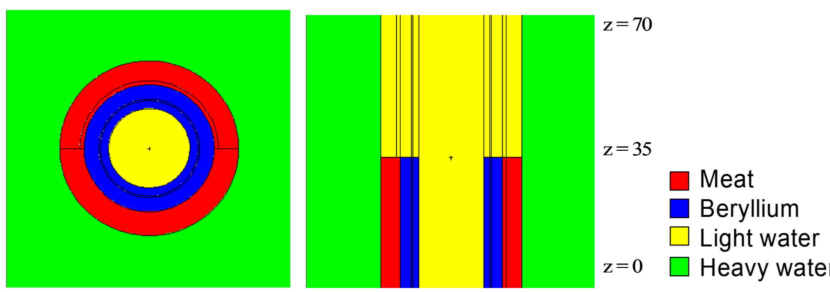

Figure 2. MCNP model for the modified FRM-II.

The first set of simulations was carried out to study the effect of the thickness and the inner radius of the cylindrical fuel element (inner radius greater than 14 centimeters to allows space for inner irradiation positions and to have at least 4 cms of inner reflector) on the thermal neutron flux peak in the outer reflector. Table II shows the results of this parametric study. The amount of U5 is shown for comparison purposes (note that FRM-II has 0.325 KgU5/MW and a life cycle of about 52 days). Thermal neutron fluxes higher than $4x10^{14}$n·cm^{-2}sec^{-1} were found with thinner fuel elements which allow greater neutron leakage to the reflector. However, the excess reactivity of these assemblies is not enough to sustain a critical core for an acceptable period of time or, in some cases, even to produce it.

Table II. MTF as a function of thickness and inner radius of the cylindrical fuel element.

Case	I	II	III	IV	V	VI
Inner core radius (cm)	15	15	15	14	16	17
Outer core radius (cm)	20	19	18	17	20	20
Multiplication factor	1.15	1.10	1.03	1.02	1.12	1.07
U5 ratio to FRM-II (Kg/Kg) [a]	1.4	1.1	0.8	0.7	1.1	0.9
MTF (*E14)	2.31	2.74	3.06	3.11	2.58	2.77

Case	VII	VIII	IX	X[b]	XI[b]
Inner core radius (cm)	20	19	15	15-16	15-15.5

Outer core radius (cm)	23	20	16	19-20	19.5-20
Multiplication factor	1.12	0.87	0.78	1.00	0.86
U5 ratio to FRM-II (Kg/Kg)[a]	1.0	0.3	0.2	0.5	0.1
MTF (*E14)	2.55	4.13	4.47	3.20	3.88

[a]Normalized with power.
[b]Two concentric fuel elements with beryllium in between.

Clearly, for this given core shape, desirable thermal neutron fluxes and core life cannot be achieved simultaneously. In addition, the parametric study reported in Table II, as expected, shows that thick cores may have an acceptable life cycle (amount of U5 and multiplication factor) and thin ones produce the expected thermal neutron flux peak. Consequently, we varied the geometry and numerically experimented with asymmetric cores, seeking a compromise solution: a core that may produce a region in the reflector with high thermal neutron fluxes required for applications such as thermal beam and cold neutron sources, and a region in the reflector with moderate thermal neutron fluxes suitable for applications such as industrial processing. The core must also have an inner irradiation zone and an acceptable life cycle.

4. ASYMETRIC CORE MODEL

The asymmetric core shown in Fig. 3 consists of two segments: a thinner part of angle θ, and a thicker part of angle (2π-θ). There is beryllium and light water in the center. Thinner meat section is padded with beryllium to make its inner and outer radii equal to those of the thicker meat section. A set of simulations were carried out to parametrically study the thermal neutron flux peak as a function of the inner and outer radii of both core sections and the aperture angle of the thinner part. As expected in this case, the neutron flux is not symmetric and the maximum of the thermal neutron flux is on a line passing through the center of the thicker core section. Results of this parametric study are given in Table III.

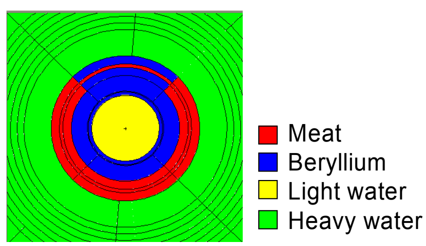

Figure 3. Asymmetric cylindrical core.

Results show that thermal neutron fluxes greater than $4\text{x}10^{14}$ $n\cdot cm^{-2}s^{-1}$ with acceptable life cycles (as indicated by multiplication factors at the BOC) are possible with this core configuration. For instance, case VII in Table III shows an excess of reactivity of 12% (Δk) and a MTF of $4.05\text{x}10^{14}\cdot cm^{-2}s^{-1}$. In this case, the minimum MTF on a line passing through the center in the thinner core section is $0.87\text{x}10^{14}$ $n\cdot cm^{-2}s^{-1}$. Due to asymmetry, instead of having an evenly distributed thermal flux in the reflector, this core produces both, a region with high thermal neutron fluxes and a region with low ones.

Table III. Parametric study for the asymmetric cylindrical core.

Case	I	II	III	IV	V	VI	VII
Thick core inner radius (cm)	15	15	15	16	15	16	16
Thick core outer radius (cm)	20	20	20	22	20	22	22

Thin core inner radius (cm)	17	17	17	18.5	17	18.5	16
Thin core outer radius (cm)	18	18	18	19.5	18	19.5	17
Angular aperture thin section (º)	90	120	150	150	180	180	180
Multiplication factor	1.11	1.09	1.08	1.15	1.07	1.11	1.12
MTF center thin section (*10E14)	2.2	2.12	1.96	1.74	1.73	1.56	0.87
MTF center thick section (*10E14)	3.01	3.57	4.04	3.78	4.4	3.86	4.05

Case VII in Table III was selected to study the asymmetric model in more detail. In this case, half of the core is thin (16-17cm) and the other half is thick (16-22cm). This model is analyzed in more detail in the next section for neutron flux distribution, core life and reactivity effects.

5. ASYMMETRIC CORE WITH LONGER LIFE

Carrying out preliminary burnup calculation, it was found that Case VII in Table III must have an excess reactivity of about 14% (Δk / k) to produce the desired life cycle (note that the life cycle is expected to be greater than 40 days and the value shows in Table III for the multiplication factor yields an initial excess reactivity of 10.7% Δk / k). Therefore, it was decided to model cores with increasingly smaller inner light water region. Light water in those models was replaced by beryllium. Results showed that a water hole with a radius of 7 cm, instead of 10 cm as in Case VII, leads to an excess reactivity of about 14% (Δk / k). This corresponds to a final inner radiation area of 154 cm^2. The core of this final design, which will be called Asymmetric Model VIII (AM-VIII) is shown in Fig. 4.

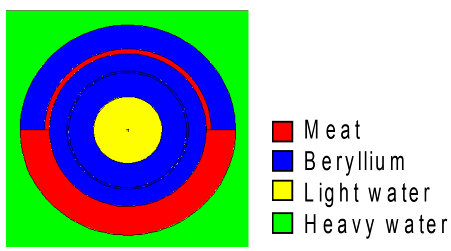

Figure 4. R-θ view of the MCNP model for the AM-VIII.

To further assess the viability for the model presented in Fig. 4, the AM-VIII, it is important to compare cooling and safety related parameters with those for the FRM-II reactor. The AM-VIII is loaded with 4.71 KgU5 or 0.471 KgU5/MW, whereas the FRM-II is loaded approximately with 0.375 KgU5/MW. The core volume for the AM-VIII is 28700 cm^3 producing a power density of 348 MW/cm^3 or 0.6 KW/m^2 (assuming concentric cylindrical plates of the same thickness as in FRM-II case). Corresponding values for the FRM-II core are: 806 MW/cm^3 and 1.8 KW/m^2. Therefore, the model produces half the power with approximately the same volume as in the FRM-II. A priori, this model may not present any challenging issues from the core cooling point of view. From the safety point of view, the AM-VIII presents four different regions that may be suitable for control rod insertion: inner irradiation zone (this may be the least suitable), inner reflector, core, and outer reflector. These, together with the well-known shut down methods used in research reactors (poison, reflector drain, etc), may allow several independent shut down systems.

5.1. Core life analysis of the AM-VIII

The initial reactivity of the AM-VIII is very sensitive to the material placed in the inner irradiation zone. Variations of the model presented in Fig. 4 were developed to study the impact of other possible configurations on reactivity. Simulations were carried out using MCNP, considering 1/4 of the real core (reflected in $z = 0$ and $y = 0$, vertical plane) and simulating 200 cycles of 1000 particles per cycle (15 inactive cycles). In all cases, the standard deviation in k_{eff} is less than 0.0025. Table IV shows the variation in the multiplication factor with material in the inner-irradiation zone. Cases 4, 5 and 6 in Table IV show that significant gain in initial excess reactivity can be achieved by altering the inner cavity material, and by replacing the light water of the inner-irradiation zone with a smaller absorption cross section material. This would allow irradiating material with high absorption cross section. In addition to changes in the material for the inner-irradiation zone, one case in which the geometry of the inner irradiation-zone was altered, was also studied. In this case, light water holes were introduced in the inner reflector (last case in Table IV). These water holes can be located at different distances from the inner face of the core to provide irradiation positions for different neutron spectrums. Hence, the AM-VIII presents a large spectrum of possibilities to control the core and irradiate materials in the inner irradiation zone. Note that the inner core surface is equivalent to a square 28 cm on edge. A part of this surface area however must be covered with a reflector material to assure an acceptable life cycle.

Table IV. Reactivity effects due to changes in the configuration of the inner-irradiation zone (changes involve entire active core height, 70 cm).

Case	k_{eff}
Critical with Hf-CR from 11.0 to 11.4 cm	1.000
Base case (AM-VIII, Fig. 4)	1.162
Black absorber from 0-7 cm	1.080
Be from 0-7 cm	1.230
Heavy Water from 0-7 cm	1.231
Be from 0-7 cm plus 16 cylindrical holes of 2 cm of diameter filled with light water located at 9 cm from the center of the core and evenly distributed in a circle	1.207

Core life for the AM-VIII was estimated using MONTEBURNS 2.0 [6]. This computational tool links MCNP transport code and ORIGEN2 burnup code [7]. The MCNP model was 1/4 of the real core and each MCNP run involved 250 cycles of 1000 particles (standard deviation in k_{eff} was lower than 0.0025 and tallies in the core cells passed all statistical checks). As ORIGEN2 is a zero dimensional code, within MCNP, the core was divided in 36 different regions to account for the variation of the burnup with position. The thinner part of the core was divided in 9 regions of equal volume (3 angular and 3 axial intervals). The thicker part of the core was divided in 27 regions, as in the thinner case for θ and z, and additionally it was split also in 3 different radial zones (16-18, 18-20, 20-22 cm). The number of days considered for the burnup was 50 and the neutron fluxes were actualized (MCNP calculation) every 2 days. The number of burnup steps performed in ORIGEN2 every 2 days was 40 and 1 predictor step was considered every 2 days. The PWRU library was used in ORIGEN2. Finally, the fractional importance in MONTEBURN 2.0 was chosen to be equal to 1.0E-5. Figure 5 shows the variation of k_{eff} as a function of time for the AM-VIII. Reference [2] sets the value of marginal reactivity due to temperature effects and facilities in the reflector equal to 7% Δk / k for the FRM-II reactor. In our calculation, we have partially considered some temperature effects (MCNP calculation performed at 45 °C and heavy and light water densities evaluated at this temperature). Conservatively, we estimate the life cycle of the final asymmetric model to be 41 days, which gives us a marginal reactivity of 6.8% ± 0.3% Δk / k (considering that the error in k_{eff} is twice its standard deviation). However, a longer cycle can easily be achieved by placing more inner reflector or using heavy water in the inner-irradiation area. In addition, this reactor and surrounding facilities may be less complex than the FRM-II, requiring a marginal reactivity due to facilities in the reflector lower than that in the German case (several beams). Note that error in k_{eff} (equal to two standard deviations; ±0.005) at day 27 is shown in Fig. 5.

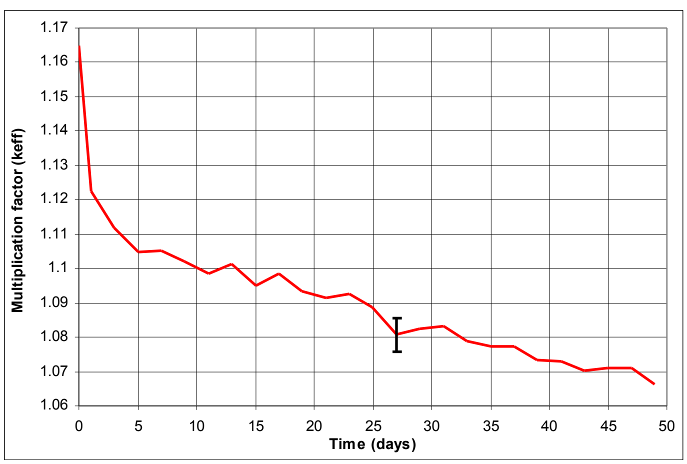

Figure 5. Multiplication factor for the burnup of the AM-VIII core.

5.2. Neutron Fluxes for the AM-VIII

Stable and high neutron flux levels are desirable features in a modern pool type research reactor. For the AM-VIII, we calculated thermal and fast fluxes in the $z = 0$ plane to visualize the asymmetry in the fluxes due to the core configuration. The fluxes were calculated in cubes of 1 cm^3 for the critical version of the AM-VIII (first case in Table IV) along three different lines from the center of the core in the $z = 0$ plane (north, east and south lines in Fig. 6) that are shown in Fig. 6.

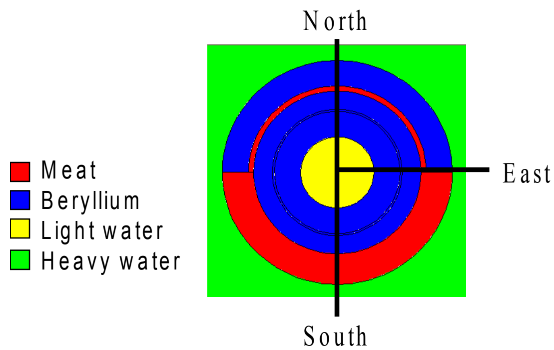

Figure 6. Schematic diagram of the reactor (z = 0 plane).

Also shown in Fig. 7 is the thermal neutron flux for the simplified model of the FRM-II (azimuthally symmetric, see section 3). Over the south-line, results for the AM-VIII show a peak similar to the one calculated for the FRM-II case but located at 35 cm from the core center (3.91×10^{14} $n \cdot cm^{-2} s^{-1}$). A flux peak of 2.4×10^{14} $n \cdot cm^{-2} s^{-1}$ and 1.0×10^{14} $n \cdot cm^{-2} s^{-1}$ occur along the east and north-lines, respectively.

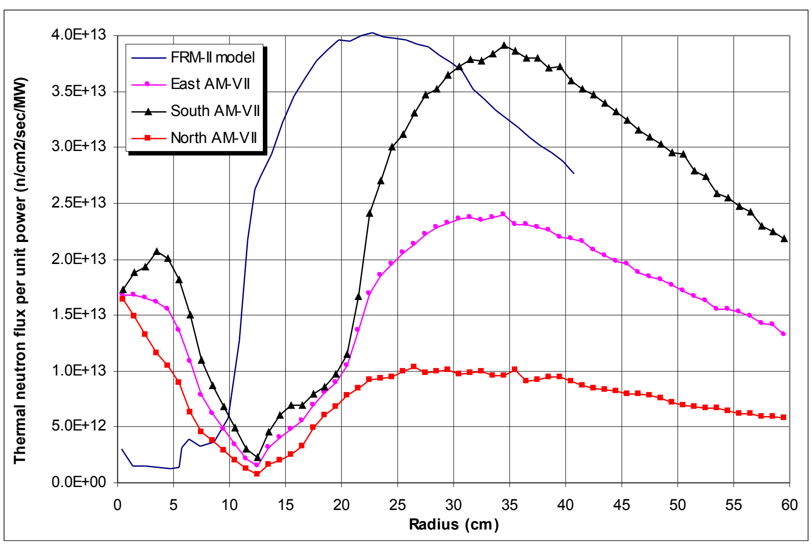

Figure 7. Thermal neutron fluxes for the AM-VIII and simplified FRM-II model.

6. ASYMMETRIC COMPACT CORE WITH A SHORTER LIFE

The advantages in the capabilities of the AM-VIII model are the relatively large inner-core area available for irradiation positions, a relatively small zone in the outer reflector with high thermal neutron fluxes and, in addition, a life cycle conservatively calculated in 41 days. However, if we relax the requirements for the space available for the inner-core area and for the life cycle, we can develop a more competitive model from the neutron flux level point of view. In this case, we have considered asymmetric cores, half thick and half thin, following the AM-VIII design but with radii between 3 and 16 cm. Numerical experiments with different core dimensions show MTFs in the outer of the thicker core part in the range of 3.8 - 5.0 E10^{14} n·cm^{-2}s^{-1} and in the thinner part of 3.0 - 4.0 E10^{14} n·cm^{-2}s^{-1}. The range in the reactivity excess at the BOC is 10 - 18 % (Δk).

We have chosen one of these cases with higher MTF and initial reactivity excess greater than 15% (Δk), to show the potentiality of this design regarding neutron flux levels. This model called AM-IX is shown in Fig. 8 (critical and non critical versions). The core volume is 19022 cm^3.

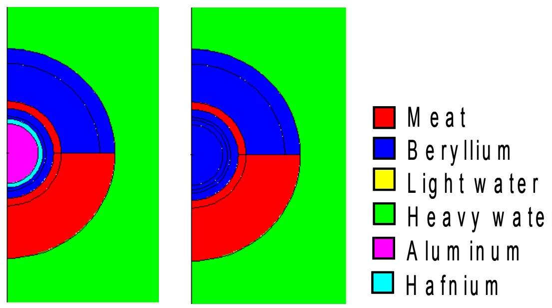

Figure 8. R-θ view of the AM-IX, critical (left) and non critical.

Data about the AM-IX model is presented in Table V. Although this model may not present enough free space in the inner-core area to irradiate materials, the beryllium reflector in the outer part of the thin core half may be an alternative for this purpose.

Table V. Characteristics of the AM-IX.

AM-IX	
Thick core radii (cm)	6 - 14
Thin core radii (cm)	6 - 7
Angular aperture thin section (º)	180
Multiplication factor (BOC)	1.152

6.1. Core life analysis of the AM-IX

The burnup of this core is represented in Fig. 9. The calculation was carried out in similar fashion to the one showed in section 5.1, dividing the core in 36 different regions. In this case, we are trying to push neutron fluxes to a higher limit and then we need to have a detail model to accurately estimate the life cycle. In order to gain some reactivity, different things can be done. For instance, one possibility is to place a reflector below and above the core (at least between 0-6 cm) and/or to slightly reduce reduced the inner radius of the core (this does not deeply affect thermal flux levels in the reflector). The life cycle of this model is defined in 25 days, which gives us a marginal reactivity 5.8% Δk / k, a close value to the one defined for the AM-VIII model.

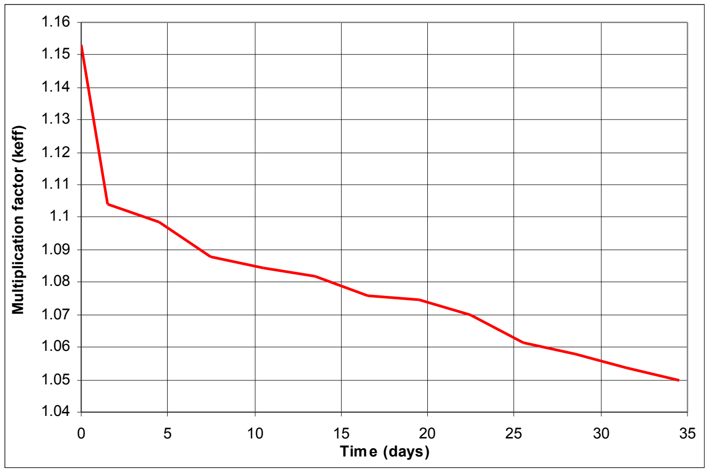

Figure 9. Multiplication factor for the burnup of the AM-IX core.

The space for irradiation positions in the outer beryllium reflector of the thinner part has an area of 230 cm^2 (15x15 cm^2). Placing neutron absorbers in this region produce a drop in the reactivity as it is shown in the case presented in Fig. 10. In this case, eight holes of 2cm of diameter of light water were placed surrounding the thinner part of the core (all active core height, 70cm). The reactivity drop at the BOC is 2% Δk.

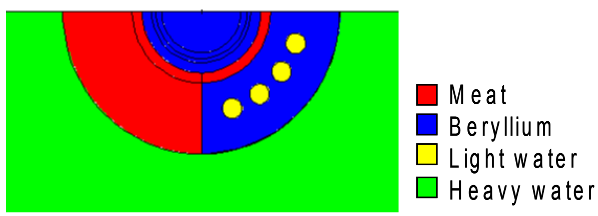

Figure 10. R-θ view of the AM-IX with four irradiation positions (half core).

6.2. Neutron Fluxes for the AM-IX

For the AM-IX, we calculated thermal fluxes in the $z = 0$ plane to visualize the asymmetry in the fluxes due to the core configuration. The fluxes were calculated in cubes of 1 cm^3 for the critical version. Figure 11 shows the thermal neutron flux distribution as a color map together with the location of the core within the map. The real dimension of the figure is 120 x 120 cm^2. The limit of the region with neutron fluxes higher than 4×10^{14} n·cm^{-2}sec^{-1} (orange color) shows up in almost the entire south part of the reflector (lower half).

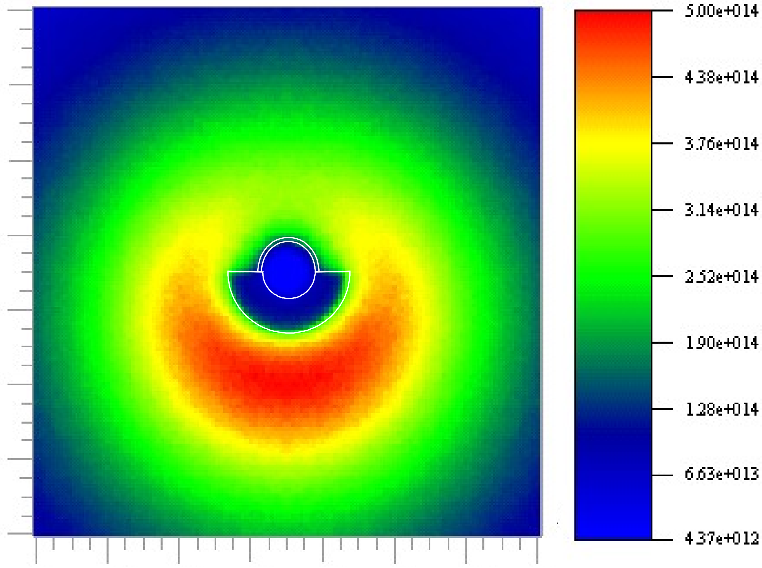

Figure 11. Thermal neutron flux in the z = 0 plane.

Thermal neutron fluxes for the east, south and north lines are shown in Fig. 12. The average flux (located over the east line) is quite similar to that in the German model. The maximum flux is given by 4.95×10^{14} $n \cdot cm^{-2} sec^{-1}$ along the south line and located 25cm far from the core center.

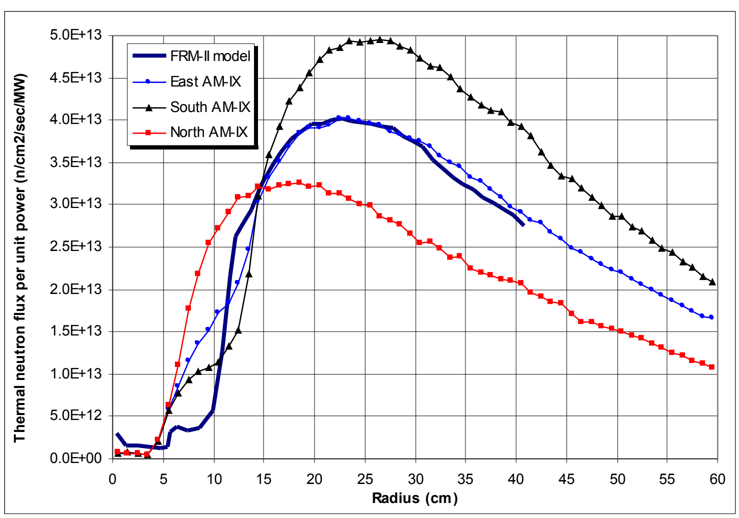

Figure 12. Thermal neutron fluxes for the AM-IX and simplified FRM-II model.

Another parameter of interest is the area in the reflector available to locate facilities that require a specified neutron flux level (considering unperturbed neutron fluxes). Table VI shows the comparison between the AM-IX and the FRM-II simplified model for areas in the reflector with thermal fluxes greater than 2.0, 3.0, 3.5 and 4.0×10^{13} $n \cdot cm^{-2} s^{-1}$ MW^{-1}.

Table VI. Areas in the reflector satisfying thermal flux level requirements.

Area in z = 0 plane (cm^2)	FRM-II simplified model	AM-IX	AM-VIII areas as % of FRM-II
>2.0E13 $n{\cdot}cm^{-2}s^{-1}MW^{-1}$	7439	8236	110
>3.0E13 $n{\cdot}cm^{-2}s^{-1}MW^{-1}$	3921	4210	107
>3.5E13 $n{\cdot}cm^{-2}s^{-1}MW^{-1}$	2413	2584	106
>4.0E13 $n{\cdot}cm^{-2}s^{-1}MW^{-1}$	-	1378	-

7. CONCLUSIONS

We have developed a preliminary design of a modern 10 MW research reactor. MCNP and ORIGEN2 were used to analyze this design which is based on a core loaded with standard 20 % enriched fuel. The asymmetric design allows reaching an unperturbed thermal peak per unit power comparable to that in the FRM-II. In addition, the life cycle for the LEU fuel was conservatively calculated to be 41 days. An extension in the life cycle can be easily achieved by adding reflector material in the inner-irradiation area.

The AM-VIII design produces a high thermal neutron flux zone (3.9E14 $n{\cdot}cm^{-2}s^{-1}$), a moderate thermal neutron flux zone (2.4E14 $n{\cdot}cm^{-2}s^{-1}$), and a low thermal flux zone (1.0E14 $n{\cdot}cm^{-2}s^{-1}$) in the outer reflector. Moreover, an inner-irradiation area of at least 154 cm^2 is provided. This region may be useful to irradiate material with harder spectrum than in the outer reflector without perturbing the neutron fluxes there. All these features make the design an interesting candidate for the next generation of research reactor.

The AM-IX model produces a high thermal neutron flux zone (4.9E14 $n{\cdot}cm^{-2}s^{-1}$), a moderate thermal neutron flux zone (4.0E14 $n{\cdot}cm^{-2}s^{-1}$), and a low thermal flux zone (3.2E14 $n{\cdot}cm^{-2}s^{-1}$) in the outer reflector. The MTF/MW is higher than the one calculated for the FRM-II model. The life cycle of this design is calculated in 25 days. Depending on the spam of applications defined for this core, this time period may be enough.

Summarizing, the asymmetric core presents a feature that may be interesting for a multipurpose research reactor of moderate power. It produces a region in the outer reflector with high thermal neutron fluxes per unit power where applications that require high neutron fluxes can be located. This design is also characterized by an acceptable life cycle using LEU.

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