CONDOR CALCULATION PACKAGE

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ABSTRACT

The present work describes the CONDOR calculation package to perform neutronic calculation of Fuel Assemblies of nuclear reactor cores. CONDOR uses a two dimensional Heterogeneous Response Method (HRM) with angular dependent coupling currents to calculate the neutron flux distribution. In this method the whole Fuel Assembly is divided in cells or elements which are coupled by interface currents and the cells are internally calculated by the collision probability method. Collision probabilities are numerically integrated using the Carlvik's method with a smart ray-tracing scheme, followed by normalization to reduce instabilities. Transformation laws on response fluxes and multiple collision escape and transmission probabilities are used to reduce the computational time, this method is applied not only during burnup but when two geometrically identical elements have small difference on its cross sections, as well. The CONDOR calculation package contains a set of nuclear data libraries, and auxiliaries programs, which are briefly described. The interfaces with other codes like CITVAP and MCNP are also described. Finally a summary of the validation status is also presented.

1 INTRODUCTION

The collision probability method in general two dimensional cylindrical geometry provides a flexible and accurate method as it was used in an early version of CONDOR code [1], but it requires a large amount of calculation time for a whole Fuel Assembly. The right selection is to use a two dimensional HRM [2] with angular dependent coupling currents[3-4]. In the particular case of CONDOR code a Fuel Assembly (rod or plate type) is divided in elements usually for each pin (or plate) and gap elements for the outer border of the Fuel Assembly.

The angular dependence of the coupling currents is described by discretizing their directional half-sphere at the interface into equal azimuthal sectors, like in Phoenix-H[5]. The polar angular dependence on the coupling currents has not been considered because it increases the calculation time[3].

The multigroup method is used to treat the energy dependence of the flux, so only one group equations are described. The response fluxes and multiple collision escape and transmission probabilities can be calculated in two different ways:

- from first flight collision probabilities, described in section 3
- or from previously calculated values, using transformation laws described in section 4.

Section 5 describes the auxiliary programs belonging to the CONDOR calculation package, making emphasis on the interfaces with CITVAP[6] and MCNP[7] codes.

2   HETEROGENEOUS RESPONSE METHOD

The whole system, usually a Fuel Assembly, is divided into space elements. Normally, the number of geometrically different space elements is small. In Figure 1 VVER, PWR and MTR Fuel Assemblies are shown including the element types of each of them.
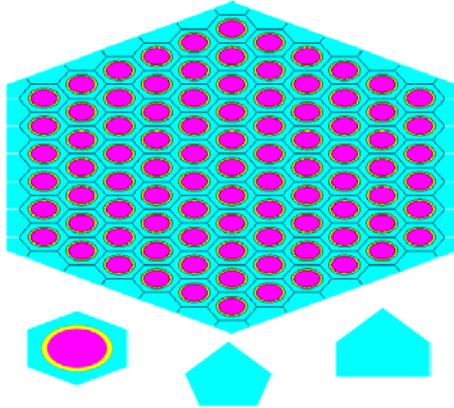
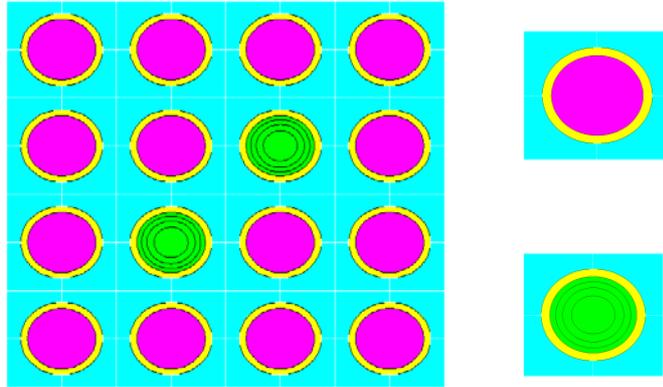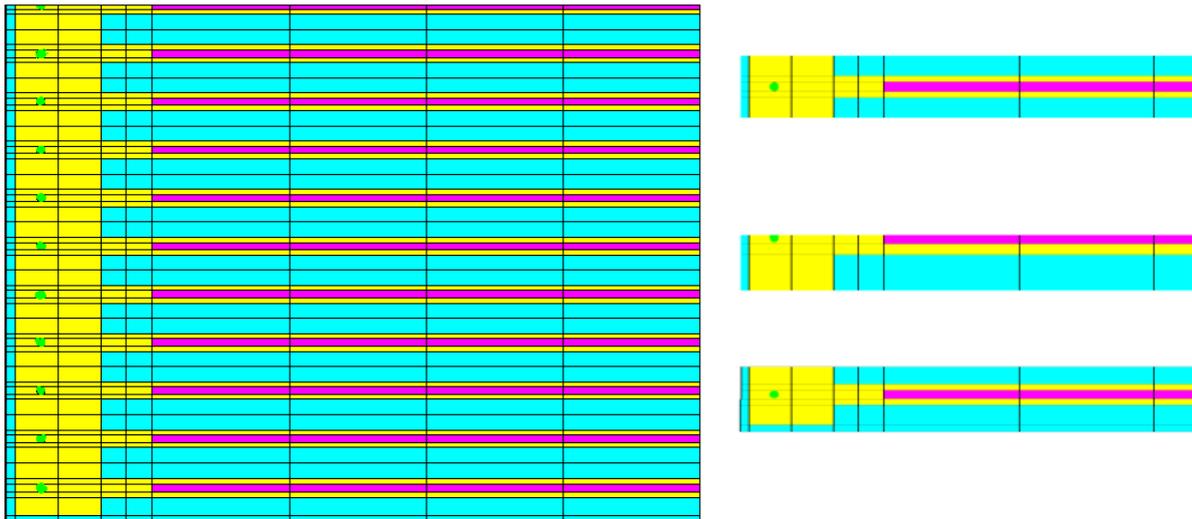Figure 1.a: VVER type Fuel Assembly.   Figure 1.b: PWR type Fuel Assembly.

Figure 1.c: MTR type Fuel Assembly.

Each heterogeneous element is arbitrarily partitioned in homogeneous regions (indexed with i or j) on which flat flux approximation is applied. The external surface is arbitrarily partitioned in segments on which flat coupling currents are calculated and each segment is arbitrarily partitioned in azimuthal sectors (indexed with s or t).
The HRM [2] method is used for the flux calculation of the system, and the matrix equation is:

$$\phi = X\,Q + Y\,j^- \tag{1}$$

Where
ϕ :   is the volume integrated flux array. Φ_i is the integrated flux in region i.
X :   is the matrix of source response fluxes. X_{ij} is the volume integrated flux in region i due to a unit uniform and isotropic source in region j.

$$\tag{2}$$

Q :   is the volume integrated source array. Q_j is the source in region j.

$\tilde{Y}$:   is the matrix of in-current response fluxes. Y_{is} is the volume integrated flux in region i due to a unit in-current through sector s.

j^- :   is the in-current array. J^-_s is the in-current through sector s.

X and Y are diagonal block matrices. Each block is the local matrix of a space element.

The response fluxes and currents are obtained from the HRM method. This defines two problems:

- Global problem: To calculate the coupling or interfaces currents between space elements j^-.
- Local problem: To calculate the response fluxes X and Y and multiple collision probabilities of the space elements.

2.1 GLOBAL PROBLEM

The currents j^- are solved using the following equations [8]

$$j^+ = T\, j^- + E\, Q \tag{2}$$

Where:

j^+ :   is the out-current array. J^+_s the out-current through sector s.

T :   is the multiple collision transmission matrix. T_{st} is the number of neutrons that escape through s due to a unit in-current through sector t.

E :   is the multiple collision escape probability matrix. E_{si} is the number of neutrons that escape through s due to a unit source in region i.

T and E are diagonal block matrices. Each block is the local matrix of a space element, which are obtained from the local problem. To solve iteratively the in-currents (by inner iterations), a geometry relation between in-currents and out-currents (the matrix H) is given:

$$j^+ = H\, j^- \tag{3}$$

2.2 LOCAL PROBLEM

The local problem is the main subject described in this paper. Its objective is to calculate the parameters needed in the global; i.e. response fluxes (X and Y) and multiple collision probabilities (escape E and transmission T). In CONDOR each block of these matrices is calculated per element according to one of the following methods:

- Using first flight collision probabilities,
- Applying a transformation law to earlier calculated data.

2.3 RESPONSE FLUXES

The calculation of response fluxes due to unit sources in regions and unit in-currents in the sectors has been described in [8]:

$$X = M^{-1} P$$
$$Y = M^{-1} \gamma \tag{4}$$

Where

P :   Is the matrix of first flight collision probabilities. P_{ij} is the number of first flight collisions in region i due to a unit uniform and isotropic source in region j.

γ :   is the matrix of in-current partial blacknesses. γ_{is} is the number of first flight collisions in region i due to a unit in-current through sector s.

The components of the matrix M are:

$$M_{ij} = \delta_{ij}\, \Sigma_i - \Sigma_{s,i}\, P_{ij} \qquad (5)$$

Where:

Σ_i: is the transport cross section of region i.

$\Sigma_{s,i}$: is the self-scattering cross section of region i.

δ_{ij}:   is the Kronecker symbol.

2.4 MULTIPLE COLLISION PROBABILITIES DATA.

The multiple collision escape probabilities and transmission are also found in [8]:

$$E = e + K\,X$$
$$T = t + K\,Y \qquad (6)$$

Where:

e :   is the first flight escape probability matrix. e_{si} is the number of uncollided neutrons that escape through s due to a unit uniform and isotropic source in region i.

t :   is the first flight transmission matrix. t_{st} is the number of uncollided neutrons that escape through s due to a unit in-current through sector t.

The components of matrix K are:

$$K_{sj} = \Sigma_{s,j}\, e_{sj} \qquad (7)$$

2.5 ANGULAR SECTORS

The directional half-sphere of the entering neutrons can be divided into angular sectors. The basic principle used for the calculation of the limits of each angular sector is that each one has the same surface S_s. In other words $S_s = S/NFI$, with NFI being the total number of angular sectors and S the surface of the segment.

As it is shown [3] the weight of the surface with the azimuthal angle is $\mathrm{Cos}(\varphi)$. The value of the φ_m limits are (m=0 to NFI):

$$\varphi_m = \cos^{-1}\left[\cos(\varphi_{m-1}) - \frac{2}{NFI}\right] \qquad (8)$$

With $\varphi_0 = 0.0$ and $\varphi_{NFI} = \pi$

3   COLLISION PROBABILITIES

The CONDOR code calculates angularly-dependent collision probabilities (CP's) for almost any element types as shown in Figures 1. All the algorithms and equations needed for the calculation of first flight collision probabilities can be found with more details in reference [3].

This section describes how the collision probabilities are evaluated in CONDOR and emphasizes the differences with respect to the reference [3].

- One of the most important differences is the limitation to only azimuthal angular discretization, in other words, cosine currents are used and only Bickley functions are needed.

- The Carlvik's ray tracing method with the smart macroband method is used to numerically integrate the CP's. The integration scheme is with separated volume and surface integrations. Volume integration is used for region to region CP's, and surface integration is for partial blacknesses and transmission. Escape probabilities are calculated from partial blacknesses by reciprocity relation.

- The same normalization method is used to satisfy the reciprocity and balance equations between CP's.

4   TRANSFORMATION LAWS

Takahashi (reference [9]) derived a transformation law for collision probabilities between two geometrically identical systems with different total cross sections. Krishnani (reference [10]) expanded the transformation law to the collision probabilities used in the interface current method.
Wio (reference [11]) derived a transformation law for response fluxes between two geometrically identical systems with different total and self-scattering cross sections. This method is faster than the previous one because only one linear system equation must be solved instead of two.
The cpu time required for the calculation of angularly dependent CP is minimized by an efficient ray tracing scheme which depends on the type of CP's:

- region to region CP: it is proportional to the number of integration chords and to the square of the number of the intersections per integration chord.
- surface to region CP: it is proportional to the number of integration chords and to the number of region intersections.

The cpu time needed to calculate CP's from the transformation laws for collision probabilities [12] is the time needed to solve a linear system of equations. This time is proportional to the cube of the number of regions. In some abnormal cases it can be bigger than the integration time of the CP's. With collision probability matrix one has still to solve a linear system of equations to find responses fluxes. This time is needed in both methods: Integrated CP's or using variational approach based on the transformation lows of CP's.
The cpu time needed to apply the transformation laws to response fluxes is the time needed to solve only one linear system of equations. This time will never be higher than that needed in the other approaches.

4.1 TRANSFORMATION LAWS FOR RESPONSE FLUXES

The transformation laws for reponses fluxes derived [11] have to be expanded to include angularly dependence of the interfaces currents used in the CONDOR code.
The starting point is the one group transport equation for an isotropic source.

$$\Omega \, \Delta\Phi(\Omega, \vec{r}) + \Sigma(\vec{r})\Phi(\Omega, \vec{r}) = \frac{q(\vec{r}) + \Sigma_s(\vec{r})\phi(\vec{r})}{4\pi} \tag{9}$$

where the source q(r) is the fission and scattering source (excluding self scattering).
A small perturbation of the total and self-scattering XS from a given state can be writtes as:

$$\Sigma(\vec{r}) = \Sigma^0(\vec{r}) + \Sigma^1(\vec{r}) \tag{10}$$

$$\Sigma_s(\vec{r}) = \Sigma^0_{\ s}(\vec{r}) + \Sigma^1_{\ s}(\vec{r}) \tag{11}$$

Superscript 1 denotes the perturbation of XS, superscript 0 the reference state while actual state has no superscripts. Subtitution of Eqs (10) and (11) into Eq (9) yields:

$$\Omega \, \Delta\Phi(\Omega, \vec{r}) + \Sigma^0(\vec{r})\Phi(\Omega, \vec{r}) = \frac{q(\vec{r}) + \Sigma^0_{\ s}\phi(\vec{r})}{4\pi} - \Sigma^1(\vec{r})\Phi(\Omega, \vec{r}) + \frac{\Sigma^1_{\ s}\phi(\vec{r})}{4\pi} \tag{12}$$

If the XS perturbation are small one may neglect the anisotropic dependence of the source correction as follows:

$$\frac{q'(\vec{r})}{4\pi} \cong \frac{q(\vec{r}) - \Sigma^1_{\ r}(\vec{r})\phi(\vec{r})}{4\pi} \tag{13}$$

With Σ_r the removal XS ($\Sigma_r = \Sigma - \Sigma_s$). Subtitution of Eq. (13) into Eq. (12) results in:

$$\Omega \, \Delta\Phi(\Omega,\vec{r}) + \Sigma^0(\vec{r})\Phi(\Omega,\vec{r}) = \frac{q'(\vec{r}) + \Sigma^0{}_s\,\phi(\vec{r})}{4\pi} \tag{14}$$

This equation shows that the neutron distribution in the perturbed system (with Eq. 9) is equal to the neutron distribution in the reference system but with the modified source q'(r). This is so if the geometry is the same and if the difference between Σ and Σ^0 is small (Σ^1) (no approximation on Σ_s^1).

In the HRM method one can calculate fluxes and currents (in a matrix notation) using Eqs. (1) and (2). As a consequence of eq. (14) the particle distribution can be calculated from a previous reference state.

Let Σ_r^1 be a diagonal matrix with the removal XS differences between the reference and actual state, then Eqs (14) and (12) become

$$\phi = X^0 (Q - \Sigma^1{}_r\,\phi) + Y^0\,J^- $$
$$J^+ = E^0 (Q - \Sigma^1{}_r\,\phi) + T^0\,J^- \tag{15}$$

It is possible to get the integrated flux as follows:

$$[I + X^0 \Sigma^1{}_r]\,\phi = X^0\,Q + Y^0\,J^- \tag{16}$$

Comparing this equation with eq. (1) yields:

$$X = [I + X^0 \Sigma^1{}_r]^{-1}\,X^0 $$
$$Y = [I + X^0 \Sigma^1{}_r]^{-1}\,Y^0 \tag{17}$$

To calculate the escape probabilities one can use the reciprocity between partial blacknesses and escape probabilities. However to obtain transmission probabilities Eq (1) for the integrated flux must be introduced in eq. (15) for the out currents. Comparing with eq. (2) shows:

$$T = T^0 - E^0\,\Sigma_r^1\,Y \tag{18}$$

As was mentioned the transformation law method (TL) will give good results when the approximation eq. (13) is good. In other words when the difference between total XS and reference total XS is small or the flux is isotropic. CONDOR has a preset value as limit for the application of this method, which can be modified by input.

5   CONDOR CALCULATION PACKAGE

The following figure shows the whole CONDOR calculation package and its interfaces with CITVAP Diffusion core calculation code [6] and MCNP Montecarlo code [7]. These interfaces improve the calculation capability of the overall package. Two interfaces are used with CITVAP code and one with MCNP code:
- Coupling with CITVAP code using macroscopic Cross Sections
- Coupling with CITVAP code using microscopic Cross Sections
- Coupling with MCNP code using burnup dependent numerical densities.

CONDOR CALCULATION PACKAGE
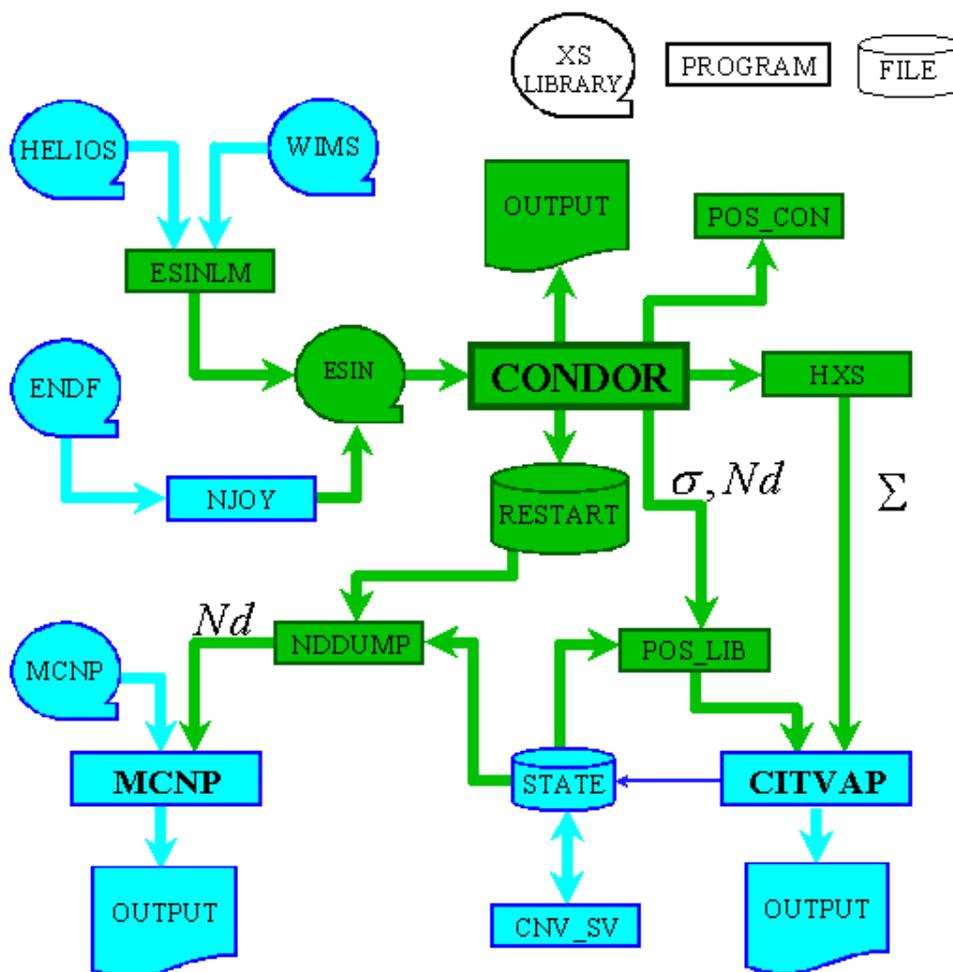
Nd: Numerical Densities. σ: Microscopic Cross Section. Σ: Macroscipoc Cross Section.

Figure 2: Condor Calculation Package flowchart.

5.1 INTERFACES WITH CITVAP

The CITVAP [6] reactor calculation code is a new version of the CITATION-II [13] code, developed by INVAP's Nuclear Engineering Division. The code was developed to improve CITATION-II performance. The code solves 1, 2 or 3-dimensional multi-group diffusion equations in rectangular or cylindrical geometry. Spatial discretization can also be achieved with triangular or hexagonal meshes. Nuclear data can be provided as microscopic or macroscopic cross section libraries.

CITVAP generate an "state file" which contains general core parameters like burnup, fuel temperature, coolant temperature and density, power density, control rod position. Two interfaces were developed between CONDOR and CITVAP:

a) The HXS program (Cross section handler) represents a major utility. It handles macroscopic cross-sections (identified by a name) in library form. This program is the interface between CONDOR and CITVAP when macroscopic XS option is used by CITVAP.

b) POS_LIB program uses the CITVAP "state file" with a given core burnup distribution and generate a microscopic CITVAP cross section (which depends on the burnup). It also generates the burnup dependent numerical densities to be used in the core calculation.

(7)

5.2 INTERFACES WITH MCNP

This well-known Montecarlo transport code for neutron and gamma calculations uses ENDF/B-VI cross sections [14] in any order and performs 3-D calculations.
CONDOR code can generate burnup dependent numerical density to be used by MCNP. This interface is efficiently managed by NDDUMP program.
NDDUMP uses the CITVAP "state file" and CONDOR "restart file" to generate burnup dependent materials in MCNP format.

5.3 NUCLEAR DATA LIBRARY

Two different sources were used to generate ESIN nuclear data library.
a) Primary data from the WIMS library [15], which has good thermal detail as well as resonant parameters. Moreover, it has isotopes added from the ENDF/B-IV library for control absorber material definition (Ag, In, Cd). A new set of isotopes was added from the ENDF/B-VI: Ir and Te, using NJOY system[16].
b) Primary data from HELIOS [17]. The HELIOS data are from the ENDF/B-VI library. The library has three different group structures: 190, 89 and 34 groups.

5.4 AUXILIARY PROGRAMS

Different auxiliary programs are used in the CONDOR calculation package
a) ESINLM is an administrative program, which handle ESIN-type libraries. It can add/remove isotopes, It can convert formatted/unformatted libraries. It can convert WIMS or HELIOS libraries to ESIN-type. It can print general or specific information, etc.
b) CNV_SV is an administrative program to handle CITVAP "state file".
c) POS_CON is a graphical post processor. It can plot the system under calculation, it can plot 1 and 2D fluxes or power densities. It can also plot several variables against burnup as Multiplication factor, numerical densities, fluxes, etc. It can also plot flux against energy (spectra).
d) ESINPLOT is a graphical program, which can plot microscopic cross sections.

6   EXPERIMENTAL VALIDATION

The code CONDOR and the CONDOR-CITVAP calculation line were validated against different experimental benchmarks:
a) CONDOR has been validated:
- PWR critical pin cell: 110 cases of UO_2 systems gave Keff=1.00065 ± 0.00800,
- PWR critical pin cell: 86 cases of U-metal systems gave Keff=1.00444 ± 0.00430 and
- 26 VVER-type cells gave Keff=0.99528 ± 0.00890
b) CONDOR-CITVAP calculation line has been validated:
- VVER reactors with Keff=0.99720±0.00300 and
- MTR reactors with Keff=1.00240±0.00090.

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