VALIDATION AND BENCHMARKING OF THE HELIOS/RAMONA MODEL OF DODEWAARD

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ABSTRACT

The Interfaculty Reactor Institute (IRI) has developed a coupled thermal hydraulic and neutronic model of the natural circulation cooled Dodewaard reactor based upon the codes HELIOS and RAMONA.[1,2] The technique used to validate the HELIOS cross section model consisted of a "blind test" to compare the results of static and transient RAMONA coupled thermal hydraulic and neutronic calculations performed for operating cycle 18 using the neutron cross section libraries prepared by IRI using HELIOS and by Scandpower using the RECORD code. The normalized axial power profile obtained with the HELIOS cross sections shows superior agreement with the measured TIP data relative to the results obtained using the RECORD cross sections, particularly at the core inlet and outlet. RAMONA static calculations were performed to determine the xenon, control rod, void, and Doppler reactivity worths predicted with each cross section set, and acceptable agreement was obtained for each case. Transient RAMONA calculations consisting of sinusoidal control rod and pressure perturbations were also performed with each cross section library, and again excellent agreement was obtained. Thus, the Dodewaard model can be considered validated. IRI is now benchmarking the HELIOS/RAMONA model against the measured conditions for Dodewaard operating cycle 26. This particular set of measurements was selected because it contains a wide range of operating conditions including nominal, low pressure, and low flow situations, and one case that was not stable. Thus, these data should identify the range of applicability of the model.

I. INTRODUCTION

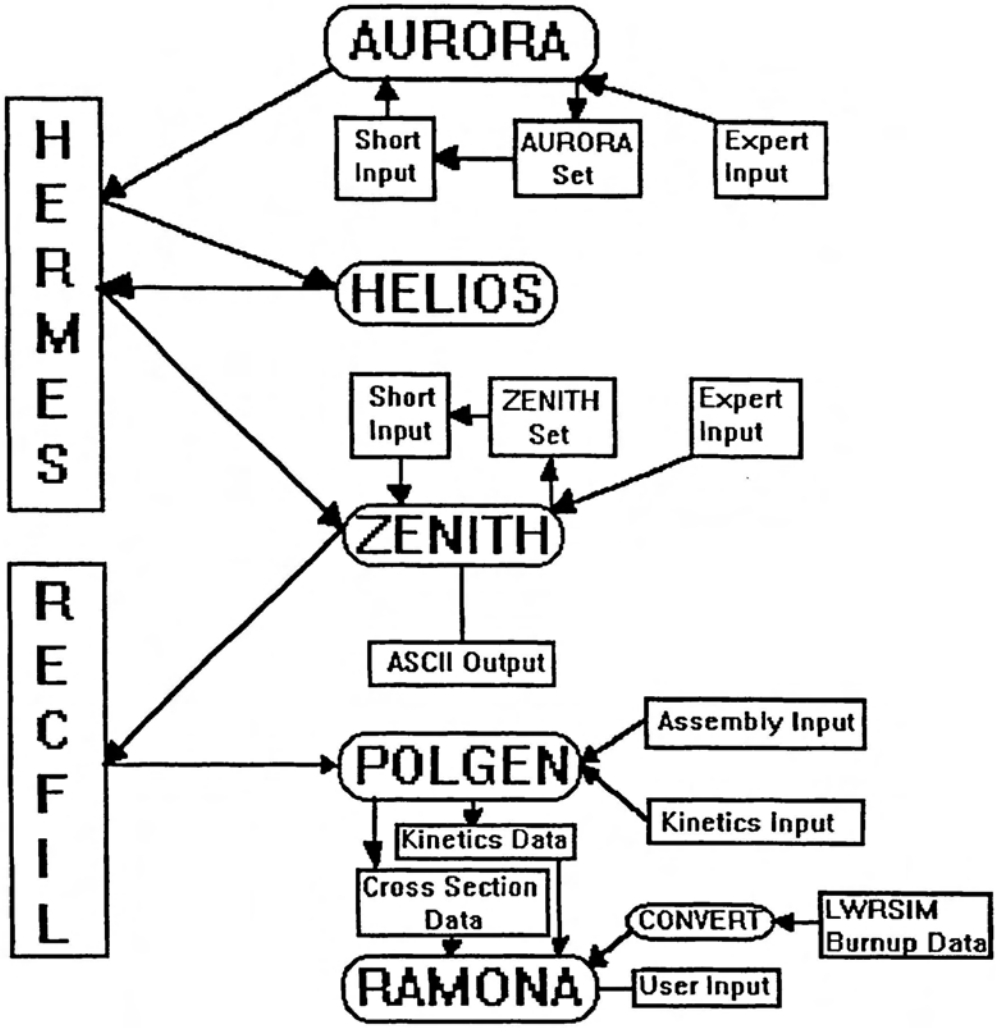
The use of natural circulation cooling, rather than forced circulation via pumps, is an essential passive safety feature of many advanced reactor designs. The underlying physical phenomenon that affect the natural circulation coolant flow are not completely understood, however. The Netherlands was fortunate in this respect to have operated the Dodewaard boiling water reactor (BWR), which relied on natural circulation for core cooling during normal operation. The Department of Reactor Physics at the Interfaculty Reactor Institute (IRI) has been performing reactor physical measurements at Dodewaard for more than 15 years, and we have built an extensive data file of measured signals under a wide range of operating conditions during the course of these experiments. Last year we began the development of a coupled thermal hydraulic and neutronic Dodewaard model using the commercial codes HELIOS and RAMONA from the Scandpower corporation. HELIOS is a collision probability code that is used to generate homogenized neutron cross sections representative of a fuel assembly.[1] RAMONA is a coupled thermal hydraulic and neutronic code designed for modelling BWR systems.[2] The development effort to generate the HELIOS/RAMONA model of Dodewaard was completed in 1996, but the model was neither validated against previous calculations nor benchmarked against experimentally measured data. Thus, IRI decided to apply the model in two parts: first validate the HELIOS cross section model by comparing the RAMONA predictions to the operating cycle 18 measured TIP data and to the previous RAMONA calculations that were performed using cross sections generated with the RECORD code[3]; and compare the model predictions to the measured data obtained for cycle 26. This report summarizes the IRI validation and benchmarking effort of our HELIOS/RAMONA Dodewaard model.

II. DESCRIPTION OF THE HELIOS/RAMONA DODEWAARD MODEL

The standard RAMONA BWR model explicitly simulates the upper and lower downcomers, the upper and lower plenums, the core, the riser, and the steam dome within the reactor pressure vessel. The flow is modelled as one-dimensional in each of these loop components, but branches into several parallel channels in the core. The riser section is treated as a single flow channel. The coolant flow conditions within the reactor vessel are calculated using a basic four-equation drift flux model describing the mass balances for water and steam and the energy and momentum balance equations for the mixture of the two phases. The recirculation loop is also included, and the code can calculate the flow in a natural circulation system such as Dodewaard. Full three-dimensional neutron kinetics is included. The IRI RAMONA model of Dodewaard assumes 1/8th core geometry, so that there are twenty-three heated coolant channels plus a separate bypass channel. The heated and bypass channels connect the upper plenum and the riser sections. Each of the heated channels corresponds to a single fuel assembly for the neutronics calculations radially, with either twelve or thirty-six nodes assigned in the axial direction. An average fuel pin model is associated with each neutronic node for the fuel temperature and heat flux calculations. RAMONA also contains additional models to describe the response of auxiliary systems, such as the main steam line dynamics, control systems for pressure regulation and feedwater control, etc., but these components were not included in the Dodewaard model.

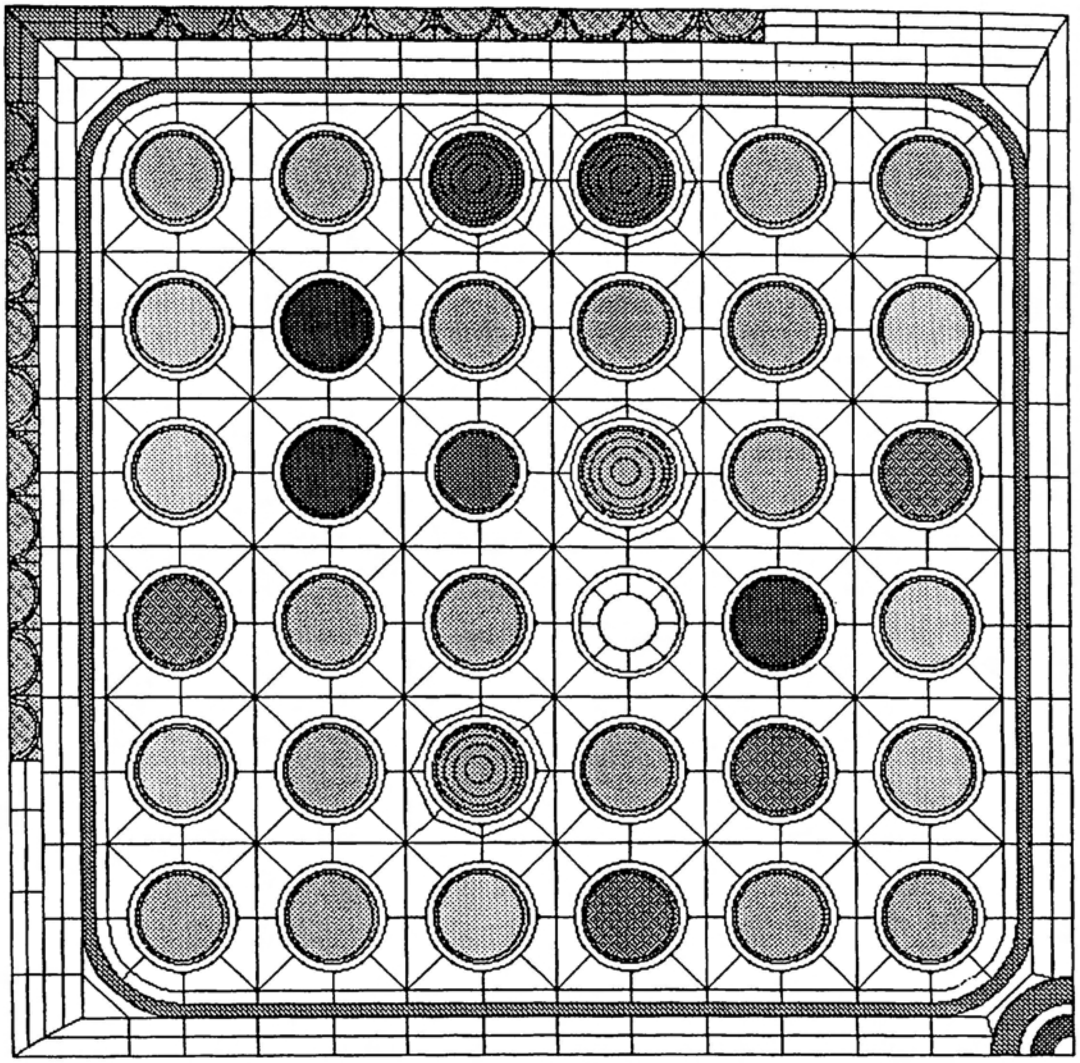
The dependence of the neutron cross sections on instantaneous and historical void, burnup, control rod presence, fuel and moderator temperature, and xenon is represented using polynomials in RAMONA. The Scandpower code POLGEN can be used to generate these polynomials in the required RECFIL structure from an existing cross section library.[4] Historically, the codes RECORD and ECLIPSE were used to generate the cross section libraries used by POLGEN. The RECORD code determines reactivity, reaction rates, power and burnup distributions in two dimensions across a fuel assembly, and generates the few group cross sections, isotopic densities and other nuclear data. The code ECLIPSE is used in conjunction with RECORD for calculating the space-time depletion of assemblies that contain gadolinium. This is the basic approach that was taken by Scandpower in developing the Dodewaard cross section set, although the code PHOENIX was also used to calculate the fuel Doppler coefficients of reactivity.[5] We have deviated from this historical approach by coupling HELIOS to RAMONA as shown in Figure 1.

Figure 1 - Cross Section Generation Methodology



The input pre-processor for HELIOS is AURORA. The expert input set for AURORA describes the fuel assembly geometry, materials, temperatures, densities, calculation cases, and desired cross section outputs in terms of uninitialized parameters. The expert input is used by AURORA to generate a "set". The user then only has to initialize the various parameters referenced in the set using the AURORA short input deck. The AURORA short input contains values for such parameters as the dimensions and materials for the control and fuel rods, assembly, detectors, and spacers, as well as the power, void values, and temperatures to be considered. IRI simplified this procedure further by generating a short input deck for a "generic" Dodewaard assembly, illustrated in Figure 2 with the hafnium control blade type (a boron carbide control blade type is also defined in the generic input, but only one control blade type can be assigned to a single assembly).[6] The various gray-scales in the figure represent different materials including varying fuel pin

Figure 2 - "Generic" HELIOS Dodewaard Assembly



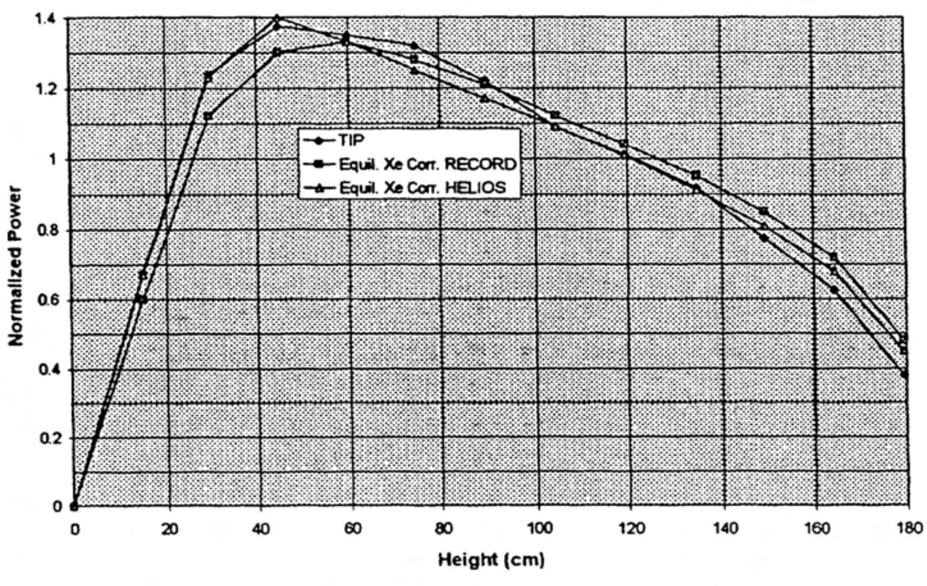
enrichments and gadolinium concentrations. This generic input deck contains material specifications and dimensions for every fuel pin and control rod type that has ever been used in the Dodewaard reactor core. Thus, the user only has to combine and locate the various fuel pins in the short generic input deck to generate the AURORA inputs for an actual Dodewaard fuel assembly. All of the information required by HELIOS is written by AURORA into the HERMES database, which is also used to output the calculated cross section information. The ZENITH post-processor can then be used to manipulate this data base. Again, expert and short input sets are utilized, with the expert sets containing basic subroutines to process the data and the short input decks consisting of the user's selection of which of these subroutines to execute. The conversion of the HELIOS cross section library into the RECFIL format required by POLGEN is actually performed by the ZENITH post-processor. IRI developed the expert set that performs this conversion from Scandpower recommendations.[7,8] The subsequent execution of POLGEN is not changed by the use of this HELIOS cross section generation methodology. Finally, the FORTRAN code "CONVERT" is used to translate the exposure weighted void values provided by the Dodewaard operators into the format required by RAMONA.

III. VALIDATION OF THE HELIOS/RAMONA DODEWAARD MODEL

The Dodewaard reactor contained two fuel assembly designs during cycle 18. The first design contained either 2, 3, or 4 gadolinium rods in the core axial midsection, while the second design contained 5 gadolinium rods at these locations. Scandpower chose to represent both of these fuel assembly designs with the second option, with a second fuel type defined to represent the fuel assembly axial end sections where no gadolinium is present. A burnup bias was added to some assemblies to compensate for the "fictitious" burnable-poison rods generated with this approach. HELIOS cross sections libraries were generated using these same assumptions. The Scandpower model was provided to IRI as binary POLGEN libraries for the core axial mid- and end-sections and a RAMONA input deck for Dodewaard that uses these libraries. Nominal full-power (183 MW) conditions are assumed, with the recirculation flow rate fixed at a value of 1276 kg/sec. It should be noted that the RAMONA standard riser model consists of a single channel that is common to all fuel assemblies and the bypass flow, whereas four assemblies share a common riser channel in the actual Dodewaard reactor. This limitation has been shown to be neglible.[6]

RAMONA static calculations were performed using the RECORD cross section libraries generated by Scandpower and the HELIOS libraries generated by IRI. Figures 3 and 4 display, respectively, the normalized axial and radial power profiles predicted by RAMONA using these cross section libraries, as well as the measured TIP data, with a local equilibrium xenon correction applied at each neutronic node. It can be seen that the

Figure 3 - Axial Power Profile



axial power profile predictions obtained with the HELIOS data show superior agreement with the measured TIP data relative to the results obtained using the RECORD libraries, particularly at the core inlet and outlet. This indicates that the axial void profile will be simulated more accurately with the new HELIOS cross sections, which has a significant affect on the natural circulation flow. The radial assembly powers predicted with the two libraries show excellent agreement with the measured TIP data, with the most significant deviation between the code predictions occurring along the low-power core periphery.

Figure 4 - Normalized Power Distribution

LEGEND	
RECORD	(Relative Difference)%
HELIOS	(Relative Difference)%
TIP	

96 (0.00%) 98 (2.08%) 96				
124 -(0.80%) 125 (0.00%) 125	142 (11.81%) 142 (11.81%) 127			
131 -(0.76%) 132 (0.00%) 132	145 (2.84%) 144 (2.13%) 141	158 (5.33%) 157 (4.67%) 150		
143 (0.00%) 143 (0.00%) 143	140 -(0.71%) 139 -(1.42%) 141	132 -(7.04%) 133 -(6.34%) 142	132 (2.33%) 132 (2.33%) 129	
129 (4.03%) 128 (3.23%) 124	122 -(1.61%) 122 -(1.61%) 124	111 (3.74%) 110 (2.80%) 107	79 (5.33%) 80 (6.67%) 75	59 -(13.24%) 57 -(16.18%) 68
98 -(2.00%) 98 -(2.00%) 100	85 -(5.56%) 86 -(4.44%) 90	65 -(5.80%) 66 -(4.35%) 69	52 -(7.14%) 52 -(7.14%) 56	39 (0.00%) 37 -(5.13%) 39
57 (7.55%) 58 (9.43%) 53	50 (2.04%) 51 (4.08%) 49	44 (2.33%) 44 (2.33%) 43		

The RAMONA radial albedo input parameters were "adjusted" by Scandpower to obtain agreement between their calculated radial power distributions and the measured TIP data. These same albedos were used with the new HELIOS generated cross sections without adjustments, so minor improvements in the radial distribution could probably be obtained by manipulating these parameters. It was also noted that the assembly burnups calculated with the HELIOS cross sections have a positive bias of 0.5% relative to the burnups predicted with the RECORD libraries. This small deviation is believed to be a result of the number of significant digits used to express the fuel enrichment, since identical exposure weighted void values were used in each case.

Additional RAMONA calculations were performed to determine the xenon, control rod, void, and Doppler worths predicted with each cross section set as shown in Table 1, where the reactivity worths are expressed relative to the base case with no local equilibrium xenon correction. The effective multiplication predicted with the HELIOS base cross sections exhibits a negative bias of 0.70% relative to the predictions obtained with the RECORD cross sections, at least a portion of which can be attributed to the burnup bias noted with the HELIOS data. Referring to the table, the xenon worth calculated with the HELIOS model provides excellent agreement with the RECORD results. Similarly, very good agreement is obtained for the cases where rod groups 1 and 5 are removed from their initially inserted positions. A larger deviation is obtained for the case where rod group 6 is inserted, however. This case corresponds to the insertion

Table 1 - Calculated Reactivity Worths

Case	Multiplication			Reactivity Worth		
	RECORD	HELIOS	Rel Diff.	RECORD	HELIOS	Difference
Base	0.99475	0.98783	-0.70%	N/A	N/A	N/A
Local Xe	0.99375	0.98653	-0.73%	-0.10%	-0.13%	0.03%
No Xenon	1.02130	1.01379	-0.74%	2.67%	2.63%	-0.04%
Rod 1 Out	1.00342	0.99634	-0.71%	0.87%	0.86%	-0.01%
Rod 5 Out	0.99536	0.98861	-0.68%	0.06%	0.08%	0.02%
Rod 6 In	0.99102	0.98265	-0.84%	-0.37%	-0.52%	0.15%
0.10 Void	0.97931	0.97234	-0.71%	-1.55%	-1.57%	-0.02%
0.25 Void	0.95164	0.93843	-1.39%	-4.33%	-5.00%	-0.67%
Fuel Pert.	0.99333	0.98632	-0.71%	-0.14%	-0.15%	0.01%
Mod Pert.	0.99475	0.98783	-0.70%	0.00%	0.00%	0.00%

length of 45 cm used in the transient calculations. The insertion of this rod group results in a significant change in the axial void profile, whereas the removal of the other two rod groups results in only minor axial variations of this parameter. The calculated void profile differs using the two cross section libraries, so it is not surprising that larger deviations occur for this case. The results obtained using the HELIOS data should be representative of the real Dodewaard response based upon the superior correlation with the measured TIP data. The void coefficient of reactivity was studied by artificially perturbing the local void fractions by constant values of 0.10 and 0.25. In these calculations, RAMONA applies the void fraction bias (e.g., 0.10) to the calculated void fractions only when the cross sections are evaluated - the void fractions used in the evaluation of the thermal hydraulic solution are not altered. An examination of the resulting axial void profiles indicated that the prediction obtained with the RECORD cross sections converge to that obtained with the HELIOS library for the 0.25 void perturbation. This indicates that the two cross section libraries have the same void dependence for high values, and the noted deviations must occur at low void values. The RECORD cross sections were generated for void values of 0.00, 0.40, and 0.70, while void values of 0.00, 0.35, and 0.70 were used to determine the cross sections with HELIOS. The fact that the HELIOS cross sections used a lower void fraction value in the middle of the void range could result in the improved predictions at low voids. For the fuel and moderator perturbations, a bias of 100 degrees centigrade was applied to the calculated temperatures when the cross sections were evaluated in RAMONA. No deviations were anticipated from the perturbation in fuel temperature, since the Doppler coefficients were input directly to POLGEN in both cross section libraries rather than being calculated from the neutronic data. There is no detectable reactivity effect associated with the moderator temperature perturbation.

A transient case in which control rod group 6 was driven into and out of the core sinusoidally in 0.7 seconds was calculated with RAMONA using both the RECORD and HELIOS cross section libraries. A second transient case in which the steam load was instantaneously reduced to zero for 0.2 seconds was also considered. This transient is equivalent to closing and subsequently reopening the main steam line valve in an actual reactor. These transients were initiated after a 10 second steady-state period. The time-dependent reactor power level (PO) and the total reactivity (RO) resulting from the control and pressure transients, respectively, are shown in Figures 5 -6. The HELIOS predicted variables are denoted by having the first two letters of the parameters preceded by HL, while the first two characters of the corresponding RECORD predicated variables are RC. Referring to Figure 5, excellent agreement is obtained when the time-dependent

FIGURE 5 - Normalized Power Profile for Control Rod Perturbation

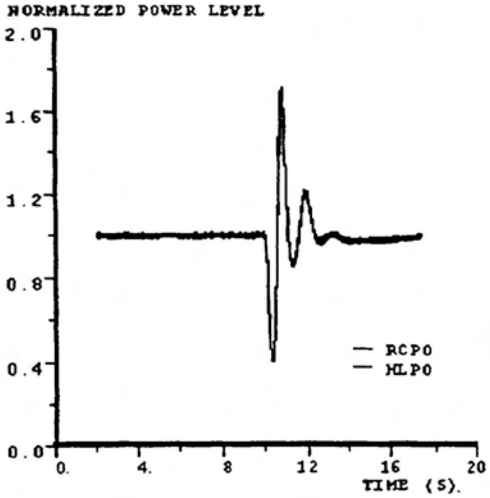
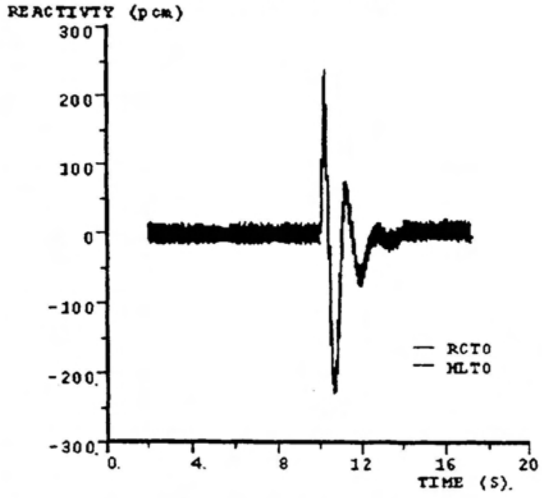


FIGURE 6 - Total Reactivity for Pressure Perturbation



powers are compared. The initial decrease in reactivity due to the control rod insertion causes a reduction in power that reduces the void fraction in the core, yielding a positive reactivity feedback, that results in the power increase subsequently displayed in the figure. No discernible difference can be ascertained between the power predicted using the HELIOS and RECORD cross sections. Similarly, the reduction in steam load resulting from the pressure transient collapses some of the core void which has a positive reactivity feedback effect, as shown in Figure 6. Comparing the reactivities obtained using the two cross section libraries, no significant deviations occur. RAMONA predicts equivalent results regardless of which cross section library is used for this pressure transient. The predicted total reactivity, reactor power level, core inlet subcooling, system pressure, and core inlet and downcomer inlet and outlet mass flow rates for these transients were also compared using each cross section library and no significant deviations were noted. A comparison of the predicted relative axial powers and the active coolant and total core void fractions obtained with the two libraries indicated some minor deviations which were anticipated based on the results of the static calculations.

III. BENCHMARKING OF THE HELIOS/RAMONA DODEWAARD MODEL

IRI performed numerous well-documented experiments at Dodewaard over a period of several years. The power and the pressure of the reactor, together with the feedwater temperature and vessel water level, were manipulated to change the reactor condition. The subcooling at the reactor inlet and the circulation flow rate were some of the measured dependent variables. The intention of these measurement activities was to gain insight into the physical characteristics of such a reactor and to create a reliable database with respect to items such as the statics and dynamics of the natural circulation flow rate, inlet subcooling, and reactor kinetic stability. A large number of process data were collected in each measurement, including: data from the plant computer, data from special purpose incore neutron detectors, data from a subcooling measurement device, and circulation flow rate measurements by correlation of downcomer temperatures. Table 2 illustrates the measured operating conditions for the end of cycle (EOC) 26. As can be

Table 2 - Measured Dodewaard Operating Data for EOC 26

Power (MW)	Pressure (bar)	Mass Flux (kg/s)	T_{sub} (K)	DR	Frequency (Hz)
179	75.2	1278	4.5	0.36	1.17
180	64.8	1224	5.1	0.48	1.23
176	55.3	1207	5.6	0.65	1.28
172	50.4	1225	5.7	0.71	1.31
155	45.6	1257	5.6	0.54	1.19
149	40.7	1268	5.6	0.61	1.21
142	36.6	1246	5.5	0.63	1.22
132	31.8	1239	5.1	0.70	1.22
147	34.4	1240	5.7	1.02	1.39

seen from the table, the reactor was not only studied in its normal operating regime, but was also maneuvered to the extremes of its operational map where an instability occurred at high power and unusually low pressure.[11] This case should also present a challenging benchmark problem. Thus, the cycle 26 data represent a significant range of operating conditions and provide an excellent test for the range of applicability of the model.

IRI is now proceeding to benchmark our HELIOS/RAMONA Dodewaard model against the experimental data for Dodewaard operating cycle 26. This reactor core had three different fuel assembly designs and two different control blade types (Hf and B_4C). We have generated the six HELIOS libraries required to model this operating cycle and are proceeding to develop the accompanying RAMONA input model. The benchmarking of our HELIOS/RAMONA model of Dodewaard is being conducted as a portion of a Concerted Action (CA) within the 4th Framework Programme of the European Union. This CA specifies that coupled thermal hydraulic and neutronic models be developed for Dodewaard by the various team members. The task we have set for ourselves is to test state-of-the-art numerical means (codes like TRAC-BF, RAMONA-3, RAMONA-5, ATHLET and DYN3D) on measured data from Dodewaard. The distribution of data and the compilation of the results have been performed in an informal basis since this group is relatively small. However, the NEA has recently asked IRI to consider broadening these efforts so that the Dodewaard study would become an international BWR benchmark.

IV. CONCLUSIONS

The static calculations that have been performed with RAMONA validate the basic HELIOS cross section data set and the functional dependence of these cross sections on parameters such as burnup, void, xenon, etc. The excellent agreement obtained for the transient cases considered validate the HELIOS kinetic parameters such as the delayed neutron fractions, decay constants, etc. IRI has also begun the development of a post-processing code to calculate transient parameters such as resonance frequencies, decay ratios, etc. from the RAMONA output data. Based upon the results achieved from our validation effort, IRI is now proceeding to benchmark the HELIOS/RAMONA model against the data measured for Dodewaard operating cycle 26. The NEA is currently considering expanding this study into an international BWR benchmark.

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