EPRI CORETRAN METHODOLOGY

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ABSTRACT

A new simulation tool has been developed by the Electric Power Research Institute (EPRI) in order to provide its participating members with the independent capability of performing reload analysis as well as providing plant operational support. This tool, CORETRAN [1], has been recently released to the EPRI community. The purpose of this paper is to introduce this new simulation code to the Reactor Physics Division of the ANS community. The paper addresses the many different models (neutronic/numerical solution, cross-section methodology, historic and transient feedback, thermal-hydraulic options and other special features) that make up the new code as well as the modeling capabilities that are achieved. CORETRAN is now in the process of review by a Design Review Team of experts.

1. BACKGROUND & OBJECTIVE

For the last several years the Electric Power Research Institute (EPRI) has directed the effort of developing a state-of-the-art industry-standard depletion and transient core simulation code. This effort had been identified by participating member utilities in their pursuit of an independent reload analysis capability as a response to INPO's SOER 96-2 recommendations and the NRC's generic letter 83-11, "Licensee Qualification for Performing Safety Analysis in Support of Licensing Actions". In order to develop an industry-standard code, a thorough list of specifications/requirements was prepared by participating members of the development team. By combining three-dimensional depletion and transient capabilities under one code the intention was to develop a modern tool that can not only be used for the standard (steady-state) reload analysis calculations but also for treating some of the safety analysis events under a true 3-D time-dependent approach instead of conservatively simplifying point kinetics or 1-D assumptions or bounding steady-state comparisons. The methodology for analyzing a PWR's rod ejection

accident (REA) seems to be the first contender for going under a 3-D approach, as the NRC is expected to considerably lower the threshold for fuel failure from (currently at 180 cal/g) and make it burnup dependent. A three-dimensional transient simulation should give enough acceptance margin as indicated by preliminary studies [2].

CORETRAN is based on two early EPRI codes: ARROTTA [3] & VIPRE-02 [4]. The ARROTTA code is a two-group nodal code based on the Analytical Nodal Method (ANM) and was developed for three-dimensional transient simulation of LWR cores. It has been applied in a series of exploratory and benchmarking efforts such as PWR REA's [2], BWR CRDA's [2], BWR stability analyses, PWR Steam Line Break [5]. An SER was issued to Duke Power for its REA methodology [6] using ARROTTA. The VIPRE-02 code allows a 6-equation solution of the thermal-hydraulic conditions affecting the core (plenum to plenum) and it was the natural "choice" to upgrade the original thermal-hydraulic option that existed in ARROTTA. Also available within VIPRE-02 is a simplified HEM solution similar to VIPRE-01 since CORETRAN is expected to be also used as a stand-alone subchannel thermal-hydraulic analysis tool. There are however more than enough modifications to the two original codes to grant the use of a new name. First and foremost, there is a depletion capability which also allowed revisiting the cross-section model in order to guarantee a wider range of applications: handling of historic & transient feedback variables, continuity between cold and hot cases, pinpower prediction, inclusion of detector response. Also upgraded was the numerical solver, leading to faster execution times. CORETRAN is definitely not a coupled ARROTTA/VIPRE.

2. NUMERICAL SOLUTION

The Analytical Nodal Method [7] adopted in CORETRAN results in a system of equations to be numerically resolved where the unknowns are the node-averaged fluxes and the face-averaged net leakages (x-, y-, and z-direction). Different numerical schemes [3,7] have been proposed and used to solve this system of equations. However, the efficiency of the transverse-integrated methods (such as the Analytical Nodal Method) was considerably improved when Smith [8] proposed a solution technique which reduced the number of unknowns by employing a nonlinear iteration method. This scheme is based on an iteration between "global" solutions of the Coarse Mesh Finite Difference (CMFD) form of the two-group diffusion equation and "local" (or "two-node") solutions of the transverse integrated nodal method. Nodal couplings are determined from the local "two-node" problem and, upon convergence, the modified CMFD interface currents are the same that would have been obtained had the nodal method been used directly. The method is referred to as nonlinear because the coupling factors contained in the coefficient matrix depend on the flux solution. The accuracy of the Analytical Nodal Method is preserved in the nonlinear nodal method by deriving the "two-node" higher order coupling based on the ANM itself.

One advantage of the nonlinear scheme is the reduction in computer storage that results from not having to save the expansion coefficients. However, an equally important advantage is a reduction in execution time because the solution variables in the global CMFD portion of the algorithm are the node averaged fluxes for which efficient solution schemes have been developed. Furthermore, the two-node problems lend themselves naturally to parallel solution

and when solved in conjunction with parallel CMFD method, significant execution time reductions can be achieved with the nonlinear nodal method on multiprocessors.

In order to achieve the best performance for both serial and parallel applications, the CMFD solution in the nonlinear method is based on a Krylov subspace method, Bi-Conjugate Gradient Stabilized (BICGSTAB), accelerated with a preconditioning scheme based on a blockwise incomplete LU factorization [9]. Parallelism can be achieved using an incomplete domain decomposition preconditioning method [9].

On average, the new numerical solution has decreased the execution time by a factor of 3, bringing CORETRAN to a competitive level among existing advanced nodal codes. The parallel multi-processor option is not currently available in the distribution version of CORETRAN, even though tests have indicated an almost linear speedup when solving the nodal equations.

3. CROSS-SECTION METHODOLOGY

The CORETRAN cross-section formalism makes modeling easier for the user by simplifying the path between the spectrum code and the nodal code as well as allowing some fuel-related data to be specified only once (front-end) during the core modeling process. As a start, the lattice information (in CPM-3 format) is directly passed to CORETRAN. There is no need for a pre-processing code to prepare the cross-section library for CORETRAN's use. Instead, CORETRAN "understands" the caselist structure suggested by the user and is able to internally generate the cross-section library. Of course, successive/future runs of CORETRAN can access a previously prepared library and even expand an existing library with new fuel type information.

An appropriate way to describe the CORETRAN cross-section library is as a multidimensional database where each record contains data retrieved or inferred from the lattice code calculations for a given fuel. The terminology "cross-section" will be continuously applied throughout the text for an easier visualization of what is been described even though it is not general enough. In fact, each record in the database contains a lot more information than the standard 2-group cross-sections. The contents of a record are:

2-group cross-sections
assembly discontinuity factors
fission products (Xe, I, Sm, Pm) parameters
kinetics parameters (6 precursor families)
detector data
pin power distribution (form function)

An example of a library preparation should help understanding what is being described here. Beginning with a SIMPLIFIED caselist structure for a PWR fuel as shown in Table I:

Table I: Example of Caselist Structure for PWR fuel

				Exposure (GWD/MTU)					
ρ_{MOD}	T_{Fuel}	Boron	Rod	0.0	1.0	2.0	4.0	6.0	8.0
HI	HFP	Base	Out	X	X	X	X	X	X
AV	HFP	Base	Out	B		B			B
LO	HFP	Base	Out	B		B			B
HI	HFP	Base	In	B		B			B
HI	HZP	Base	Out	B		B			B
HI	HFP	Low	Out	B		B			B
HI	HFP	Base	Out	B		B			B
AV	HFP	Base	Out	X	X	X	X	X	X
LO	HFP	Base	Out	B		B			B
AV	HFP	Base	In	B		B			B
AV	HZP	Base	Out	B		B			B
AV	HFP	Low	Out	B		B			B
HI	HFP	Base	Out	B		B			B
AV	HFP	Base	Out	B		B			B
LO	HFP	Base	Out	X	X	X	X	X	X
LO	HFP	Base	In	B		B			B
LO	HZP	Base	Out	B		B			B
LO	HFP	Low	Out	B		B			B
AV	HFP	Lowe	Out	X	X	X	X	X	X

Note: X = depletion case, B = branch case

CORETRAN initially scans the whole lattice file identifying all the independent variables that are being used. In the example above we have:

6 exposure (EXP) points
3 moderator density history (DMH) points
3 moderator density (DM) points
1 fuel temperature (TF) point
1 soluble boron (BOR) point
1 control rod presence (CT)
1 soluble boron history (BORH) point

A two-dimensional grid (exposure versus moderator density history) is then prepared in order to receive the lattice information. CORETRAN then goes over the lattice file again, this time accepting and properly storing the data. The partially complete library database can be sketched as shown in Table II:

Table II: Partially Complete Database

				EXP		
DMH	0.0	1.0	2.0	4.0	6.0	8.0
HI	T	–	T	–	–	T
AV	T	–	T	–	–	T
LO	T	–	T	–	–	T

Note: T = cross-section table

Each cross-section table T indicates a complete set of records containing the base and perturbed cases for a given (exposure, moderator density history) point. The contents of the table can be described as:

Table III: Contents of Table T

Σ at (EXP, DMH)	← base case
$\Delta\Sigma$ due to low moderator density	← perturbed case
$\Delta\Sigma$ due to average moderator density	"
$\Delta\Sigma$ due to high moderator density	"
$\Delta\Sigma$ due to low fuel temperature	"
$\Delta\Sigma$ due to low soluble boron	"
$\Delta\Sigma$ due to presence of control rod	"
$\Delta\Sigma$ due to low soluble boron history	"

Each row in the table above is a "record". As mentioned before, each record contains not only the two-group cross-section data, but also all the extra data required for the code to perform according to specifications (i.e. account for Xenon & Samarium, transient simulations, pinpower calculations).

Note that there are "points" in the grid that are still not complete (not enough information to "fill up" all base and perturbed cases records). However this missing information can be inferred from the neighboring completed points by simple linear interpolations. The two-dimensional grid can then be expressed as:

Table IV: Complete Database

				EXP		
DMH	0.0	1.0	2.0	4.0	6.0	8.0
HI	T	T	T	T	T	T
AV	T	T	T	T	T	T
LO	T	T	T	T	T	T

Note: T = cross-section table

At this point the preparation of the library is complete and CORETRAN can proceed with the nodal calculation. Cross-section parameters can be obtained by "consulting" the grid for any given exposure, moderator density history (EXP, DMH) condition. Once the corresponding point T is determined (using two-dimensional linear interpolation), all other feedback effects are accounted for by simply adding to the base cross-section record the appropriate contributions from the perturbed case records.

What was presented above was a fairly simplified example of the process of generating the cross-section library database. CORETRAN is a lot more general than this. Even the number of allowed perturbed cases for a given feedback variable (fuel temperature, for example) can be modified by the user (default = 10, but easily increased).

Mathematically, the CORETRAN cross-section functionality can be expressed as a function of historical (EXP, DMH, TFH, BORH, CTH, SDC, …) and instantaneous (DM, TF, BOR, CT, …) feedback variables:

$$\Sigma = f\,(\text{EXP, DMH, TFH, BORH, CTH, BPH, SDC, … , DM, TF, BOR, CT, …}) \qquad (1)$$

where: EXP is exposure
DMH is moderator density history
TFH is fuel temperature history
BORH is soluble boron history
CTH is control rod history
BPH is the burnable poison history
SDC is shutdown cooling time
DM is moderator density
TF is fuel temperature
BOR is soluble boron concentration
CT is presence of control rod

Notes:
- these are the current feedback variables handled by CORETRAN. This list can be easily expanded.
- the moderator effect is treated as a function of moderator density independently of the type of core (PWR or BWR). There is no void feedback.

This functionality is better expressed as:

$$\Sigma = \Sigma_{base}(\text{EXP, DMH}) + \sum c_i \Delta\Sigma_i(\text{EXP, DMH, TFH, BORH, CTH, … , DM, TF, BOR, CT, …}) =$$

$$\Sigma_{base}(\text{EXP, DMH}) + c_1\Delta\Sigma_1(\text{EXP, DMH, TFH}) + c_2\Delta\Sigma_2(\text{EXP, DMH, BORH}) + \ldots + c_j\Delta\Sigma_j\,(\text{EXP, DMH, DM}) + c_k\Delta\Sigma_k(\text{EXP, DMH, TF}) + \ldots + \qquad (2)$$

The expression above closely agrees with the previous description of how the cross-section library database is consulted: a given point (EXP, DMH) is mapped against the known 2-D grid,

once localized, all the records associated with this point are generated so that each contribution can be added to the base case.

Once again, for the sake of simplifying the presentation, the full ability of CORETRAN when handling the feedback effects was not fully detailed. Equation (2) above may lead to the conclusion that the cross-section methodology assumes a complete separability of effects. CORETRAN in fact goes beyond this first order approach, allowing "multiple effects" such as the interdependence of fuel temperature and moderator density or boron and control rod presence to be accounted for.

$$\ldots + c_j\Delta\Sigma_j(EXP, DMH, DM) + c_k\Delta\Sigma_k(EXP, DMH, TF) + c_{jk}\Delta\Sigma_{jk}(EXP, DMH, DM, TF) + \ldots \quad (3)$$

In summary, the feedback methodology can be described as:

- macroscopic approach for cross-section behavior
- feedback effects applied in the same manner to all lattice parameters (i.e., cross-sections, ADF's, kinetics data, …)
- no limits in the number of perturbed cases for any given feedback variable
- strongest feedback components: EXP & DMH. All other feedback effects are treated in a piecewise linear interpolation mode

4. DEPLETION IMPLEMENTATION

As indicated in the previous section, the CORETRAN cross-section model uses a macroscopic approach for representing the gradual change in local nodal conditions due to the continuous burning of the fuel. Instead of trying to follow unique families of nuclides and account for their effect on nodal cross-sections (microscopic model), historic feedback variables are defined in order to quantify these changes as functions of nodal time-integrated operating conditions. The basic historic feedback variable is nodewise exposure which is defined as the integrated nodal power over the time interval. Other historical variables (moderator density history, control rod history, fuel temperature history, soluble boron history) are accrued by exposure-weighting the corresponding feedback variables over the time interval. A predictive option allows the code to use a guessed nodal power value at the middle or the end of the time step for inferring the historic feedback variables. This guessed power is based on a linear extrapolation using the two previously calculated power values for a given node.

5. THERMAL-HYDRAULIC OPTIONS

Three options are available for modeling the core coolant in CORETRAN, depending on the degree of detail that is desired.

The Homogeneous Equilibrium Mixture (HEM) thermal-hydraulic option addresses the coolant as a single-component two-phase mixture. The governing equations are the transient balance laws for mass, energy and linear momentum. Constitutive models are included for vapor generation due to subcooled boiling and unequal phase velocities. This option is a three-equation model and is fairly similar to the use of the EPRI code VIPRE-01. The intended application of this model is to perform coupled transient analyses and stand-alone VIPRE-type analyses including sub-channel simulations.

The Closed-Channel Drift Flux thermal-hydraulic option is a one-dimensional, inhomogeneous, nonequilibrium, two-phase model with constant cross-sectional area that is applied to each flow channel. It is basically a four-equation model: an energy balance equation for each of the two phases (liquid and vapor), a mass balance equation for the liquid-vapor mixture, and an algebraic slip correlation. The algebraic slip correlation is used as a constitutive model to obtain the void fraction. The drift flux model can be used with or without the consideration of a mixture momentum, depending on the boundary conditions that are specified. The assumption of one-dimensional flow in each channel is justified for BWR applications since a BWR core is composed of several individual fuel assemblies with no cross flows among fuel assemblies in the active fuel region. In a PWR core, the fuel assemblies are open and cross-flow can occur; however, unless a reasonable amount of boiling is present, this extra modeling detail should be negligible. The Drift Flux option is the one recommended for core simulations involving steady-state calculations (depletion, searches) or somewhat mild transients since it is quite accurate and the fastest of the three.

The Two-Fluid thermal-hydraulic option is the most elaborate of the three options available. It uses a two-fluid representation of the two-phase flow, solving conservation equations for mass, momentum and energy for each phase. Models based on flow regime mapping use semi-empirical interfacial correlations for heat and mass transfer. The two-fluid model also has an optional interfacial drag model which uses the EPRI void model.

All three thermal-hydraulic solutions can optionally use the FIBWR leakage model for determination of BWR flow distribution. The thermal-hydraulics models can represent the same nodalization as the neutronics model or assemblies can be mapped to lumped thermal-hydraulic channels to reduce computation time during transient simulations.

The ability to execute VIPRE-style thermal-hydraulics models has been retained within CORETRAN. Cross-flow can be used with the HEM and the Two-Fluid options for PWR or sub-channel steady-state and transient applications.

6. SPECIAL FEATURES

Like any other modern nodal code, CORETRAN was specified such that its use is convenient and instructive for its users. At the beginning of the development effort, code specifications were set down so that the code has the "correct feel". Some features however, make CORETRAN unique among other codes.

The direct access to lattice information and internal handling of cross-section library has already been detailed including the continuity from cold to hot conditions by relying on moderator density (instead of void fraction, for BWR's cores) as the independent feedback variable.

Another interesting feature implemented in CORETRAN is the idea of a "pool file". This is a file that contains all the assemblies that have been removed from the core during a shuffle calculation. During each reload, assemblies are "removed" from the CORETRAN core model and "inserted" in the CORETRAN pool file; therefore, mimicking very closely its physically equivalent spent fuel pool at the plant site. This ASCII file resembles a restart file where for each assembly (identified by its unique name) follows the complete information about its historic condition (nodewise EXP, DMH, CTH, TFH, …) and its fission product condition (nodewise Xenon, Iodine, Samarium, Promethium) at the time the assembly was removed from the core. If the assembly happens to be brought back into the core, there is enough information to know how long the assembly remained in the spent pool so that some of the historic variables can be properly adjusted.

Restart files can be used not only to continue with a steady-state calculation (depletion, search, state-point) but also to start a transient simulation. It is up to the user to provide the correct forcing functions (boundary conditions). In either case, the cross-section database library being accessed is exactly the same.

CORETRAN generates files that can be passed on to RETRAN-03 (another EPRI code) for system analysis in either 1-D or 3-D core geometries.

Also to be mentioned are the GUI interfaces (both front and back) that are being developed so that the use of CORETRAN is even more intuitive.

CONCLUSIONS

CORETRAN possesses all the required features for use by both reload analyses (including Chapter XV transients) as well as core-follow calculations. It runs in any modern platform (PC's, workstations) under operating systems such as Windows and/or UNIX.

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