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CORD-2 PACKAGE FOR PWR CORE DESIGN CALCULATIONS

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ABSTRACT

The CORD-2 package is designed to provide a modern, independent calculational tool for reactor core calculations. It provides options that are essential for modelling the advanced features of fuel assemblies. Its development is part of a wider effort to establish country's own expertise in nuclear design and safety analysis. The package provides not only the calculational modules, but also the data management support facilities. It has been implemented on VAX/VMS and on PC/DOS, but extension to other systems is quite straightforward. The main components and the calculatinal methods are briefly described. The results of the validation programme are presented. They include the comparison of the calculated results with the measured values for ten cycles of the Krško NPP and for the IAEA test case Almaraz, with special emphasis on the first cores at hot-zero-power conditions. The results of the validation programme show that CORD-2 is applicable for design level PWR core calculations.

1 Introduction

Reactor core calculations are of interest to the nuclear designers, the power reactor utilities and to the nuclear regulatory authorities. For this purpose there are validated code packages available on the market, which are applicable for a certain range of problems. The drawbacks of such packages are their commercial nature and limited flexibility in the sense that they are not necessarily validated for certain reactor and fuel types that may be of interest.

Institute *"Jožef Stefan"* has been providing technical support services to the Krško NPP utility [a 600 $MW(e)$ PWR by Westinghouse] and to the national nuclear regulatory authority. With the appearance of advanced fuel design features, it was decided to develop a code system, which would have sufficient flexibility to account for such features, and include the three-dimensional (3D) core modelling capability. For practical purposes the selection of the candidate reactor physics codes was limited to the non-commercial ones. These design objectives of the code package have recently been fulfilled with the completion of the CORD-2 package. The development provided a good insight into the physical phenomena which affect the reactor core calculational models.

Parameters which appear in a nuclear core design can be calculated from a series of calculations for the effective multiplication factor k_{eff} and the power distribution for different core configurations and operating conditions. These can be obtained by solving the neutron diffusion equation over the domain of the reactor core. Using modern nodal codes, such a solution is not very computationally intensive, even in 3D geometry. Most of the time is spent in generating the coarse mesh homogenized few group cross sections. Since this is a crucial step in core design calculations, it is essential that simple and reliable procedures for producing the cross sections are available.

2 CORD-2 package description

The CORD-2 package consists of two basic reactor physics codes, namely WIMS [1] and GNOMER [2]. WIMS is a well known and widely used lattice code. Version WIMS-D/4 is available from the NEA Data Bank in Paris. GNOMER solves the neutron diffusion equation in three-dimensional cartesian geometry by the Green's function NOdal MEthod [3]. It also includes advanced features for cross section homogenization and a simple thermohydraulics module from the CTEMP code [4], so that thermal feedbacks can be taken into account. The remaining parts of the CORD-2 software are utility codes which perform various functions, such as: library maintenance, data managements and input preparation for the reactor physics codes.

Standard FORTRAN-77 has been used as much as possible, with the minimum use of the job-control language for better portability. The package has been tested on VAX/VMS and on PC-386 under DOS-5.1.

A set of data libraries is defined to contain various classes of data, such as reactor core geometry, material composition etc. All codes of the package share the data from the same libraries. This reduces the user-input to the essential parameters which need to be varied in a calculational sequence and simplifies the quality assurance and quality control procedures. The list of libraries is the following:

DIMlib - dimensions and geometry description,

FASlib - fuel assembly ident, mass, enrichment and burnup history,

ISOlib - burnup-history dependent fuel isotopic inventory,

WIMlib - summary file for WIMS material assignment,

CORlib - core distributions data (e.g. power, temperature, burnup etc.),

RCFlib - reactivity coefficient library.

3 The methods of CORD-2

A solution for the whole core in 3D geometry is sought in several steps. On the reactor lattice level, transport methods are applied. From the solution, cell-homogenized multigroup cross sections are obtained. These are used in the calculations for a fuel assembly, where it was found that the solution in the multigroup diffusion approximation is adequate. Assembly-homogenized effective two-group cross sections can then be defined, which are suitable for solving the diffusion equation for the whole core by a coarse mesh nodal method.

Lattice cell homogenization: To homogenize a reactor lattice cell with WIMS, an array of 3×3 lattice cells is considered. The geometry is shown schematically in Figure 1 where the detailed internal structure of cells has been omitted for clarity. The outer cells f always contain fuel, while the central cell c may contain a fuel pin, a water hole, a burnable poison pin or another type of special cell. With a fuel cell in the centre, an extra layer of water is added on the outside of the cell array to preserve the total fuel assembly moderator to fuel ratio,

A solution for the array of cells is obtained using WIMS. Since an accurate solution is required for the central cell only, the surrounding cells are smeared into concentric rings so that the problem is reduced to 1-D radial geometry. This is done automatically in WIMS. Transport calculations are performed in 32 energy groups.

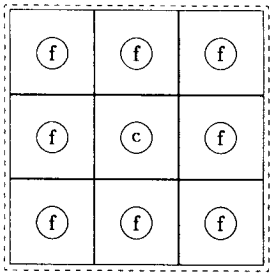

Figure 1: Lattice cell array configuration (schematic drawing).

From the WIMS results the cell-homogenized few group cross sections are obtained for the central cell. The effective diffusion homogenization method (EDH) is used [5], which guarantees not only the reaction rate conservation but also the conservation of partial currents on the boundary of an equivalent homogeneous cell in the diffusion approximation.

The calculation for the array of cells is performed for each type of cell in an assembly, for each axial region (usually ten regions are considered) and for each assembly in the core. To reduce the computation time, core symmetry assumptions (i.e. core quadrant or octant) may be applied.

WIMS input instructions for all cell types in the core are generated automatically. WIMS outputs are processed by an auxilliary program to calculate the cell cross sections for fuel assembly calculations.

Fuel assembly calculations: An array of homogeneous cells which constitute a fuel assembly are considered. By default ten energy groups are used. The solution is obtained in the diffusion approximation using GNOMER. Critical core conditions, for which k_{eff} is equal to one are usually of interest, therefore a *critical albedo* search is performed. Although such treatment is approximate and ignores the specific properties of the neighbouring fuel assemblies, it nevertheless represents the assembly surrounding correctly in an average sense. It is considered superior to the critical buckling search, which is commonly applied.

The result of the calculation are assembly-homogenized two-group cross sections. Like in the lattice cell case, the EDH method for homogenization is used. The calculation is repeated for each axial region of an assembly, for all assemblies in the core, considering core symmetries, if any.

The GNOMER input instructions for all assemblies are generated automatically.

Global core calculations: Calculation to determine the global core power distribution and the excess reactivity is the last step in the sequence. Solution is obtained with GNOMER in two energy groups and on a coarse mesh which usually corresponds to one node per assembly and ten regions in the core axial direction, with two additional regions for the axial reflector.

For a certain type of global core calculation the GNOMER input depends on the reactor core geometry and does not change. For this reason any automatic input generation is impractical and unnecessary.

Thermohydraulic feedbacks: In calculating the global core power distributions, the cross sections should be generated, taking into account the actual boron concentration and temperature

distributions. However, these depend on the power distribution which we are trying to calculate. An iterative procedure is required. Due to the complex nature of the thermohydraulic feedback effects and because the flux distributions are sensitive to small perturbations, about ten iterations are necessary.

Fuel material burnup: The treatment of burnup in CORD-2 differs from the approach commonly adopted in other code systems, where burnup-dependent cross sections are parameterized. In CORD-2 a library of isotopic composition vectors ISOlib is constructed as a function of average fuel assembly operating conditions. An isotopic composition vector gives the masses (in *grams*) of all isotopes in the WIMS library per ton of heavy metal in fresh fuel. An axial section of a fuel assembly is assumed to have operated at constant, average operating conditions. An isotopic composition vector which corresponds to such conditions is retrieved from the ISOlib library by interpolation and is used to prepare input for WIMS. When equilibrium xenon conditions are required, a burnup step of zero length is performed in WIMS. The cross sections are calculated from the WIMS output.

At present, the parameters for tabulating the ISOlib library are the fuel assembly type, the enrichment, the moderator density, the fuel temperature and the average number of inserts during burnup.

4 Validation

Validation has been performed by comparing the calculated results to the measured values at the Krško NPP and the Almaraz NPP which is a benchmark for design calculations [6] proposed by the International Atomic Energy Agency (IAEA).

Whenever possible, the *as built* data for the core constituents were used. The *recommended* materials in the WIMS library were used in the WIMS calculations except for control rods. Cross sections for silver, indium and cadmium were added [7], because the original WIMS library was deficient for these materials. It must be emphasized, that no empirical adjustments to the calculated results were made at this stage, except for a 10 % reduction in the control rod absorber radius. This was found necessary due to a systematic overprediction in control rod worth. Strong resonance absorbers like control rod materials can not be treated adequately by a lattice code like WIMS.

A detailed analysis has been completed for the fresh cores at zero power. A summary of some other results at zero power for the ten cycles of the Krško NPP is also given.

Critical boron concentration: The difference between the calculated critical boron concentrations and the measured values at beginning of cycle (BOC), hot zero power conditions (HZP) for ten refueling cycles of the Krško NPP are shown in Table 1. Specific features of the core, such as the number of burnable poison rods (BPR), number of integral fuel burnable absorber pins (IFBA), the use of fuel with axial blankets and low leakage fuel loading pattern (L^3P) are also indicated. Table 1 shows that CORD-2 predicts the critical boron concentration very well, even in the presence of BPR's, IFBA pins, axial blankets and L^3P cores. On average the boron concentration is overpredicted by 8 *ppm* with a spread of ± 13 *ppm*. The maximum difference from the measurement is 29 *ppm*.

For the Almaraz NPP the critical boron concentration prediction is equally good. The calculated value was 1346 *ppm* and the measured value was 1332 *ppm*.

Table 1: CORD-2 prediction of critical boron concentration with respect to the measurements at BOC, HZP conditions for the Krško NPP.

Cycle	Core loading	BPR	IFBA	Axial blanket	ΔC_b [ppm]
1		512	-	No	-3
2		-	-	No	-10
3		-	-	No	29
4		-	-	No	26
5	L^3P	112	-	No	2
6	L^3P	112	-	No	-2
7	L^3P	48	-	Yes	15
8	L^3P	176	1024	Yes	9
9	L^3P	-	3744	Yes	-11
10	L^3P	-	3600	Yes	26

Reactivity coefficients: The boron coefficient α_{Cb} was measured and the isothermal temperature coefficient α_{iso} was measured at different control rod configurations. The calculated values and differences from measurements at BOC, HZP conditions for Cycle 1 of Krško and Almaraz are given in Table 2. From the table, excellent agreement between measurement and calculation can be observed.

Table 2: CORD-2 prediction and differences from measurements of the boron and the isothermal temperature coefficients at BOC, HZP conditions for Cycle 1 of Krško and Almaraz NPP. ($1pcm = 10^{-5}\Delta k/k$).

Coefficient	Units	Krško		Almaraz	
		CORD-2	Diff.	CORD-2	Diff
α_{iso}(ARO)	pcm/K	-4.5	-0.4	-1.6	0.6
α_{iso}(D-In)	pcm/K	-8.2	-0.6	-8.9	-0.7
α_{iso}(DC-In)	pcm/K	-14.8	0.2	–	–
α_{Cb}	pcm/ppm	-9.10	0.06	-10.89	-0.03

Table 3: CORD-2 prediction of control rod worth (in the presence of other control rods) at BOC, HZP conditions for Cycle 1 of the Krško NPP.

Control rod bank	Calculated worth [pcm]	Diff.from measurement [%]
D	950	1
C(+D)	1421	4
B(+CD)	814	-3
A(+BCD)	2090	0

Control rod worth: The calculated integral control rod worths and % errors from the measured values are given in Table 3. It can be seen that the integral worths for all control rods agree within 5 % with the measurements.

Core power distribution: The core power distribution was measured at Krško Cycle 1 at BOC, HZP conditions for different control rod configurations. The relative errors in the calculated power distributions with reference to the measured values are given in Figure 2. Label ARO implies D-bank at 190 steps, label D-In means D-bank fully inserted, C-bank at 194 steps and label C-In means D-bank fully inserted, C-bank at 44 and B-bank at 172 steps. Control rod position zero steps means fully inserted and 225 steps just out of the active core.

Krško NPP core octant

-3.1 0.0 -4.1	-3.1 -1.2 -3.0	-1.2 -0.3 -1.5	-2.1 -1.9 -1.6	-0.6 -2.1 -0.6	-0.5 -2.1 0.2	2.0 -2.0 2.6
	-2.8 -0.6 -2.3	-1.2 -0.9 -2.6	-0.8 0.3 0.0	-0.6 -1.0 -0.7	0.5 0.2 2.5	1.8 -0.3 0.9
		0.0 1.5 0.1	0.5 -0.2 -2.7	1.1 2.3 1.3	2.0 0.7 1.8	
			-0.4 1.7 -0.4	1.2 1.0 1.6	2.0 0.1 2.5	
ARO Din Cin				-0.4 -0.8 1.4		

Figure 2: Percent difference in the calculated relative power distribution with reference to the measured values for different control rod configurations at BOC, HZP conditions for Cycle 1 of the Krško NPP.

It can be observed that the calculated power distributions agree well with the measurements even for the rodded core. The third measurement is particularly interesting, since two control rod banks are only partly inserted. For this configuration the calculated and measured core-average axial power distributions are compared in Figure 4. Excellent agreement between calculation and measurement is observed.

In Figure 3 the comparison for the Almaraz NPP is made. For the fuel assembly enrichments and masses of uranium the *as built* data were used [8].

Core burnup: With partly burnt fuel only a preliminary qualitative analysis has been completed. The analysis shows, that the differences between the calculated and the measured power assembly distributions slightly increase, but the errors are still acceptable. One of the major sources of error is thought to be the WIMS multigroup data library, in which the resonance integrals of ^{238}U and the fission product absorption cross sections have been adjusted. The adjustments correctly compensate the overall reactivity effects (hence the correct critical boron concentration prediction), but the ratio of $^{235}U/^{239}Pu$ is probably incorrect. A further indication of an inconsistency is the observed overprediction in the power axial offset (i.e. the % difference in power production between the top and the bottom half of the core). A WIMS Library Update Project [9], organized through the International Atomic Energy Agency is in progress and nearly thirty laboratories participate in it. Hopefully it will resolve the ambiguities related to the WIMS multigroup data library.

Almaraz NPP core octant

1.138 -4.9	1.061 -4.0	1.176 -2.6	1.078 -1.2	1.192 0.9	1.189 2.1	1.082 1.7	0.843 2.2
	1.157 -2.1	1.142 -2.3	1.178 -0.4	1.126 0.5	1.143 1.9	1.022 1.9	0.633 2.0
		1.200 -1.5	1.127 -1.6	1.123 -0.5	0.989 0.4	0.911 2.9	
			1.120 -1.6	0.977 -1.8	0.913 0.6	0.593 2.1	
				0.855 -0.1	0.630 1.3		

Figure 3: Measured relative power and percent difference in the calculated values for the Almaraz benchmark.

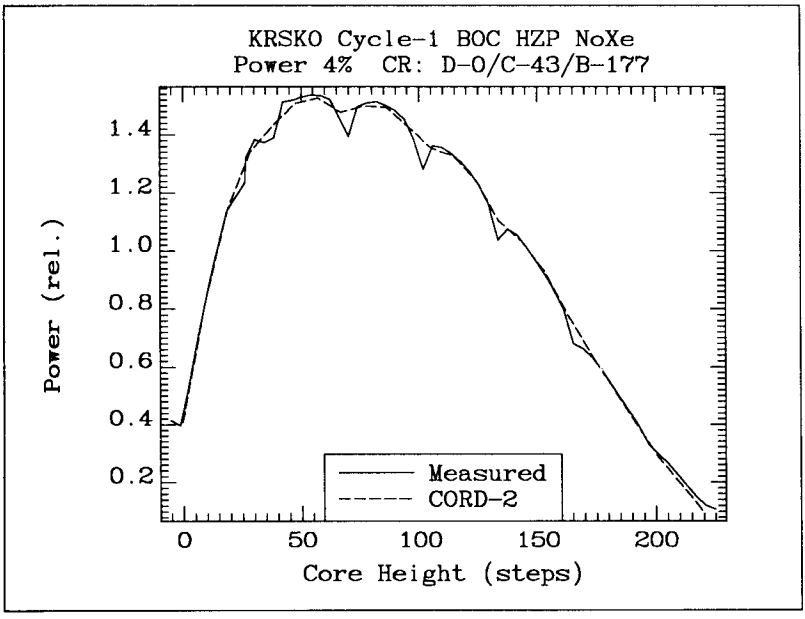

Figure 4: CORD-2 prediction of axial power distribution at BOC, HZP conditions and partly rodded core for Cycle 1 of the Krško NPP.

5 Conclusions

CORD-2 is a non-commercial integrated package for design calculations of PWR-type reactors. It has been implemented on VAX/VMS and on PC-386/DOS-5 or higher. The package is user-friendly, requiring a minimum input from the user. The relevant data are stored in a system of libraries. All programs acquire some particular parameter from the same library. If that parameter is to be changed, a single library needs to be modified, what simplifies quality assurance procedures for the calculations.

Validation of CORD-2 has been completed for hot-zero-power calculations on fresh cores. The results show that CORD-2 is capable of predicting integral core parameters very accurately. With burnup, the accuracy of the calculations is slightly reduced. The problems seem to lie in the WIMS multigroup data library. Work is in progress to update the WIMS library based on newly available evaluated nuclear data files. Validation at hot-full-power conditions is in progress. No significant problems were encountered so far.

The CORD-2 package has been successfully used for core design verification of the Krško NPP. Future work on the package will be focused on the completion of the validation programme, testing of the new WIMS library and further optimization for better computational efficiency.

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