Multi-Physics Coupled Code Reactor Analysis with the U.S. NRC Code System TRACE/PARCS

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1.0 Introduction

During the last several years, the U.S. NRC has undertaken the development of an advanced safety analysis code system based on the consolidated thermal-hydraulics code TRACE (Trac Relap Advanced Computational Engine). The neutronics codes are based on the ORNL Lattice Physics code TRITON and the Purdue core neutronics simulator, PARCS. The overall code system is depicted in Figure 1.

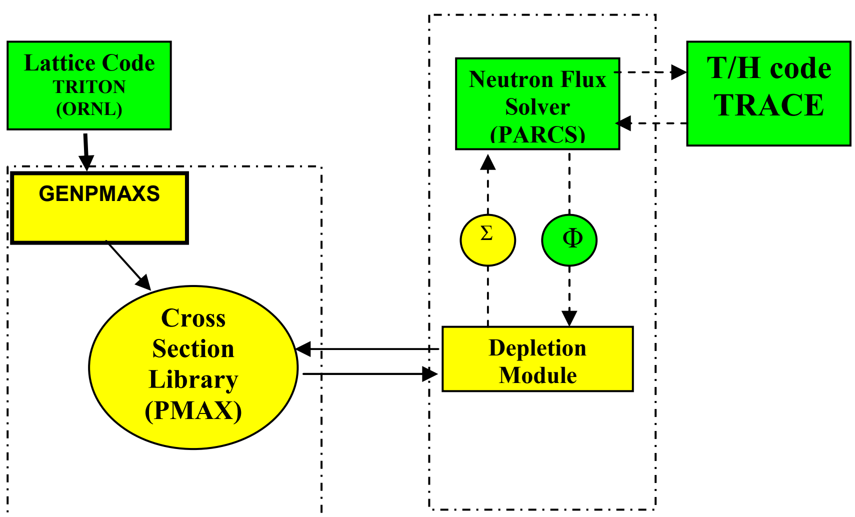

Figure 1 NRC Coupled Code Analysis System

The TRITON Lattice Physics code is described in another paper at this meeting [DeHart, 2006] and the TRACE code has been described extensively at previous meetings. This paper will focus on the PARCS code and some of the recent applications of the coupled TRACE/PARCS codes to OECD LWR benchmarks and to the Advanced CANDU Reactor, the ACR-700.

2.0 PARCS

PARCS [Downar, 2002] is a three-dimensional reactor core simulator that solves the steady-state and time-dependent neutron diffusion or SP_3 transport equations to predict the dynamic response of the reactor to reactivity perturbations such as control rod movements, boron concentration or changes in the temperature/fluid conditions in the reactor core. The code is applicable to both PWR and BWR cores loaded with either rectangular or hexagonal fuel assemblies, as well as to cores which require cylindrical geometry such as the Pebble Bed Modular Reactor. Recent modifications to PARCS have also enabled application of the code to the CANDU and ACR-700. A multigroup diffusion or SP_3 solution kernel can be used for the rectangular or cylindrical geometry option. Kernel options available for different geometry types and their solution methods are summarized in Table I.

The PARCS code was chosen by the U.S. Nuclear Regulatory Commission (NRC) as its best estimate core neutronics code, and PARCS is coupled to the U.S. NRC thermal-hydraulics systems codes TRACE and RELAP5. The thermal-hydraulic solution is incorporated into PARCS as feedback into the few group cross sections. A depletion capability has also recently been added to PARCS that includes a cross section interface capability to the lattice physics codes TRITON. The major features in PARCS include the ability to perform eigenvalue calculations, a transient (kinetics) calculation including decay heat and xenon and samarium treatment, the adjoint calculation and the depletion calculation. The primary use of PARCS involves a 3D calculation model for the realistic representation of the physical reactor. Numerous sophisticated spatial kinetics calculation methods have been incorporated into PARCS in order to accomplish the various tasks with high accuracy and efficiency.

Table I Solvers Available in PARCS

Geometry Type	Kernel Name	Solution Method	Energy Treatment	Angle Treatment
Cartesian 3D	CMFD	FD	2G	Diffusion
	ANM	Nodal	2G	Diffusion
	FMFD	FD	MG	SP_3
	NMG	Nodal	MG	SP_3
Hexagonal 3D	CMFD	FD	2G	Diffusion
	TPEN	Nodal	MG	Diffusion
Cylindrical 3D	CMFD	FD	2G	Diffusion
	FMFD	FD	MG	SP_3

3.0 Coupled Code Applications

Some of the recent applications of TRACE/PARCS will be described in this section. First an application to an OECD BWR Stability Benchmark will be presented and then a preliminary analysis of the Advanced Canadian Reactor (ACR-700) will be described.

3.1 BWR Coupled Code Applications: Ringhalls Stability Benchmark

There are several examples of inadvertent power oscillations in Boiling Water Reactors (BWRs) that have motivated research and development (R&D) into the modeling and analysis of instabilities in BWRs. The Ringhals 1 Stability Benchmark was organized and conducted by NEA/OECD (Nuclear Energy Agency Organization for Economic Co-operation and Development) in direct response to the need for R&D in BWR stability, as well as part of its continuing effort to validate and verify the computer programs utilized in the nuclear industry [Lefvert, 1994, 1996]. The Ringhals Unit 1 (RH1) Stability Benchmark contains significant spatial kinetics phenomena and therefore was an appropriate problem to be analyzed as part of the BWR assessment of the coupled TRACE/PARCS code.

The PARCS core neutronics model was developed using the neutronics data provided in the benchmark specifications. The core nodalization is based on one node per assembly in the radial plane (32x32 planar nodes) and 27 axial nodes. The nodalization includes explicit modeling of both the radial and axial reflectors. The PARCS neutronics solution for both the steady-state and transient were based on the two-group nodal diffusion option. The benchmark cross-section library specified for Cycle 14 of RH1 was based on the CASMO-3/SIMULATE-3 codes and was reformatted to comply with the cross section format required in PARCS.

One of the most important issues for coupled code analysis is the use of sufficient thermal-hydraulics (T-H) channels such that the respective field equations can be solved with sufficient accuracy for the particular application. The Peach Bottom Turbine Trip (PBTT) transient was modeled with TRACE/PARCS by using only 33 thermal-hydraulic channels in the TRACE model. However, for a transient such as stability it is expected that many more T-H channels would be required. For the Ringhalls stability benchmark several TRACE models were developed with various numbers of T-H channels in order to determine the mapping of neutronics to T-H channels that would provide acceptable accuracy for stability modeling. TRACE models were developed with 20, 128, 204, 486, and 648 TRACE CHAN components. The model with 204 channels shown in Figure 2 was found to be sufficient for preliminary stability analysis of points 9 and 10 of cycle 14.

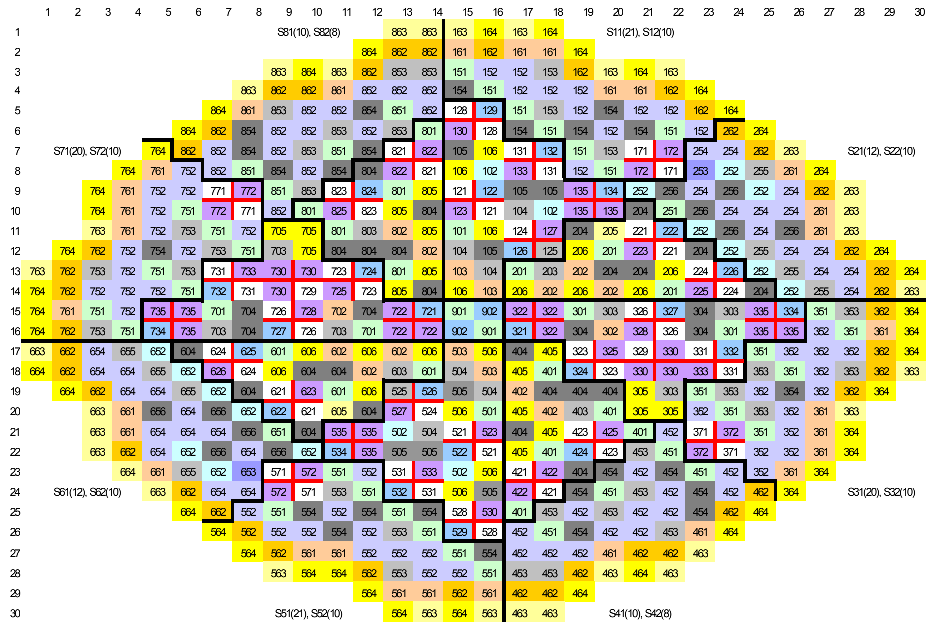

Figure 2 TRACE 204 Channel Model

The transient was then performed using three different methods to initiate the instability: control rod perturbation, pressure perturbation, and density noise perturbation. The results for the noise analysis method is depicted in Figure 3 and summarized in Table II for all methods. The results compare well with measure values of 0.71 and 0.5 for the decay ratio and frequency of oscillation, respectively.

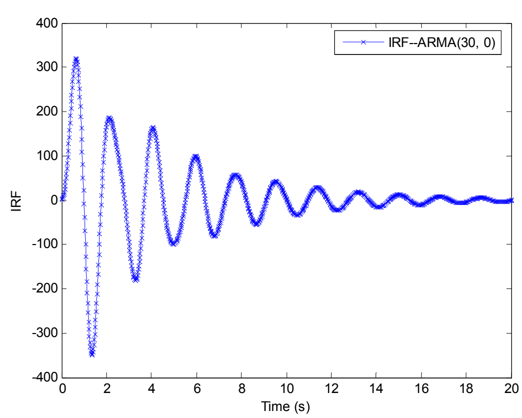

Figure 3 Impulse Response Function for Point 10 - Noise Analysis

Table II Summary of TRACE/PARCS Stability Results for Point 10

Method	Decay Ratio	Frequency
Control Rod Perturbation	0.737	0.565
Pressure Perturbation	0.731	0.560
Noise Analysis Method	0.670	0.551

3.2 Modeling of the ACR-700

The ACR-700 had been proposed by AECL [AECL, 2004] as an advanced reactor design with enhanced safety features compared to the CANDU-6 reactor. Several modifications were made to the PARCS code to enable coupled code analysis of the ACR-700 [Downar, 2004]. This section will describe these modeling efforts and some preliminary applications of both the RELAP5/PARCS and TRACE/PARCS codes to the ACR-700.

The PARCS model used for the analysis here is similar to that used in previously reported work [Downar, 2004]. The cross section model used here takes into account the impact of "neighboring" assembly conditions on the homogenized cross sections of an assembly by explicitly modeling the conditions of the adjacent fuel assembly as a feedback variable into the cross sections of the assembly being modeled. The PARCS full core model was constructed with 284 fuel channels having a 51 cm thick average radial reflector region and 12 fuel bundles in the axial direction. A time averaged burnup distribution consistent with that reported by AECL [AECL, 2004] was modeled. Figure 4 illustrates the typical burnup distribution used for plane 1 of the PARCS model. Fuel assemblies were modeled using four nodes per assembly in PARCS in order to implement a model with the neighboring effects correction.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
A					0.93	14.66	0.87	14.61	0.90	14.67	0.84	14.62	0.80	14.53				
B				0.97	14.90	0.92	21.27	1.36	21.35	1.39	21.26	1.28	14.93	0.79	14.58			
C			0.97	14.91	1.45	21.31	1.38	25.05	1.72	25.16	1.63	21.26	1.26	21.31	0.77	14.55		
D		0.93	14.90	1.47	21.27	1.73	25.16	1.68	25.05	1.67	25.03	1.60	25.17	1.23	21.33	0.75	14.53	
E	0.89	14.86	1.43	21.27	1.74	25.16	1.73	25.03	1.68	25.03	1.63	25.42	1.57	25.16	1.21	21.27	0.74	14.49
F	14.61	1.64	24.62	1.67	24.61	1.73	25.74	1.74	25.74	1.72	25.74	1.67	25.42	1.51	24.61	1.44	24.61	0.73
G	0.90	24.60	1.62	24.37	1.72	25.42	1.75	25.57	1.72	25.57	1.70	25.74	1.64	25.42	1.49	24.61	1.44	15.45
H	15.45	1.54	24.37	1.60	26.15	1.77	26.15	1.73	25.57	1.72	25.57	1.74	26.15	1.70	24.37	1.49	24.36	0.83
I	0.86	24.36	1.55	24.37	1.74	26.14	1.77	25.57	1.72	25.57	1.71	26.14	1.74	26.15	1.55	24.37	1.49	15.44
J	15.44	1.49	24.37	1.55	26.15	1.74	26.14	1.72	25.57	1.72	25.57	1.76	26.14	1.74	24.37	1.55	24.36	0.86
K	0.83	24.36	1.50	24.37	1.70	26.14	1.74	25.57	1.72	25.57	1.72	26.15	1.77	26.15	1.59	24.37	1.54	15.45
L	15.45	1.44	24.61	1.50	25.42	1.64	25.74	1.70	25.57	1.72	25.57	1.74	25.42	1.71	24.37	1.62	24.60	0.90
M	0.73	24.61	1.44	24.61	1.52	25.42	1.68	25.74	1.72	25.74	1.74	25.74	1.73	24.61	1.67	24.62	1.64	14.61
N	14.49	0.74	21.27	1.21	25.16	1.57	25.42	1.64	25.03	1.67	25.03	1.72	25.16	1.73	21.27	1.42	14.86	0.89
O		14.53	0.75	21.33	1.23	25.17	1.60	25.03	1.67	25.05	1.68	25.16	1.73	21.27	1.47	14.90	0.93	
P			14.55	0.77	21.31	1.27	21.26	1.63	25.16	1.72	25.05	1.37	21.31	1.45	14.91	0.97		
Q				14.58	0.79	14.93	1.28	21.25	1.39	21.35	1.36	21.27	0.92	14.90	0.97			
R					14.53	0.80	14.62	0.84	14.67	0.90	14.61	0.87	14.66	0.93				

Figure 4 Plane 1 Burnup Distribution (GWd/MT)

The thermal-hydraulics of the ACR was modeled with both RELAP5 and TRACE. Both models used in the calculation of the ACR-700 were provided by ISL [Caraher 2005]. The system model is shown in Figure 5 and provides for the 284 ACR channels to be modeled with in two separate groups, 142 of the channels are oriented parallel to the reactor's axis and the other 142 channels are oriented anti-parallel to the reactor's axis. Calculations were performed with both RELAP5/PARCS and TRACE/PARCS to provide a consistent comparison of the codes for the ACR-700.

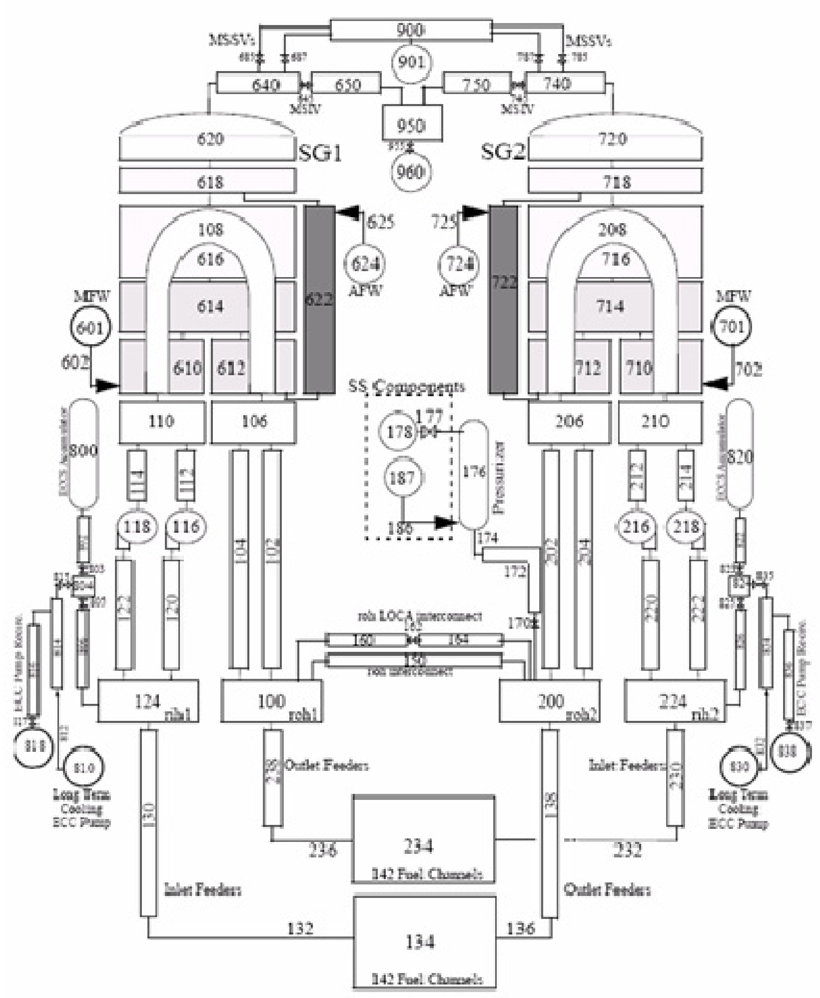

Figure 5 T-H Model of ACR-700 [Caraher 2004]

The coupled code calculations was performed using a sequence of three calculations with the PARCS and RELAP5 or TRACE models. The first calculation was a "standalone" steady state TH calculation used to initialize the temperature/flow fields by running a 150 second "null" transient. The second calculation used the "standalone" result to initialize the coupled code calculation during another "null" transient. The third calculation was the actual LOCA transient initiated with a 25% break of header RIH1. The steady-state results for RELAP5 and TRACE are compared in Table III. As indicated, there is good agreement in the predications of the two codes.

Table III Comparison of RELAP5 and TRACE Steady-State Results

Node	Quantity	TRACE	RELAP5	% Diff
134	Pressure [Pa]	1.29E+07	1.28E+07	*0.55*
	Mass Flow [kg/s]	3299.4	3294.1	*0.10*
	Den Cool [kg/m3]	703.2	703.4	*-0.03*
234	Pressure [Pa]	1.29E+07	1.28E+07	*0.78*
	Mass Flow [kg/s]	3452.4	3439.8	*0.37*
	Den Cool [kg/m3]	703.3	703.4	*-0.01*

4.0 Summary and Conclusions

During the last several years, the U.S. NRC has undertaken the development of an advanced safety analysis code system based on the consolidated thermal-hydraulics code TRACE (Trac Relap Advanced Computational Engine). The neutronics codes are based on the ORNL Lattice Physics code TRITON and the Purdue core neutronics Simulator, PARCS. This paper described some of the preliminary applications of the coupled codes using OECD LWR benchmarks and the ACR-700. Work was suspended on the ACR-700 project before final analysis could be completed.

Further coupled code assessment and validation is currently underway at ORNL and Purdue/PSU. At ORNL work is underway using TRITON/PARCS/TRACE to perform the core follow analysis of cycles 1 and 2 of the Peach Bottom reactor [EPRI, 1980]. Detailed in-core TIP measurement data is provided at several burnup points in the cycle and will establish the ability of the NRC code system to perform core depletion analysis. The OECD Peach Bottom Turbine Trip Benchmark will then be performed at the end of cycle 2 with the cross sections from the core depletion. Work is also continuing on the assessment of several other points in the OECD Ringhalls Stability Benchmark using TRACE/PARCS.

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