AECL EACL

*Time-Average Model (*TIME-AVER Module)*

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March, 2000

*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 (using equivalent to eq. 4.10) 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:

$$\omega_{out,jk} = \omega_{in,jk} + \hat{\phi}_{jk} T_j \qquad (4.11)$$

Time-Average Model (con't)

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

$$\Sigma_{i,jk}(t.av.) = \frac{\frac{1}{T_j}\int_0^T \Sigma_{i,jk}(\omega)\hat{\phi}_{jk}dt}{\frac{1}{T_j}\int_0^T \hat{\phi}_{jk}dt} \qquad (4.12)$$

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

$$\Sigma_{i,jk}(t.av.) = \frac{1}{\omega_{out,jk} - \omega_{in,jk}} \int_{\omega_{in,jk}}^{\omega_{out,jk}} \Sigma_{i,jk}(\omega)d\omega \qquad (4.13)$$

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

∴ 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 8-bundle-shift in a 12–bundle channel

Immediately after refuelling, first 8 bundles are fresh while positions 9-12 contain shifted bundles:

$$\omega_{in,jk} = \begin{cases} 0 & \text{for} \quad 1 \le k \le 8 \\ \omega_{out,j(k\text{-}8)} & \quad 9 \le k \le 12 \end{cases} \qquad (4.14)$$

Time-Average Model (con't)

Exit irradiation in channel j is average of values of out-going irradiation over 8 bundles leaving channel:

$$\omega_{exit,j} = \frac{1}{8}\sum_{k=5}^{12} \omega_{out,jk} \qquad (4.15)$$

Using Eq. (4.11) we have:

$$\omega_{exit,j} = \frac{1}{8}\sum_{k=5}^{12} \left[\omega_{in,jk} + \hat{\phi}_{jk} T_j\right] \qquad (4.16)$$

Now use Eq. (4.14) to get

$$\omega_{exit,j} = \frac{1}{8}\left[\sum_{k=9}^{12} \omega_{out.j(k-8)} + \sum_{k=5}^{12} \hat{\phi}_{jk} T_j\right] = \frac{1}{8}\left[\sum_{k=1}^{4} \omega_{out,jk} + \sum_{k=5}^{12} \hat{\phi}_{jk} T_j\right] \qquad (4.17)$$

Time-Average Model (con't)

Using Eq. (4.11):

$$\omega_{exit,j} = \frac{1}{8}\left[\sum_{k=1}^{4} \hat{\phi}_{jk} T_j + \sum_{k=5}^{12} \hat{\phi}_{jk} T_j\right]$$

i.e.,

$$\omega_{exit,j} = \frac{T_j}{8} \sum_{k=1}^{12} \hat{\phi}_{jk} \qquad (4.21)$$

Show that, in general, for an N-bundle shift

$$\omega_{exit,j} = \frac{T_j}{N} \sum_{k=1}^{12} \hat{\phi}_{jk} \qquad (4.22)$$

Time-Average Model (con't)

or, equivalently:

$$T_j = \frac{N\omega_{exit,j}}{\sum_{k=1}^{12} \hat{\phi}_{jk}} \qquad (4.23)$$

The calculational scheme for the time-average model is complete. It consists of the neutron diffusion equation plus Eqs. (4.11), (4.13), (4.14) and (4.23). This equation set must be solved iteratively until cross-consistency is attained.

*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. 8-bundle-shift for all channels, or regions of 8-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.

But if the conditions are not satisfied, adjustments have to be made and the calculation repeated:

- If criticality has *not* been obtained, the *average* value of $\omega_{exit,j}$ has to be adjusted.
- If the flux shape is not as desired, the *relative* values of $\omega_{exit,j}$ 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) - the degrees of freedom are available!

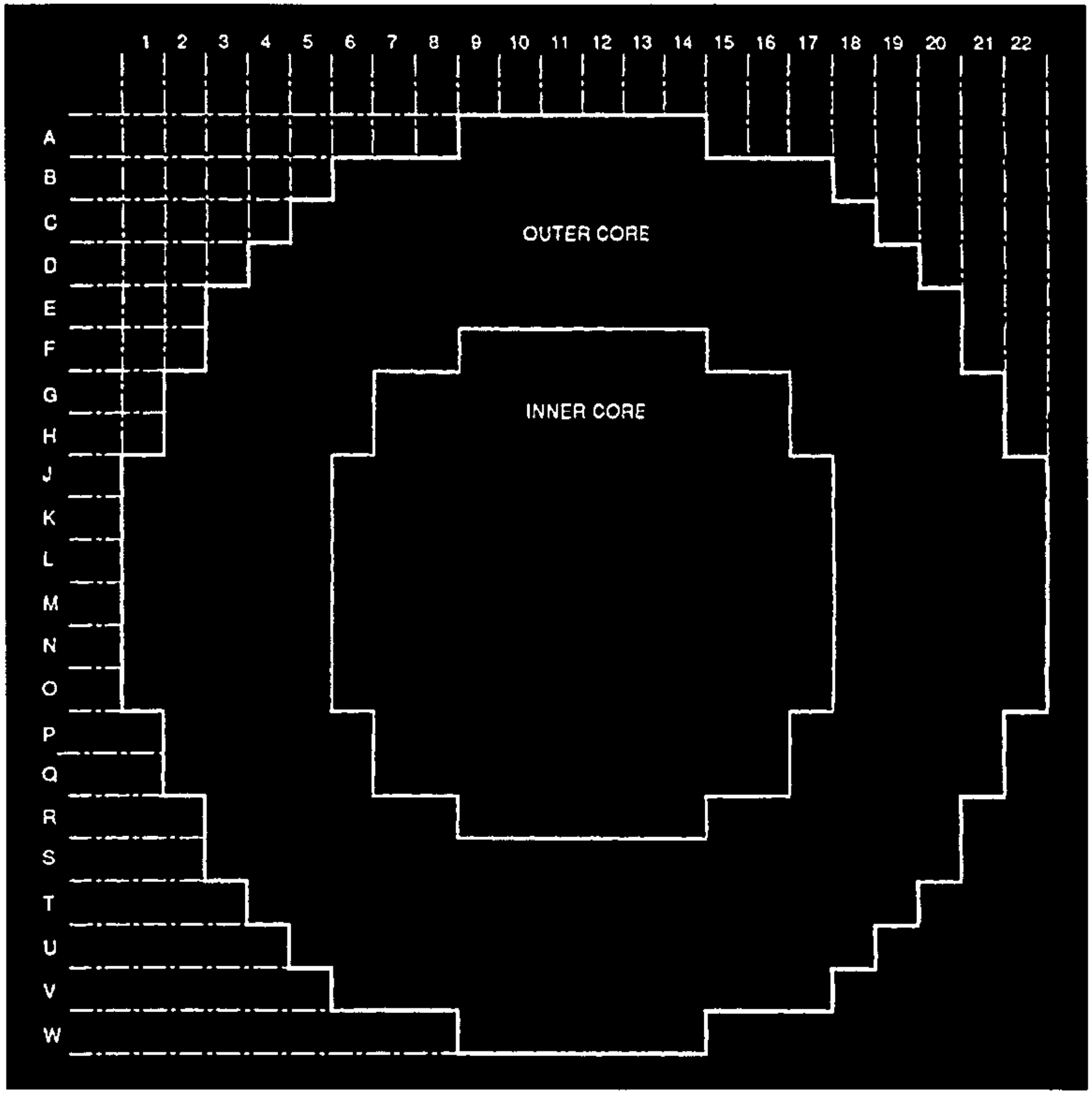
Example: the flux shape obtained has too much radial peaking; radial flattening is required to satisfy channel-power license limits; the user will flatten the radial flux by increasing the values of $\omega_{exit,j}$ in *inner* core relative to those in *outer* core; trial and error may be needed to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


1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
A B C D E F G H J K L M N O P Q R S T U V W
OUTER CORE
INNER CORE

*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., adjuster withdrawal). 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.*

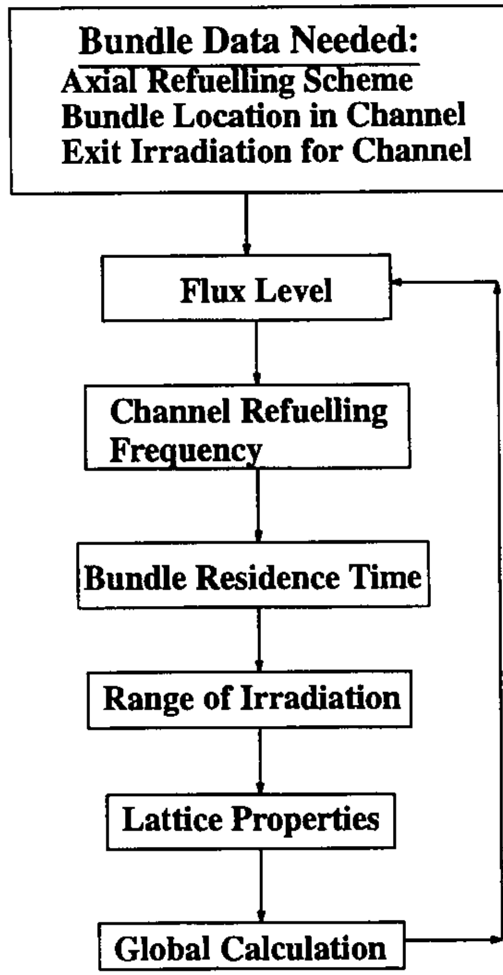
*TIME-AVER Module (con't)

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.

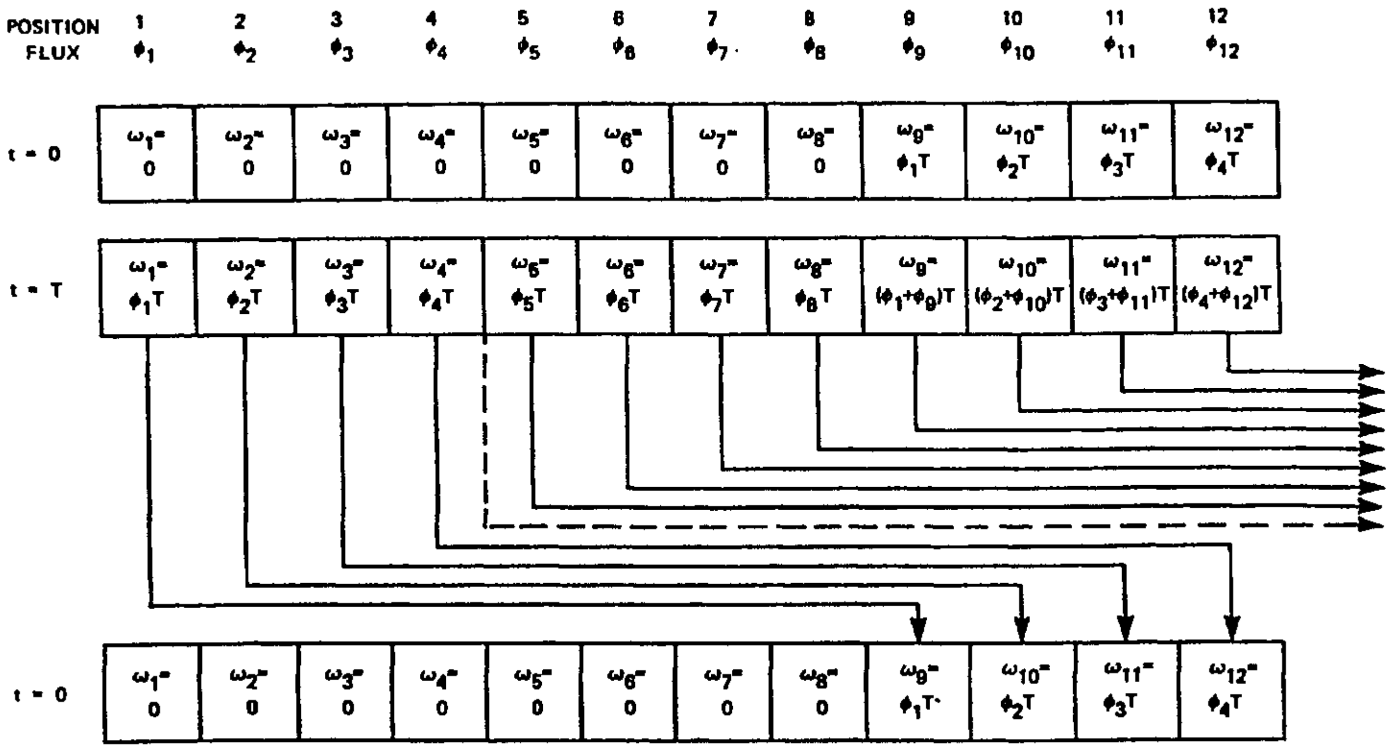
*TAVEQUIV Module (con't)

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

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

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

*Instantaneous Model (*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*.**

Instantaneous Model (con't)

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. Remember to modify appropriate core conditions - e.g., boron concentration, zone-control-compartment fills, channels refuelled.

The irradiations from the earlier snapshot at t to new snapshot at ($t + \Delta t$) are updated according to

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

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

Instantaneous Model (con't)

At each snapshot diffusion equation is solved with instantaneous cross-sections corresponding to instantaneous irradiation distribution (and other instantaneous conditions).

- XE trailer card should be used when consistency is desired between flux distribution and ^{135}Xe concentration (recommended option).
- Instantaneous model will feature a refuelling ripple since individual channels are refuelled at various times.

<u>XE Card</u> - *Calculation of the Xe-135 Distribution*

Format (A2, 8X, I10, 4F10.0, I10)

Col. 1 to 2	- the characters XE
Col. 20	- IDEQUIL - control parameter = 1, calculate Xe-135 distribution in steady-state equilibrium with flux distribution.
Col. 21 to 30	- TIMEX (F10.0) - time step in hours - significant only when IDEQUIL=2, (Note: TIMEX is internally converted to seconds by the program).
Col. 31 to 40	- FNP (F10.0) - fractional power level for xenon calculation. This value is needed for IDEQUIL=1. If IDEQUIL=2, this is the power level at the beginning of the time step TIMEX.
Col. 41 to 50	- GNP (F10.0) - fractional power level at end of time step TIMEX (if blank, GNP is set equal to FNP) - significant only if IDEQUIL=2.

***XE Card* - Calculation of the Xe-135 Distribution (con't)**

Col. 51 to 60 - EPSRMP (F10.0) - convergence criterion on Xe-135 distribution in the iterations between flux and xenon.

Col. 61 to 70 - NRPMX - (I10) - maximum number of flux/xenon iterations (default = 1).

Notes:

1 A value of 1 for IDEQUIL (col.20) requests a calculation of the Xe-135 distribution in equilibrium with the flux distribution, at the fractional power level FNP. The self-consistency between every IXENON flux iterations, where IXENON is defined on the *SIMULATE control card.

2 When IDEQUIL=2, a calculation of the transient distribution of Xe-135 is requested. In this case TIMEX, FNP and GNP are all significant.

3 The XE card cannot be used in conjunction with the HI card or the FI card.