AECL EACL

Spatial Kinetics (*CERBERUS Module)

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*CERBERUS Module

- Time-dependent problem in 3 dimensions and 2 energy groups
- Fast transients (e.g., LOCA arrested by SDS action)
- Delayed-neutron effects very important; assume G delayed-neutron precursor groups (G=6 or 17)
- Time–dependent neutron diffusion equation in two energy groups and three spatial dimensions (in matrix notation):

$$\left(-M+F_p\right)\phi(\vec{r},t)+\sum_{g=1}^{G}\lambda_g C_g(\vec{r},t)\begin{pmatrix}1\\0\end{pmatrix}=\begin{pmatrix}\frac{1}{v}\end{pmatrix}\frac{\partial\phi(\vec{r},t)}{\partial t}$$

*CERBERUS Module Cont….

where,

$$\phi(\vec{r},t) = \begin{pmatrix} \phi_1(\vec{r},t) \\ \phi_2(\vec{r},t) \end{pmatrix} \qquad ($$

$$\left(\frac{1}{v}\right) = \begin{pmatrix} \frac{1}{v_1} & 0 \\ 0 & \frac{1}{v_2} \end{pmatrix} \qquad ($$

M is the leakage, absorption, and scattering matrix:

$$M = \begin{pmatrix} -\vec{\nabla}\cdot D_1\vec{\nabla} + \Sigma_{a1}(\vec{r},t) + \Sigma_{1\to 2}(\vec{r},t) & 0 \\ -\Sigma_{1\to 2}(\vec{r},t) & -\vec{\nabla}\cdot D_2\vec{\nabla} + \Sigma_{a2}(\vec{r},t) \end{pmatrix} \qquad ($$

*CERBERUS Module Cont….

F_P is the prompt-production matrix:

$$F_p \equiv (1-\beta(\vec{r},t))F_T = \begin{pmatrix} 0 & \dfrac{(1-\beta(\vec{r},t))\nu\Sigma_f(\vec{r},t)}{k_0} \\ 0 & 0 \end{pmatrix}$$

and $\beta(\vec{r},t)$ is the total delayed fraction at position $(\vec{r},t)$:

$$\beta = \sum_{g=1}^{G} \beta_g$$

$C_g(\vec{r},t)$ = space-time concentration of group-g delayed-neutron precursor with decay constant λ_g. Satisfies balance equation:

$$\frac{\partial}{\partial t} C_g(\vec{r},t) = \beta_g(r)\frac{\nu\Sigma_f(\vec{r},t)}{k_0}\phi_2(\vec{r},t) - \lambda_g C_g(\vec{r},t)$$

k_0 = initial multiplication constant of reactor (*not* related to time-dependent dynamic reactivity ρ)

Improved Quasi-Static (IQS) Method

CERBERUS based on IQS method. Flux factorized into space-independent amplitude *A* and space-and-time-dependent shape function ψ:

$$\phi(\vec{r},t) = A(t)\psi(\vec{r},t)$$

[Normalization A(0) = 1]

Most of time dependence cast into *amplitude* by demanding that an integral in the shape function be constant in time:

$$\int \left[\frac{1}{v_1} \phi_1^*(\vec{r})\psi_1(\vec{r},t) + \frac{1}{v_2} \phi_2^*(\vec{r})\psi_2(\vec{r},t) \right] d\vec{r} = K$$

ϕ^* = initial adjoint flux

IQS Method Cont….

Equations for shape ψ and precursor concentrations *C_g*:

$$\left(-M+F_p\right)\psi(\vec{r},t)+\frac{1}{A(t)}\sum_{g=1}^{G}\lambda_g C_g(\vec{r},t)\begin{pmatrix}1\\0\end{pmatrix}=\left(\frac{1}{v}\right)\frac{\dot{A}(t)}{A(t)}\psi(\vec{r},t)+\frac{\partial\psi}{\partial t}$$

$$\frac{\partial}{\partial t}C_g(\vec{r},t)=\beta_g(\vec{r})\frac{\nu\Sigma_f(\vec{r},t)}{k_0}A(t)\psi_2(\vec{r},t)-\lambda_g C_g(\vec{r},t)$$

Similar to time-independent equation, with extra terms in the amplitude and the precursor concentrations.

IQS Method Cont….

Equation for amplitude obtained by integrating - weighted by adjoint. Get point-kinetics-like equation:

$$\dot{A}(t) = \frac{(\rho(t) - \beta_{eff})}{l^*(t)} A(t) + \frac{1}{K} \sum_{g=1}^{G} \lambda_g \eta_g(t)$$

where: $$\rho(t) = 1 - \frac{\left\langle \phi^*(\vec{r}), M\psi(\vec{r},t) \right\rangle}{\left\langle \phi^*(\vec{r}), F_T\psi(\vec{r},t) \right\rangle}$$

"Dynamic reactivity" $= 1 - \dfrac{\text{losses}}{\text{production}}$

Neutron generation time: $$l^*(t) = \frac{K}{\left\langle \phi^*(\vec{r}), F_T\psi(\vec{r},t) \right\rangle}$$

IQS Method Cont….

Effective total delayed fraction:

$$\beta_{eff} \equiv \sum_{g=1}^{G} \beta_{g,eff} = \sum_{g=1}^{G} \frac{\left\langle \phi^*(\vec{r}), \beta_g F_T \psi(\vec{r},t) \right\rangle}{\left\langle \phi^*(\vec{r}), F_T \psi(\vec{r},t) \right\rangle}$$

and adjoint-weighted integrated precursors:

$$\eta_g(t) = \int \phi_1^*(\vec{r}) C_g(\vec{r},t) d\vec{r} \qquad g = 1,\ldots,G$$

which satisfy the balance equations

$$\dot{\eta}_g(t) = K \frac{\beta_{g,eff} A(t)}{l^*(t)} - \lambda_g \eta_g(t)$$

We have a coupled system of equations for the shape, the amplitude, and the precursor concentrations

General Scheme of Solution

- *CERBERUS follows from a *SIMULATE calculation
- The starting point is:
  - a specific point in a reactor operating history
  - or an instantaneous snapshot calculated with random or patterned channel ages
  - or an instantaneous snapshot constructed to be neutronically equivalent (or nearly so) to the time-average model
- *CERBERUS is coupled to the thermal-hydraulics code, and expects thermal-hydraulic data from that code at each execution,i.e.
  - coolant density
  - coolant temperature,
  - and fuel temperatures at specified “nodes” of the thermal-hydraulic model

Scheme of Solution Cont….

- A two-energy-group WIMS grid-based fuel table is required for each fuel type in the core
- The WIMS grid-based fuel table is contained in the single file:
  - The first line in the file is a case identifier
  - The second line in the file is the number of values in the fuel table, needed for transferring the fuel table into RFSP-IST
  - The third and following lines contain irradiation-dependent lattice properties for the reference condition followed by irradiation-dependent lattice properties for the perturbed conditions

Scheme of Solution Cont….

- Delayed neutron parameters are also required
  - delayed-neutron partial fractions vary with the fuel irradiation (or burnup)
  - bundle-specific (spatially varying) delayed-neutron partial fractions and core-average precursor decay constants are used in the *CERBERUS calculation
- Delayed neutron parameters can be generated by the WIMS post-processing program KINPAR
- It produces a table containing:
  - delayed-neutron partial fractions for each delayed-neutron group for each bundle
  - as well as the total delayed-neutron partial fractions for each bundle, and
  - core-average precursor decay constants for each delayed-neutron group

Scheme of Solution Cont….

- Choose points in time, $t_0 = 0$, t_1, t_2,. . . at which shape function will be calculated
  - Intervals of 50-100 ms found appropriate for the first 2 or 3 seconds of LOCA transients
  - During SDS action, t_j normally selected as, e.g., times when leading edge of shutoff rods coincides with model mesh lines
  - Following SDS action, larger intervals, up to several seconds, may be used
  - Solution follows recursively from each t_j to t_{j+1}.
- Starting point is solution to initial steady-state problem

Scheme of Solution Cont…

- At each subsequent time step the coupled set of equations is solved to find flux shape, amplitude, reactivity, precursors
- The point-kinetics equations for the amplitude and integrated precursors are very quick to solve over a smaller time step
- The shape equation requires most effort
- A transient is solved as a sequence of flux-shape cases:
  - Case 1 = initial steady state
  - Case 2 = steady-state adjoint
  - Cases 3 and beyond... = time-dependent cases

Scheme of Solution Cont….

Other features:

- **Capability to couple to thermalhydraulics calculation (e.g. CATHENA, TUF or NUCIRC) - files exchanged at each flux-shape time step or as "outer" iteration**
- ***TRIP_TIME module used to determine SDS actuation time**
- **SDS *dynamic reactivity* more negative than *static reactivity* because precursors not in equilibrium with flux**

Scheme of Solution Cont….

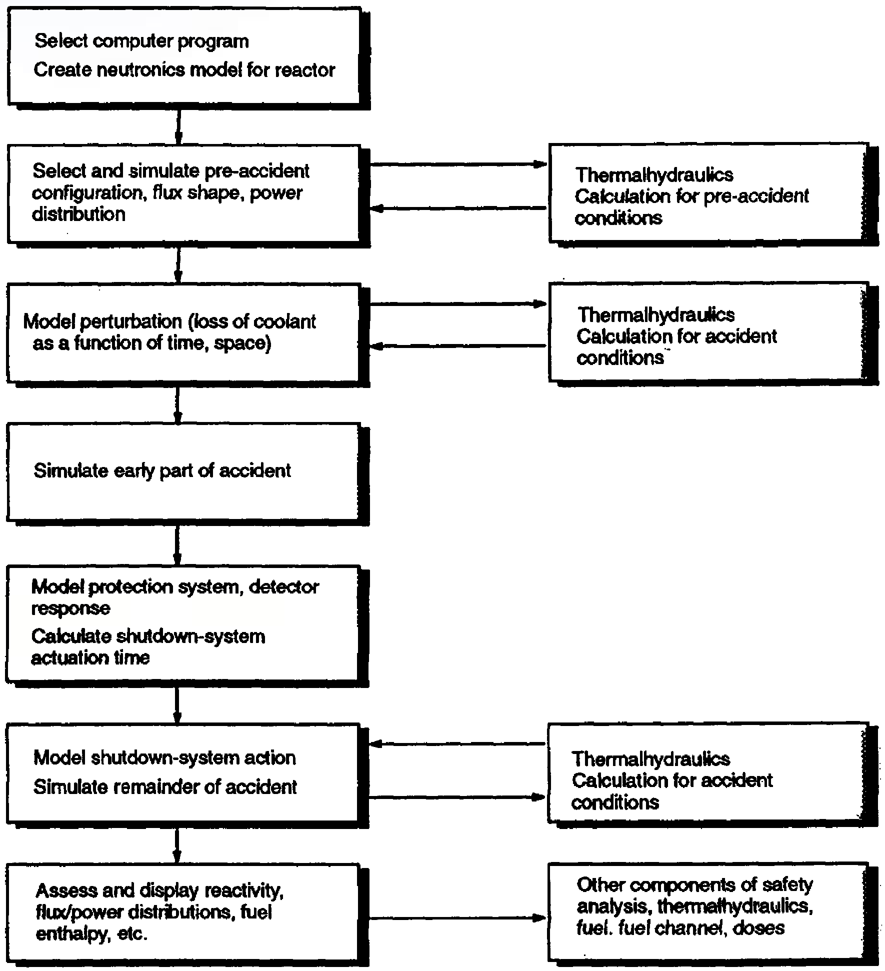
The total bundle power during the transient can be written as:

$$P_T(t) = P_P(t) + D(t) + d(t)$$

Where:

- t is the time, with an origin of 0 at the start of the transient,
- $P_T(t)$ is the total bundle power at time t,
- $P_P(t)$ is the prompt component of bundle power at time t,
- $D(t)$ is the decay power at time t due to fission products existing before time zero, and
- $d(t)$ is the extra decay power at time t due to fission products created after time zero

Schematic of a Physics Analysis for a Large LOCA



Two-Tiered Numerical Computational Scheme