LECTURE 5: TIME DEPENDENCE SIMULATION

OBJECTIVES:

At the end of this lecture, you will be able to specify the combination of numerical methods and their interactions used to calculate:

1. **Reactivity and power distribution during a power transient.**
2. **Reactivity and power distribution during a loss of coolant accident.**

TIME DEPENDENT ANALYSES

Once the basic reference design of the reactor core is established based on "static" simulations with 3-dimensional two-group diffusion codes, it is necessary to verify the dynamic performance of the regulating and protective systems. Time dependent phenomenon which need to be studied fall into thre general time domains:

(a) The day to day refuelling of the reactor must be simulated during the design phase to a sufficient degree to assess the discrete effects associated with the fact that fuelling is in reality not continuous but is done by replacing small batches of fuel at a time.

- **The reference fuelling scheme for the CANDU-600 calls for replacing 8 fuel bundles within a channel upon each visit to a fuel channel.**
- **Because of fuel scheduling restraints several channels may be fuelled within a relatively short interval of time and then no fuelling done for a longer period. These effects cause localized distortions in the power distribution relative to that calculated with the reaction rate averaged model that was described previously.**

(b) Transient trends in ^{135}Xe concentration occur in the time domain of hours rather than days and these effects are treated by a different computer program than used for fuel management simulations.

(c) The time response of the shutdown systems following an assumed accident results in gross change in the reactor flux distribution on a time scale of seconds. This again is a different class of problem as delayed neutrons have a substantial impact on the flux shape.

We will discuss in some detail the methods used to treat the xenon problem and the reactor shutdown transient problem in the following.

XENON TRANSIENTS

The ability to simulate space and time variation of ^{135}Xe concentration in the reactor is important for two main reasons:

(1) to verify that the liquid zone control system can adequately control the power distribution following localized disturbances that can occur during normal operation such as refuelling channels. Spatial variation of 135Xe in response to a local disturbance is the main reason a spatial control system is provided.

(2) the xenon transient following a reduction in reactor power does vary spatially as the ^{135}I precursor distribution is proportional to the flux distribution in the steady state full power operating mode.

A computer program has been developed to permit calculation of:

- **xenon distribution in the reactor in space and time**
- **the corresponding effect of xenon on power distribution and overall reactivity**
- **the program is based on the two-group diffusion equations, but the equations describing the xenon and iodine variation as a function of the local flux are also included**
- **the code is "quasidynamic" in the sense that transients are simulated as a series of steady state cases with the flux assumed constant over a time interval but then updated in the next interval**
- **the program also includes capability to simulate the response of the liquid. zone control system to re-distribution of the xenon and iodine or in response to other localized perturbations.**
- **the response of the spatial control system of the reactor which couples changes in local or regional flux and/or power to response of the individual zone controller compartments.**

LIQUID ZONE CONTROL SYSTEM RESPONSE

The performance of the zone control system is typically verified by assuming that various fuel channels are completely refuelled with fresh fuel and observing the response of the zone control system to this disturbance.

It is followed in time long enough to be sure that either the new stable condition has been reached or is clearly being approached.

Figure 5-1 shows typical variation of the side-to-side and top-to-bottom tilt in the reactor following a refuelling disturbance.

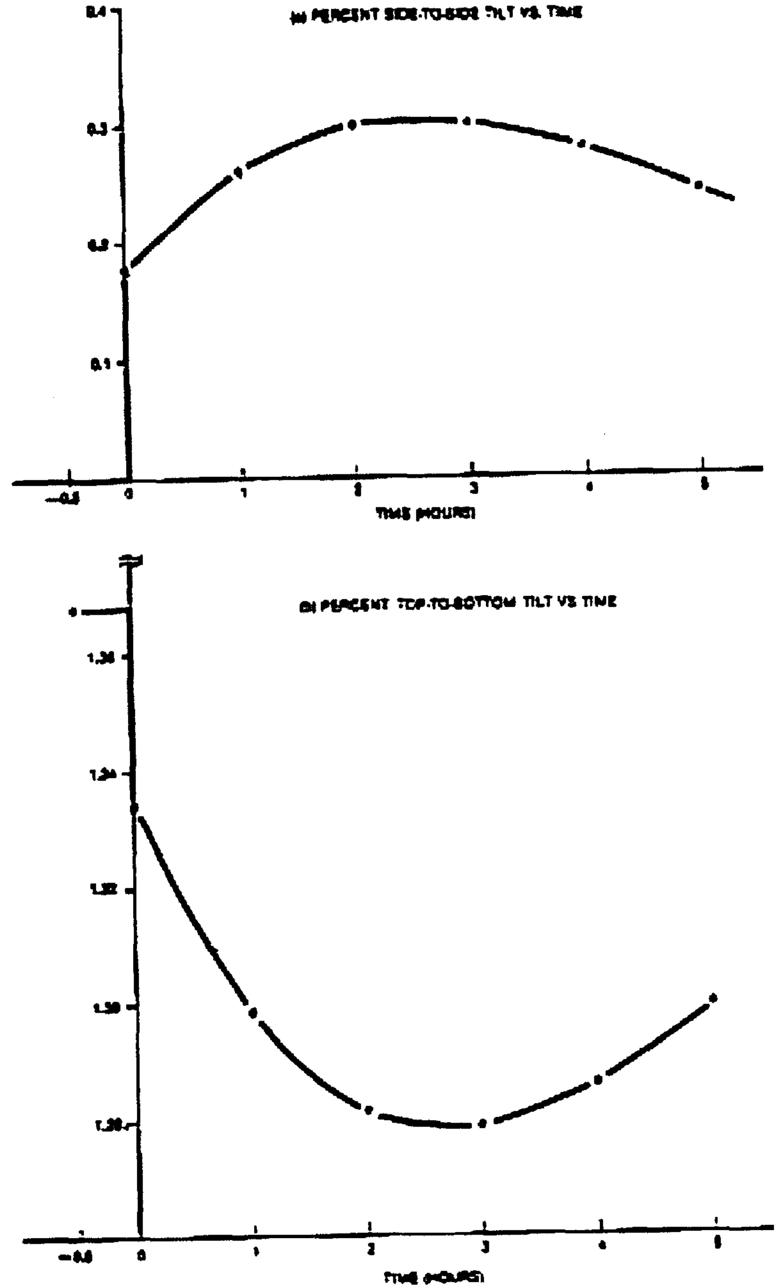


Figure 5-1: Transient Response of the Liquid Zone Control System after a Refuelling Perturbation

REACTOR REGULATING SYSTEM RESPONSE

Another application of the spatial control simulation computer program is to calculate the performance of the reactor regulating system and to predict accurately the time variation of reactor power distribution following a reduction in reactor power or during recovery from a reactor trip.

- **When the reactor power is quickly set back to some lower level and held there for some time the ^{135}Xe concentration will temporarily increase and then decay to a level slightly lower than the original value.**
- **As the xenon concentration increases the liquid zone control system will tend to empty to compensate.**
- **Before it reaches the empty condition, the regulating system activates one group of the adjuster rods and they are withdrawn. Since they are driven out steadily until fully out, the zone control system must fill to compensate.**
- **The rods are divided into a number of banks selected such that a complete withdrawal of any one bank can be more than compensated by filling of the liquid zone control system. (The withdrawal o the adjusters causes a change in the reactor power distribution so it is important to simulate that as well with the computer program.**
- **As the xenon concentration continues to increase the zone levels will be allowed to drain again at which time another group of adjusters will be withdrawn.**
- **This process means that the reactor does not operate for significant periods of time with adjusters partly inserted and hence partial insertion conditions do not need to be simulated in detail.**

REACTOR STARTUP FOLLOWING A SHORT SHUTDOWN

- **If the reactor has been shutdown to the time limit allowed by the design of the adjuster rod system, all of the adjuster rods will have to be withdrawn to restart the reactor and raise power to a level sufficiently high to turn the xenon transient over.**
- **In this case the simulation consists of tracing the power history and reactivity as xenon burns out and adjuster rods are driven in one bank at a time.**
- **This is necessary to verify that the reactor power can be raised sufficiently high to turn the xenon transient over without overrating the fuel due to the peaking effect caused by adjuster rods being withdrawn. A typical startup power history is shown in Figure 5-2.**

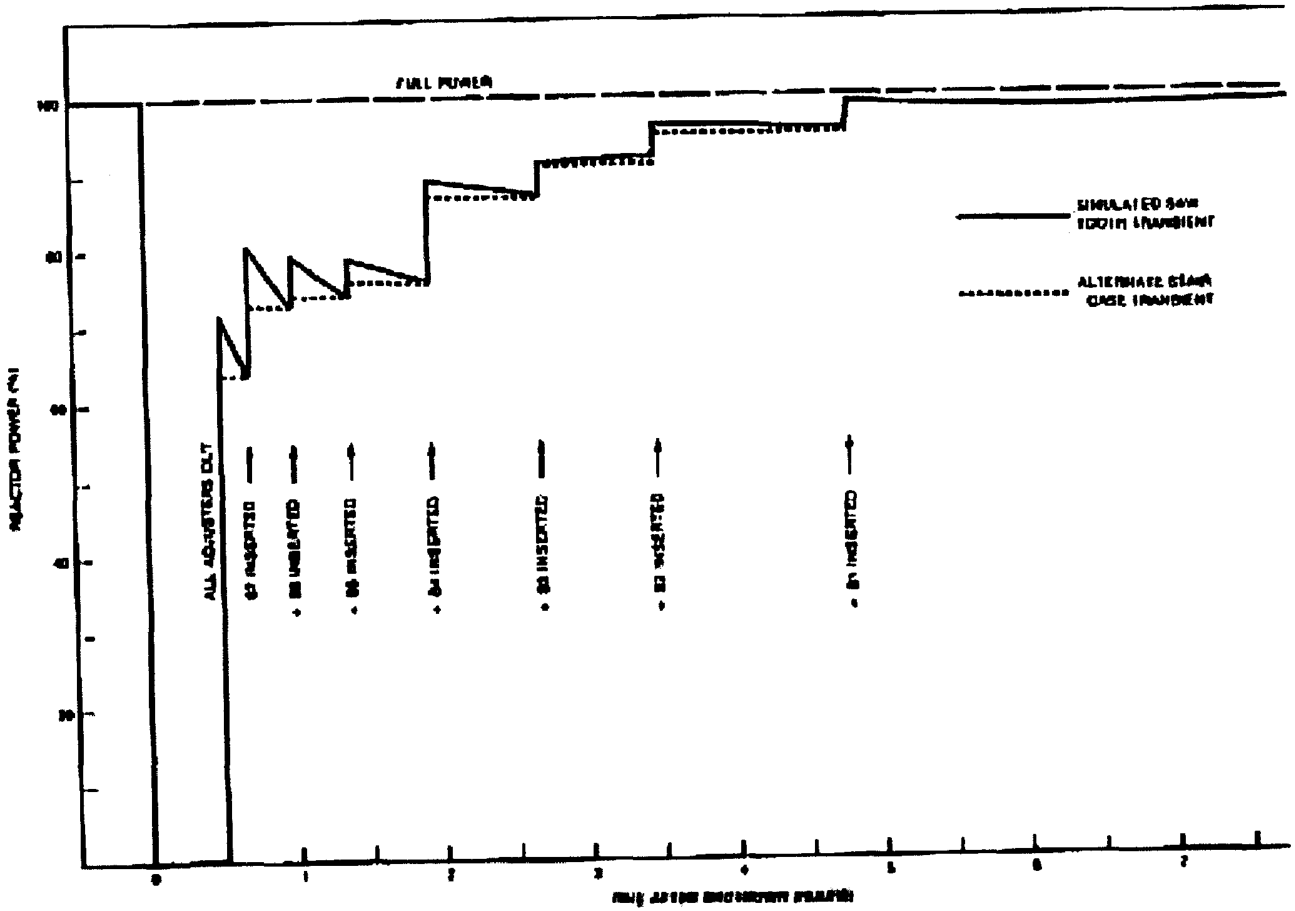


Figure 5.2: Reactor Power Transient Durir Following a 30 minute Shutdo

SHUTDOWN SYSTEM PERFORMANCE ANALYSIS

- It is the loss of coolant accident that tends to determine the design requirements of the shutdown systems.
- It is important to be able to predict the time variation of the power in each fuel bundle in the reactor reasonably accurately.
- In the CANDU-600 the primary transport system is divided into two circuits. When one of these circuits loses the coolant the channels in one half of the reactor are voided.
- Because of the associated small positive reactivity effect, the power rises somewhat preferentially in that side of the reactor which activates an overpower trip and causes the shutdown system to activate.
- In the case of the shutoff rod system, the rods are dropped into the core within about two seconds
- Since this time is comparable to the half-life of many of the delayed neutrons precursors it is important in simulating this event to correctly account for the space-time variation of the delayed neutron precursors.
- When the power decreases their relative contribution to the overall neutron balance becomes increasingly important.
- A computer program has been developed to permit this type of calculation to be done. It is a 3-dimensional code which employs the improved quasi static approximation (IQS).
- In this method the space and time dependent flux is factored into an amplitude function which is only time dependent and a space function which is only weakly depending on time.
- The IQS method is a flux factorized method developed to solve the time-dependent multigroup diffusion equation.

POINT KINETICS EQUATION

$$\frac{d\phi(t)}{dt} = \frac{[\rho(t) - \beta(t)]}{\Lambda(t)} \phi(t) + \sum \lambda_k C_k(t)$$

where the integral quantities $\rho(t)$, $\bar{\beta}(t)$, etc. must be derived by suitable averaging with the time dependent shape function $\Psi(r,E,t)$.

The unique approach in the IQS method is to use a backward difference of first order:

$$\frac{\partial}{\partial t}\Psi(r,E,t) = \frac{[\Psi(r,E,t) - \Psi(r,E,t-\Delta t)]}{\Delta t}$$

This approximation is valid when $\Psi(r,E,t)$ changes slowly, compared to $\phi(t)$. It then allows larger at intervals and the integral constraint condition is automatically satisfied within the interval Δt.

- **The space function is calculated in 3-dimensions, two energy groups, using a variable X-Y-Z mesh. Generally six delayed neutron precursor groups are used although more groups (to accommodate photo-neutrons explicitly) may be used.**
- **The code can simulate accurately flux shape retardation effects due to delayed neutron "hold-back" following an asymmetric coolant voiding, shutdown system action, etc.**
- **Point kinetics codes are used to analyze situations where spatial effects are not important or may be used to do parametric studies involving small changes in variables relative to a case which has been done with the complete 3-dimensional approach.**
- **This code is used to simulate both shutoff rod performance and performance of the liquid injection shutdown system.**

Poison Injection Shutdown System

- **The geometrical characterization of the distribution of the poison as a function of time after activation of the system is difficult.**
- **The flow characteristics of the jets of poison penetrating into the moderator from each of the small holes in the poison injection nozzle was determined empirically.**
- **Typical modelling of the system for purposes of simulating the neutronic behaviour is shown in Figure 5-3.**

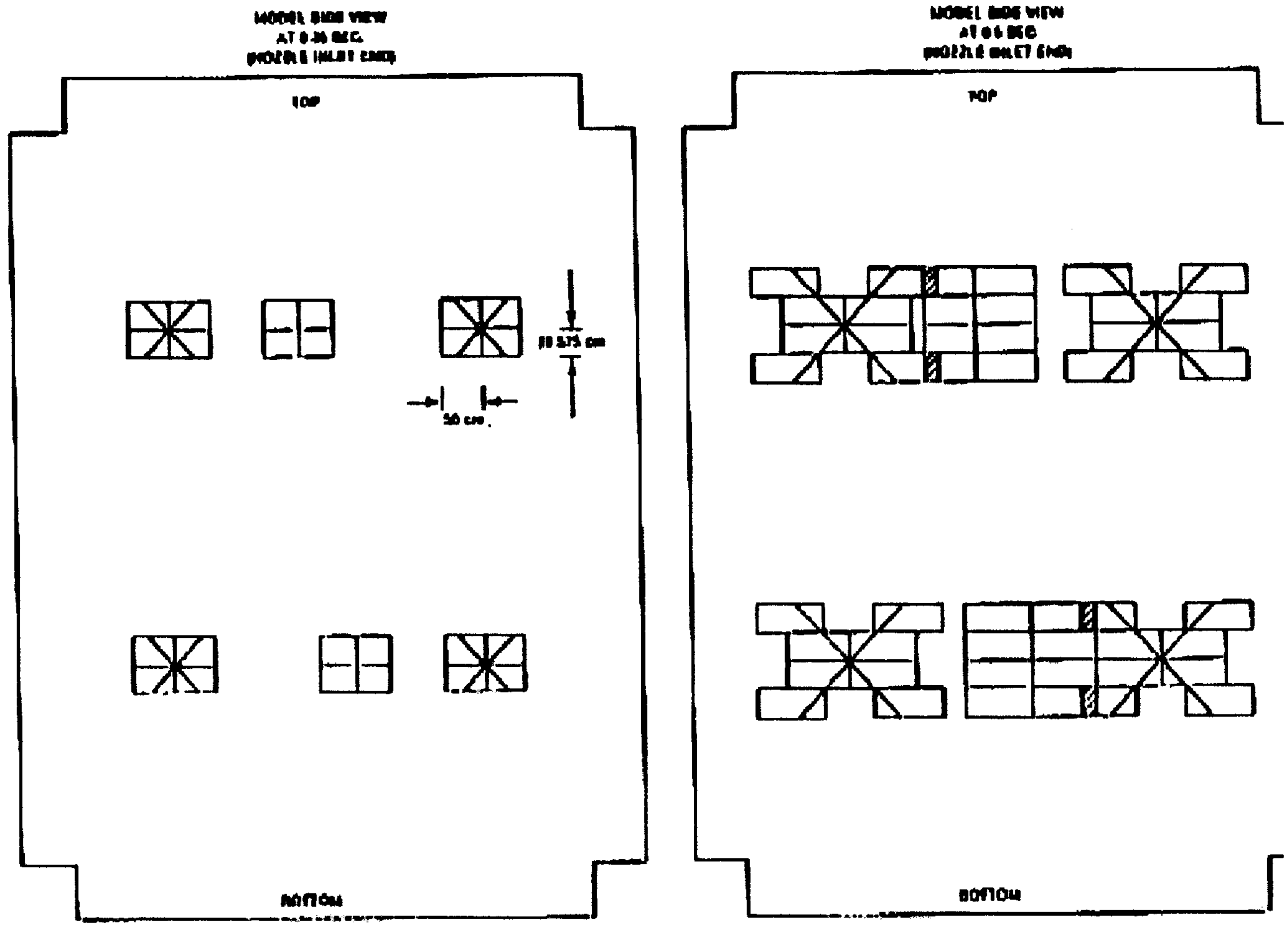
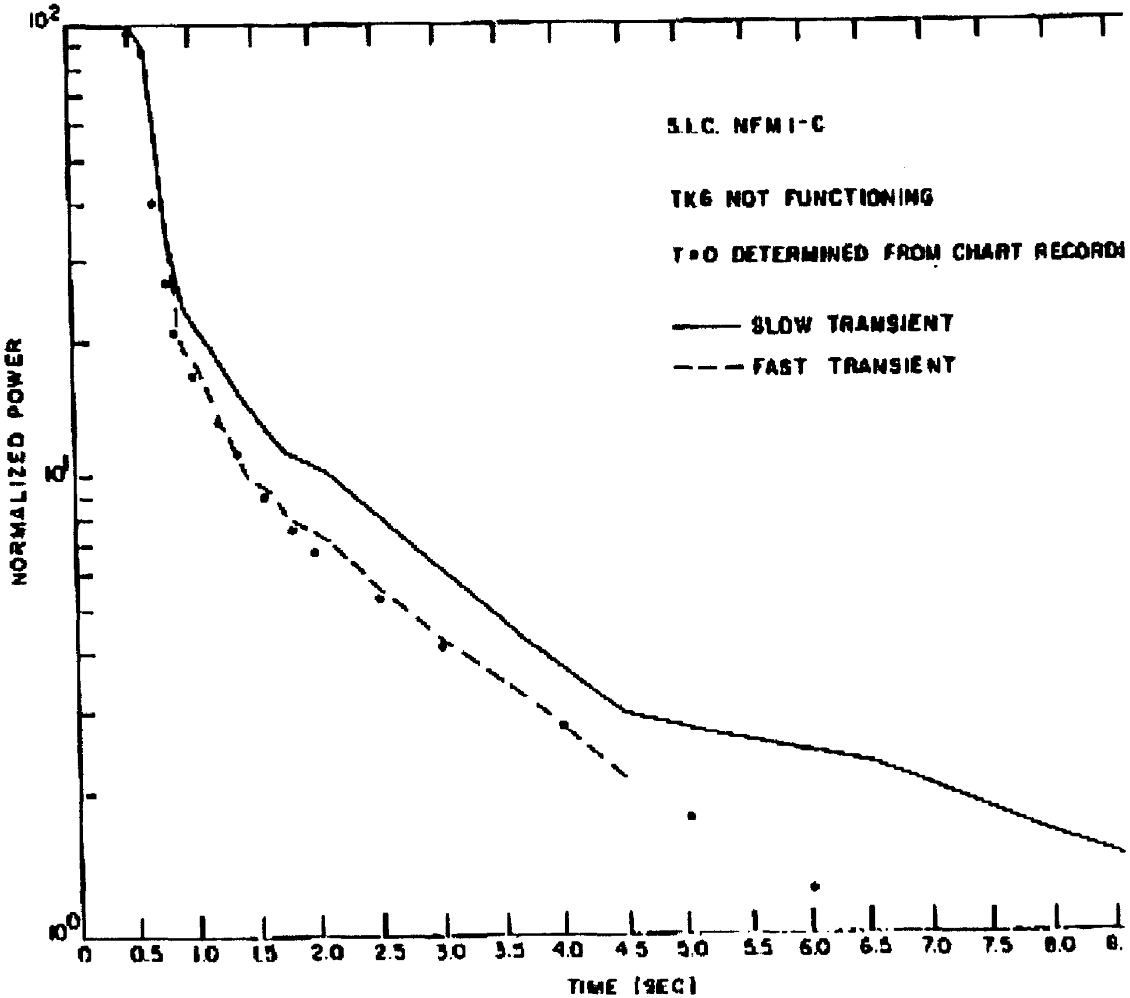


Figure 5-3: Cheby Full Core Model Used for Studying Worth of Poison Injection System.

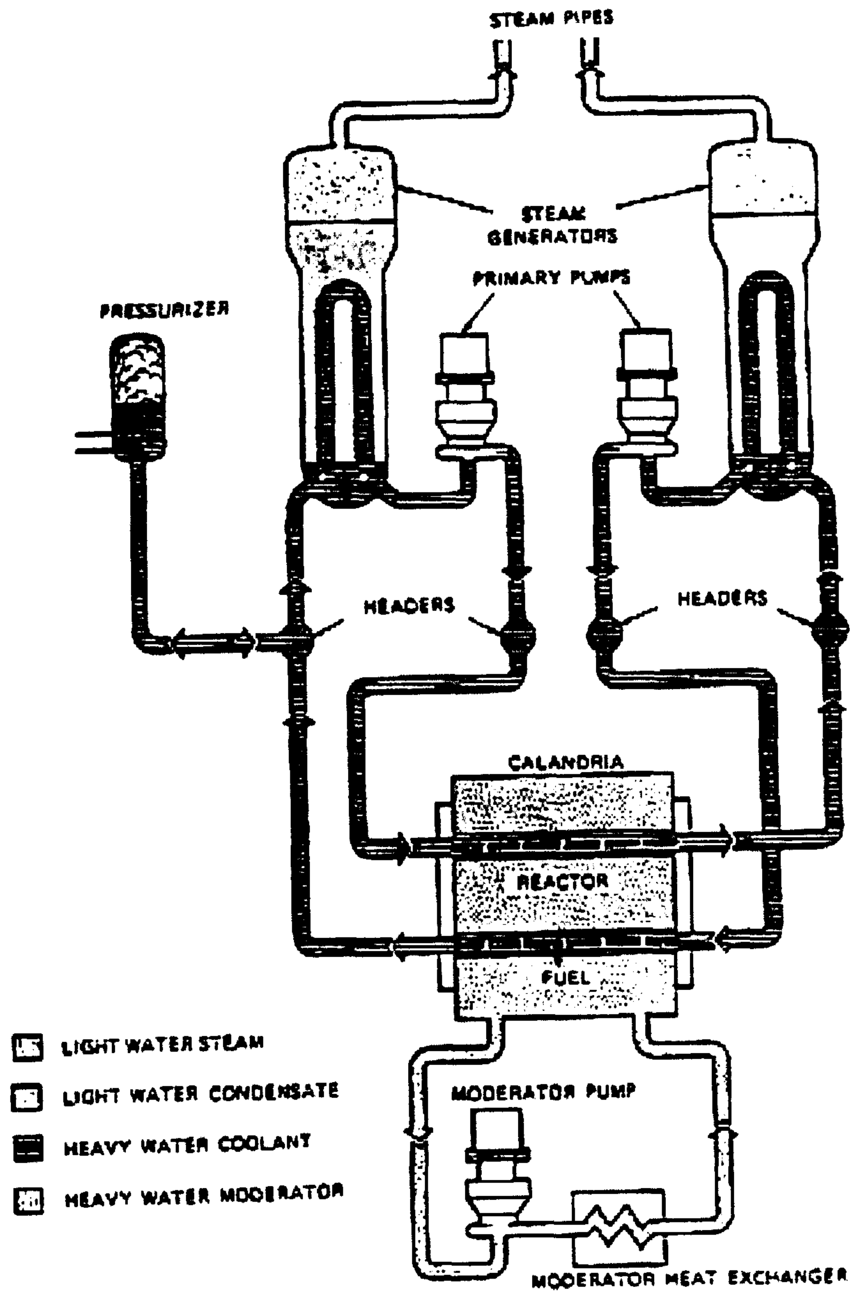
Model Accuracy

- Although the modelling does represent significant approximations, the calculated power transient following activation of this system agreed quite well with the experimental data as shown below.
- The curve labeled "fast transient" is the best estimate with no conservatism built in.
- The "slow transient" calculation has conservative input and is used in safety analysis.
- Note that the agreement between prediction and experiment is very good during the early part of the transient and then deviates from the experimental data with the calculation giving a slower reduction in the neutron flux with time than the experiment.
- This is not unexpected as the modelling of the poison injection into the moderator beyond the time at which the jets no longer have any geometrical definition is not possible.



MODELLING OF LOSS OF COOLANT ACCIDENTS

- **As mentioned before, the void reactivity effect in the CANDU-PHW is positive.**
- **Therefore the initial effect associated with a loss of coolant incident would be a tendency for the power to rise until the shut-down system is called into play.**
- **There are three factors which mitigate the power pulse due to a loss of coolant accident:**
  - ⇒ **subdivision of the coolant circuit;**
  - ⇒ **a long prompt neutron lifetime;**
  - ⇒ **the magnitude of the delayed neutron fraction due to the photo-neutron contribution.**
- **The primary heat transfer system is divided into two independent figure-of-eight circuits.**
- **These circuits are interconnected only via a pressurizer and a purification system. If one circuit suddenly depressurizes due to a break the inter-connect valves are closed, so the LOCA effect is confined to only half the core.**



Inlet Header Break

- **Figure 5-4 shows the variations of average coolant density with time in the voided circuit for a hypothetical 100% break of the inlet header.**
- **The density variation is calculated with a thermohydraulic blow-down code. The density change is assumed to take place throughout the fuel channels which are cooled by that circuit.**
- **Figure 5-4 also shows the reactivity transients (with and without shutdown system action).**
- **One second after the break the reactivity would be about 3 mk.**
- **The shutdown system will turn over the reactivity transient at about 0.65 seconds after the break.**
- **The maximum reactivity insertion is limited to less than 2.5 mk.**

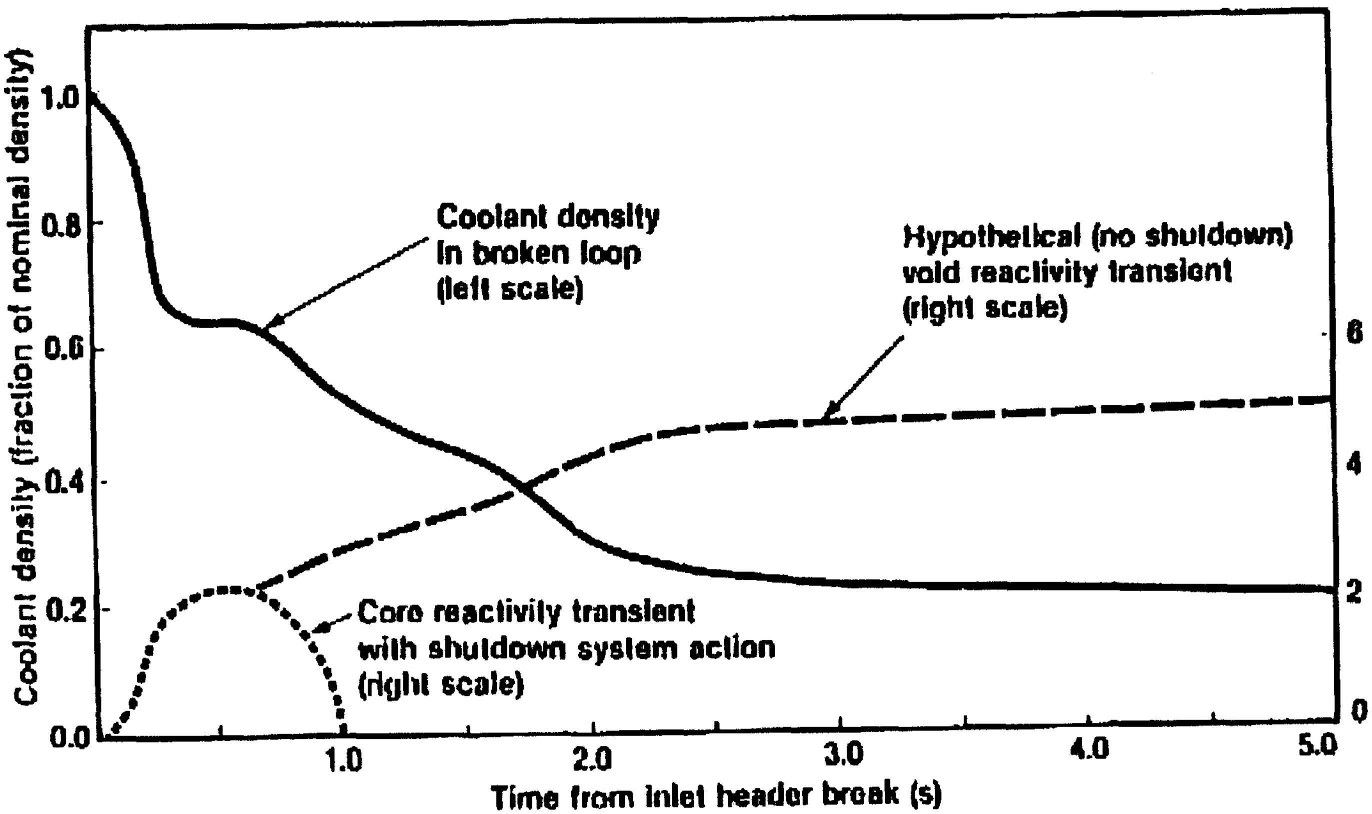


Figure 5-4: Coolant Density Change and Core Reactivity for 100% Break of the Inlet Header.

Neutronic Response to 100% Reactor Inlet Header Break

- **The prompt neutron lifetime in a CANDU lattice is relatively long (0.9 milli-sec.) compared to most other reactor designs.**
- **The delayed neutron fraction is enhanced due to the presence of delayed photo neutrons (produced by dissociation of deuterons by high energy gamma rays from fission products). These two factors slow down a potential power excursion considerably.**
- **Figure 5-5 shows typical power pulse for the hottest fuel bundle due to header breaks of different sizes followed by the action of one of the shutdown systems.**

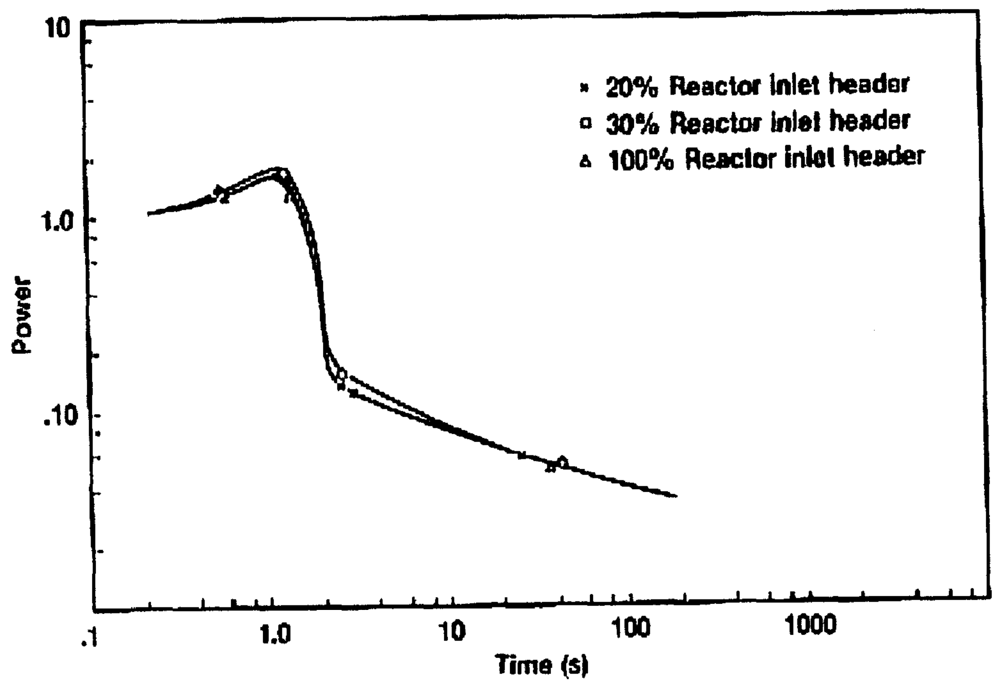


Figure 5-5: Hot Bundle Power Transient.

- **The peak power is only about a factor of 1.5 above the operating level and the short term (0 → 2.5 s) power pulse is only 2.6 full power seconds.**
- **Experimentally it has been found that a heat content of at least 200 calories per gram is required for spontaneous fuel breakup. This is equivalent to about 9 full power seconds for the maximum rated fuel pin. This means that spontaneous fuel breakup is not a safety concern during LOCA in the CANDU-PHW.**

Effect of Prompt Neutron Lifetime

- The influence of a longer prompt neutron lifetime on a power excursion is illustrated more clearly in Figures 5-6 and 5-7. These figures show two hypothetical reactivity transients and their associated power pulses with different values of ℓ^* (prompt neutron lifetime).
- Reactivity transient 1 roughly corresponds to a LOCA event followed by a shutdown system action in a 600 MWe CANDU.
- Transient 2 is a hypothetical transient with a reactivity insertion almost equal to the delayed neutron fraction (a condition called prompt critical).

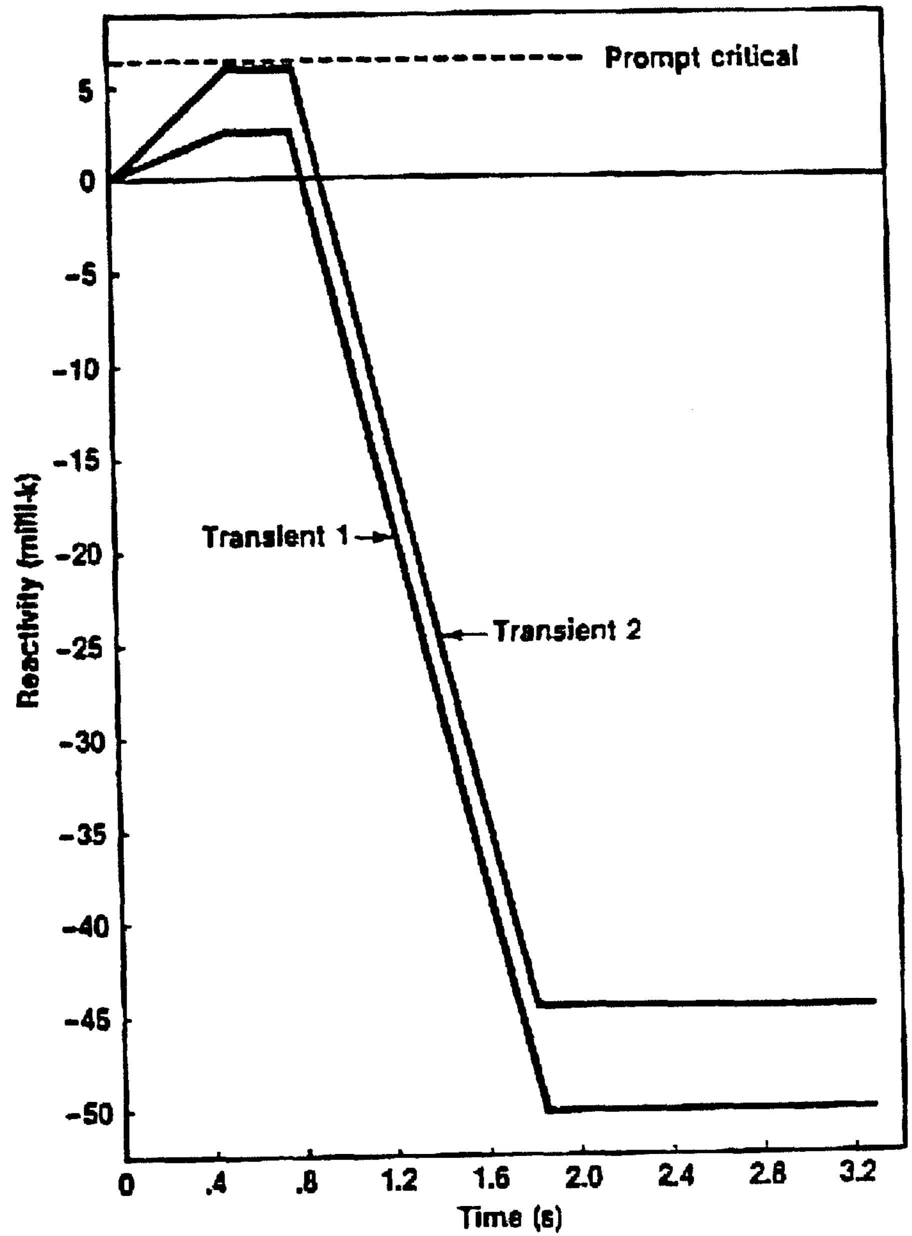


Figure 5-6: Hypothetical Reactivity Excursion.

Effect of Prompt Neutron Lifetime (continued)

- Neutron power transients marked A and B correspond respectively to an ℓ^* value of 0.9 milli-secs. (characteristics of the CANDU) and a value of 0.03 milli-secs (characteristics of light water reactors).
- For reactivity transients well below prompt critical the effect of different ℓ^* values is small.
- For reactivity insertions at or near prompt critical the larger ℓ^* retards the power pulse significantly.
- This is an important consequence since it reduces the demands placed on the shutdown design for CANDU reactors to relatively modest performance requirements.

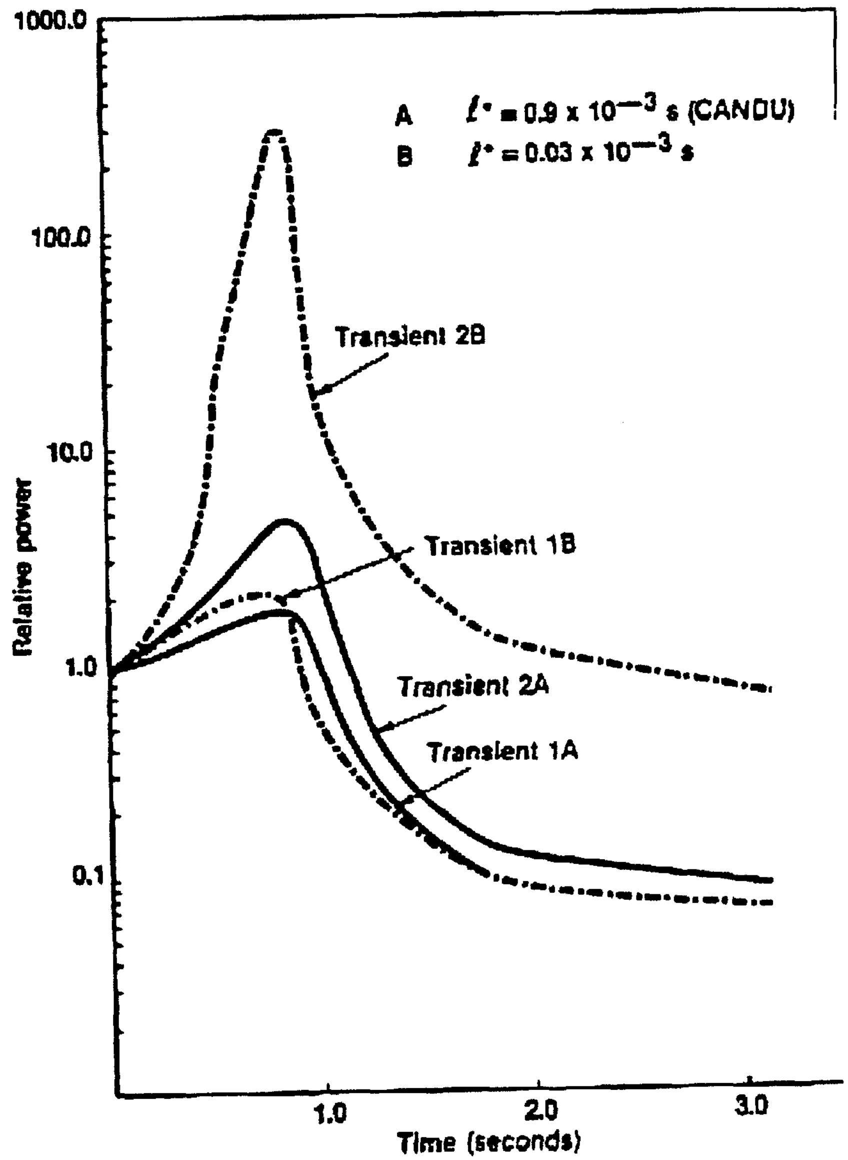


Figure 5-7: Sensitivity of Power Excursion to ℓ^*.

Effect of Delayed Neutrons

- The importance of the delayed neutron precursor distribution on the flux shape during a shut-off rod insertion transient, and hence on the "effective" reactivity of the shut-off rods at a given time is illustrated in Figure 5-8.
- A parametric study was done of the effect of the speed of insertion of shut-off rods on the dynamic performance of the system for a typical CANDU reactor.
- The only difference in the two calculations used to produce the curves in this figure is the speed of insertion of the rods. The arrow shown on each curve is the time at which the rods reached the centre-line of the core.
- Note that although the same amount of absorbing material is in the core at each of these points, the "effective" dynamic reactivity worth of this material is significantly different. Only a small part of that difference is due to the fact that more voiding of the core has occurred in the "slower" case.
- Most of the difference arises from the fact that in the "faster" case the flux shape is more strongly influenced by the delayed neutron precursor distribution that existed in the core prior to the initiation of the postulated loss-of-coolant and subsequent shut-off rod insertion.

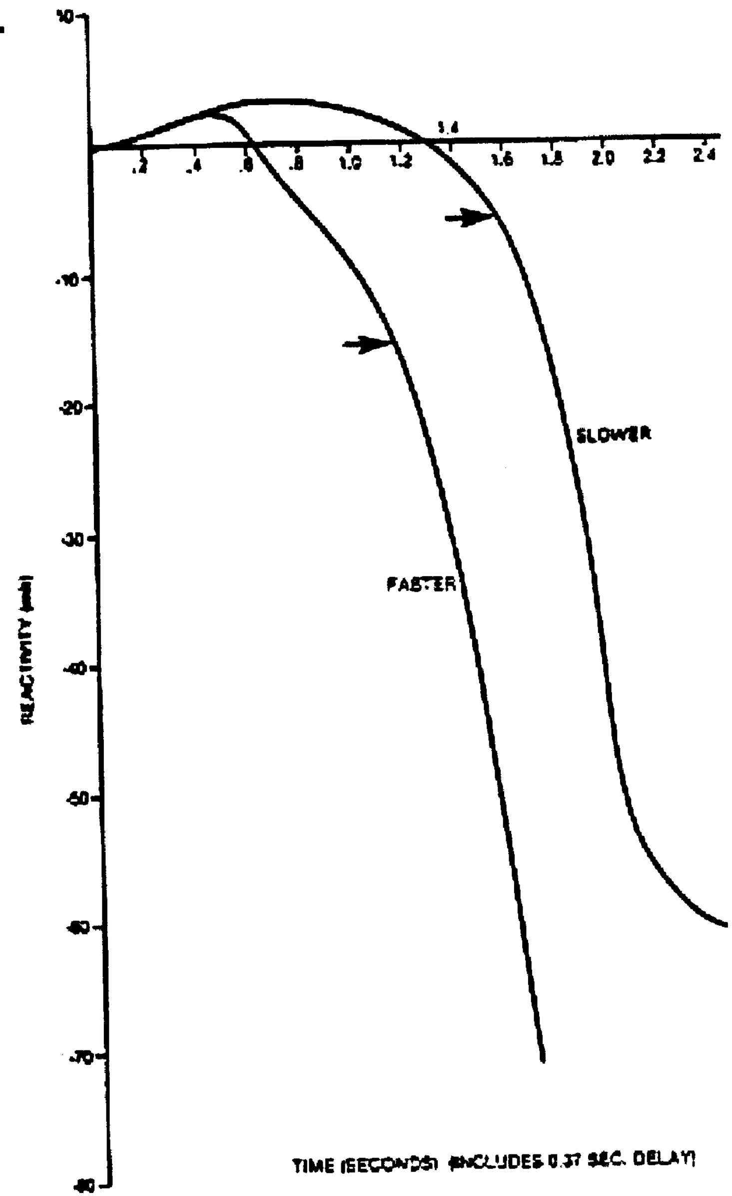


Figure 5-8: Dynamic System Reactivity vs. Time after Inlet Header Break.

On-Line Flux Mapping

- The CANDU-600 is provided with an on-line flux mapping system as part of the regulating system software.
- The system produces detailed flux and channel power distributions based on in-core self powered vanadium flux detectors.
- This information is used to provide a calibrated average zonal flux signal for use by the spatial control system, local overpower detection which activates the power setback routine, and on-line power distribution data for reactor operator information.
- It may also be used as a means of producing current power distribution information for purposes o calibrating the regional overpower protective system.
- A flux map is typically calculated automatically in approximately two minute intervals.

The task of the reactor physicist in the design of this system is to develop the software for the on-line control computer which can operate on the measured fluxes as indicated by the vanadium detector currents and produce a more comprehensive picture of the flux distribution in the reactor. The power distribution can also be determined from the flux distribution if the fuel burnup characteristics are known.

On-Line Flux Mapping (continued)

- The techniques of flux mapping consists essentially of a synthesis of the flux distribution from a pre-selected set of flux shape calculations, called flux modes.
- The amplitudes (i.e. the relative contributions) of the various flux modes are calculated by basically a least squares fitting of relative fluxes measured by vanadium incore flux detectors.
- The flux modes usually consists of a fundamental node plus thirteen of the higher harmonics of the flux distribution, plus a set of "perturbation" modes.
- The "perturbation" modes are flux distributions calculated for a variety of normal operating conditions that may occur such as during periods when the adjusters are not all inserted because they are compensating for transient variation in xenon concentration in the reactor.
- All the flux shapes or modes are pre-calculated once in an off-line simulation using the standard two-group diffusion codes that have been discussed previously. A set of coupling coefficients are obtained from these simulations.
- The coefficients are stored in the generating unit's digital control computer. The least squares fitting algorithm involves essentially one matrix vector multiplication to obtain the mode amplitudes, and a second matrix vector multiplication to obtain an extended flux map.
- The input to the flux mapping system is provided by outputs from about 100 vanadium self-powered incore detectors. The vanadium detectors are calibrated individually prior to their installation in the reactor so that they accurately reflect the correct relative flux at their respective locations.