NUCLEAR REACTOR SIMULATOR IN REAL TIME

Cuya T.[1] rcuya@ipen.gob.pe; Guarnizo J.[2] J.Guarnizo@iaea.org

(1) Departamento de Cálculo, Análisis y Seguridad – IPEN / Lima, Perú
(2) International Atomic Energy Agency (IAEA)

ABSTRACT

Numerical methods are present to solve space-independent transport equations for 6 delayed neutron groups and the isotopic evolution of poisons produced in a reactor, as well as their implementation in the development of a real time nuclear reactor simulator. An asymptotic performance is assumed for the spatial component of the neutron flux. The inhour equation, the control and safety rod effect, the reactivity transients and an interface to help the user become familiar with the setting, were considered to develop the simulator. An access routine to the PC timer has been developed to make the simulator work in real time

1. CONTENT

The transport theory and its impact on a reactor dynamics are usually difficult to understand. To make it more comprehensible, and to train the staff working in a nuclear center, a real time nuclear reactor simulator has been developed at the IPEN facilities, in Labview 4.0 (see figure 1).

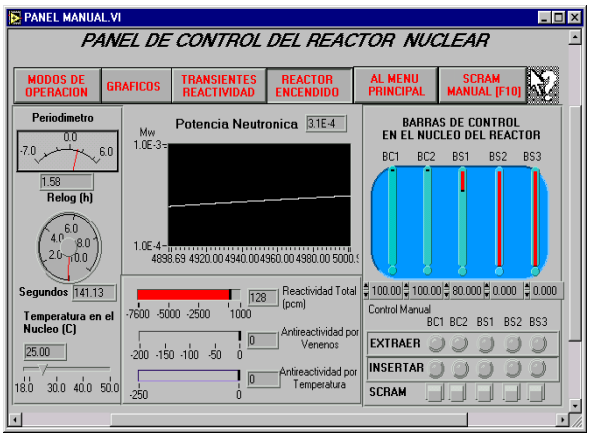

Figure 1.

Solving method: Hansen's and T. England's methods were adapted to develop neutron densities and the poison evolution.

The neutron kinetic equations for *n* delayed neutron groups are:

$$\frac{dn(t)}{dt} = \frac{\rho(t) - \beta}{\Lambda} n(t) + \Sigma_i^N \lambda_i C(t) \qquad (1)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} n(t) - \lambda_i C_i(t) \qquad (2)$$

Where:
n(t): Is the neutron density
$C_i(t)$: Is the *ith*-group-delayed neutron precursor density
$\rho(t)$: Reactivity
β_i: the *ith*-group delayed neutron's fraction
$\beta = \Sigma_i^N \beta_i$ is the total fraction of the delayed neutrons
A: Generation time
λ_i: decay constant of the *ith*-group precursors

Here a summarized method is presented. Details could be commented in the respective reference[1]. Based on equations (1) and (2) a 7-element column vector Ψ is defined. The first one is related to the neutron density and the others to the delayed neutron concentrations.

$$\psi(t) = \begin{bmatrix} n(t) \\ C^1(t) \\ . \\ . \\ . \\ C^6(t) \end{bmatrix} \qquad (3)$$

and a 7x7 a (t) matrix

$$A(t) = \begin{bmatrix} \frac{\rho(t)-\beta}{\Lambda} & \lambda_1 & & & & & \lambda_6 \\ \frac{\beta_1}{\Lambda} & -\lambda_1 & & & & & \\ & & & & & 0 & \\ & & & & & & \\ & & & 0 & & & \\ \frac{\beta_6}{\Lambda} & & & & & & -\lambda_6 \end{bmatrix} \qquad (4)$$

So the equation system (1) and (2) becomes:

$$a_{11}=\frac{\rho(t)-\beta}{G};\ a_{ii}(diagonal\ \ i=2,...7)=-\lambda_{i-1}$$

$$a_{i1}(first\ \ row-i=2,..7)=\lambda_{i-1};$$

$$a_{1j}(first\ \ column-j=2,..7)=\frac{\beta_{j-1}}{G} \qquad (5)$$

$$such\ \ that:$$

$$\frac{d\psi(t)}{dt}=A(t)\psi(t)$$

For the method's derivation, matrix A is split into an inferior triangular matrix (L), a superior triangular matrix (U) and a diagonal matrix (D).

Hence A(t) becomes:

$$A(t) = L + D(t) + U \quad (7)$$

Therefore, to develop an iterative process, equation (5) is expressed as follows:

$$\frac{d\psi(t)}{dt} - D(t)\psi(t) = (L + U)\psi(t) \qquad (8)$$

In time interval $h=t_1-t_o$, for which we assume an invariable reactivity, we integrate (8) between 0 and h. For this purpose the integration factor exp(-Dt) is introduce:

$$\psi(t_o+h)=\exp(Dh)\psi(t_o)+\left(\int_o^h \exp[D(h-\varepsilon)]\right)(L+U)\psi(t_o+\varepsilon)d\varepsilon \qquad (9)$$

Where $0<=\varepsilon<=h$ y $d\varepsilon=dt$

To provide a reasonable approach to the performance of $\Psi(t_o + \varepsilon)$ we assume it is exponential.

$$\Psi(t_o + \varepsilon) = \exp.(\omega_o\,\varepsilon)\Psi(t_o) \qquad (10)$$

Where ω_o is A largest self-value, which is obtained after solving the equation.

$$|A-\omega I| = 0 \qquad (11)$$

Where I is the matrix unit

Equation (11) is the well-known Inhour equation and would be solved in every temporal interval with variable reactivity.

Inserting (10) in (9) and writing

$\Psi(t_o)= \Psi_j$ and $\Psi(t_o+h) = \Psi_{j+1,}$ hence:

$$\Psi_{j+1} = G(t_j)\,\Psi_j \quad (12)$$

Where matrix G represents the expression

$$G=\exp(Dh)+(\omega_o I - D)^{-1}\left|\exp(\omega_o hI)-\exp(Dh)\right|(L+U) \qquad (13)$$

Developing this expression we have:

$$G=\begin{bmatrix} e^{-d_o h} & \frac{e^{w_o h}-e^{-d_o h}}{w_o+d_o}\lambda_1 & . & \frac{e^{w_o h}-e^{-d_o h}}{w_o+d_o}\lambda_6 \\ \frac{e^{w_o h}-e^{-\lambda_1 h}}{w_o+\lambda_1}\frac{\beta_1}{\Lambda} & e^{-\lambda_1 h} & . & 0 \\ . & 0 & . & \\ \frac{e^{w_o h}-e^{-\lambda_6 h}}{w_o+\lambda_1}\frac{\beta_1}{\Lambda} & 0 & . & e^{-\lambda_6 h} \end{bmatrix} \qquad (14)$$

Where:

$$-d_o=\frac{\rho-\beta}{\Lambda}$$

We can observe from its nature, that matrix G is unconditionally stable for every real value of h and ω_o and gives as a result the right asymptotic solution (Frobenius' theorem).

The linear chain solution method will be used for the analysis of fission products [2].

This development by linear chains does not involve a generality loss and the results provide a notable flexibility. The *ith*-nuclide concentration in the chain is determined by following the sequence of the coupled equations:

$$\frac{dN_1}{dt}=\sum_k Y_i^k S^k + \gamma_{i-1}N_{i-1} - (\lambda_1 + A_1)N_i$$

$$i = 1,2,3.....$$

(15)

Where:

Y^k_i: production fraction by k fissil nucleid fission.
S^k : fission ratio of the *kth* fissil nucleid.
λ_i : radioactive decay constant.
A_i : $\Sigma\ g^j{}_i\ \sigma^j{}_i\ \phi^j$ where $\sigma^j{}_i$ is the j absorption cross-section (n, γ) of the *ith* nuclide in energy group j; $g^j{}_i$ is the spectrum or shielding factor, and ϕ^j is the neutron flux in the *jth* energy group.
γ_{i-1} : is λ_{i-1} or A_{i-1} depending on the coupling of precursor i-1 (Here, A_{i-1} is not necessarily the total absorption ratio, it is only the reaction portion (n, γ) which originates N_i. Thus, in fissile nuclides, A_{i-1} is the capture ratio.

$\overline{y_m S} = \sum_k y_m^k S^K$ is the average production ratio during time interval Δt added to all k fissile nuclides.

The general solution for set (15) to the *nth* nuclide, assuming a constant flux and an average fission ratio during an increase of time Δt, is:

$$N_n(t+\Delta t) = \sum_m^n \frac{1}{\gamma_n} \prod_{k=m}^n \gamma_k \left\{ \overline{y_m S} \left[\frac{1}{\prod_{k=m}^n (\lambda_l + A_l)} - \sum_{j=m}^n \frac{\exp[-(\lambda_j + A_j)\Delta t]}{(\lambda_j + A_j) \prod_{\substack{i=m \\ \neq j}}^n (\lambda_i + A_i - \lambda_j - A_j)} \right] + N_m(t) \left(\sum_{j=m}^n \frac{\exp[-(\lambda_j + A_j)\Delta t]}{\prod_{\substack{i=m \\ \neq j}}^n (\lambda_i + A_i - \lambda_j - A_j)} \right) \right\} \quad (16)$$

Where the time interval Δt is the value read by the PC timer.

2. DEVELOPMENT

The program consists of the following routines:

- Equation solving routines
- Operating initial condition routines. (see fig.2)
- Routine to obtain the poison solution (xenon, iodine, samarium and promethium)
- Inhour obtained by/developed by the Newton-Rhapson's method
- Routines to access to the PC timer
- control and safety rod monitoring routines
- Logical comparators
- Xenon, coolant temperature and rod feedback routines
- Coolant temperature routines
- Ramp, sinusoidal and constant reactivity insertion routines
- User-aid routines
- Routines of data storage in files
- Display monitoring routines

All these routines integrate the simulator's main programs. The source code for the main routines is shown below.

3. RESULTS

A comparison between the program performance and a RP-10 reactor in critical condition was made on January 22 1998, at 10:46:36 during 9635.25 seconds, with the following configuration:

Core : 17
Operation mode: IV
Power : 7 kW

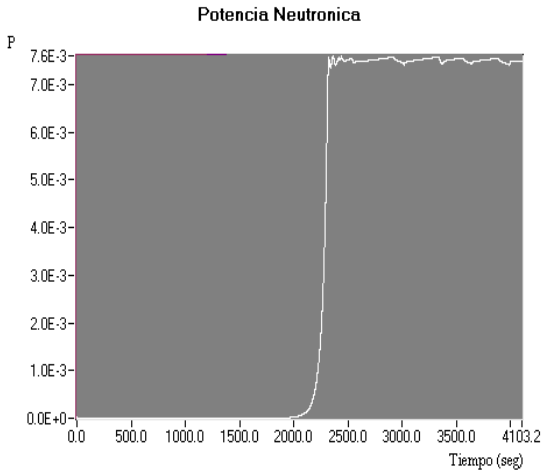

Figure 2. Power vs. time (simulator critical condition).

The results are shown in two diagrams. There is a great qualitative similarity between both, though there is no quantitative similarity because the equations used have been enormously simplified and the punctual approximation with all its limitations has been used.

4. CONCLUSIONS

1.- Hansen's an T. England methodologies has been applied with successful result in a nuclear reactor simulator development.

2.- Simulations of critical conditions can be doing, as well as rod control calibrations, poison behavior will be studied, reactor configuration will be change in order to have specified reactor conditions and characteristics parameters will be added using another controls, such to increasing the program complex.

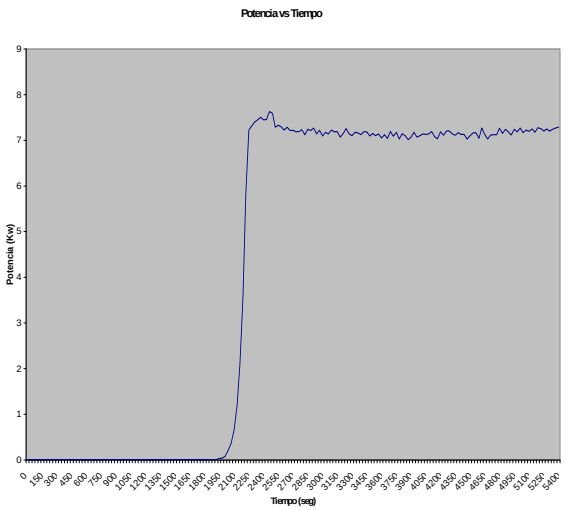

Figure 3. Critical condition (RP-10 nuclear reactor).

5. REFERENCES

[1]. Stable Numerical Solutions of the Reactor Kinetics Equations. K. F. Hansen, B. V. Koen and W. W. Little, Jr. Nuclear Science and Engineering: 22, 51-59 (1965).

[2]. Time – Dependent Fission- Product Thermal and Resonance Absorption Cross Sections. T. R. England. WAPD-TM-333 (1962).