A PRELIMINARY MODEL FOR START UP OF A PULSED ANNULAR CORE

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ABSTRACT

A new reactor concept, designed to produce very high neutron flux levels, involves a sub-critical annular core modulated for its reactivity by use of an efficient reflector or fissile element, called modulator, which takes the region near the modulator to super-prompt critical state. The present analysis relates to the start up of the reactor to the quasi-static state where the modulator is brought in from its retracted position, to the normal operating position by upward movement along a helicoidal path. Flux development during the modular insertion is studied using a simplified model with inclusion of reactivity effect based on interaction using solid angle between the sub-critical core and modulator that is moving in closer to the sub-critical core. A moving coordinate system is adopted to circumvent the moving boundary conditions with rotating modulator. An idea of the "figure of merit" of the new concept can be obtained from the maximum to average flux ratio in the quasi-static conditions of the core. The figure of merit, as expected, is proportional to the perimeter of the core. It is expected that this analysis model would help choose certain design parameters like retraction distance, pitch of helicoidal insertion path etc.

1. INTRODUCTION

A new concept for production of extremely high neutron fluxes has been proposed as a successor to the periodically pulsed reactor IBR operating in Dubna, Russia [1,2]. The scheme of the new concept involves a sub-critical annular core modulated for its reactivity by use of an efficient reflector or fissile element, called modulator, which takes the region near the modulator to super-prompt critical state. Figure 1 shows a perspective view of the geometrical arrangement including modulator in the "OUT" and "IN" positions. As the modulator rotates around the annular core, a rotating pulse synchronized with the modulator location is generated in the core. An irradiation sample synchronized with the pulse would be continually exposed to the peak flux of the pulse. The width of the pulse in a fast system is very small compared to the thermal fuel time constant of the system. As a result of thermal inertia effect of the core can be used to increase the maximum flux inside the pulse without surpassing the fuel thermal limits. An idea of the "figure of merit" of the new concept can be obtained from the maximum to average flux ratio in the quasi-static conditions of the core. The figure of merit, as expected, is proportional to the perimeter of the core. A value of 7.7 was estimated for a core with a perimeter of 360 cm using fuel properties corresponding to the IBR reactor [1].

The present analysis relates to start up of the reactor where the modulator is brought in from its retracted position, shown in the figure 2 to the normal operating position by upward movement along a helicoidal path. Flux development during the modular insertion is studied using a simplified model with inclusion of reactivity effect based on solid angle interaction between the sub-critical core and modulator that is moving in closer to the sub-critical core.

An analysis of the quasi-static neutron flux distribution [2] shows that the flux distribution in the core near the modulator region is sinusoidal – corresponding to a supercritical condition and is exponential in nature outside the modulator region – corresponding to sub-critical condition. Furthermore, if the extension of the modulator region exceeds a certain critical value the modulator region becomes self-sufficient and the flux exceeds all bounds. As a result, the modulator extension (length along the perimeter) needs to be restricted.

2. FORMALISM FOR ANALYSIS OF THE SYSTEM

A one neutron group model for neutron flux analysis is analyzed by opening up the ring into a geometric shape of a parallelepiped of length equal to the perimeter of the ring. The position of the rotating pulser at time t is x = V.t. With the approximation of constant precursor concentration the neutron diffusion equation can be written as

$$\frac{1}{v}\frac{\partial\phi}{\partial t} = D\frac{d^2\phi}{dx^2} + \left[\nu\Sigma_f - \Sigma_a - DB_T^2\right]\phi \tag{1}$$

Where the terms have their usual reactor physics meaning and B_T^2 represents transverse leakage in the y and z directions. The Neumann boundary conditions for zero neutron flux are time dependent due to motion of the modulator. However, this complication can be removed by using a moving coordinate system synchronized to the modulator. This change of space variable is made to eliminate the problem with time dependent boundary conditions. The variables x and t are transformed to $x' = (x - V.t)$ and $t' = t$, where V is the linear velocity of the pulser. The transformed space coordinate corresponds to a moving frame of reference whose origin moves along the core length with the velocity of the pulser. We have the modified equaton as:

$$\frac{1}{Dv}\frac{\partial\phi}{\partial t'} = \frac{\partial^2\phi}{\partial x'^2} + B\frac{\partial\phi}{\partial x'} + A\phi \tag{2}$$

where

$$A = \frac{1}{D}\left[\nu\Sigma_f - \Sigma_a - DB_T^2\right] \tag{3}$$

$$B = \frac{V}{vD} \tag{4}$$

The transverse leakage term is different along the core and depends on the presence or absence of the modulator. Transverse leakage is normalized to the reactivity effect of the modulator using the solid angle interaction between the annular core and modulator. If Ω_1 and Ω_2 are respectively average solid angle subtended by core at the central point of modulator and solid angle subtended by modulator at the central point of core (nearest to modulator), then assuming a constant reflection coefficient (Albedo), the reactivity effect of the modulator is given by

$$\text{Reactivity Effect at a general location} = \frac{\Omega_1}{2\pi}.\frac{\Omega_2}{2\pi}.\text{Reactivity Effect at IN location} \tag{5}$$

The relationship for solid angle depends on the separation, which decreases linearly with time for a helicoidal approach. For a rectangle of side A and B the solid angle at a transversal distance H is given by [3,4]

$$\Omega = Arc\sin\left[\frac{AB}{\sqrt{A^2+H^2}\sqrt{B^2+H^2}}\right] \tag{6}$$

The equation for transverse leakage with modulator in a retracted position can be written in terms of transverse leakage values with modulator (suffix m) and without modulator (suffix 0) as follows:

$$DB_T^2 = DB_0^2 + \frac{\Omega_1}{2\pi}.\frac{\Omega_2}{2\pi}\left[DB_0^2 - DB_m^2\right] \tag{7}$$

During numerical simulation of differential equation 2 for flux errors arise due to discretization, truncation and round off. Numerical schemes that allow growth in error are unstable and the results may not correspond to the differential equation under investigation. For dicretization of parabolic equations, explicit, implicit and other schemes have been considered. Explicit schemes generally need small time step; else the solution of the difference equation may bear little resemblance to the reality. In the Crank-Nicolson scheme, the space derivatives are replaced by the average of its finite difference representation at time step n and time step (n+1). In the generalized Crank-Nicolson scheme a weighting parameter "r" is introduced between the time step n and (n+1). It has been shown that the Generalized generalized Crank-Nicolson scheme is unconditionally stable for choice of space and time steps for "r" between 0.5 and 1.0. For choice of "r" between 0.0 and 0.5, a relationship must be maintained between space and time steps to ensure stability.

Equation (2) is now discretized in time and space. The symbol ϕ_i^n represents the flux at location $x' = i.\Delta x$ and time $t' = n.\Delta t$ where $\Delta x'$ and $\Delta t'$ are the mesh size for space and time. Generalized Crank - Nicolson implicit scheme weighs the flux and its derivatives as follows. (For clarity now $\Delta x'$ is replaced by Δx as these are equal.)

$$\phi \Rightarrow r\ \phi_i^{n+1} + (1-r)\phi_i^n \tag{8}$$

$$\frac{\partial \phi}{\partial x'} \Rightarrow r\left(\frac{\partial \phi}{\partial x'}\right)^{n+1} + (1-r)\left(\frac{\partial \phi}{\partial x'}\right)^{n} = \frac{r}{\Delta x}\left[\phi_{i+1}^{n+1} - \phi_i^{n+1}\right] + \frac{(1-r)}{\Delta x}\left[\phi_{i+1}^{n} - \phi_i^{n}\right] \tag{9}$$

$$\frac{\partial^2 \phi}{\partial x'^2} \Rightarrow r\left(\frac{\partial^2 \phi}{\partial x^2}\right)^{n+1} + (1-r)\left(\frac{\partial^2 \phi}{\partial x^2}\right)^{n} = \frac{r}{\Delta x^2}\left[\phi_{i-1}^{n+1} - 2\phi_i^{n+1} + \phi_{i+1}^{n+1}\right] + \frac{1-r}{\Delta x^2}\left[\phi_{i-1}^{n} - 2\phi_i^{n} + \phi_{i+1}^{n}\right] \tag{10}$$

For $r \geq 0.5$, the scheme is unconditionally stable that makes the choice of Δx and Δt free of any constraints. Nevertheless Δx and Δt have to chosen small to reduce truncation errors and obtain an accurate representation of the reactor situation.

Time-dependent Transverse Leakage linked to approaching modulator is used in the solution of time dependent neutron diffusion equation. Crank-Nicolson Formalism, which is inherently stable, is employed in the algorithm for finite difference numerical solution. However, for obtaining a realistic physical solution the time step has to be maintained small and linked to the prompt neutron lifetime.

3. ADDITIONAL CONSIDERATIONS

The startup simulation with a helicoidal rotating approach of the modulator from its "OUT" position to its "IN" position is considered adequate from the reactivity point of view with adjustment in the angular speed of the modulator. For the time step of the order of nanosecond the observed flux growth is uniform from a uniform flux distribution for 50 rpm for the modulator.

It may be remarked that the use of diffusion theory by opening up of the annular core for analysis of neutron flux distribution does not involve any significant error when the ratio of annular thickness to the radius is negligible and curvature of the annular core is small. In other words, the small curvature of the core does not lead to deviations from the straight parallelepiped geometry considered in the study. However, some experimental confirmation and support with respect to minimum critical dimension of the modulator length may be appropriate.

The reactor entails a large fuel inventory and rigorous specifications for the geometry, composition etc. of the design are imperative. The safety of the system can be improved by use of additional safety rods to drop inside the core region at regular intervals (distance less than the critical length) along the core perimeter in addition to the drop of the modulator block from its "IN" position to its "OUT" position. The reactor shutdown system would be governed principally by the maximum signal in a series of detectors located around the core perimeter.

As has been pointed out, the modulator rotated around the core and so it seems natural to that its approach from the OUT to IN position is carried out while its rotation is maintained. Helicoidal path has been visualized for the inward movement of the modulator and parameters like helicoidal pitch would need to be specified in a detailed design. It may be prudent to attain the angular speed of the modulator before its inward motion along the helicoidal path starts.

Need of a neutron Source The concept in its initial operation phase (till a certain level of delayed precursors are built up) may need a small neutron source distributed along the annular core for efficient monitoring of the flux development.

Flux Values attainable in such a concept would depend upon the heat transport system employed. The concept envisages an augmentation by the figure of merit of this

4. RESULTS AND CONCLUSIONS

For the analysis startup of VICHFPR concept, IBR-2 reactor fuel properties have been used. The reactor is fueled with plutonium fuel elements clad in stainless steel and cooled by sodium.
*IBR data***.** IBR-2 fuel box consists of 7 fuel pins of about 7.5 mm diameter clad in stainless steel housed in a hexagonal stainless steel box. Effective one-group properties of the fresh core are given below.

$D = 1.55$ cm
$\Sigma_a = 0.01937\ cm^{-1}$
$\nu\Sigma_f = 0.05282\ cm^{-1}$
$\Sigma_{tr} = 0.2156\ cm^{-1}$

Core Geometry. The core analyzed has the following details.

Perimeter of the core	= 3.60 m
Height of the core	= 0.40 m
Width of the core	= 0.24 m
Reflector Saving of the pulser	= 0.0 8 m
Δx	= 0.0 6 m
Δt	= 4.6 E-9 s

No. of nodes in core region	=	56
No. of nodes in pulser region	=	4
Implicit Scheme Parameter, r	=	0.7
Neutron Velocity	=	1.4 E5 m/s
Pulser Velocity	=	3.0 E2 m/s

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- Retraction Distance of the Modulator
- Reactivity Addition Rate due to Modulator
- Pitch of the Helicoidal Path
- Angular and Linear Velocity of the Modulator

The study indicates that an annular reactor modulated by the reflecting modulator can be conveniently started up by bringing up the rotating modulator in a helical fashion adjacent to the core.

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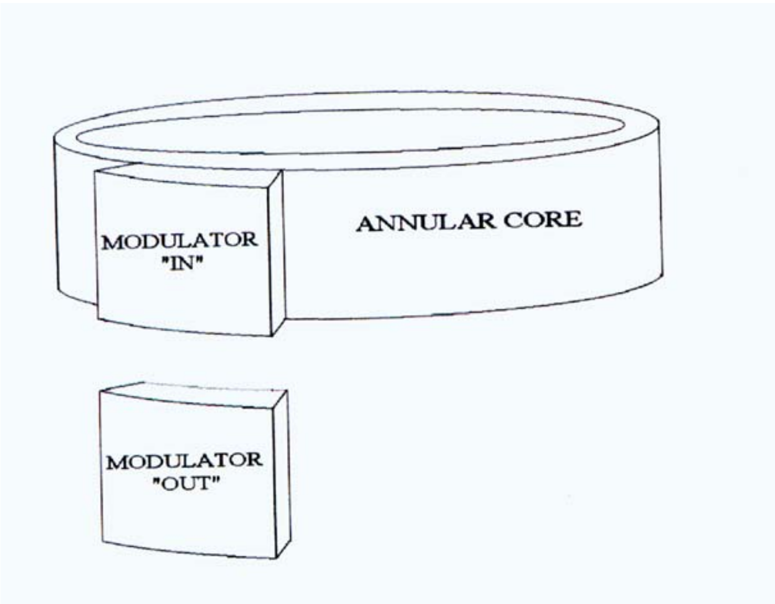

Figure 1. A Perspective View of the Annular Core with Modulator in the IN and OUT positions.

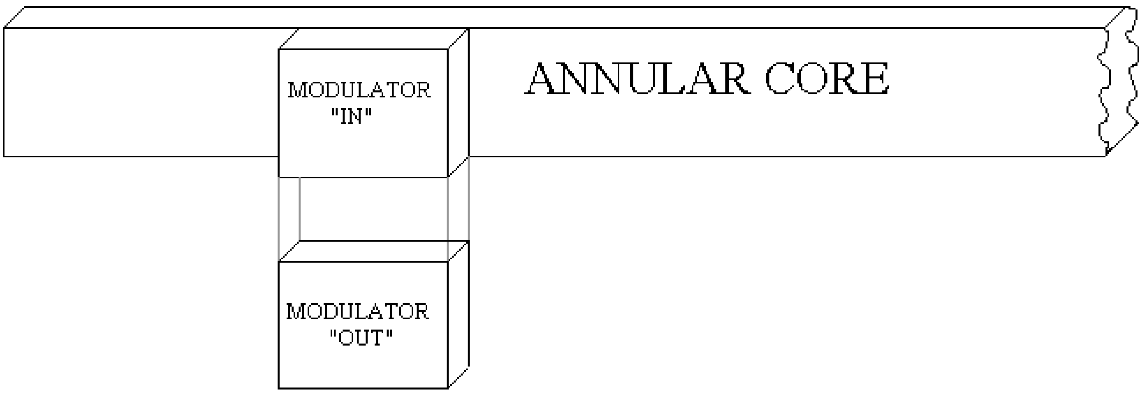

Figure 2. An Opened Out View of the Annular Core with Modulator IN and OUT Positions