AECL EACL

Time-Average Model (*TIME-AVER Module)

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AECL
Atomic Energy of Canada Limited

EACL
Énergie atomique du Canada limitée

Time-Average Model (*TIME-AVER Module)

- The time-average model is *not* an average over time of core snapshots
- It is a model in which *lattice cross-sections* at each location (bundle) are averaged over the residence time of the fuel at that location

Features of time-average model:

- Bundle-specific properties
- Lattice properties of each bundle averaged over irradiation interval experienced by fuel at that location - *assuming flux constant in time*
- Axial refuelling scheme taken into account

Time-Average Model (con't)

- Use indices j = channel, k = axial position
- Let $\hat{\phi}_{jk}$ be the average (assumed constant) fuel flux at position jk
- Let T_j denote average time between refuellings ("dwell time") for channel j
- Let $\omega_{in,jk}, \omega_{out,jk}$ be the irradiation of the fuel as it *comes into* and *exits from* position jk

Then: $$\omega_{out,jk} = \omega_{in,jk} + \hat{\phi}_{jk} T_j \qquad (1)$$

Time-Average Model (con't)

Time-average value of cross-section Σ_i at position jk is the value which preserves average reaction rate:

$$\Sigma_{i,jk}(t.av.) = \frac{\frac{1}{T_j}\int_0^{T_j} \Sigma_{i,jk}(\omega)\hat{\phi}_{jk}dt}{\frac{1}{T_j}\int_0^{T_j} \hat{\phi}_{jk}dt}$$

Change variables to $d\omega = \hat{\phi}_{jk}dt$ as before:

$$\Sigma_{i,jk}(t.av.) = \frac{1}{\omega_{out,jk} - \omega_{in,jk}} \int_{\omega_{in,jk}}^{\omega_{out,jk}} \Sigma_{i,jk}(\omega)d\omega$$

i.e., time-average cross sections are functions of time-average flux, and time-average flux is function of cross-sections (via diffusion equation)

$\therefore$ Self-consistency problem

Time-Average Model (con't)

- Calculational scheme *not complete* without relationship between dwell time and flux. This relationship is derived below for an N-bundle-shift in a 12–bundle channel

- Immediately after refuelling, first N bundles are fresh while positions 12-N contain shifted bundles:

$$\omega_{in,jk} = \begin{cases} 0 & \text{for} \quad 1 \le k \le N \\ \omega_{out,j(k-N)} & \quad N < k \le 12 \end{cases}$$

Time-Average Model (con't)

- Exit irradiation in channel j is average of values of out going irradiation over N bundles leaving channel:

$$\omega_{exit,j} = \frac{1}{N} \sum_{k=13-N}^{12} \omega_{out,jk}$$

- It can be show that, in general, for an N-bundle shift we have:

$$\omega_{exit,j} = \frac{T_j}{N} \sum_{k=1}^{12} \hat{\phi}_{jk}$$

- or, equivalently:

$$T_j = \frac{N\omega_{exit,j}}{\sum_{k=1}^{12} \hat{\phi}_{jk}}$$

*TIME-AVER Module

- **The $\omega_{exit,j}$ and the axial refuelling scheme are the *degrees of freedom* of the problem.**

The code user must first:

- **define regions of refuelling scheme (e.g. 2-bundle-shift for all channels, or regions of 2-bs and others of 4-bs, etc...); in the limit, a different fuelling scheme could be defined for *every* channel**
- **define *guess* values for the $\omega_{exit,j}$; again, this can be by region, or, in the limit, by *channel***

*TIME-AVER Module (con't)

- **The time-average calculation then proceeds and should be allowed to iterate until convergence: convergence in the flux *and* in the irradiation ranges [$\omega_{in,jk}$, $\omega_{out,jk}$] (and consequently in the dwell times)**
- **Once convergence is attained, the user must examine the result to decide if:**
  - **criticality has been obtained (k_{eff} = 1, or appropriately close to 1)**
  - **the desired flux shape has been obtained (look at zone or region fluxes)**

*TIME-AVER Module (con't)

- **If these conditions are satisfied, the calculation can be considered complete.**
- **if the conditions are not satisfied, adjustments have to be made and the calculation repeated:**
  - If criticality has *not* been obtained, then the *average* value of $\omega_{exit,j}$ has to be adjusted.
  - If the flux shape is not as desired, the *relative* values should be adjusted, or new regions with different values of $\omega_{exit,j}$ should be defined (e.g., to obtain more or less radial flattening, or compensate for specific local features such as hardware at bottom of calandria)

Example: the flux shape obtained has too much radial peaking; radial flattening is required to satisfy channel-power license limits; the user will flatten the radial flux by increasing the values of $\omega_{exit,j}$ in *inner* core relative to those in *outer* core; trial and error may be needed to achieve all desired conditions.

*TIME-AVER Module (con't)

- One more self-consistency problem needs to be considered: the consistency of the ^{135}Xe concentration with the flux (power).

Two choices are available:

- Do all calculations with an *average* ^{135}Xe concentration; ignore self-consistency - do not use XE trailer card.
- Demand self-consistency of ^{135}Xe concentration with power by using XE trailer card - this is the more correct treatment: the ^{135}Xe concentration will be re-calculated at each iteration of the irradiation ranges (or axial flux shape, or dwell times).

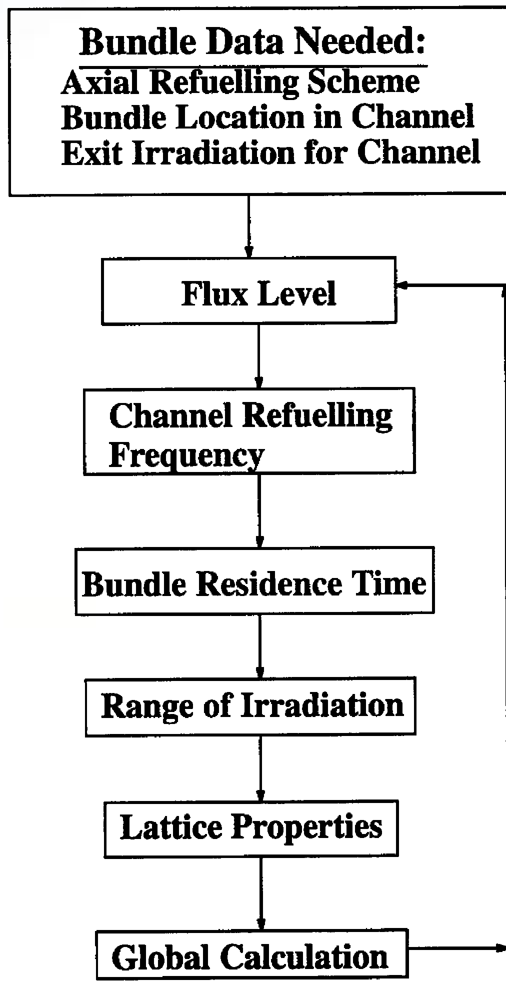
*TIME-AVER Module (con't)

- Within the *TIME-AVER module, there are two main calculational *regimes* or *options* which are very important to distinguish from each other:
  - Solving for the time-average flux shape. Here the full self-consistency problem is solved, i.e. the fluxes $\hat{\phi}_{jk}$, the dwell times T_j, and the irradiation ranges $[\omega_{in,jk}, \omega_{out,jk}]$ are all calculated in self-consistent fashion. This is what has been described above. ***This option is selected by setting IPRESRV = 0.***
  - Solving for a *perturbation* in a given time-average core (e.g., calculating device worths). Here only the *perturbed flux distribution* is calculated - the irradiation ranges (and dwell times) obtained previously are kept fixed; self -consistency is not sought. ***This option is selected by setting IPRESRV = 1.***

*TIME-AVER Module (con't)

- Both options yield a k_{eff} value and a flux shape. Only the first option yields also irradiation ranges [$\omega_{in,jk}$, $\omega_{out,jk}$] and dwell times T_j.
- Note that in both options the XE trailer card can be used to demand self-consistency between the flux distribution and the ^{135}Xe concentration
- Note also that the flux distribution obtained with the *TIME-AVER module *has no refuelling ripple* - since all bundles have properties averaged over an irradiation range, and there are no channels which have "recently been refuelled". Therefore the target time-average channel and bundle powers must be sufficiently lower than the license limits to allow for the refuelling ripple which will be obtained in instantaneous snapshots.

Time–Average Calculation



*TAVEQUIV Module

- The time-average model gives cross-sections which are averaged over the fuel residence time. The model therefore provides a good approximation to a *long-term-average* picture of the flux and power distributions in the core.
- However, the time-average model is numerically complicated by the fact that the lattice properties must be obtained by integrating over bundle-specific irradiation ranges.
- It is useful to have a (much simpler) "snapshot" model which reproduces the time-average power distribution.

This is obtained with the *TAVEQUIV module.

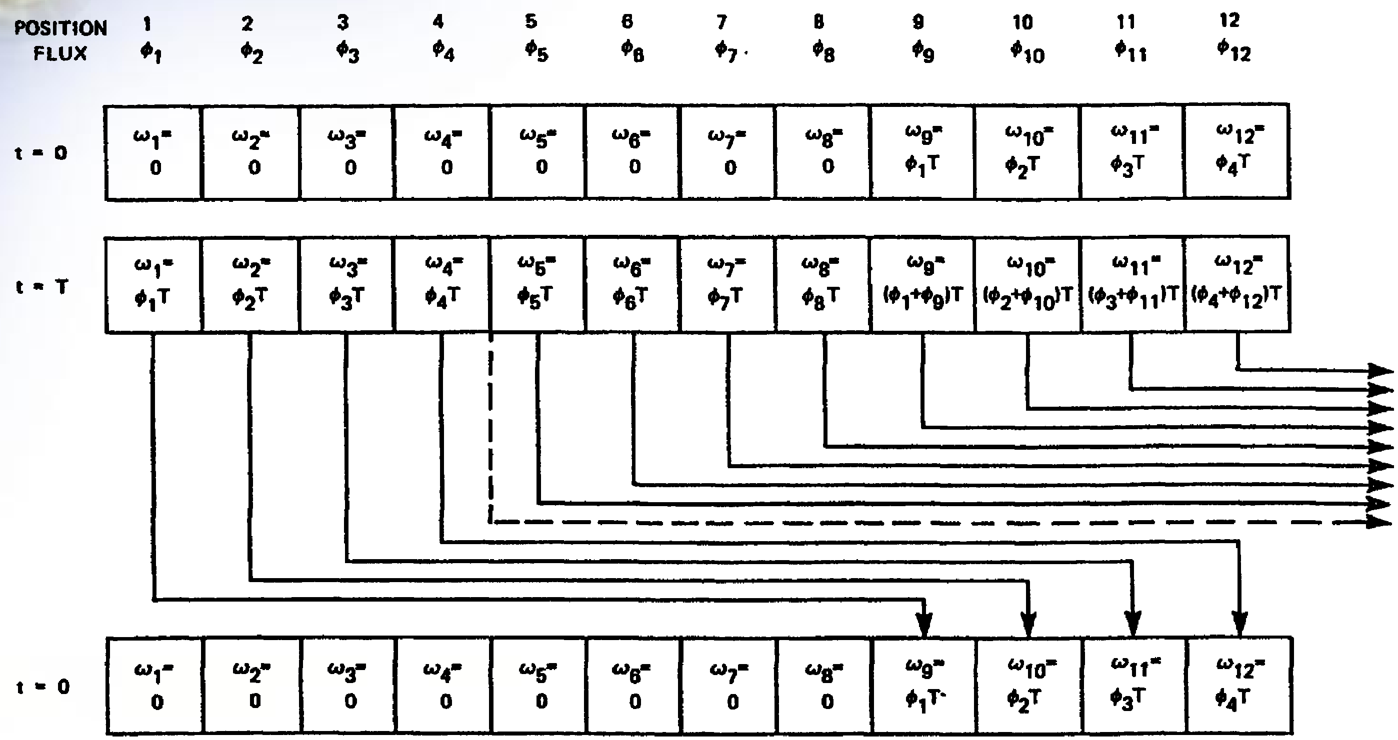
*TAVEQUIV Module (con't)

- For each bundle in core, this module defines a *single* value of irradiation $\omega_{inst,jk}$ (i.e., a snapshot model) whose *net effect* is to essentially reproduce the time-average properties. This is achieved by demanding that the local time-average *infinite multiplication constant k* be matched for each bundle:

$$k_{\infty,inst,jk} = k_{\infty,t.av.,jk}$$

- The instantaneous time-average-equivalent value of irradiation will normally be close to the mid-point of the irradiation range; this serves as the *first guess*, which is then refined:

$$\omega_{inst,jk} \approx (\omega_{in,jk} + \omega_{out,jk}) / 2$$



AVERAGE DISCHARGE IRRADIATION

$$= \frac{1}{8} \left\{ \phi_5 T + \phi_6 T + \phi_7 T + \phi_8 T + (\phi_1 + \phi_9)T + (\phi_2 + \phi_{10})T + (\phi_3 + \phi_{11})T + (\phi_4 + \phi_{12})T \right\}$$

$$= \frac{T}{8} \left\{ \phi_1 + \phi_2 + \phi_3 + \phi_4 + \phi_5 + \phi_6 + \phi_7 + \phi_8 + \phi_9 + \phi_{10} + \phi_{10} + \phi_{11} + \phi_{12} \right\}$$

*INSTANTAN Module

Based on time average beginning and end of cycle irradiations, bundle burnup is defined as:

$$\omega(i,j,k) = \omega_1(k) + f(i,j)\,(\omega_2(k) - \omega_1(k))$$

Where f(i,j) = channel age (0-1.0) as a fraction of dwell time

Two main options:

1. random age distribution (based on time average beginning and end of cycle)
   - User provides seed for random generator
2. patterned age distribution
   - User provides repeating age pattern, usually 7x7 matrix

*INSTANTAN Cont….

- Module used to estimate, at the preliminary design stage, snapshot results based on time-average design, i.e.
  - Ripple
  - Maximum channel and bundle powers
  - Generally results in overestimate of these parameters due to "hot spots", especially using the random age option
  - But can be used to compare time-averages
- Can also be used as a starting point for equilibrium fuelling study (with *SIMULATE)

*SIMULATE Module

This model is the most realistic because it represents the reactor as it is on one particular day - a snapshot.

Each bundle has an *instantaneous* value of irradiation ($\omega_{inst,jk}$)

- not a *range* of irradiations as in the time-average model.

The *SIMULATE module tracks the reactor operating history by advancing time from a previous snapshot by a ***burnup step***.

*SIMULATE Cont….

The *SIMULATE process is thus:

- Start at the *initial* core: 0 full-power-days (FPD); the irradiation of all bundles is zero. Solve for the flux in this snapshot.
- Take a burn step Δt (e.g., a few FPD) and solve for new snapshot at the same time modifying core conditions if necessary - e.g., boron concentration, device positions, channels refuelled.
- The irradiations from the earlier snapshot at *t* to new snapshot at ($t + \Delta t$) are updated according to:

$$\omega_{\mathrm{inst,jk}}(t + \Delta t) = \omega_{\mathrm{inst,jk}}(t) + \hat{\phi}_{\mathrm{jk}} \Delta t$$

- Take another burn step, repeat irradiation update and flux/power calculation. Etc...

*SIMULATE Cont….

- At each snapshot diffusion equation is solved with instantaneous cross-sections corresponding to instantaneous irradiation distribution (and other instantaneous conditions).
- Choices for lattice properties:
  - 2-group WIMS tables with only burnup dependency with or without distributed xenon
    - XE trailer card should be used when consistency is desired between flux distribution and ^{135}Xe concentration (recommended option)
  - Micro-depletion option (WIMSHI trailer card) takes into account both local-parameter effects and the individual nuclide history of each bundle
- Instantaneous model will feature a refuelling ripple since individual channels are refuelled at various times.