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Research

Feasibility Study of Coupling the CASMO-4/TABLES-3/SIMULATE-3 Code System to TRACE/PARCS

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SKI

SKI Perspective

Background

During the last years, SKI has investigated the possibility to apply the code package TRACE/PARCS from the US Nuclear Regulatory Commission (NRC) for analysis of events which have occurred in Swedish nuclear power plants and safety issues associated with the power uprates. As a complement to this, the Department of Reactor Physics at Chalmers has been asked to perform a feasibility study on possibility of coupling the code package CASMO/SIMULATE from Studsvik Scandpower to the TRACE/PARCS.

Purpose

The purpose of the project is:

- to build up competence at the Department regarding coupled neutronic and thermal-hydraulic codes,
- to investigate the possibility of coupling the code package CASMO/SIMULATE to TRACE/PARCS.

Results

In the study, the advantages and disadvantages of different options have been investigated and described thoroughly. The results show that the option which is most feasible is to couple SIMULATE-3 with PARCS.

Project information

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Feasibility Study of Coupling the CASMO-4/TABLES-3/SIMULATE-3 Code System to TRACE/PARCS

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Summary

This report investigates the feasibility of coupling the Studsvik Scandpower CASMO-4/TABLES-3/SIMULATE-3 codes to the US NRC TRACE/PARCS codes. The data required by TRACE/PARCS are actually the ones necessary to run its neutronic module PARCS. Such data are the macroscopic nuclear cross-sections, some microscopic nuclear cross-sections important for the Xenon and Samarium poisoning effects, the Assembly Discontinuity Factors, and the kinetic parameters. All these data can be retrieved from the Studsvik Scandpower codes. The data functionalization is explained in detail for both systems of codes and the possibility of coupling each of these codes to TRACE/PARCS is discussed. Due to confidentiality restrictions in the use of the CASMO-4 files and to an improper format of the TABLES-3 output files, it is demonstrated that TRACE/PARCS can only be coupled to SIMULATE-3. Specifically-dedicated SIMULATE-3 input decks allow easily editing the neutronic data at specific operating statepoints. Although the data functionalization is different between both systems of codes, such a procedure permits reconstructing a set of data directly compatible with PARCS.

Sammanfattning

Denna rapport undersöker möjligheterna av att sammanföra Studsvik Scandpowers CASMO-4/TABLES-3/SIMULATE-3-koder med US NRC TRACE/PARCS-koderna. De data TRACE/PARCS behöver är samma som behövs för att köra dess neutronik modul PARCS. Exempel på data är makroskopiska tvärsnitt, vissa mikroskopiska tvärsnitt som är viktiga för Xenon och Samarium förgiftning, diskontinuitetsfaktorer för bränslepatroner (“Assembly Discontinuity Factors”) och de kinetiska parametrarna. Alla dessa data kan erhållas från Studsvik Scandpowers koder. Datafunktionalisering är förklarad i detalj för båda systemens koder och möjligheten att sammanföra alla dessa koder till TRACE/PARCS diskuteras. Trots de konfidentiella restriktionerna för användning av CASMO-4-filerna och de ohanterliga formaten på TABLES-3 utdatafiler, visar det sig att TRACE/PARCS endast kan kopplas ihop med SIMULATE-3. Specialbyggda indata filer för SIMULATE-3 låter på ett enkelt sätt neutronikdatan utges vid specifika driftpunkterna. Trots att datafunktionalisering är olika mellan de båda kodsystemen, tillåter en sådan procedur rekonstruktion av datauppgifter direkt kompatibla med PARCS.

1. Introduction

In Sweden, many power utilities have applied to the Swedish Nuclear Power Inspectorate (SKI) for power upratings. Both Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs) are concerned by these power uprates. It has thus become important to develop reliable coupled neutronic/thermalhydraulic models of the Swedish nuclear power plants.

Within the framework of CAMP (Code Applications and Maintenance Program), SKI has actually access to the TRACE/PARCS code package from the US Nuclear Regulatory Commission (NRC). It is therefore planned to use TRACE/PARCS in order to study the relevant safety issues associated to these power uprates by developing state-of-the-art models. As will be discussed in this report, the TRACE/PARCS codes do not include any nuclear cross-section preparation code, i.e. these data have to be provided externally to TRACE/PARCS by using one of the many available lattice physics codes. In Sweden, the Studsvik Scandpower CASMO-4/TABLES-3/SIMULATE-3 code package is very often used for in-core fuel management, with CASMO-4 being the lattice physics code, SIMULATE-3 being the core physics code, and TABLES-3 the linking code between CASMO-4 and SIMULATE-3.

The goal of this report is to examine the possibility of coupling the Studsvik Scandpower CASMO-4/TABLES-3/SIMULATE-3 suite to the TRACE/PARCS codes. By coupling to TRACE/PARCS, it is meant that CASMO-4 and/or TABLES-3 and/or SIMULATE-3 would be used as source of cross-section data and related parameters. In the first part of the report, the TRACE/PARCS codes are presented and emphasis is put on the data required by the PARCS neutronic module. In the second part of the report, each of the codes from the Studsvik Scandpower suite is presented. The available data from each of the codes are presented, and the feasibility of coupling each of these codes to TRACE/PARCS is considered. Finally, some conclusions and recommendations are drawn with respect to the coupling between the Studsvik Scandpower codes and the TRACE/PARCS codes.

Warning: This report is based on the next release of the TRACE/PARCS codes (the actual available version of TRACE being 4.050 beta). More specifically, the neutronic module of TRACE/PARCS discussed in this report corresponds to PARCS v2.6 (the actual available version of PARCS being 2.5). The main difference between PARCS v2.5 and PARCS v2.6 is, among others, the cross-section model. In PARCS v2.6, this model relies on the use of a special cross-section file (called PMAXS) generated by a dedicated code called GenPMAXS.

2. The TRACE/PARCS codes

In this Section, the TRACE/PARCS codes are presented in detail, and the data required by the PARCS neutronic module are highlighted.

2.1. Presentation

TRACE, which stands for TRAC/RELAP Advanced Computational Engine, provides advanced best-estimate predictions of postulated accidents in light-water reactors (PWRs, BWRs, and many thermal-hydraulic test facilities) (Odar *et al*, 2003a). The capabilities of the old TRAC-P, TRAC-B, RAMONA and RELAP5 codes were all combined in TRACE. The code features either a one-, two-, or three-dimensional treatment of the reactor pressure vessel and its associated internals, a two-fluid non-equilibrium hydrodynamics model with a non-condensable gas field and solute tracking, flow-regime-dependent constitutive-equation treatment, optional reflood tracking capability for bottom-flood, and consistent treatment of entire accident sequences including the generation of consistent steady-state initial conditions. In some specific situations, a point-kinetic treatment of the core neutronics is not satisfactory. In such cases, the neutronics can be handled by the PARCS code (Purdue Advanced Reactor Core Simulator).

PARCS is a 3-dimensional reactor core simulator (Odar *et al*, 2003b). The dynamic response to any external perturbation is calculated by solving the space- and time-dependent 2-group or multigroup neutron diffusion equations, or the SP_3 transport equations (Downar *et al*, 2002). The spatial discretization is based on either fuel assemblies or fuel cells. The coupling with the thermal-hydraulic part of TRACE provides the temperature and flow field information, that allows updating the two-group cross-sections according to the actual operating conditions of the reactor. A Coarse Mesh Finite Difference (CFMD) formulation is used to determine the neutron fluxes for the homogenized nodes, while the Analytical Nodal Method (ANM) is used to estimate the accurate coupling between adjacent nodes in the core. PARCS is able to perform eigenvalue calculations, transient (kinetics) calculations, depletion calculations, Xenon transient calculations, decay heat calculations, pin power calculations, and adjoint calculations.

Since the goal of this feasibility study is to examine the coupling between the TRACE/PARCS codes and the neutronic code package CASMO-4/TABLES-3/ SIMULATE-3, emphasis will be put on the PARCS code, i.e. the neutronic calculational module of TRACE/PARCS.

2.2. Required neutronic data

Originally in 1997, PARCS used a rather simple macroscopic cross-section model since the code was not intended to perform any depletion calculation. Namely, the macroscopic nodal cross-sections were functionalized as a function of the boron concentration (C_b in ppm), the square root of the effective[1] fuel temperature (T_f in K), the moderator density (D_m in g/cm^3) and temperature (T_m in K), the void fraction (α in %) and the effective[2] rodded fractions (α_{CR} expressed as a fraction of unity) according to (Odar *et al*, 2003b):

$$P(C_b, T_f, T_m, D_m, \alpha, \alpha_{CR}) \tag{1}$$

$$\begin{aligned}
&= P(C_{b,0}, T_{f,0}, T_{m,0}, D_{m,0}, \alpha_0, \alpha_{CR,0}) + \left.\frac{\partial P}{\partial C_b}\right|_{C_{b,0}} \times (C_b - C_{b,0}) \\
&+ \left.\frac{\partial P}{\partial \sqrt{T_f}}\right|_{T_{f,0}} \times (\sqrt{T_f} - \sqrt{T_{f,0}}) + \left.\frac{\partial P}{\partial T_m}\right|_{T_{m,0}} \times (T_m - T_{m,0}) + \left.\frac{\partial P}{\partial D_m}\right|_{D_{m,0}} \times (D_m - D_{m,0}) \\
&+ \frac{1}{2}\left.\frac{\partial^2 P}{\partial D_m^2}\right|_{D_{m,0}} \times (D_m - D_{m,0})^2 + \left.\frac{\partial P}{\partial \alpha}\right|_{\alpha_0} \times (\alpha - \alpha_0) + \frac{1}{2}\left.\frac{\partial^2 P}{\partial \alpha^2}\right|_{\alpha_0} \times (\alpha - \alpha_0)^2 \\
&+ \left.\frac{\partial P}{\partial \alpha_{CR}}\right|_{\alpha_{CR,0}} \times (\alpha_{CR} - \alpha_{CR,0})
\end{aligned}$$

where the subscript *0* denotes the base case. Here, *P* has a broad meaning, and can be any parameter such as a macroscopic cross-section, a microscopic cross-section, an Assembly Discontinuity Factor (ADF), a kinetic parameter, etc. In this simplified model, the partial derivatives with respect to a given variable were assumed to be independent of the variation of the other variables, i.e. the model provides only first-order accuracy. This model is satisfactory when the actual operating conditions are very close to the base case. Nevertheless, for transients (which usually cover a wide range of thermal-hydraulic conditions), the actual operating conditions might be far from the reference case.

In 2000, PARCS was made capable of performing core depletion analysis via an external depletion module called DEPLETOR, where the node-wise power determined from PARCS is used to calculate the region-wise burnup increment. Recently, a new cross-section model was also added to PARCS so that the rather simple model given by Eq. (1) could take the burnup and history effects of the macroscopic cross-section dependence into account. Furthermore, the partial derivatives in Eq. (1) were made

1. The effective fuel temperature can be estimated as either the volume-averaged fuel temperature or the Doppler temperature using the Rowlands relation as described in (Rowlands, 1961) and in the PARCS theory manual.
2. The effective rodded fraction is defined as the product of the volumetric rodded fraction and the flux depression factor computed by a decusping routine in PARCS for the partially rodded node.

dependent on the other variables. The new cross-section model is explained in detail in the following. A code named GenPMAXS was developed to create a cross-section file called PMAXS to be directly used by the new cross-section model in PARCS (Downar and Xu, 2004). It has to be pointed out that lattice calculations have to be performed prior to the use of GenPMAXS, since GenPMAXS is a functionalization code of the neutronic data, i.e. GenPMAXS does not perform transport calculations. The links between the different modules of TRACE/PARCS and their associated pre-processing codes are presented in the following Fig. 1.

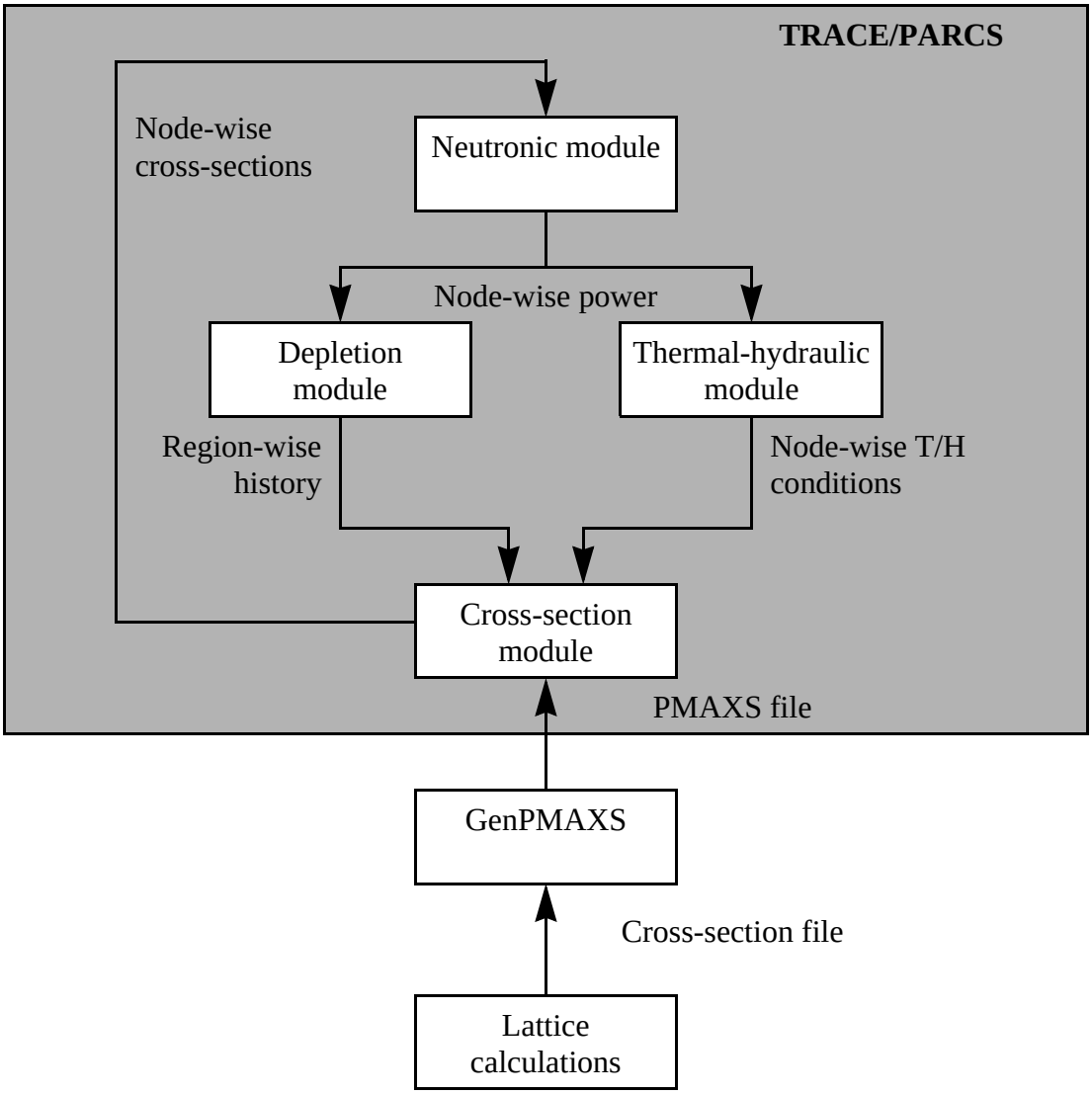

Figure 1: Overview of the different modules in TRACE/PARCS and of the pre-processing of the results of lattice calculations [derived from (Downar and Xu, 2004)]

As can be seen in this Figure, the burnup, the history effects, and the thermal-hydraulic conditions fully determine the macroscopic cross-sections that can be used in PARCS, i.e. the neutronic module, to perform the calculations of the neutron flux. The burnup and history effects are themselves estimated by the depletion module from the results of PARCS. Likewise, the thermal-hydraulic conditions are calculated by the thermal-hydraulic module (e.g. TRAC-P, TRAC-B, RAMONA or RELAP5) from the

results of PARCS. This iterative process is repeated until convergence at a given exposure is attained. Then the depletion module generates the cross-sections for the next burnup point and the same procedure is applied again. It has to be pointed out that PARCS currently uses a macroscopic depletion model in which the microscopic cross-sections and number densities are not tracked individually (except for the nuclides involved in the Xenon and Samarium poisoning). Compared to the simplified model given by Eq. (1), the macroscopic cross-sections are now functionalized as a function of burnup (b), up to two history variables[3] ($H1$ and $H2$), and as before the boron concentration (C_b in ppm), the square root of the effective fuel temperature (T_f in K), the moderator density (D_m in g/cm^3) and temperature (T_m in K), and the effective[4] rodded fractions (α_{CR} expressed as a fraction of unity):

$$P(b, H, \alpha_{CR}, D_m, C_b, T_f, T_m) \tag{2}$$

$$\begin{aligned} &= P(b, H, \alpha_{CR,0}, D_{m,0}, C_{b,0}, T_{f,0}, T_{m,0}) + \left.\frac{\partial P}{\partial \alpha_{CR}}\right|_{(b, H, \alpha_{CR,ref})} \times (\alpha_{CR} - \alpha_{CR,0}) \\ &+ \left.\frac{\partial P}{\partial D_m}\right|_{(b, H, \alpha_{CR}, D_{m,ref})} \times (D_m - D_{m,0}) + \left.\frac{\partial P}{\partial C_b}\right|_{(b, H, \alpha_{CR}, C_{b,ref})} \times (C_b - C_{b,0}) \\ &+ \left.\frac{\partial P}{\partial \sqrt{T_f}}\right|_{(b, H, \alpha_{CR}, C_b, T_{f,ref})} \times (\sqrt{T_f} - \sqrt{T_{f,0}}) + \left.\frac{\partial P}{\partial T_m}\right|_{(b, H, \alpha_{CR}, C_b, T_f, T_{m,ref})} \times (T_m - T_{m,0}) \end{aligned}$$

where H represents either one history variable or a vector of two history variables. Each history state is fully determined by two history variables together with the fuel burnup. Here, P has a broad meaning, and can be any parameter such as a macroscopic cross-section, a microscopic cross-section, an Assembly Discontinuity Factor (ADF), etc. Kinetic parameters are treated as history- and burnup-dependent only parameters. Another main difference with Eq. (1) is that the partial derivatives with respect to a given variable are now dependent on variation of some of the other variables[5]. Due to the dependence of the partial derivatives on the actual operating conditions of the reactor, the quadratic dependence on moderator density/void fraction is not necessary any longer. As before, the subscript *0* denotes the base case, whereas the subscript *ref* represents the reference point, defined as the midpoint between the instantaneous value and the base value. This can be written in a generic form as:

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3. A history variable, denoted Hv, is the burnup-weighted value of the variable v, i.e. is defined as:

$$Hv(b) = \frac{1}{b}\int_0^b v(b')db'$$

with b being the burnup.

4. See Footnote 2.

5. Sensitivity studies demonstrated that the sequence of the independent variables for each partial derivative in Eq. (2) affects significantly the accuracy of the cross-section model (Downar and Xu, 2004). The sequence adopted in Eq. (2) for the dependence of each partial derivative is the recommended one, where the independent variables were put in decreasing order of influence on the partial derivatives.

$$v_{ref} = \frac{v + v_0}{2} \tag{3}$$

where v is the instantaneous value. Consequently, the reference point depends itself on the instantaneous value. This way of doing provides a second-order accuracy in the estimation of the cross-sections (Downar and Xu, 2004).

Obviously, a special formatting of the macroscopic cross-section is required. This is carried out from the results of the lattice calculations by the GenPMAXS code, which creates the data file PMAXS in a format directly compatible with this new cross-section model. PMAXS is actually a text file that can be read by PARCS and has therefore a very specific structure for the storage of the cross-sections and the related data for core calculations. GenPMAXS is meant for post-processing the data coming from lattice calculations. Therefore, the partial derivatives have to be estimated from these data provided at different operating conditions by the lattice physics code. The partial derivative required in Eq. (2) for any parameter P with respect to a variable v can thus be calculated according to the following generic formulation:

$$\left.\frac{\partial P}{\partial v}\right|_{(u,\, v_{ref})} = \frac{P(u, v, w_0) - P(u, v_0, w_0)}{v - v_0} \tag{4}$$

In this Equation, u represents all the variables having their instantaneous values, whereas w_0 represents all the variables having their base values (therefore explaining the subscript *0*). The sequence of the independent variables in the partial derivatives was chosen so that there is no dependence of the partial derivatives on any of the variables w_0.

GenPMAXS follows an innovative structure for storing the data. For each parameter X, the data structure has three levels (Downar and Xu, 2004), each level having a "tree-leave" structure. The highest level represents the history cases, i.e. corresponds to depleting the lattice with different sets of operating conditions. The second level represents different possible instantaneous states for each history case, i.e. corresponds to perturbations at given burnup points of the instantaneous variables from the state used to deplete the history case. Finally, the third and lowest level is the subsequent burnup dependence of the data after the perturbation. Usually, the first level has a two-level tree structure, with several branches for the history variable $H1$ and for each $H1$ branch, several leaves for the history variable $H2$. For the second level, the states are divided into 6 groups: a base branch and different branches corresponding to different values of α_{CR}, D_m, C_b, T_f, and T_m. The partial derivatives are thus evaluated between the different leaves of the different branches, as illustrated by Eqs. (3) and (4).

When any parameter is needed by PARCS at a given set of operating conditions, the data are retrieved within PARCS via two modules: a DEPLETION module (which deals with the dependence of the data on the history variables $H1$ and $H2$ and the burnup b), and a FEEDBACK module (which deals with the dependence of the data on the instantaneous variables $\alpha_{CR}, D_m, C_b, T_f, T_m$). The DEPLETION module performs multi-dimensional linear interpolation with respect to the history variables and to the burnup for $P(b, H, \alpha_{CR,0}, D_{m,0}, C_{b,0}, T_{f,0}, T_{m,0})$ and each partial derivative in Eq. (2). The FEEDBACK module performs multi-dimensional linear interpolation with respect

to the instantaneous values of the variables $\alpha_{CR}, D_m, C_b, T_f, T_m$ for the partial derivatives from the set of partial derivatives stored in GenPMAXS. It has to be pointed out that the set of branches does not need to form a regular grid, and the points in each linear interpolation do not need to be equidistant. This demonstrates the obvious advantage of a "tree-leave" structure compared to a table form.

3. The CASMO-4/TABLES-3/SIMULATE-3 code system

In this Section, the CASMO-4/TABLES-3/SIMULATE-3 codes are presented in detail. The available data from each of these codes are then listed, and the feasibility of coupling each of these codes to TRACE/PARCS is discussed.

3.1. The CASMO-4 code

3.1.1. Presentation

CASMO-4 is the latest available version of the fuel assembly burnup program of Studsvik Scandpower (Ekberg *et al*, 1995). CASMO-4 is a multigroup two-dimensional transport theory code used to perform fuel assembly depletion calculations and to collapse cross-sections for subsequent input to less rigorous models. Thus its main goal is to provide all the pertinent data regarding one (or a set of 2x2) fuel assembly(ies) in an infinite lattice to SIMULATE-3. All these calculations are performed for different operating conditions and the branch case calculations between these different situations are also computed.

The CASMO-4 code performs lattice calculations according to the following methodology, which is summarized in Fig. 2 (Ekberg *et al*, 1995), (Demazière, 1999). In the first part (represented as "problem set-up" in Fig. 2), the macroscopic group cross-sections are prepared from the nuclear data library (70 or 40 energy groups structure), the geometry of the problem, and the densities of the different materials. The effective cross-sections in the resonance energy region for resonance absorbers are calculated using an equivalence theorem which relates tabulated effective resonance integrals for each resonance absorber in each resonance group to the particular heterogeneous problem. In the second part (represented as "cross-sections condensation & homogenization scheme" in Fig. 2), the cross-sections thus prepared are used in three subsequent calculation schemes in order to provide the assembly-homogenized data in a 2-group energy structure: a series of collision probability micro-group calculations performed for each fuel cell, a 2-D macro-group (typically 23 energy groups) calculation performed for the entire fuel assembly via the response matrix method, and finally a 2-D macro-group (typically 7 energy groups) calculation performed for the entire fuel assembly via the heterogeneous method of characteristics. Each of these calculations provides the neutron flux (either scalar or angular) that can be used to condense and homogenize the cross-sections in a structure adequate for the following calculations. In the last part of the

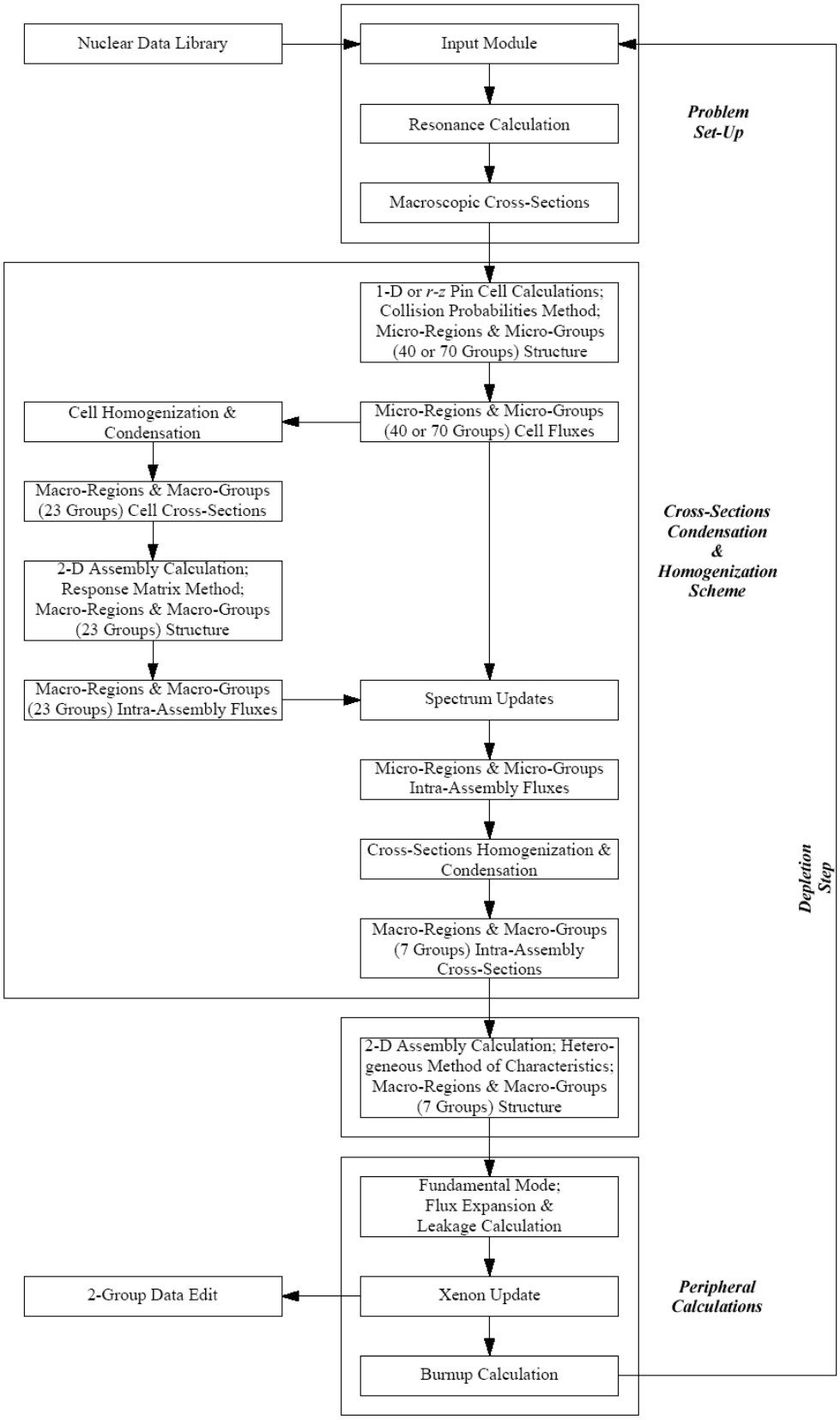

Figure 2: Overview of the methodology used in CASMO-4 [from (Demazière, 1999)]

calculational scheme (represented as “peripheral calculations” in Fig. 2), a fundamental buckling mode is used for modifying the results obtained from the transport calculation to include effects of leakage. This sequence of calculations is carried out for each burnup point. A predictor-corrector approach is then used for the burnup calculations.

It has to be pointed out that reflector data, including data for homogenised baffle/ water, are accurately generated by an explicit two-dimensional modelling of one fuel assembly having the reflector on one side.

3.1.2. Available data

After using CASMO-4, two output files are available to the user, both of them in ASCII format: a .out file, presenting the results in a user-friendly way, and a .cax or card image file, presenting the results in a tabulated form, each section of tabulated data starting with a specific keyword that allows identifying the edited data. This second file is meant for post-processing of the results, and is also the file used by TABLES-3 for building the cross-section library. These output files contain all the results of the lattice calculations, for different burnup points and different history cases, as required by the user.

The data that are relevant for core calculations are the two-group cross-sections, the ADFs, the fission product data, the detector data, the pin power reconstruction data, the kinetics data, and the isotopic data. Different sets of operating conditions and branch cases are typically modelled, so that the whole operating range is covered. These sets are summarized in the following Table 1, for both PWRs and BWRs (Ekberg *et al*, 1995), (Garis, 1995a), (Garis, 1995b). The different variables used in this Table are abbreviated by: T_f for the fuel temperature, C_b for the boron concentration, T_m for the moderator temperature, α_{CR} for the control rod insertion, $T_{cooling}$ for the shutdown decay time, and α for the void fraction.

Table 1: Typical calculation types performed by CASMO-4 in order to cover the whole range of operating conditions

Reactor type	Types of calculations performed for the fuel	Types of calculations performed for the reflector
PWR	• base depletion at nominal operating conditions; • branch cases from base depletion for different values of T_f, C_b, T_m, α_{CR}, and $T_{cooling}$; • boron history depletion; • moderator history depletion; • optionally depletion without the removable burnable poisons.	• single calculations for different values of C_b for radial and bottom reflectors; or • single calculations for different values of C_b and for different values of T_m for top reflector.
BWR*	• void histories depletion; • branch cases from void histories depletion for different values of α, α_{CR}, T_f; • cold branches and cold rodded branches from void histories depletion; • void history depletion with a control rod and control rod branch.	• single calculations for different values of T_m for radial and bottom reflectors; or • single calculations for different values of α for top reflector.

*. Only hot BWR cases are considered here. The data functionalization is usually different for cold cases. Furthermore, the cold cases have limited application for the type of investigation performed via TRACE/PARCS.

3.1.3. Feasibility of coupling CASMO-4 to TRACE/PARCS

Obviously, the coupling between CASMO-4 and TRACE/PARCS can be easily carried out via the GenPMAXS code, since all the data required by GenPMAXS for PARCS (see Section 2.2) are usually available from the CASMO-4 card image files (see Section 3.1.2). Nevertheless, such a coupling does not exist for the time being. Only a coupling between HELIOS and TRACE/PARCS was actually performed (Downar and Xu, 2004). Although this coupling appears to be straightforward, it is very likely that only the Purdue University group, i.e. the developers of GenPMAXS, would be able to extend the capabilities of GenPMAXS to CASMO-4. The amount of work required to carry out such a work by other groups might be equivalent to develop such an interface from scratch, since it is usually very difficult to modify a code of which one is not the developer. It is interesting to point out that several interfaces between CASMO-4 and different codes were actually developed in the past. One could mention, among others, the interface that the Department of

Mechanical and Nuclear Engineering, Pennsylvania State University created with its NEM code (Ivanov, 2004), the CASPAR interface that Studsvik EcoSafe developed for PARCS [but unfortunately for the old cross-section model given by Eq. (1)] (Eriksson, 1999), (Eriksson, 2000), the CAXCON interface that the Div. of Nuclear Power Safety, Department of Energy Technology, The Royal Institute of Technology developed for the NORGEP/ARROTA codes (Romas, 1999). In the second case, it was also necessary to rerun CASMO-4 in order to provide the data in a specific way to this interface. In any case, if GenPMAXS is extended to handle CASMO-4 results, some experience could probably be gained from these interfaces.

Another problem surfacing with the coupling between CASMO-4 and TRACE/ PARCS is the fact that access to the CASMO-4 files is required (either the output files, which are in ASCII format, or the input files if one wants to rerun the lattice calculations for creating all the data required by GenPMAXS in case some data were missing in the original calculations). Nevertheless, fuel vendors very often do not want power utilities to provide the CASMO-4 files to third parties (such as universities or research organizations), since these files might contain proprietary information about the fuel (Kurcyusz, 2001). Furthermore, it is very likely that GenPMAXS would require the data to be processed/edited is a specific way from CASMO-4, so that rerunning CASMO-4 could not be avoided anyway.

Therefore, due to confidentiality reasons, it does not seem that the CASMO-4 files could be used by an extended version of GenPMAXS to create the PMAXS files. One possibility would be to develop anyway the coupling between GenPMAXS and CASMO-4, and ask power utilities to use GenPMAXS themselves in order to create the PMAXS files (Edenius, 2004). Nevertheless, this way of doing seems to be very impractical. In case of any problem occurring when applying GenPMAXS to the CASMO-4 files, the utilities would not know how to solve the problem, and the universities/research organizations would not be able to give much help without having access to the CASMO-4 files.

Finally, it has to be mentioned that a slight difference between the variables used in the Studsvik Scandpower code system and PARCS is related to the moderator. In CASMO-4, the moderator is characterized by its temperature T_m and in case of BWRs, by its void fraction α. In PARCS, the moderator is characterized by its temperature T_m and its density D_m. Obviously, the mixture density can easily be deduced from the moderator temperature and the void content by using the following relationship:

$$D_m(T_m, \alpha, p) = \rho_{\text{saturated water vapour}}(p) \times \alpha + \rho_{\text{saturated liquid water}}(T_m) \times (1 - \alpha) \qquad (5)$$

where, in addition to the variables and parameters defined previously:

- p is the static pressure;
- $\rho_{\text{saturated water vapour}}$ is the density of saturated water vapour (which can be found in any nuclear engineering handbook as a function of pressure);
- $\rho_{\text{saturated liquid water}}$ is the density of saturated liquid water (which can be found in any nuclear engineering handbook as a function of temperature).

Such a conversion is actually performed by the Studsvik Scandpower codes and can be retrieved from the output files.

3.2. The TABLES-3 code

3.2.1. Presentation

TABLES-3 is a linking code between CASMO-4 and SIMULATE-3 (Ver Planck *et al*, 1995), (Demazière, 1999). More precisely, all the results for every single fuel assembly calculation performed by CASMO-4 are directly made available to SIMULATE-3 via TABLES-3. The output file from TABLES-3, which is a binary file, thus contains for all the fuel assemblies present in the core the following types of data: macroscopic and microscopic two-group cross-sections, discontinuity factors, fission product data, detector data, pin power reconstruction data, kinetics data, and isotopic data. These data were generated for many different sets of operating conditions and histories.

3.2.2. Available data

In SIMULATE-3, the macroscopic and microscopic two-group cross-sections, discontinuity factors, fission product data, and detector data are developed as the summation of partials, where each partial can be a function of up to three variables (Ver Planck *et al*, 1995). Any of these parameters P can thus be expressed in a generic form as:

$$P(A, B, C) = P(A_0, B_0, C_0) + \Delta P_A(A) + \Delta P_B(A, B) + \Delta P_C(A, B, C) \tag{6}$$

where $P(A_0, B_0, C_0)$ is the base value and with:

$$\Delta P_A(A) = \int_{A_0}^{A} \frac{\partial}{\partial A'} P(A', B_0, C_0) dA' \tag{7}$$

(A being the primary variable),

$$\Delta P_B(A, \boldsymbol{B}) = \int_{B_0}^{B} \frac{\partial}{\partial B'} P(A, B', C_0) dB' \tag{8}$$

(B being the primary variable, and A the secondary variable),

$$\Delta P_C(A, B, \boldsymbol{C}) = \int_{C_0}^{C} \frac{\partial}{\partial C'} P(A, B, C') dC' \tag{9}$$

(C is the primary variable, and A and B being the secondary and tertiary variables, respectively).

The construction of data from Eqs. (6)-(9) is graphically represented in Fig. 3. TABLES-3 reduces the raw multi-dimensional data from the CASMO-4 result files into the additive series of partial function tables. TABLES-3 cannot handle more than three variables for

the dependence of macroscopic and microscopic two-group cross-sections, discontinuity factors, fission product data, and detector data. Consequently, assumptions have to be made to reduce the number of variables used to describe these parameters with three or fewer variables. Where assumptions of separability are needed, the variables that are not varied are supposed to be at their base case conditions, usually taken as the reactor-averaged or beginning-of-life states. When data from the CASMO-4 lattice calculations are not available for constructing the tables, second-order Lagrangian interpolation is used to generate the missing values.

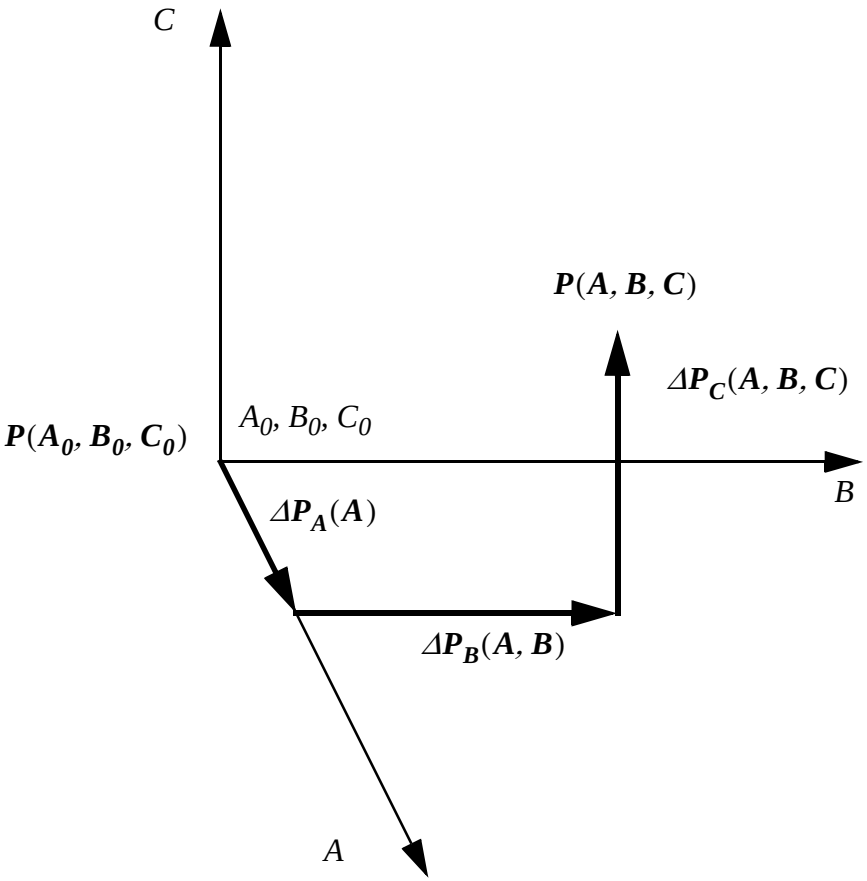

Figure 3: Construction of the macroscopic and microscopic two-group cross-sections, discontinuity factors, fission product data, and detector data in TABLES-3 [derived from (Ver Planck et al, 1995)]

For the pin-by-pin power distributions, corner-point flux ratios, detector flux peaking factors, detector microscopic cross-sections, two-group neutron velocities, effective neutron precursor yields, and precursor decay constants, only one-dimensional table sets in exposure are used for representing the principal variation of the data (Ver Planck *et al*, 1995). The additional dependencies of the data are modelled by one-dimensional tables of the derivatives of the data as a function of exposure. Any of these parameters *P* can thus be expressed in a generic form as:

$$P(b, B, C, ..., Z) = P(b, B_0, C_0, ..., Z_0) + \Delta P_B(b) + \Delta P_C(b) + ... + \Delta P_Z(b) \quad (10)$$

with b representing the exposure (burnup) and:

$$\Delta P_B(b) = \int_{B_0}^{B} \frac{\partial}{\partial B'} P(b, B', C_0, ..., Z_0) dB', \quad (11)$$

$$\Delta P_C(b) = \int_{C_0}^{C} \frac{\partial}{\partial C'} P(b, B_0, C', ..., Z_0) dC', \quad (12)$$

$$\Delta P_Z(b) = \int_{Z_0}^{Z} \frac{\partial}{\partial Z'} P(b, B_0, C_0, ..., Z') dZ', \quad (13)$$

Since the additional dependencies are only functions of exposure, the base values for the independent variables have to be chosen in the mid-range of variation. A second-order polynomial fit to the base value and its two neighbouring points is used for the evaluation of the additional dependencies, i.e. for Eqs. (11)-(13).

Table 2 and Table 3 summarize the data functionalization usually performed for PWR and BWR cases, respectively (Ver Planck *et al*, 1995), (Garis, 1995a), (Garis, 1995b). These Tables are intended to give an overview of the most typical data dependence. In some specific cases, additional variables and different data dependence might exist, depending on the user's needs. The different variables used in these Tables are abbreviated by:

- b, for the exposure (burnup) in GWd/tHM;
- α, for the void fraction in %;
- $H\alpha$, for the history-averaged void fraction in %;
- T_f, for the fuel temperature in K;
- HT_f, for the history-averaged fuel temperature in K;
- T_m, for the moderator temperature in K;
- HT_m, for the history-averaged moderator temperature in K;
- C_b, for the boron concentration in ppm;
- HC_b, for the history-averaged boron concentration in ppm;
- α_{CR}, for the control rod insertion (0 when no insertion, 1 when control rod present);
- $H\alpha_{CR}$, for the history-averaged control rod insertion (0 represents no control history, 1 represents maximum control history);
- b_{BP}, for the burnable absorber exposure (burnup) in GWd/tHM;

- $T_{cooling}$, for the shutdown decay time in thousands of hours;
- b_{RES}, for the restart exposure (burnup) in GWd/tHM.

Table 2: Typical data functionalization for PWR cases (the variables in bold represent the primary variables)

Parameter *P*	**Fuel**	**Reflector**
D_1, D_2 $\Sigma_{1\to 2}$ $\Sigma_{a,1}$, $\Sigma_{a,2}$ $\nu\Sigma_{f,1}$, $\nu\Sigma_{f,2}$ κ/ν $\sigma_{a,1}^{B^{10}}$, $\sigma_{a,2}^{B^{10}}$	$P(b, \boldsymbol{HT_m})$ $+ \Delta P_{HC_b}(b, \boldsymbol{HC_b})$ $+ \Delta P_{C_b}(b, \boldsymbol{C_b})$ $+ \Delta P_{T_m}(b, \boldsymbol{T_m})$ $+ \Delta P_{T_f}(b, \boldsymbol{T_f})$ $+ \Delta P_{\alpha_{CR}}(b, \boldsymbol{\alpha_{CR}})$ $+ \Delta P_{T_{cooling}}(b, \boldsymbol{T_{cooling}})$ optionally $+ \Delta P_{b_{BP}}(b, \boldsymbol{b_{BP}})$	$P(\boldsymbol{C_b})$ for radial and bottom reflectors $P(C_b, \boldsymbol{T_m})$ for top reflector
ν $\gamma_{I^{135}}$, $\gamma_{Xe^{135}}$ $\gamma_{Pm^{149}}$, $\gamma_{Sm^{149}}$ $\sigma_{a,2}^{Xe^{135}}$, $\sigma_{a,2}^{Sm^{149}}$ Gd fraction remaining	$P(b, \boldsymbol{HT_m})$ $+ \Delta P_{HC_b}(b, \boldsymbol{HC_b})$ $+ \Delta P_{C_b}(b, \boldsymbol{C_b})$ $+ \Delta P_{T_m}(b, \boldsymbol{T_m})$ $+ \Delta P_{T_f}(b, \boldsymbol{T_f})$ $+ \Delta P_{\alpha_{CR}}(b, \boldsymbol{\alpha_{CR}})$ $+ \Delta P_{T_{cooling}}(b, \boldsymbol{T_{cooling}})$ optionally $+ \Delta P_{b_{BP}}(b, \boldsymbol{b_{BP}})$	-
discontinuity factors (west, groups 1 and 2) (south, groups 1 and 2) (east, groups 1 and 2) (north, groups 1 and 2)	$P(b, \boldsymbol{T_m})$ $+ \Delta P_{C_b}(b, \boldsymbol{C_b})$ $+ \Delta P_{T_f}(b, \boldsymbol{T_f})$ $+ \Delta P_{\alpha_{CR}}(b, \alpha_{CR})$ $+ \Delta P_{T_{cooling}}(b, \boldsymbol{T_{cooling}})$ optionally $+ \Delta P_{b_{BP}}(b, \boldsymbol{b_{BP}})$	$P(\boldsymbol{C_b})$ for radial and bottom reflectors $P(C_b, \boldsymbol{T_m})$ for top reflector

Table 3: Typical data functionalization for BWR cases (the variables in bold represent the primary variables)*

Parameter *P*	**Fuel**	**Reflector**
D_1, D_2 $\Sigma_{1\to 2}$ $\Sigma_{a,1}$, $\Sigma_{a,2}$ $\nu\Sigma_{f,1}$, $\nu\Sigma_{f,2}$ κ/ν $\sigma_{a,1}^{B^{10}}$, $\sigma_{a,2}^{B^{10}}$	$P(b, \boldsymbol{H}\alpha)$ $+\Delta P_{\alpha}(b, H\alpha, \alpha)$ $+\Delta P_{T_f}(b_{RES}, \alpha, \boldsymbol{T_f})$ $+\Delta P_{\alpha_{CR}}(b_{RES}, \alpha, \boldsymbol{\alpha_{CR}})$ $+\Delta P_{H\alpha_{CR}}(b, \alpha_{CR}, \boldsymbol{H\alpha_{CR}})$ $+\Delta P_{T_{cooling}}(b, \boldsymbol{T_{cooling}})$	$P(\boldsymbol{T_m})$ for radial and bottom reflectors $P(\alpha)$ for top reflector
ν $\gamma_{I^{135}}$, $\gamma_{Xe^{135}}$ $\gamma_{Pm^{149}}$, $\gamma_{Sm^{149}}$ $\sigma_{a,2}^{Xe^{135}}$, $\sigma_{a,2}^{Sm^{149}}$ Gd fraction remaining	$P(b, \boldsymbol{H}\alpha)$ $+\Delta P_{\alpha}(b_{RES}, \alpha)$ $+\Delta P_{T_f}(b_{RES}, \alpha, \boldsymbol{T_f})$ $+\Delta P_{\alpha_{CR}}(b_{RES}, \alpha, \boldsymbol{\alpha_{CR}})$ $+\Delta P_{T_{cooling}}(b, \boldsymbol{T_{cooling}})$	-
discontinuity factors (west, groups 1 and 2) (south, groups 1 and 2) (east, groups 1 and 2) (north, groups 1 and 2)	$P(b, \boldsymbol{H}\alpha)$ $+\Delta P_{\alpha}(b_{RES}, \alpha)$ $+\Delta P_{T_f}(b_{RES}, \boldsymbol{T_f})$ $+\Delta P_{\alpha_{CR}}(b_{RES}, \alpha, \boldsymbol{\alpha_{CR}})$ $+\Delta P_{T_{cooling}}(b, \boldsymbol{T_{cooling}})$	$P(\boldsymbol{T_m})$ for radial and bottom reflectors $P(\alpha)$ for top reflector
fission rate of U^{235} in detector position peaking factor	$P(b, \boldsymbol{H}\alpha)$ $+\Delta P_{\alpha}(b_{RES}, \alpha)$ $+\Delta P_{T_f}(b_{RES}, \boldsymbol{T_f})$ $+\Delta P_{\alpha_{CR}}(b_{RES}, \alpha, \boldsymbol{\alpha_{CR}})$	-

*. Only hot BWR cases are considered here. The data functionalization is usually different for cold cases. Furthermore, the cold cases have limited application for the type of investigation performed via TRACE/PARCS.

As can be seen from Table 2 and Table 3, TABLES-3 contains multidimensional tables of three variables at the most for both the base values and the additional dependencies (referenced in some cases as deltas). It has to be mentioned that an equivalent code to TABLES-3 is sometimes used for performing the data functionalization from CASMO-4. This code, named CMS-Link, applies roughly the

same procedures and algorithms as in TABLES-3 and is directly integrated in the CASMO-4 execution.

3.2.3. Feasibility of coupling TABLES-3 to TRACE/PARCS

As can be seen from Section 2.2 and from Section 3.2.2, the binary output file from TABLES-3 contains a lot of information that can be useful for the neutronic module of TRACE/PARCS. Nevertheless, the data functionalization performed by TABLES-3 is much simpler than the data functionalization present in PARCS. As can be seen from Eq. (2), PARCS can handle a dependence of the partial derivatives on up to 7 variables, whereas TABLES-3 can provide a data dependence of the deltas on up to 3 variables. Nevertheless, the sum of the base case and the different deltas in the model used by TABLES-3 actually provides a dependence of the data on up to 7 variables[6].

Consequently, one way of using the TABLES-3 results would be to use the base case and the different deltas to reconstruct the whole dependence of the data. Namely, the different operating points required by GenPMAXS to construct the PMAXS data file should be listed, and the data from TABLES-3 should be generated for each of these operating points. This is schematically presented in Fig. 4. The list of operating points in the PMAXS file could be obtained directly from the ones present in the TABLES-3 library file. Two programs should be developed: a program to edit the data from the TABLES-3 binary output file at the requested operating conditions, and a program to construct the PMAXS file, program which, in essence, would resemble GenPMAXS. The development of this second program could be easily done from scratch or by slightly modifying the GenPMAXS code. This is, in a way, equivalent to the coupling of CASMO-4 to TRACE/PARCS discussed in Section 3.1.3. Nevertheless, this does not require to run any of the codes, i.e. CASMO-4 or TABLES-3. Only the TABLES-3 output file is required since the TABLES-3 data functionalization, although different from the one required by PARCS, is assumed to cover the whole operating range of the reactor which is considered for the analysis.

Unfortunately, the TABLES-3 output file is a binary file. No documentation is available from Studsvik Scandpower concerning this binary file and how it could be read (Edenius, 2004).

3.3. The SIMULATE-3 code

3.3.1. Presentation

SIMULATE-3 is an advanced 2-group nodal code for the analysis of both PWRs and BWRs (Covington *et al*, 1995), (Demazière, 1999). The code is based on a neutronic model which uses the transverse integration technique with quadratic transverse leakage inte-

6. For the sake of simplicity, the dependence of the data on the shutdown decay time and the restart exposure in TABLES-3 is not considered, since this dependence is usually not required for the analysis of transients.

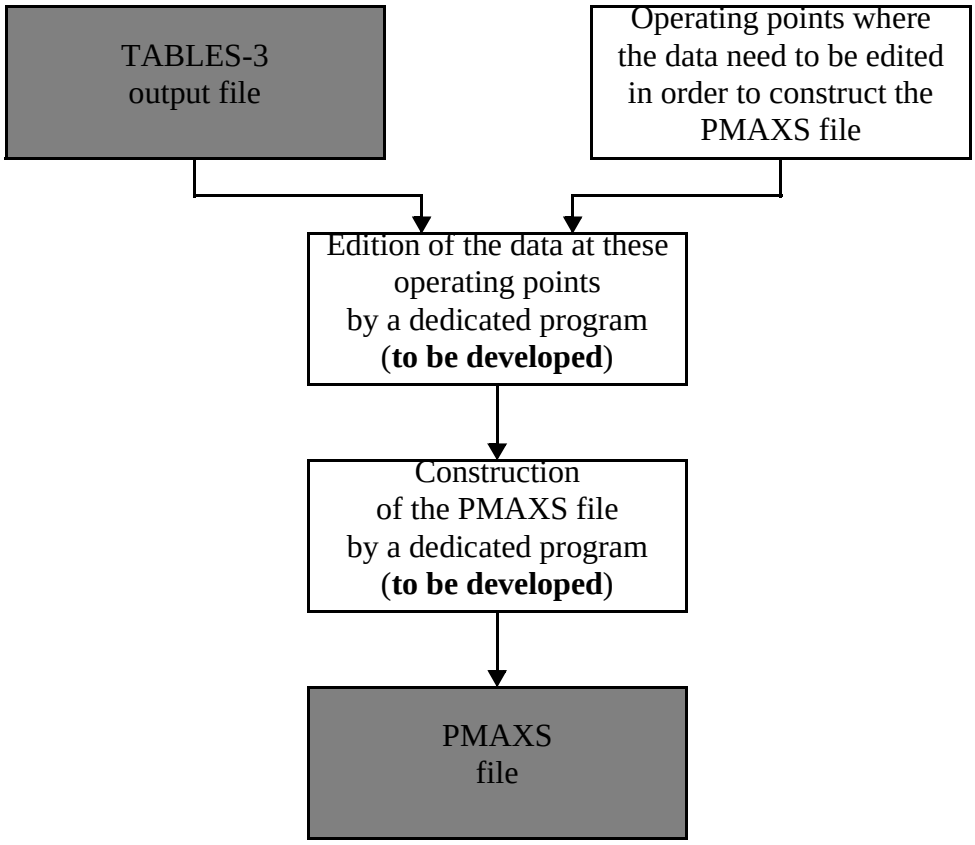

Figure 4: Flow chart explaining the conversion of the TABLES-3 output file into the PMAXS file

gration, for both static cases and kinetic cases. The 2-group, 3-dimensional, transverse-integrated neutron diffusion equations are solved using fourth-order fast group flux expansions and fourth-order or analytic thermal flux expansions. Regarding the thermalhydraulics, an explicit channel hydraulic calculation is performed for each fuel assembly. Two models are available: a simple transient mixture mass and energy model, and an explicit mixture mass, energy, and momentum model that solves the drift flux equations.

Needless to say, SIMULATE-3 is only able to model the nuclear reactor core, with a relatively simple plant thermalhydraulic model compared to TRACE/PARCS. This thermalhydraulic model is nevertheless good enough to give a set of thermalhydraulic conditions from which the actual nuclear cross-section can be obtained via TABLES-3 in some cases. These are all the static calculations and some specific non-stationary phenomena involving mostly the neutron kinetics (when the thermalhydraulics can be treated in a simplified way compatible with the SIMULATE-3 models).

3.3.2. Available data

SIMULATE-3 was not meant to provide any macroscopic cross-sections, microscopic cross-sections, ADFs, kinetic parameters, etc., rather to use these data to perform core calculations. In most cases, two output files, both of them in ASCII format, are generated by a SIMULATE-3 run: a .out file, presenting the results in a user-friendly way, and a .sum

file or summary file, presenting the results in a tabulated form, each section of tabulated data starting with a specific keyword that allows identifying the edited data. This second file is mainly meant for post-processing of the results.

Nevertheless, SIMULATE-3 offers the possibility of editing some of the data from the TABLES binary file via the AUD input cards (AUD for audit of TABLES data) for each of the fuel assemblies or segments present in the core. This is the case for the macroscopic cross-sections, the microscopic cross-sections for the nuclides involved in the Xenon/Samarium poisoning, and the ADFs. It is unfortunately impossible to edit the kinetic parameters via the AUD cards. The main advantage of the AUD cards is that the data can be edited at operating conditions specified by the user. Several AUD cards are of interest (Covington *et al*, 1995):

- the AUD.PRI card, which is used to select the parameters to be audited from the binary data library;
- the AUD.EXP card, which specifies the exact exposure(s) at which the data from the library will be audited;
- the AUD.VAR card, which indicates the statepoint variables for which data from the library will be audited; all the variables present in the PARCS new cross-section model given by Eq. (2) are available[7]; the AUD.VAR card is limited to 5 variables;
- the AUD.VAL card, used in conjunction with the AUD.VAR card, and which specifies the values for each statepoint variable for which data from the binary library will be audited;
- the AUD.FIX card, which is used to extend the list of statepoint variables that can be set for audit; it is typically used to fix values such as history variables that remain constant while several other statepoints are varied.

Regarding the kinetic parameters, the only possibility is to edit the core-averaged (point-like) kinetic data at a specific core-averaged burnup via the KIN.EDT input card in SIMULATE-3.

3.3.3. Feasibility of coupling SIMULATE-3 to TRACE/PARCS

As pointed out in Section 3.2.3, the coupling between TABLES-3 and TRACE/PARCS would be possible if one could read the TABLES-3 binary data file. Such a possibility arises with the AUD cards in SIMULATE-3. The partial derivatives required in Eq. (2) can be easily evaluated from Eq. (4), where one actually needs the data at two sets of operating conditions: the set given by the variables having the values (u, v, w_0), and the set given by the variables having the values (u, v_0, w_0), where u represents all the variables having their instantaneous values, whereas w_0 represents all the variables having their base values. These two sets of data could be easily edited by SIMULATE-3.

As an illustrative example, let us assume that one wants to estimate the most complicated partial derivative, i.e. $\left.\frac{\partial P}{\partial T_m}\right|_{(b,\, H,\, \alpha_{CR},\, C_b,\, T_f,\, T_{m,\, ref})}$, which can be evaluated according to Eq. (4) as:

7. The void content α_0 can be deduced from the moderator density $D_{m,\,0}$ via Eq. (5).

$$\left.\frac{\partial P}{\partial T_m}\right|_{(b,\, H,\, \alpha_{CR},\, C_b,\, T_f,\, T_{m,\, ref})} = \frac{P(b, H, \alpha_{CR}, C_b, T_f, T_m, D_{m,\,0}) - P(b, H, \alpha_{CR}, C_b, T_f, T_{m,\,0}, D_{m,\,0})}{T_m - T_{m,\,0}} \quad (14)$$

$P(b, H, \alpha_{CR}, C_b, T_f, T_m, D_{m,\,0})$ and $P(b, H, \alpha_{CR}, C_b, T_f, T_{m,\,0}, D_{m,\,0})$ can be simply edited by SIMULATE-3 with the following few generic command lines:

'AUD.PRI' 'FULL'/ All the possible data will be edited (except the kinetic parameters)

'AUD.EXP' *b*/ Exposure at which the data will be edited. One can edit up to 9 burnup points in one single run. If more exposure points are required, one can stack several runs.

'AUD.FIX' 'HVOI', *H*1, 'HCRD', *H*2, 'VOI', α_0 [8]/ Variables that usually do not change for calculating a given partial derivative. Each variable is followed by its value. Stacked cases with different values for these variables allow nevertheless taking these variations into account. In the presented example, one has chosen two history variables (void history and control rod history, typical of a BWR case).

'AUD.VAR' 'CRD', 'BOR', 'TFU', 'TMO'/ Variables that are going to be varied between the different edits. In principle, only the moderator temperature is required to change for estimating the corresponding partial derivative. Nevertheless, since this partial derivative is also a function of other variables, one can perform edits of the data for all the necessary statepoints simply by stacking as many 'AUD.VAL' cards as necessary.

'AUD.VAL' 1, α_{CR}, C_b, T_f, T_m/ Values of the variables at which the data will be edited.
'AUD.VAL' 2, α_{CR}, C_b, T_f, $T_{m,\,0}$/

A practical example is presented in Appendixes for a General Electric BWR/6 generic model (Demazière, 2000). The relevant part of the SIMULATE-3 input file is given in Appendix A, whereas the relevant part of the SIMULATE-3 output file is given in Appendix B. In this example, the edits are made at an exposure of 0 GWd/tHM. All the variables have their base values, and the moderator temperature is varied from 560 K to 570 K.

Consequently, the coupling between SIMULATE-3 and TRACE/PARCS seems to be possible and relatively straightforward to carry out. SIMULATE-3 can be run to read the TABLES-3 binary data library. This binary file is furthermore portable across UNIX and Windows NT/2000/XP platforms (Cronin, 2004). As for the coupling with TABLES-3 considered in Section 3.2.3, the list of operating points in the PMAXS file could be obtained directly from the ones present in the TABLES-3 library file. Contrary to the direct coupling to TABLES-3, only one program should be developed: a program to construct the PMAXS file, program which, in essence, would resemble GenPMAXS

8. See Footnote 7.

and which could be easily developed from scratch or by slightly modifying GenPMAXS. The links between the different files and codes for generating the data to PARCS are presented schematically in Fig. 5. The main difference with the flow chart presented in Fig. 4 is the use of SIMULATE-3 to read the data from the TABLES-3 library.

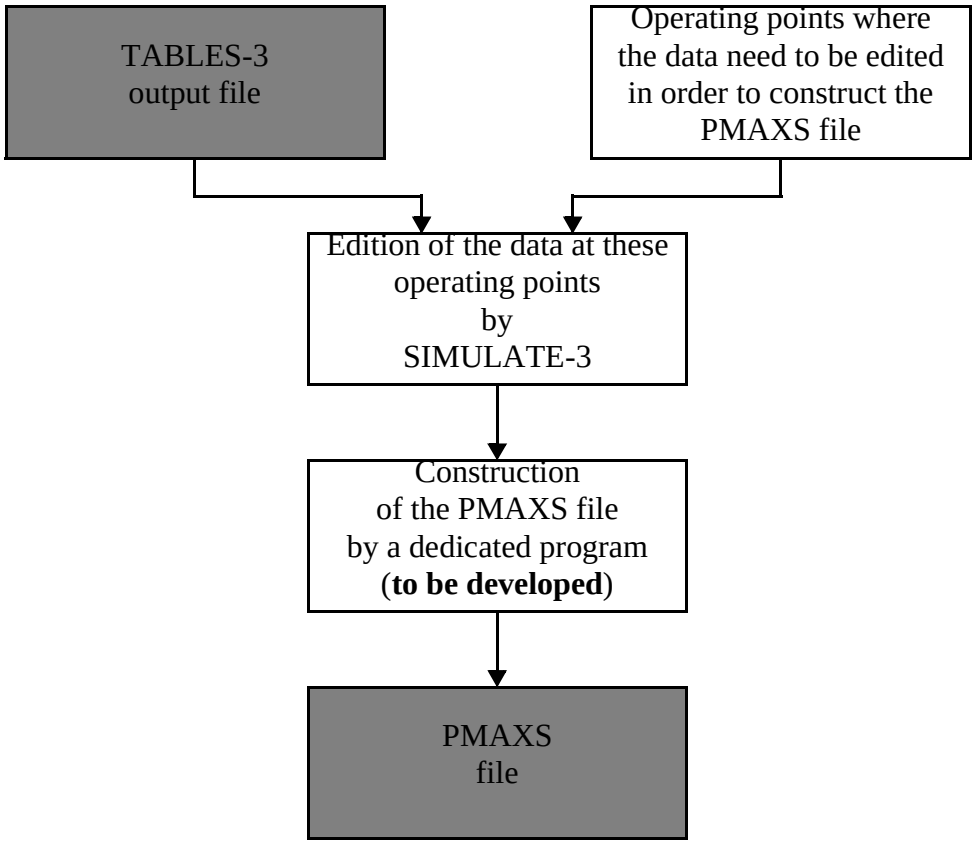

Figure 5: Flow chart explaining the conversion of the SIMULATE-3 output file into the PMAXS file

Linking SIMULATE-3 to PARCS has nevertheless a few drawbacks. The first one is related to the fact that many input files need to be constructed (as requested by the list of necessary operating points requested for the PMAXS file) and that consequently many SIMULATE-3 runs have to be performed. This can of course be done in an automatic way, but the amount of data and the CPU time necessary to cover the whole operating range can be quite large. Finally, it is unfortunately impossible to edit the kinetic data from the library at different operating points. The only kinetic parameters that can be edited are the core-averaged (point-like) data at different core-averaged exposures via the KIN.EDT input card. This might be an acceptable alternative if the different fuel assemblies present in the core are quite similar.

4. Conclusions and recommendations

The following Table summarizes the advantages/disadvantages of coupling each of the Studsvik Scandpower codes to TRACE/PARCS. Clearly, the option of coupling TABLES-3 to TRACE/PARCS is very attractive, since no access to the Studsvik Scandpower codes is required. Nevertheless, the binary character of the TABLES-3 data file makes this solution impossible. If one has access to CASMO-4 and the different CASMO-4 output and/or input files, then an extended version of GenPMAXS could easily create the PMAXS file. Unfortunately, access to the CASMO-4 files is very often restricted due to confidentiality reasons imposed by the fuel vendors. The SIMULATE-3 coupling to TRACE/PARCS thus appears to be the only realistic and feasible option. This of course requires access to the SIMULATE-3 code, but no sensitive information could be extracted from these runs.

In view of these conclusions, the Department of Reactor Physics, Chalmers University of Technology would definitively recommend the last option, i.e. coupling SIMULATE-3 to PARCS. This option allows a smooth conversion between the TABLES-3 and the PARCS models for data functionalization. The list of operating points in the PMAXS file could be obtained directly from the ones present in the TABLES-3 library file. Since the data functionalization performed by TABLES-3 is known as being very reliable, the PARCS cross-section model would thus cover the whole range of operating conditions. Furthermore, extensive lattice physics recalculations can be avoided. Finally, since the PMAXS file is a text file, a dedicated code for creating it can be easily developed without any knowledge of the GenPMAXS code.

Table 4: Feasibility of coupling the Studsvik Scandpower codes to TRACE/PARCS

Coupling to TRACE/ PARCS via	**Advantages**	**Disadvantages**
CASMO-4	• could be done via an extended version of GenPMAXS.	• requires access to the CASMO-4 output and/or input files; this access might be restricted due to proprietary reasons; • requires most likely rerunning CASMO-4; • the development of GenPMAXS could probably only be done by the Purdue University group.
TABLES-3	• neither CASMO-4 nor TABLES-3 need to be run; • no confidentiality restriction since no CASMO-4 file is needed; • the development of a program that creates the PMAXS file could be easily done from scratch or by slightly modifying the GenPMAXS code.	• the development of a program for reading the TABLES-3 output file is required, but the formatting of the binary output file cannot be known; • the development of a program to create the PMAXS file is required.
SIMULATE-3	• no confidentiality restriction since no CASMO-4 file is needed; • the code for reading the TABLES-3 binary file already exists (SIMULATE-3).	• requires running SIMULATE-3; • the development of a program to create the PMAXS file is required; • no available edit of the kinetic data in a form directly suitable to PMAXS; • rather large amount of data to be processed.

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6. Nomenclature

ADF	Assembly Discontinuity Factor
BWR	Boiling Water Reactor
CMFD	Coarse Mesh Finite Difference
ANM	Analytical Nodal Method
NRC	Nuclear Regulatory Commission
PWR	Pressurized Water Reactor
SKI	Swedish Nuclear Power Inpectorate

Appendix A: Example of a SIMULATE-3 input deck for neutronic data editing

```
'AUD.PRI' 'FULL'/
'AUD.EXP' 0/
'AUD.FIX' 'HVOI' 0 'HCRD' 0 'VOI' 0/
'AUD.VAR'   'CRD'  'BOR'  'TFU'  'TMO'/
'AUD.VAL' 1    0      0   813.6   560 /
'AUD.VAL' 2    0      0   813.6   570 /

'STA'/
'END'/
```

Appendix B: Example of a SIMULATE-3 output deck for neutronic data editing

```
1S I M U L A T E - 3 ** STUDSVIK CMS STEADY-STATE 3-D REACTOR SIMULATOR ** CHALMERS_BASE   SUN CREATED 01/08/23 ** PAGE   32
 RUN: BaseDepl  ** PROJECT: Generic BWR model        ** RUN TIME: 09.07.24.** DATE: 04/09/10      100.0% FLOW  100.0% POWER
 CASE  1 STEP  0 Cycle 1 Basedeck and Depletion                                                    0.00 PPM    0.000 GWD/MT
 ____________________________________________________________________________________________________________________

 BEGIN AUDIT OPTION OUTPUT FOR SEGMENT TYPE   4 LIBRARY NAME = BWR-UOX01i          ,  FLAGS =   0  0

   AUDIT DISPLAYS SEGMENT K-INFINITY ETC. AT NODAL CONDITIONS REQUESTED BY AUDIT INPUT.

   ALL SEGMENTS TO BE AUDITED MUST FIRST BE INCLUDED IN THE CORE SO THEY ARE ALSO INCLUDED IN THE RUNTIME CROSS SECTION LIBRARY.
   AUDIT REPRESENTS A SINGLE NODE, BEGINNING WITH NOMINAL INPUT CORE AVERAGE CONDITIONS

   THESE PARAMETER VALUES COME FROM THE BASE SIMULATE INPUT:
     COR.OPE PERCTP     =    100.000%
     COR.OPE PR1-PR3    =   1035.000     0.000     0.000 PSIA
        CORE PRESSURE   =   1035.000 PSIA ......................... (SATURATION TEMP    560.248 K)
     COR.DAT POWDEN     =     50.000 KW/L ......................... (AT 100% CORE THERMAL POWER)
     COR.BOR BORON      =      0.000 PPM .......................... (MAY BE OVERRIDDEN BY AUD.VAL INPUT)
     SEG.TFU(1-4)       =      0.000   206.500    17.200     0.000 K ........ (MAY BE OVERRIDDEN BY AUD.VAL INPUT)

     UNLESS TFU IS SET BY AUD.VAL OR AUD.FIX,
        TFU FOLLOWS TMO IF SEG.TFU ALLOWS
        TAB.TFU IS INCLUDED
     DEP.TON DETERMINES THE UNITS OF EXPOSURE
     FUE.XKS ARE SET TO 1.0
     TAB.XKS/XK2 IF ANY ARE INCLUDED
     AUDIT CALCULATES EQUILIBRIUM FISSION PRODUCTS IF LIBRARY PROVIDES CROSS SECTIONS.
     LIBRARY EXPLICIT FISSION PRODUCTS  =   4  WHERE  0 = NONE , 2 = XE, 4 = SM
     LIBRARY PRESSURE   =   1035.005 WAS USED BY TABLES TO CONVERT HVOI AND HTMO TO WATER DENSITY (G/CC)

   TO MATCH CASMO, THE SIMULATE INPUTS MUST MATCH THOSE OF THE CASMO.
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 LIBRARY TABLE ARGUMENT LISTS IN CASMO AND SIMULATE FORMS:

 CASMO        EXP       0.000 *     0.100       0.500       1.000       1.500       2.000       2.500       3.000       3.500
           4.000       4.500       5.000       5.500       6.000       6.500       7.000       7.500       8.000       8.500

           9.000       9.500      10.000      11.000      11.500      12.000      12.500      13.000      13.500      14.000

          15.000      17.500      20.000      25.000      30.000      35.000      40.000
 INTERNAL SIM EXP       0.000       0.100       0.500       1.000       1.500       2.000       2.500       3.000       3.500
           4.000       4.500       5.000       5.500       6.000       6.500       7.000       7.500       8.000       8.500

           9.000       9.500      10.000      11.000      11.500      12.000      12.500      13.000      13.500      14.000

          15.000      17.500      20.000      25.000      30.000      35.000      40.000

 CASMO        VOI      80.000      60.000      40.000 *    20.000       0.000
 INTERNAL SIM VOI       0.177       0.317       0.458       0.598       0.738

 CASMO        TFU     560.000     813.600 *
 INTERNAL SIM TFU      23.664      28.524

 CASMO        HVO      80.000      40.000 *     0.000
 INTERNAL SIM HVO       0.177       0.458       0.738

 CASMO        CRD       0.000 *    10.000
 INTERNAL SIM CRD       0.000      10.000

 CASMO        HCR       0.000 *     1.000
 INTERNAL SIM HCR       0.000       1.000

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 INTERPOLATION ARGUMENTS AVAILABLE FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i          FLAGS   0  0

     -- AS INPUT TO AUDIT --              --  AS USED IN CROSS SECTION INTERPOLATION TABLES --
 CASE     CRD      BOR     TFU     TMO         2           3           4           5           6           7           8
                   PPM   DEG K   DEG K       VOI         HVO         TFU         HTF         TMO         HTM         BOR
                                           TABLES      TABLES      TABLES   NOT USED   NO TABLES   NOT USED   NO TABLES
                                         AUD.FIX     AUD.FIX     AUD.VAR                AUD.VAR                AUD.VAR
                                            G/CC        G/CC       DEG K       DEG K       G/CC        G/CC         PPM
   1    0.00     0.00  813.60  560.00       0.741       0.738     813.600       0.000       0.741       0.000       0.000
   2    0.00     0.00  813.60  570.00       0.736       0.738     813.600       0.000       0.736       0.000       0.000

 INTERPOLATION ARGUMENTS AVAILABLE FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i          FLAGS   0  0

     -- AS INPUT TO AUDIT --              --  AS USED IN CROSS SECTION INTERPOLATION TABLES --
 CASE     CRD      BOR     TFU     TMO         9          10          11          12          13          14          15
                   PPM   DEG K   DEG K       HBO         CRD         HCR         ENR         WBA         BAP         BAO
                                         NOT USED      TABLES      TABLES   NO TABLES   NO TABLES   NO TABLES   NO TABLES
                                                     AUD.VAR     AUD.FIX
                                              PPM
   1    0.00     0.00  813.60  560.00       0.000       0.000       0.000       0.710       0.000       0.000       0.000
   2    0.00     0.00  813.60  570.00       0.000       0.000       0.000       0.710       0.000       0.000       0.000
1S I M U L A T E - 3 ** STUDSVIK CMS STEADY-STATE 3-D REACTOR SIMULATOR ** CHALMERS_BASE   SUN CREATED 01/08/23 ** PAGE   33
 RUN: BaseDepl  ** PROJECT: Generic BWR model        ** RUN TIME: 09.07.24.** DATE: 04/09/10      100.0% FLOW  100.0% POWER
 CASE  1 STEP  0 Cycle 1 Basedeck and Depletion                                                    0.00 PPM    0.000 GWD/MT

 INTERPOLATION ARGUMENTS AVAILABLE FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i          FLAGS   0  0

     -- AS INPUT TO AUDIT --              --  AS USED IN CROSS SECTION INTERPOLATION TABLES --
 CASE     CRD      BOR     TFU     TMO        16          17          18          19          20          21          22
                   PPM   DEG K   DEG K       WPU         SPA         SDC                                 RES         POW
                                         NO TABLES   NO TABLES   NO TABLES   NO TABLES   NO TABLES   NO TABLES   NO TABLES

                                                                     KHRS
   1    0.00     0.00  813.60  560.00       0.000       0.000       0.000       0.000       0.000       0.000       1.000
   2    0.00     0.00  813.60  570.00       0.000       0.000       0.000       0.000       0.000       0.000       1.000

 INTERPOLATION ARGUMENTS AVAILABLE FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i          FLAGS   0  0

     -- AS INPUT TO AUDIT --              --  AS USED IN CROSS SECTION INTERPOLATION TABLES --
 CASE     CRD      BOR     TFU     TMO        23          24          25          26          27          28          29
                   PPM   DEG K   DEG K       BV          BPS         EBP         BP1         B10         BP2         B20
                                         NO TABLES   NO TABLES   NOT USED   NO TABLES   NO TABLES   NO TABLES   NO TABLES


   1    0.00     0.00  813.60  560.00       0.000       0.000       0.000       0.000       0.000       0.000       0.000
```

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  2    0.00    0.00  813.60  570.00      0.000      0.000      0.000      0.000      0.000      0.000      0.000

 INTERPOLATION ARGUMENTS AVAILABLE FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

     -- AS INPUT TO AUDIT --               --  AS USED IN CROSS SECTION INTERPOLATION TABLES --
 CASE    CRD     BOR     TFU     TMO         30
                 PPM   DEG K   DEG K        EB2
                                        NO TABLES


  1    0.00    0.00  813.60  560.00      0.000
  2    0.00    0.00  813.60  570.00      0.000
 ____________________________________________________________

 K-INFINITY FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE    CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                 PPM   DEG K   DEG K    0.000

  1    0.00    0.00  813.60  560.00  0.82994
  2    0.00    0.00  813.60  570.00  0.83030

 MIGRATION AREA FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE    CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                 PPM   DEG K   DEG K    0.000

  1    0.00    0.00  813.60  560.00    64.25
  2    0.00    0.00  813.60  570.00    64.60

 FUEL TEMPERATURE FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0
 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 TAB.TFU IS INCLUDED     F
 CASE    CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                 PPM   DEG K   DEG K    0.000

  1    0.00    0.00  813.60  560.00   813.60
  2    0.00    0.00  813.60  570.00   813.60
1S I M U L A T E - 3 ** STUDSVIK CMS STEADY-STATE 3-D REACTOR SIMULATOR ** CHALMERS_BASE   SUN CREATED 01/08/23 ** PAGE   34
 RUN: BaseDepl  ** PROJECT: Generic BWR model        ** RUN TIME: 09.07.24.** DATE: 04/09/10      100.0% FLOW  100.0% POWER
 CASE  1 STEP  0 Cycle 1 Basedeck and Depletion                                                    0.00 PPM    0.000 GWD/MT

 D1    *1.E+00 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE    CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                 PPM   DEG K   DEG K    0.000

  1    0.00    0.00  813.60  560.00  1.41713
  2    0.00    0.00  813.60  570.00  1.42032

 D2    *1.E+01 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE    CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                 PPM   DEG K   DEG K    0.000

  1    0.00    0.00  813.60  560.00  3.14012
  2    0.00    0.00  813.60  570.00  3.15203

 SIGR1 *1.E+02 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE    CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                 PPM   DEG K   DEG K    0.000

  1    0.00    0.00  813.60  560.00  2.09743
  2    0.00    0.00  813.60  570.00  2.08908

 SIGA1 *1.E+03 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE    CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                 PPM   DEG K   DEG K    0.000

  1    0.00    0.00  813.60  560.00  5.72956
  2    0.00    0.00  813.60  570.00  5.72646

 SIGA2 *1.E+02 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE    CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                 PPM   DEG K   DEG K    0.000

  1    0.00    0.00  813.60  560.00  2.80735
  2    0.00    0.00  813.60  570.00  2.80427

 NSIGF1*1.E+03 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE    CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                 PPM   DEG K   DEG K    0.000

  1    0.00    0.00  813.60  560.00  2.72369
  2    0.00    0.00  813.60  570.00  2.72127

 NSIGF2*1.E+02 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE    CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                 PPM   DEG K   DEG K    0.000

  1    0.00    0.00  813.60  560.00  2.60184
  2    0.00    0.00  813.60  570.00  2.60133
1S I M U L A T E - 3 ** STUDSVIK CMS STEADY-STATE 3-D REACTOR SIMULATOR ** CHALMERS_BASE   SUN CREATED 01/08/23 ** PAGE   35
 RUN: BaseDepl  ** PROJECT: Generic BWR model        ** RUN TIME: 09.07.24.** DATE: 04/09/10      100.0% FLOW  100.0% POWER
 CASE  1 STEP  0 Cycle 1 Basedeck and Depletion                                                    0.00 PPM    0.000 GWD/MT

 KAP/NU*1.E+11 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE    CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                 PPM   DEG K   DEG K    0.000

  1    0.00    0.00  813.60  560.00  1.32283
  2    0.00    0.00  813.60  570.00  1.32281
 ____________________________________________________________

 SA1-B *1.E+00 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0
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```
 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE     CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                  PPM   DEG K   DEG K    0.000

   1    0.00    0.00  813.60  560.00  6.91207
   2    0.00    0.00  813.60  570.00  6.91478

 SA2-B *1.E-02 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE     CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                  PPM   DEG K   DEG K    0.000

   1    0.00    0.00  813.60  560.00  2.97083
   2    0.00    0.00  813.60  570.00  2.97039

 NU    *1.E+00 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE     CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                  PPM   DEG K   DEG K    0.000

   1    0.00    0.00  813.60  560.00  2.44712
   2    0.00    0.00  813.60  570.00  2.44714

 YI135 *1.E+02 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE     CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                  PPM   DEG K   DEG K    0.000

   1    0.00    0.00  813.60  560.00  6.33606
   2    0.00    0.00  813.60  570.00  6.33609

 YXE135*1.E+03 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE     CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                  PPM   DEG K   DEG K    0.000

   1    0.00    0.00  813.60  560.00  2.26553
   2    0.00    0.00  813.60  570.00  2.26542

 YPM149*1.E+02 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE     CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                  PPM   DEG K   DEG K    0.000

   1    0.00    0.00  813.60  560.00  1.10604
   2    0.00    0.00  813.60  570.00  1.10607
1S I M U L A T E - 3 ** STUDSVIK CMS STEADY-STATE 3-D REACTOR SIMULATOR ** CHALMERS_BASE   SUN CREATED 01/08/23 ** PAGE   36
 RUN: BaseDepl  ** PROJECT: Generic BWR model        ** RUN TIME: 09.07.24.** DATE: 04/09/10      100.0% FLOW  100.0% POWER
 CASE  1 STEP  0 Cycle 1 Basedeck and Depletion                                                    0.00 PPM    0.000 GWD/MT

 YSM149*1.E+00 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE     CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                  PPM   DEG K   DEG K    0.000

   1    0.00    0.00  813.60  560.00  0.00000
   2    0.00    0.00  813.60  570.00  0.00000

 SA2-XE*1.E-06 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE     CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                  PPM   DEG K   DEG K    0.000

   1    0.00    0.00  813.60  560.00  1.68952
   2    0.00    0.00  813.60  570.00  1.68907

 SA2-SM*1.E-04 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE     CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                  PPM   DEG K   DEG K    0.000

   1    0.00    0.00  813.60  560.00  4.93032
   2    0.00    0.00  813.60  570.00  4.92926

 NIOD  *1.E+08 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE     CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                  PPM   DEG K   DEG K    0.000

   1    0.00    0.00  813.60  560.00  0.33470
   2    0.00    0.00  813.60  570.00  0.33470

 NXEN  *1.E+08 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE     CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                  PPM   DEG K   DEG K    0.000

   1    0.00    0.00  813.60  560.00  0.04278
   2    0.00    0.00  813.60  570.00  0.04279

 NPM   *1.E+08 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE     CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                  PPM   DEG K   DEG K    0.000

   1    0.00    0.00  813.60  560.00  0.00000
   2    0.00    0.00  813.60  570.00  0.00000

 NSM   *1.E+08 FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i           FLAGS   0  0

 AUD.FIX  HVO      0.00 HCR      0.00 VOI      0.00
 CASE     CRD     BOR     TFU     TMO  -------- EXPOSURES ---------
                  PPM   DEG K   DEG K    0.000

   1    0.00    0.00  813.60  560.00  0.00000
   2    0.00    0.00  813.60  570.00  0.00000
_____________________________________________________________________
1S I M U L A T E - 3 ** STUDSVIK CMS STEADY-STATE 3-D REACTOR SIMULATOR ** CHALMERS_BASE   SUN CREATED 01/08/23 ** PAGE   37
 RUN: BaseDepl  ** PROJECT: Generic BWR model        ** RUN TIME: 09.07.24.** DATE: 04/09/10      100.0% FLOW  100.0% POWER
 CASE  1 STEP  0 Cycle 1 Basedeck and Depletion                                                    0.00 PPM    0.000 GWD/MT
```

DISCONTINUITY FACTOR DF1-W FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i   FLAGS   0 0

AUD.FIX CASE	HVO CRD	0.00 HCR BOR PPM	TFU DEG K	0.00 VOI TMO DEG K	EXPOSURES 0.000
1	0.00	0.00	813.60	560.00	0.90895
2	0.00	0.00	813.60	570.00	0.90914

DISCONTINUITY FACTOR DF1-S FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i   FLAGS   0 0

AUD.FIX CASE	HVO CRD	0.00 HCR BOR PPM	TFU DEG K	0.00 VOI TMO DEG K	EXPOSURES 0.000
1	0.00	0.00	813.60	560.00	0.90939
2	0.00	0.00	813.60	570.00	0.90959

DISCONTINUITY FACTOR DF1-E FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i   FLAGS   0 0

AUD.FIX CASE	HVO CRD	0.00 HCR BOR PPM	TFU DEG K	0.00 VOI TMO DEG K	EXPOSURES 0.000
1	0.00	0.00	813.60	560.00	0.90939
2	0.00	0.00	813.60	570.00	0.90959

DISCONTINUITY FACTOR DF1-N FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i   FLAGS   0 0

AUD.FIX CASE	HVO CRD	0.00 HCR BOR PPM	TFU DEG K	0.00 VOI TMO DEG K	EXPOSURES 0.000
1	0.00	0.00	813.60	560.00	0.90895
2	0.00	0.00	813.60	570.00	0.90914

DISCONTINUITY FACTOR DF2-W FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i   FLAGS   0 0

AUD.FIX CASE	HVO CRD	0.00 HCR BOR PPM	TFU DEG K	0.00 VOI TMO DEG K	EXPOSURES 0.000
1	0.00	0.00	813.60	560.00	1.19558
2	0.00	0.00	813.60	570.00	1.19584

DISCONTINUITY FACTOR DF2-S FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i   FLAGS   0 0

AUD.FIX CASE	HVO CRD	0.00 HCR BOR PPM	TFU DEG K	0.00 VOI TMO DEG K	EXPOSURES 0.000
1	0.00	0.00	813.60	560.00	1.19447
2	0.00	0.00	813.60	570.00	1.19473

DISCONTINUITY FACTOR DF2-E FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i   FLAGS   0 0

AUD.FIX CASE	HVO CRD	0.00 HCR BOR PPM	TFU DEG K	0.00 VOI TMO DEG K	EXPOSURES 0.000
1	0.00	0.00	813.60	560.00	1.19447
2	0.00	0.00	813.60	570.00	1.19473

DISCONTINUITY FACTOR DF2-N FOR SEGMENT   4 LIBRARY NAME BWR-UOX01i   FLAGS   0 0

AUD.FIX CASE	HVO CRD	0.00 HCR BOR PPM	TFU DEG K	0.00 VOI TMO DEG K	EXPOSURES 0.000
1	0.00	0.00	813.60	560.00	1.19558
2	0.00	0.00	813.60	570.00	1.19584

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