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INTRODUCTION

The TRACE/PARCS computational package [1, 2] is designed to be applicable to the analysis of light water reactor operational transients and accidents where the coupling between the neutron kinetics (PARCS) and the thermal-hydraulics and thermal-mechanics (TRACE) is important. TRACE/PARCS has been assessed for its applicability to anticipated transients without scram (ATWS) [3]. The challenge, addressed in this study, is to develop a sufficiently rigorous input model that would be acceptable for use in ATWS analysis.

Two types of ATWS events were of interest, a turbine trip and a closure of main steam isolation valves (MSIVs). In the first type, initiated by turbine trip, the concern is that the core will become unstable and large power oscillations will occur. In the second type, initiated by MSIV closure,, the concern is the amount of energy being placed into containment and the resulting emergency depressurization.

Two separate TRACE/PARCS models of a BWR/5 were developed to analyze these ATWS events at MELLLA+ (maximum extended load line limit plus) operating conditions. One model [4] was used for analysis of ATWS events leading to instability (ATWS-I); the other [5] for ATWS events leading to emergency depressurization (ATWS-ED). Both models included a large portion of the nuclear steam supply system and controls, and a detailed core model, presented henceforth.

PARCS CORE MODEL

The neutronic portion of the ATWS-I and ATWS-ED core models was developed for use with PARCS. The ATWS-I and ATWS-ED PARCS core models are essentially identical for each of the three different exposure points in the cycle considered: beginning-of-cycle (BOC), peak-hot-excess-reactivity (PHE), and end-of-full-power-life (EOFPL). The BOC, PHE, and EOFPL models differ in the nodal exposure and moderator density history information contained in the depletion (*.dep) file, and the position of the control rod banks.

The models assume an equilibrium core of 764 GE14 assemblies. Each assembly is a 10x10 fuel bundle consisting of:

- full length fuel rods without gadolinia (with natural uranium top and bottom blankets)
- full length fuel rods with gadolinia (with natural uranium bottom blankets only)
- partial length fuel rods without gadolinia (with natural uranium bottom blankets only)
- two water rods

Fuel enrichment varies from rod to rod, and gadolinia concentration changes for different rod types and axial level. The models include multiple planar regions with unique materials, representing two reflectors (top and bottom), and several distinct axial segments in the active fuel region.

The cross sections used by PARCS were generated with SCALE/TRITON [6] at Oak Ridge National Laboratory (ORNL), in accordance with the cross-section generation guidelines found in [7]. To overcome a SCALE/TRITON limitation related to boron injection under partially voided conditions, a special correction procedure for branches containing soluble boron was used. The cross section files for the homogenized fuel assemblies include four void histories, multiple burnup steps (up to a maximum exposure of 60 GWd/MTU), and a selection of branches combining five moderator densities, three fuel temperatures, four boron concentrations, and two control states (controlled/uncontrolled).

TRACE CORE MODEL

The thermal-hydraulic portion of the ATWS-I and ATWS-ED core models was developed for use with TRACE. While the balance of plant modeling is very similar in the ATWS-I and the ATWS-ED models, the core region models differ significantly in their level of detail. Both models use CHAN components imbedded within a VESSEL component representing the reactor pressure vessel (RPV), but the number of CHAN components is 382 for ATWS-I analysis and 27 for ATWS-ED. Each CHAN represents a collection of fuel bundles, with three types of fuel rods, as described above: full length, partial length and gadolinia rods (rods with integral gadolinia as burnable poison). Each type is grouped together as a separate rod group in the CHAN component. A fourth and fifth rod group represent the hot rod in an assembly and the water rods, respectively.

The generation of the input for multiple CHAN components from a single "template" CHAN is done with a MATLAB script [4]. The MATLAB script automates the preparation of the following parameters in the CHAN component input:

(1) Junction connections

(2) Number of fuel assemblies represented by the CHAN component

(3) Inlet orifice loss coefficient

(4) The VESSEL ring where the CHAN is located and thus the interface for the canister wall heat structure

(5) Core wide radial CHAN-to-CHAN power peaking factor

(6) Gap gas composition for each fuel rod group

(7) Average burnup in each axial node of a fuel rod group

(8) Reference gap gas temperature for each fuel rod group

(9) Corresponding leakage junction in the lower tie plate.

Parameters (6) and (8) are part of the additional input required for activating the dynamic gap model in TRACE and for calculating the fuel thermal conductivity with the Modified Nuclear Fuels Industries (NFI) model [1]. The MATLAB script evaluates these parameters from axially-dependent average assembly burnup information provided by GE Hitachi and the results of FRAPCON calculations for each fuel rod type. For each axial level, the MATLAB script averages the burnup for all fuel assemblies in each CHAN component, and individualizes the resulting nodal CHAN-average burnup for each rod group, by applying a multiplicative, rod group-specific factor. The rod group-specific factors are obtained based on the average power of each rod group. The hot rod is assumed to become hot instantaneously, i.e. it is burned like a regular full length rod. The FRAPCON data is used to model the thermal conductivity of the individual gases, their mixtures, and ultimately the thermal conductivity of the gap needed to calculate the heat transfer between the pellet and the cladding. The burnup information, together with the gadolinia content in a fuel rod, is used in the evaluation of the fuel thermal conductivity according to the modified NFI correlation. The gadolinia rods are assumed to have a uniform gadolinia content of 7 wt%.

MAPPING

The mapping defines the correspondence between neutronic nodes and hydraulic volumes / heat structures. The "auto-mapping" feature of TRACE/PARCS is used, whereby the mapping file was reduced to a radial map specifying the CHAN(s) to be coupled to each neutronic node. In the TRACE model, the CHAN components themselves are distributed amongst the first two rings of the VESSEL component. With "automap" the nodes in the reflector are not mapped into any thermal-hydraulic volume, but instead have fixed properties defined in the same mapping file.

For ATWS-I, the complex neutronic-thermal-hydraulic coupling during periods of instability needs to be captured. In independent PARCS standalone steady-state calculations (with fixed thermal-hydraulic conditions), it was shown that for all points in the cycle the first harmonic had an axis of symmetry along the y-axis. Hence, 382 thermal-hydraulic channels (CHAN components) are modeled to represent all assemblies, taking into account half-core symmetry while allowing for first harmonic modes of oscillation.

For ATWS-ED, the core response is expected to be fairly uniform, allowing a coarser TRACE representation. The grouping is based on geometrical and fuel cycle considerations. This is possible because in a core with an Extended Power Uprate (EPU), the power shape is flattened and reload fractions are high [8], so position-based grouping is similar to power grouping. A clear advantage of this position-based approach is that the grouping works for all points in the cycle. The interior region of the core, mapped into Ring 1 of the VESSEL component, is divided into five annular regions with approximately the same number of assemblies in each region. In each annular region, fresh and burned assemblies are separated and assigned to two different channels (251/252 for annular region 1, 351/352 for annular region 2, 451/452 for annular region 3, 551/552 for annular region 4 and 651/652 for annular region 5). Further detail is introduced around the control rods which are "significantly" inserted (more than 10 steps inserted) either for BOC or PHE; for assemblies next to each of the seven control rods in a quadrant, two new channels are added (for fresh and burned bundles). Next, the fuel assemblies mapped into Ring 2 of the VESSEL component are selected and defined as a peripheral region. The outermost assemblies in the peripheral region (with different effective loss coefficients for the lumped leakage flow path), are lumped together into channel 752, while the remaining assemblies are assigned to channels 751 (fresh assemblies) and 753 (burned assemblies). The result is a TRACE model with 27 channels, with mapping shown in Figure 1.

								0	0	0	0	0	0	0	0
							0	0	752	752	752	752	752	752	752
					0	0	0	752	753	753	751	652	651	652	651
					0	752	752	753	751	651	651	651	652	551	552
				0	0	752	751	651	651	652	551	552	551	552	551
		0	0	0	752	753	651	651	652	551	552	551	452	451	452
		0	752	752	753	652	651	652	551	552	451	452	451	452	451
	0	0	752	751	651	651	652	551	552	451	452	451	372	371	352
0	0	752	753	651	651	652	551	552	451	452	351	352	371	372	351
0	752	753	751	651	652	551	552	451	452	351	352	351	272	271	252
0	752	753	651	652	551	552	451	452	351	352	351	352	271	272	251
0	752	751	651	551	552	451	452	351	362	361	352	251	252	251	252
0	752	652	651	552	551	452	451	352	361	362	251	252	251	252	251
0	752	651	652	551	452	451	352	351	262	261	252	251	282	281	252
0	752	652	551	552	451	452	351	352	261	262	251	252	281	282	251
0	752	651	552	551	462	461	352	351	252	251	252	251	292	291	252

Fig. 1. Mapping for ATWS-ED – 27 Channels. For each position, the number shown corresponds to the CHAN component ID number associated with the assembly in that position (0 for reflector).

STEADY-STATE RESULTS

Since the core design is symmetric, the steady-state results of the 382-channel model provide an accurate representation of actual core power distributions and are used as reference to verify the validity of the 27 channel grouping.

Figure 2 shows the comparison of the axially averaged radial power distributions for the 27- and 382-channel models for BOC. The agreement is very good; the RMS of the power difference is 0.02. For PHE and EOFPL, the results are entirely consistent; the RMSs of the radial power difference are 0.05 and 0.03, respectively.

Figure 3 shows the comparison of the radially averaged axial power distributions for the 27- and 382-channel models. The axial powers are virtually identical. For PHE and EOFPL the axial power distributions for the 27- and 382-channel models are also virtually identical.

The results of the comparison of power distributions from the 27- and the 382-channel models indicate that the 27-channel grouping strategy is acceptable for core-wide transients over the full range of exposures considered.

CONCLUSIONS

Core models for BWR/5 accident simulation have been developed that are very detailed in order to capture the complex behavior expected during ATWS and other events. Four different fuel rod types are included in each of either 382 or 27 thermal-hydraulic channels. Each fuel assembly is explicitly modeled neutronically. Advanced models in TRACE are used such as dynamic gap conductance modeling. The input specifications developed can be used for many ATWS applications as well as for many transients with reactor trip operational. The ATWS-I and ATWS-ED models give consistent results in steady-state conditions, indicating that the 27-channel grouping strategy is applicable for all points in the cycle.

								0.33 *0.36* -10.07	0.37 *0.40* -7.67	0.41 *0.43* -4.67	0.52 *0.52* 0.42	0.49 *0.48* 0.62
		27Ch *382Ch* Diff(%)					0.41 *0.43* -5.37	0.61 *0.64* -5.65	0.71 *0.72* -1.43	0.74 *0.75* -1.18	0.79 *0.81* -3.72	0.81 *0.82* -0.98
					0.31 *0.34* -9.33	0.49 *0.50* -2.21	0.65 *0.68* -3.82	0.80 *0.80* -0.58	0.85 *0.87* -1.77	0.92 *0.92* 0.57	1.01 *0.98* 3.30	1.07 *1.03* 4.00
					0.45 *0.46* -2.54	0.68 *0.71* -4.10	0.79 *0.83* -4.76	0.92 *0.93* -1.27	0.98 *0.99* -0.46	1.06 *1.07* -0.72	1.11 *1.09* 1.44	1.18 *1.14* 3.26
				0.50 *0.50* -0.06	0.79 *0.77* 1.48	0.85 *0.87* -2.20	0.96 *0.97* -0.32	1.02 *1.03* -1.70	1.04 *1.08* -3.75	1.17 *1.17* 0.47	1.24 *1.20* 3.08	1.25 *1.22* 2.54
		0.31 *0.34* -9.36	0.45 *0.46* -2.54	0.79 *0.77* 1.46	0.91 *0.92* -1.33	1.04 *1.01* 2.26	1.08 *1.06* 1.41	1.08 *1.11* -3.22	1.13 *1.16* -2.84	1.22 *1.23* -0.62	1.26 *1.24* 1.49	1.29 *1.26* 2.43
		0.49 *0.50* -2.25	0.68 *0.71* -4.13	0.85 *0.87* -2.22	1.04 *1.01* 2.24	1.14 *1.11* 3.35	1.18 *1.17* 0.48	1.21 *1.21* -0.33	1.22 *1.24* -1.56	1.24 *1.24* -0.21	1.28 *1.26* 1.08	1.28 *1.24* 2.86
	0.41 *0.43* -5.42	0.65 *0.68* -3.87	0.79 *0.83* -4.82	0.96 *0.97* -0.37	1.08 *1.06* 1.38	1.18 *1.17* 0.45	1.22 *1.22* 0.33	1.22 *1.25* -1.85	1.22 *1.24* -1.64	1.28 *1.26* 1.11	1.24 *1.22* 1.18	1.22 *1.21* 0.99
0.33 *0.36* -10.11	0.61 *0.64* -5.70	0.80 *0.80* -0.63	0.92 *0.93* -1.34	1.02 *1.03* -1.78	1.07 *1.11* -3.32	1.21 *1.21* -0.43	1.22 *1.25* -1.93	1.15 *1.20* -4.40	1.19 *1.22* -2.55	1.23 *1.22* 0.68	1.20 *1.20* 0.19	0.98 *0.97* 1.12
0.37 *0.40* -7.73	0.71 *0.72* -1.49	0.85 *0.87* -1.83	0.98 *0.99* -0.50	1.04 *1.08* -3.86	1.13 *1.16* -3.00	1.22 *1.24* -1.75	1.21 *1.24* -1.87	1.19 *1.22* -2.81	1.16 *1.20* -3.42	1.23 *1.23* -0.06	1.16 *1.17* -0.35	0.95 *0.95* -0.30
0.41 *0.43* -4.72	0.74 *0.75* -1.23	0.92 *0.92* 0.51	1.06 *1.07* -0.80	1.17 *1.17* 0.32	1.22 *1.23* -0.82	1.24 *1.24* -0.49	1.27 *1.26* 0.69	1.21 *1.22* -1.16	1.22 *1.23* -1.08	1.20 *1.21* -0.83	1.21 *1.19* 2.00	1.13 *1.13* 0.39
0.52 *0.52* 0.40	0.78 *0.81* -3.76	1.01 *0.98* 3.25	1.11 *1.09* 1.35	1.24 *1.20* 2.93	1.25 *1.24* 1.24	1.27 *1.26* 0.68	1.23 *1.22* 0.62	1.19 *1.20* -1.02	1.14 *1.17* -2.17	1.21 *1.19* 1.75	1.22 *1.19* 2.15	1.12 *1.12* -0.27
0.48 *0.48* 0.56	0.81 *0.82* -1.02	1.07 *1.03* 3.98	1.18 *1.14* 3.20	1.25 *1.22* 2.43	1.29 *1.26* 2.15	1.26 *1.24* 1.81	1.20 *1.21* -0.72	0.97 *0.97* 0.77	0.94 *0.95* -0.56	1.13 *1.13* 0.15	1.12 *1.12* -0.41	0.93 *0.93* 0.39
0.59 *0.56* 4.32	0.85 *0.86* -0.74	1.04 *1.03* 0.67	1.20 *1.16* 3.47	1.26 *1.23* 2.68	1.28 *1.25* 2.65	1.28 *1.26* 2.02	1.18 *1.18* -0.60	0.96 *0.95* 0.43	0.93 *0.94* -1.07	1.11 *1.12* -0.79	1.08 *1.10* -1.44	0.90 *0.91* -0.85
0.60 *0.57* 5.42	0.85 *0.84* 0.87	1.01 *1.01* -0.01	1.20 *1.15* 3.70	1.23 *1.20* 2.76	1.30 *1.26* 3.00	1.29 *1.24* 3.45	1.23 *1.21* 1.42	1.16 *1.14* 1.58	1.13 *1.13* 0.10	1.12 *1.12* 0.02	1.11 *1.12* -1.15	1.05 *1.08* -3.05

Fig. 2. Radial Power Comparison – 382 Channel Model vs 27 Channel Model, BOC

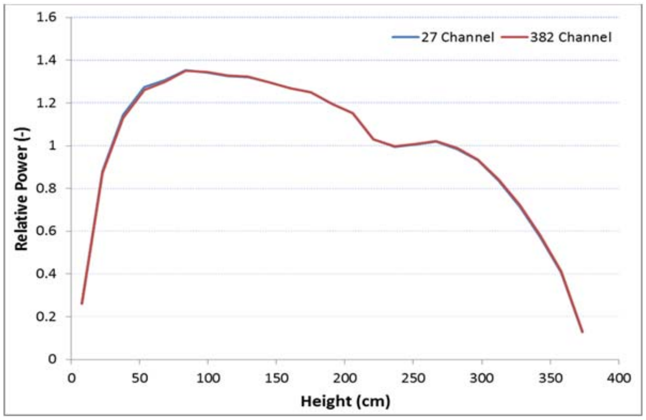

Fig. 3. Axial Power Comparison – 382 Channel Model vs 27 Channel Model, BOC

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