# SIMULATION OF A CANDU REACTOR USING A REAL-TIME ADVANCED REACTOR CORE MODEL

Hoang Tran-Duc & Christian Paquette
CEA Electronics Ltd
P.O.Box 1800, Saint-Laurent
Quebec, Canada H4L 4X4

ABSTRACT

CAE Electronics Ltd., in collaboration with Koclas Logic System Ltd. has developed a fully dynamic , multi-nodal Advanced Reactor Core model for real-time simulator. In previous papers (References 1 and 2), this Advanced Core model has been validated by carrying out a series of static and dynamic benchmark tests, and by applying the model to a PWR core. In this paper, we present the model as it is applied to a 600 MW CANDU reactor core.

Good agreements with Plant or design data have been obtained and improvement over the Modal model (used in most CANDU simulators) in the reproduction of the local effect on a detector reading is achieved.

## 1. DESCRIPTION OF THE MODEL

A brief description of the implementation of the Advanced Reactor Core model is given in the following, a more detailed presentation of the model theory can be found in (References 1 and 2).

- A fine-mesh code (of the order of 10000 mesh cells) has been designed to solve the two energy group diffusion equations by finite-difference method. This code, when running off-line, is used to generate the reference solution for calculation of parameters to be used in the real-time diffusion equation.

- When finite-difference method is used to solve the coarse node diffusion equations (of the order of a few hundred nodes) for real-time simulation, unacceptably large errors associated with the homogenization of nuclear parameters over coarse nodes occur. These difficulties are circumvented in the Advanced Reactor Core model by using the Generalized Equivalence Theory (References 3 and 4).

As a result, the application of the Generalized Equivalence theory to real-time simulation provides :

a) An introduction of the so-called discontinuity factors which are used to force practically any approximate model to match exactly the relevant integral quantities (reaction and leakage rates, eigenvalue) edited from a more detailed reference calculation.

b) A prescription to calculate appropriate average nuclear properties over coarse mesh size node for real-time simulation.

The homogenized parameters and discontinuity factors are rigorously calculated for a particular core configuration, by a fine-mesh solution of the diffusion equations. In practice, for real time, we cannot afford to have these parameters pre-computed for each and every transient. Approximate method is therfore divised to infer the time dependence of these parameters based on pre-computed solutions performed off-line for a number of core configurations.

## 2. APPLICATION OF THE MODEL TO THE 600 MW CANDU REACTOR CORE.

The CANDU reactor core consists of an array of horizontal pressure tubes containing natural uranium fuel, passing through a large cylindrical vessel (calandria) containing the heavy water moderator and reflector. Pressurized heavy water coolant is pumped through the pressure tubes.

A vertical cross-section and a top view of the calandria are shown on figures 1 and 2 respectively :

- The reactor core is discretized into 9126 (27x26x13) cells defined for fine-mesh code.

- The core is also divided into 245 nodes (7x7x5) for real-time simulation.

In the following, "heterogeneous" refers to fine-mesh calculation, while "homogeneous" means coarse-mesh or real-time computation.

The Software Utility that is used to produce real-time programs and their inputs consists of three parts :

(a) **Reference Calculation Software** : These programs execute the following tasks :

- Process reactor core data supplied by the utility or fuel manufacturer so that it can be readily used in subsequent programs.

- The main program NEUTRONIC solves numerically the fine-mesh two-group diffusion equations, computes the homogenized nuclear properties and discontinuity factors for the real-time (coarse-mesh) diffusion equation.

(b) **Variation Calculation Software** computes deviations from the reference state of homogeneous nuclear properties for each type of perturbation (rods, temperature effects, Xenon, ... )

A number of deviations due to a given type of perturbations (e.g.

gradual insertion of a control rod) are computed. These results are approximated by a polynomial of a second degree.

The above Reference and Variation Softwares will be executed off-line to compute inputs to the real-time sofware.

(c) **Real-time Model Software** includes four modules :

- Module RR computes homogeneous nuclear properties and discontinuity factors as function of control rod positions, fuel, coolant and moderator temperatures, void and Xenon concentration in the reactor core.

- Using the homogeneous properties calculated in RR, module RL computes coupling coefficients for the one-group diffusion equation.

- This equation is then solved numerically in module RA. As a result, neutron fluxes at 245 nodes are obtained. For the purpose of calculating flux at each particular detector location, a further refinement is carried out in the form of flux reconstruction (see below). Module RA also computes the reactor decay heat.

- Finally in module RD, fluxes located at detectors throughout the reactor core are calculated using a Flux Reconstruction Technique : The reconstruction of local flux is performed in each of the coarse node by approximating the local flux $\Phi$ to :

$$\Phi(x,y,z) = F(x,y,x)\ \Psi(x,y,z)$$

where the form function $F(x,y,z)$ is a tri-quadratic polynomial :

$$F(x,y,z) = C_1 + C_2x + C_3x^2 + C_4y + C_5y^2 + C_6z + C_7z^2$$

$\Psi(x,y,z)$ is the reference fine-mesh flux.

The seven constants of the polynomial are contrained by the requirement that the reconstructed flux preserve the correct values of seven flux-related quantities : the coarse node volume-averaged and the six coarse node surface-averaged fluxes.

This flux reonstruction method permits flux calculation at any fine mesh, therefore at any flux detector location in the core.

## 3. TEST RESULTS

Three tests have been carried out and their results are compared to either the design data or the actual plant data.

(a) **Full Power Steady State** :

At Full Power Steady State, using Flux Reconstruction method, flux profiles along X-, Y- and Z-axis are plotted and compared to design data. Two such flux profiles are shown on figures 3 and 4. Figure 3 shows the flux profile on a horizontal intersection of planes J = 15 and K = 5 (see figures 1 and 2 for indices I,J,K). The seven troughs on the flux profile are caused by the seven Adjusters (1 to 7) through which the line passes. When compared to the design data (figure 3A), the closeness is remarkable.

Figures 4 and 4A show reconstructed flux along an Z-axis (I=8, J=10) and the corresponding design data.

(b) **Power Maneuvering :**

From Full Power Stedy State, the power is maneuvered to 80%, through the DCC action which increases the liquid zone levels. As the power decreases, Xenon poison increases, to compensate this negative reactivity, the liquid zone level decreases steadily until it reaches 20%, then according to the control rule, the first bank of Adjusters (1,7,11,15,21) will withdraw. This withdrawal will cause a temporary increase of the liquid zone level. At the end of the Adjuster withdrawal, the liquid zone level decreases again.

The test results for the Reactor linear power, liquid zone average level, average Adjuster position and the Xenon reactivity are shown on figure 5. The corresponding plant data is shown on figure 6.

(c) **Local Flux Effect :**

Two tests will show the effect of a control rod motion on neutron flux at various locations surrounding the moving rod :

- Adjuster 1 withdrawal from the core : the dynamic changes of flux close to zones 1 and 2 are shown on figure 7. Zone 1 is on top of zone 2, since Adjuster 1 is moving out, therefore getting farther from zone 2, neutron flux in this zone increases first but eventually settles to a slightly higher than its initial value because of the control action of the liquid zones.

On the other hand, zone 1 sees more of Adjuster 1 when it starts to move, flux in this zone decreases at first, then increases when the Adjuster moves out of the zone (figure 7). In other zones (3 to 14) the change in flux is much less important during the rod motion.

- MCA 4 insertion into the core : the flux profile on the intersection line of planes J=14 and K=7 is shown on figure 8.

4. CONCLUSION :

When modelling the reactor core neutronics, one of the most important problems in real-time simulation is the capability of reproduction faithfully neutron flux at the detector locations throughout the reactor core. Even with a model of hundreds of nodes, these coarse nodes are still too large : a single node may still contain several flux detectors. Approximations are therefore nesessary to refine the flux calculation.

The Flux Reconstruction method of the Advanced Reactor Core model, based on physical constraint requirements, has demonstrated through the above test results its capability to compute flux at a fine-mesh level with high accuracy and reasonable computer resources.

REFERENCES :

(1) J.KOCLAS, F.FRIEDMAN, C.PAQUETTE & P.VIVIER "Real-time Advanced Reactor Core Model" , Proceedings of the Second European Simulation Symposium, October 22-24, 1990 at Schliersee, Germany

(2) J.KOCLAS, F.FRIEDMAN, C.PAQUETTE & P.VIVIER "Real-time Advanced Reactor Core Model - Part II" , Eastern Multi-Conference Simulators VIII, New Orleans, Louisiana April 1-5, 1991

(3) K.KOEBKE "A New Approach to Homogenization and Group Condensation", IAEA Technical Committee Meeting on Homogenization Methods in Reactor Physics. Lugano, Switzerland, November 1978.

(4) K.S.SMITH "Spatial Homogenization Methods for Light Water Reactor Analisis", Ph.D. thesis, M.I.T. 1980.

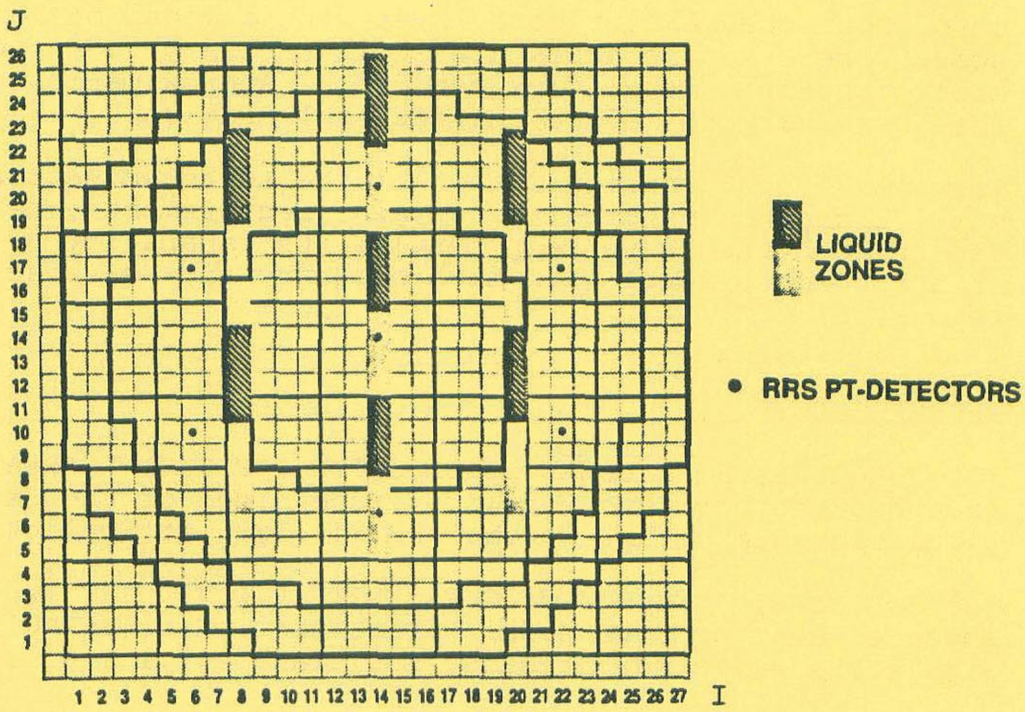


Figure 1  CANDU 600 MW NODALIZATION (FRONT VIEW)

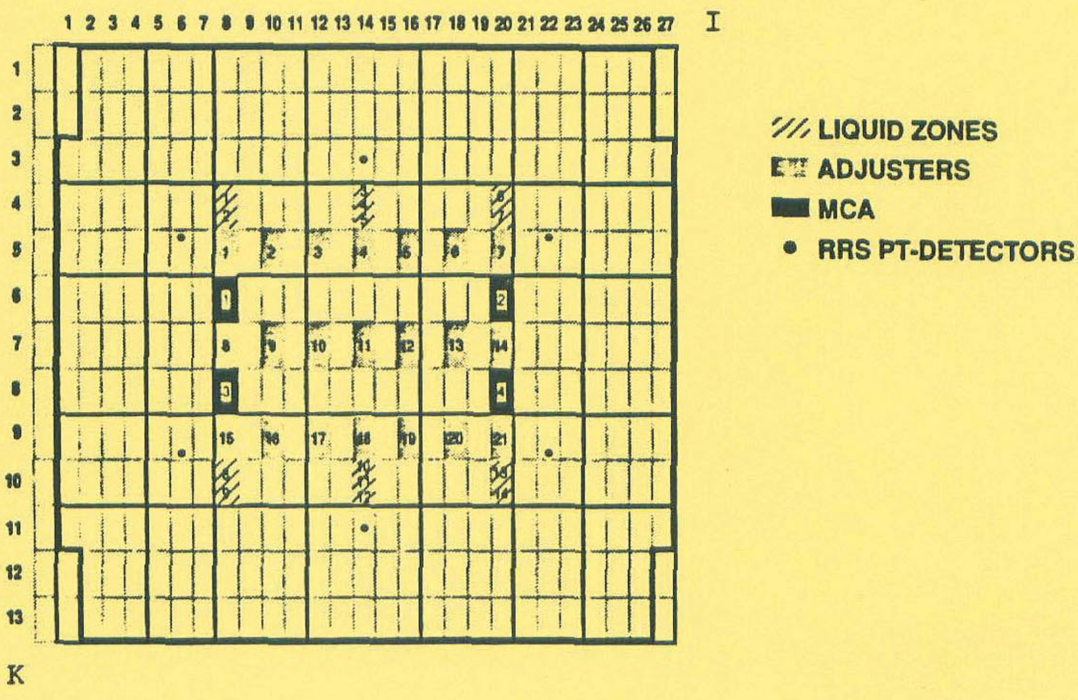


Figure 2  CANDU 600 MW NODALIZATION (TOP VIEW)

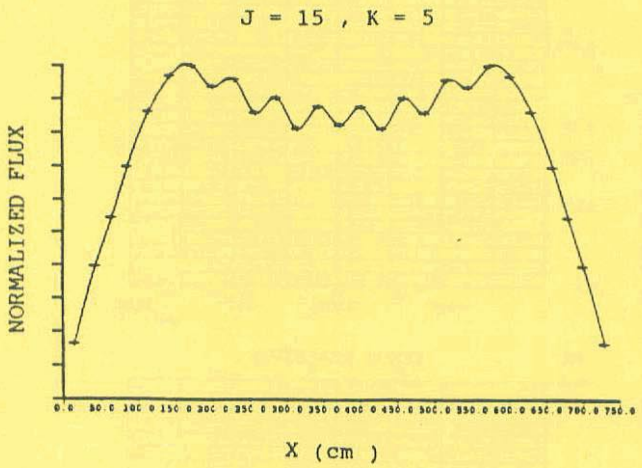


Figure 3 FLUX ALONG X-AXIS
(CALCULATED)

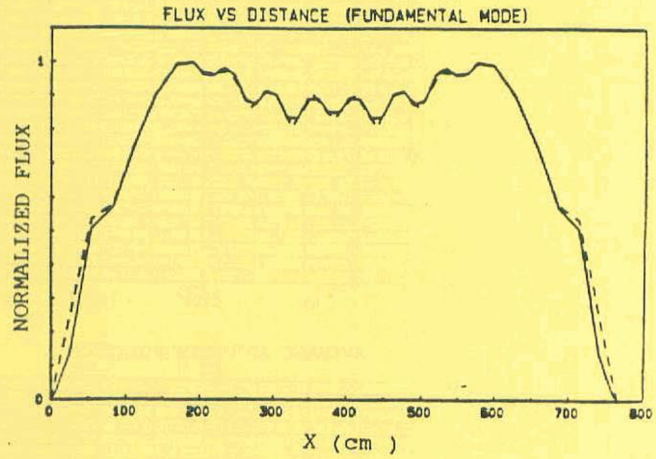


Figure 3A FLUX ALONG X-AXIS
(DESIGN DATA)

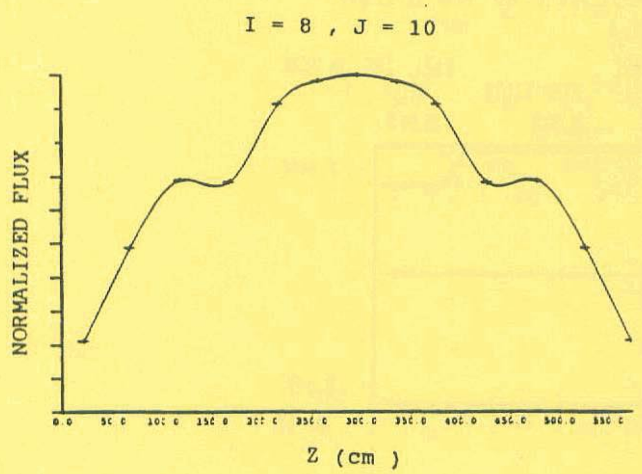


Figure 4 FLUX ALONG Z-AXIS
(CALCULATED)

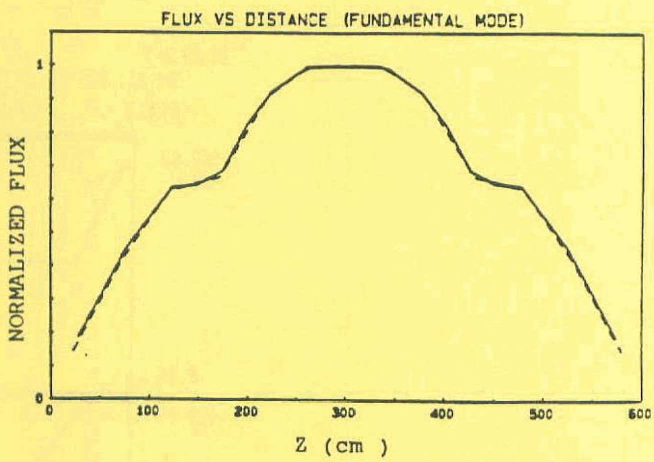


Figure 4A FLUX ALONG Z-AXIS
(DESIGN DATA)

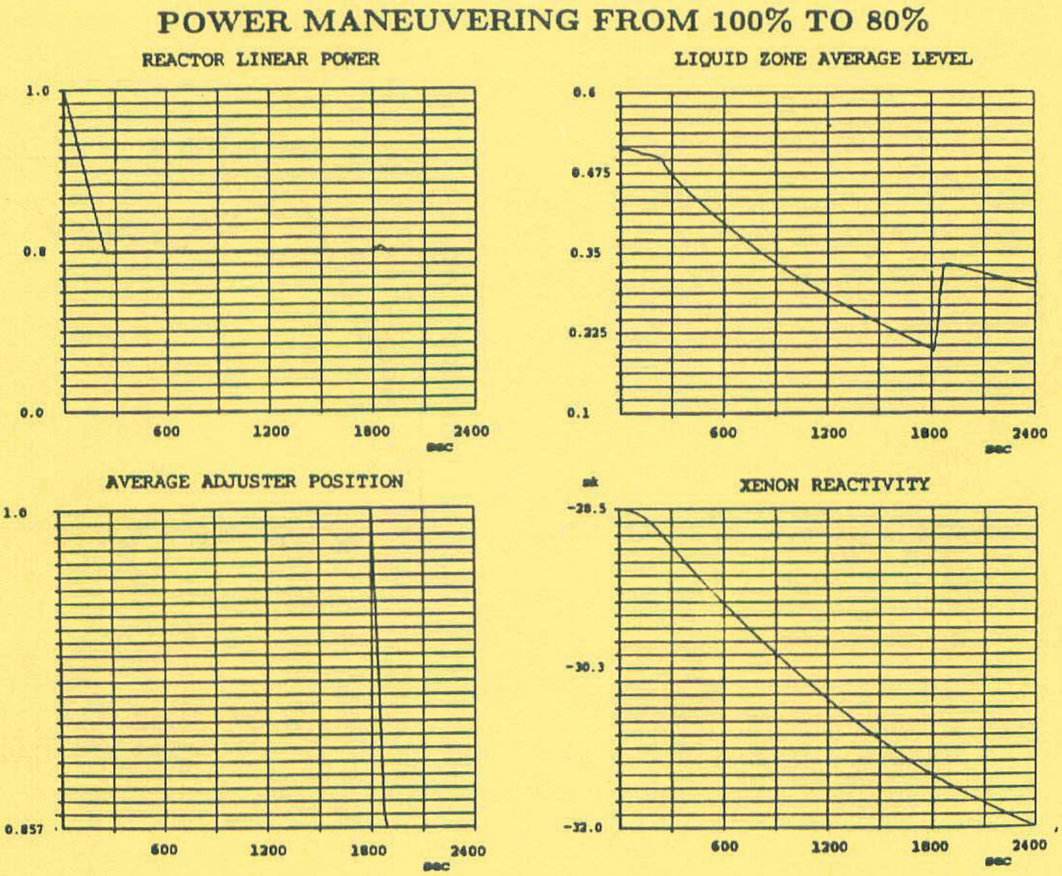


Figure 5 SIMULATION RESULTS

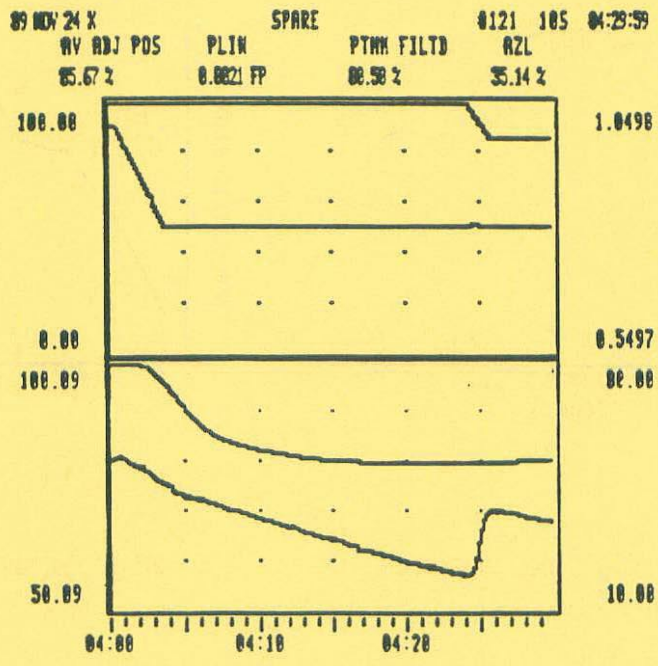


Figure 6 PLANT DATA

ADJUSTER 1 WITHDRAWAL FROM THE CORE

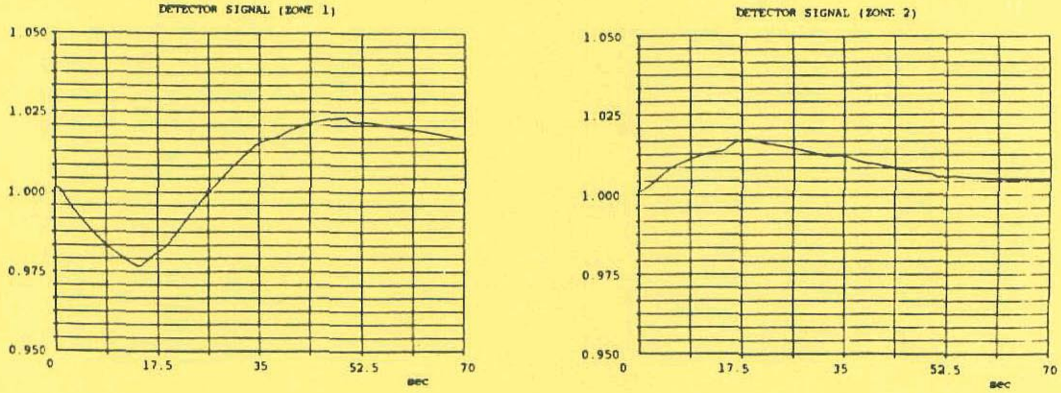


Figure 7 DETECTOR SIGNALS

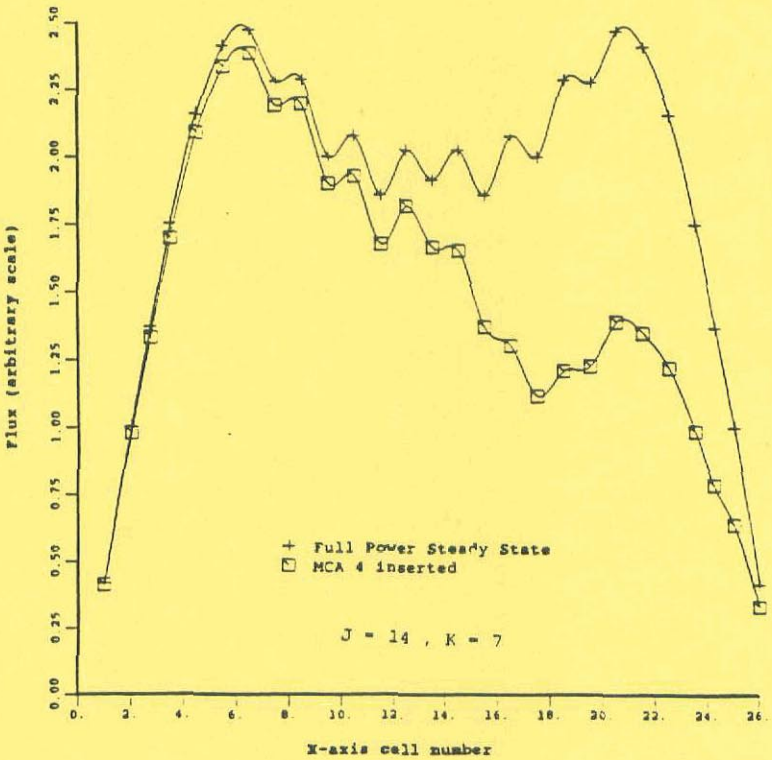


Figure 8 FLUX PROFILE ALONG X-AXIS
( J = 14 , K = 7 )