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Titolo

Neutronic analyses of the ALFRED LEADER core with deterministic (ECCO / ERANOS) and Monte Carlo (Serpent) codes: comparison between macroscopic-group constants, shutdown systems worth and spatial-angular flux distributions

Descrittori

Tipologia del documento: Rapporto Tecnico
Collocazione contrattuale: FALCON International Consortium
Argomenti trattati: Generation IV reactors, Neutronica

Sommario

Questo rapporto tecnico - realizzato in collaborazione con il Politecnico di Torino (PoliTO) - rappresenta il primo passo di un ambizioso programma di lavoro finalizzato alla produzione delle sezioni d'urto per il codice neutronico deterministico ERANOS - solitamente create con il codice di cella ECCO - mediante il codice Monte Carlo Serpent. La motivazione di questo sforzo è duplice. Da un lato, grazie a Serpent è possile modellizzare geometrie di cella complesse non riproducibili con ECCO. Dall'altro, Serpent permette di utilizzare in modo semplice librerie di dati nucleari sempre aggiornate, cosa possibile non con la medesima semplicità col sistema ECCO-ERANOS, di cui il CEA (Francia) ha cessato lo sviluppo ed il conseguente mantenimento. Le ultime versioni delle librerie valutate utilizzabili in ECCO fornite dal CEA sono la JEFF-3.1 (utilizzata in questo rapporto) e la ENDF/B-VI.8, ormai datate.

Il sistema ECCO/ERANOS è stato utilizzato diffusamente in ENEA per il progetto di nocciolo dei reattori veloci e, in particolare negli ultimi anni, per il reattore-dimostratore refrigerato a piombo di quarta generazione ALFRED, inizialmente concepito nel progetto EURATOM FP7 LEADER (2010-2014) ed attualmente sviluppato dal consorzio internazionale FALCON. Utilizzando la configurazione di riferimento definita nel progetto LEADER, è stato condotto un accurato confronto tra le sezioni d'urto macroscopiche - rappresentative delle regioni del nocciolo più significative - prodotte mediante ECCO e Serpent in strutture energetiche a 33 e 80 gruppi utilizzando diverse metodologie ed opzioni di calcolo. Dal confronto risulta evidente un generale accordo tra i due codici, con l'eccezione delle discrepanze a basse energie dove i risultati Serpent sono affetti da un'elevata incertezza statistica. Nelle parti assorbitrici (in B_4C) delle barre di controllo e sicurezza, differenze significative si sono invece riscontrate in un ampio intervallo spettrale. A livello di nocciolo ciò si riflette nella stima dell'anti-reattività fornita dall'inserzione di entrambi i sistemi che differisce del ~10%, in linea con l'usuale sovrastima dei codici deterministici rispetto a quelli stocastici per i reattori a spettro veloce, come ampiamente documentato dall'esperienza ENEA. Il presente rapporto investiga anche tale aspetto e ne individua le cause principali nelle differenti sezioni d'urto di cattura degli stessi assorbitori, che danno origine a distribuzioni spaziali e angolari di flusso nel nocciolo significativamente diverse quando gli stessi sono inseriti.

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List of Abbreviations

ACE	A Compact ENDF
ALFRED	Advanced Lead-cooled Fast Reactor European Demonstrator
BoL	Beginning of Life
CEA	Commissariat à l'énergie atomique et aux énergies alternatives (France)
CR(s)	Control Rod(s)
CSG	Constructive Solid Geometry
ECCO	European Cell Code
EDL	Ensemble de Données LU
ERANOS	European Reactor ANalysis Optimised System
FA(s)	Fuel Assembly(ies)
FALCON	FOstering ALfred CONstruction
FC	Full-Core
FMS	Ferritic Martensitic Steel
FP	Framework Program
GIF	Generation IV International Forum
HH	Heterogeneous Homogenised
LEADER	Lead-cooled European Advanced Demonstration Reactor
LFR	Lead Fast Reactor
LU	Langage utilisateur
MC	Monte Carlo
MOX	Mixed Oxide
pcm	per cent mille
PoliTO	Politecnico di Torino
RSD	Relative Standard Deviation
SR(s)	Safety Rod(s)
SS	Stainless Steel
XS(s)	Macroscopic cross-section(s)
YSZ	Yttria-stabilised Zirconia

Symbols

k_{eff}	Multiplication factor, k-effective
k_{inf}	k-infinite
Δk_{eff} (pcm)	k-effective variation in per cent mille

1 Introduction

1.1 Aim and purposes

This technical report, produced in collaboration with Politecnico di Torino (PoliTO), represents the first step of an ambitious work program whose final purpose is the production of the homogenised and condensed multi-group cross-sections for the deterministic neutronic code ERANOS [1] - usually produced with the ECCO cell code - through the Monte Carlo (MC) code Serpent [2].

The motivation of this effort is twofold. In fact, with Serpent it is possible to model complex cell geometries not reproducible by ECCO. Furthermore, the Commissariat à l'énergie atomique et aux énergies alternatives (CEA, France) decided to interrupt the ERANOS development and, consequently, the updating process of the nuclear data evaluated in multi-group energy structures suitable for the ECCO cell code [3]. The latest evaluated data available in ECCO provided by the CEA are the JEFF-3.1 [4] and ENDF/B-VI.8 [5] libraries, actually rather dated.

The ECCO/ERANOS system has been widely used in ENEA for the core design and neutronic analyses of fast reactors (*e.g.*, Sodium Fast Reactors). In the last years, it has been adopted for the design of the ALFRED (Advanced Lead Fast Reactor European Demonstrator) core, initially conceived in the EURATOM FP7 LEADER (Lead-cooled European Advanced Demonstration Reactor) project [6] and currently carried on within the FALCON (Fostering ALfred CONstruction) international consortium [7]. The Lead-cooled Fast Reactor (LFR) concept - selected by the Generation IV International Forum (GIF) [8] as one of the most promising nuclear systems for the future - is nowadays widely investigated because it could effectively represent a viable technology for safer, cleaner, cheaper and proliferation-resistant nuclear energy systems.

The ALFRED core design is challenging for the several technological constraints of the LFR systems along with the target performances aimed for this demonstrator, such as [6]: the maximum Pu enrichment (< 30%) in the Mixed OXide (MOX) fuel and the achievement of a peak burn-up of 100 GWd/t, the narrow temperature range (400/480 °C as core inlet/outlet) and the limiting temperature for the steel cladding in nominal conditions (550 °C[1]), the respect of the system integrity even in extreme conditions, etc. Therefore, the design process requires many scoping analyses, for which, relatively to neutronics, ERANOS is the main tool used in ENEA for its flexibility and reduced computational times, especially in comparison with MC codes.

The ALFRED design defined in LEADER was used as reference for the present study, carried out by adopting the JEFF-3.1 nuclear data library with both ECCO/ERANOS and Serpent codes. The core models were accurately compared and their congruence verified in detail. The comparison was limited to the Beginning of Life (BoL) conditions at full power (300 MW), with fresh fuel and the shutdown systems completely withdrawn and inserted. The reference state is represented by both shutdown systems withdrawn, which defines an over-critical core condition at BoL: at the same time, this condition represents the easiest core configuration for a code benchmark, since it does not involve the effects due the fuel burn-up and absorbers depletion.

A very detailed comparison between the deterministic and MC analyses was performed by verifying (first of all) the full consistency between the two core models. This work summarises the main outcomes of the study carried out in steady state, focusing on:

- the macroscopic cross-sections produced by the ECCO and Serpent codes, whose behaviour with respect to the incident neutron energy was accurately compared in all regions of the core models. In general, a good agreement between the two codes was found, with some noticeable exceptions (*e.g.*, the absorbing bundles of the control and safety rods);

[1] These temperature range and limit refer to the ALFRED LEADER version.

- the different calculation options available in ECCO and Serpent, with the analyses of their impact on the macroscopic-group constant values. In ECCO, the "reference" data were obtained with 2D cell geometry models of the main core regions, an energy refinement at 33 groups (ECCO-33 grid) and the P_1 consistent approximation for the solution of the multi-group transport equations. Additionally, the cross-sections were evaluated also with homogeneous cell models, 80 energy groups and different calculation options (P_1 inconsistent, B_1 consistent and inconsistent and so on; see Appendix A). In Serpent all the condensed and homogenised cross-sections were scored on the ECCO-33 grid using a 3D Full-Core (FC) model (named MC1), a 2D radially-infinite model (named MC2) and, finally, a 3D axially-limited and radially-infinite model (named MC3) for the most important core regions (*e.g.*, fissile and absorbing parts of shutdown systems). The B_1 approximation was used in order to provide leakage-corrected constants for the MC2 and MC3 cases;
- the reactivity worth of the shutdown systems that differs by ~10%, that is the usual overestimation introduced by deterministic codes (with respect to stochastic ones) for fast spectrum reactors as widely documented by the ENEA experience (*e.g.*, [9]);
- the impact of the shutdown systems insertion on the radial and axial spatial flux distribution within the core. Besides the ~10% reactivity worth difference, the flux spatial distributions result sensibly different: both effects mainly derive from the different macroscopic-group constants created by ECCO and Serpent for their absorbing regions. Additionally, the different spatial distributions are necessarily related also with the different methods adopted by deterministic and MC codes for the treatment of the flux angular dependency.

1.2 Organisation of the work

This report summarises part of the work carried out in collaboration between ENEA and PoliTO in the last year dealing with the ALFRED core neutronic analyses with ECCO/ERANOS and Serpent. It is structured as follows.

- Chapter 2 describes briefly:
  - the main features of the ALFRED core (in the LEADER version, §2.1);
  - the core conditions examined (§2.2);
  - the ERANOS model of the ALFRED core (§2.3).
- Chapter 3 describes briefly:
  - the ECCO/ERANOS system code (§3.1);
  - the procedure ("route") adopted in ECCO to produce the reference data (*i.e.*, multi-group homogenised cross-sections representative of the core zones, §2.3), together with an overview of the calculation options available whose theoretical background is described in Appendix A; furthermore, their impact on the multi-group constant values evaluated at the P_1 (and B_1) order was accurately verified (§A.8).
- Chapter 4 describes briefly:
  - the Serpent MC code and the calculation options adopted to create the multi-group homogenised cross-sections (§4.1);
  - the Serpent model of the ALFRED core (§4.2).
- Chapter 5 reports the most significant results of the cross-sections analyses and comparison. While the full data set of the Serpent-ERANOS relative differences is reported in Appendix B, in §5 are summarised:
  - the most significant ECCO (§5.1) and Serpent (§5.2) cross-section results, together with the impact of the different calculation options on their values;

- some significant comparisons between the ECCO and Serpent multi-group constants for both fissile and non-multiplying media (§5.3 and §5.4, respectively);
- the main conclusions that can be drawn from the ECCO-Serpent comparison (§5.5).

- Chapter 6 reports the most significant results of the ERANOS and Serpent full-core analyses at BoL for what concerns the core reactivity, the shutdown systems performances and the spatial distribution of the total flux within the core (with the control and safety rods completely withdrawn and inserted). In particular:
  - §6.1 reports the ERANOS values for the core reactivity and the shutdown systems worth. The impact of the different ECCO calculation options was verified at the core level, as well as the difference between the P_3 (reference) and P_1 flux order expansion in the ERANOS spatial calculations;
  - §6.2 reports the Serpent values for the core reactivity and the shutdown systems worth, while §6.3 summarises some significant comparisons between the results of the two codes;
  - §6.4 reports the comparison between the radial and axial flux distributions within the core obtained by ERANOS and Serpent with the shutdown systems fully withdrawn and inserted. A couple of significant radial directions (passing through the core positions hosting control and safety rods) were considered and their radial flux profiles compared, as well as the axial ones for each assembly intercepted by these radial traverses. The full data set of the axial flux traverses is reported in Appendix C.

Besides the most significant concluding remarks and future perspective of the present work (§7), for the sake of completeness the report includes other two appendixes:

- the ECCO/ERANOS input decks of the reference case, together with the indications of the instructions to be modified to reproduce the different calculation options (Appendix D);
- the Serpent code input decks used for the “reference” cross-sections generation and the full-core analysis (Appendix E). Even in this case, the instructions to be modified and used to explore the different calculation options are briefly provided. For more details about the code calculation options, the reader is referred to the Serpent 2 code Wiki [10].

2 The ALFRED core design and conditions examined

2.1 Brief description of the ALFRED Leader core

Fig. 2.1 shows the main features of the MOX fuel pin (60 cm fissile length) and the wrapped hexagonal Fuel Assembly (FA) made of 127 pins arranged in six rows of a triangular lattice. Fig. 2.2 shows a quarter of the core layout having a 90° symmetry, while Fig. 2.3 sketches the main features of the shutdown systems design. The core layout is essentially made of [6]:

- 57 inner FAs and 114 outer FAs, having the same architecture but a different Pu enrichment in the fuel pellet (21.7 and 27.8 at%, respectively) to flatten the core radial power distribution. The fuel clad is made of 15-15/Ti austenitic Stainless Steel (SS) and the FA wrap is made of T91 Ferritic Martensitic Steel (FMS);
- 12 Control Rods (CRs) located in the fuel outer zone, used for both normal control of the reactor (*i.e.*, start-up, reactivity control during the fuel cycle, power tuning and shutdown) and for scram in case of emergency. In control mode, they partially enter the active region from the bottom during irradiation (to compensate the initial over-criticality) and are progressively withdrawn as far as the refuelling condition is reached (with an irradiation scheme made of 5 cycles of 1 year). The absorbing pin bundle is made of 19 pins embedding Boron Carbide (B_4C) pellets enriched at 90 at.% in ^{10}B. Inversely to the FA, the CR clads are made of T91 FMS and the surrounding tube is made of 15-15/Ti SS;
- 4 Safety Rods (SRs) located in the fuel inner zone, which stay still atop the active zone during normal operation and, in emergency cases, enter the core by gravity for the reactor shutdown. The SR bundle is made of 12 pins: as for the CRs, the absorber material is B_4C (with 90 at.% ^{10}B), the clad is in T91 FMS and the surrounding tube in 15-15/Ti SS;
- the surrounding dummies, having the same structure of the FAs but with pins filled by Yttria-stabilised Zirconia (YSZ) pellets (used also as axial thermal insulators in the fuel pin, see Fig. 2.1), acting as reflector for both neutron economy and shielding of the inner vessel.

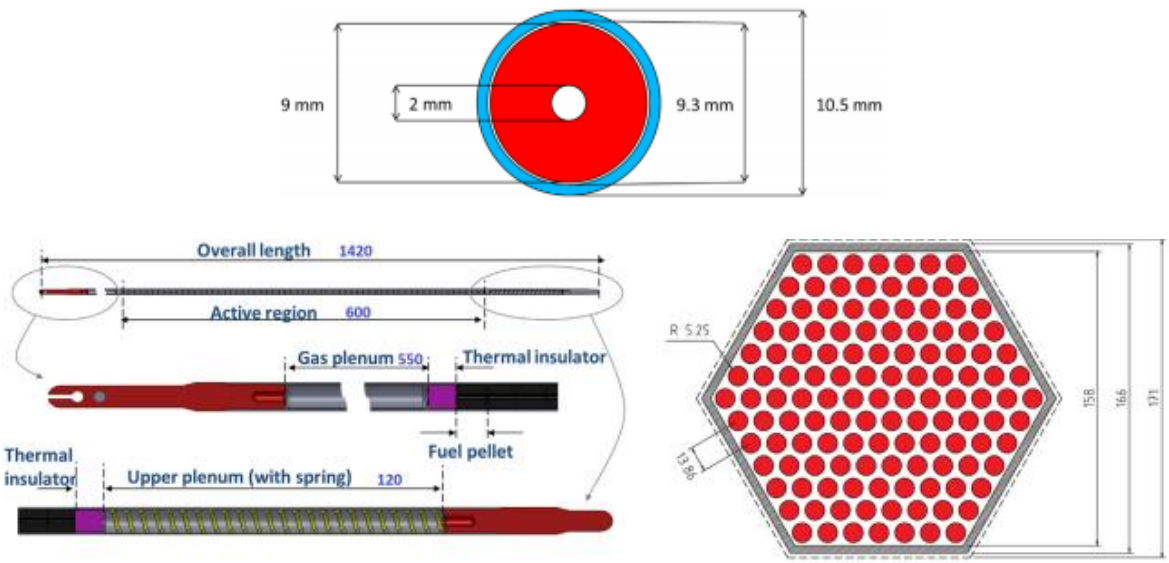

Figure 2.1 Alfred fuel pin and FA main dimensions [mm] [6].

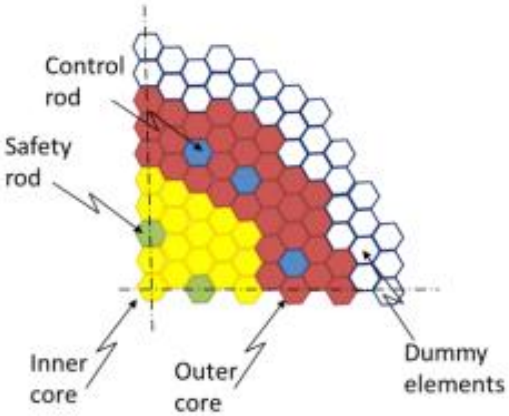

Figure 2.2 ALFRED core layout [6].

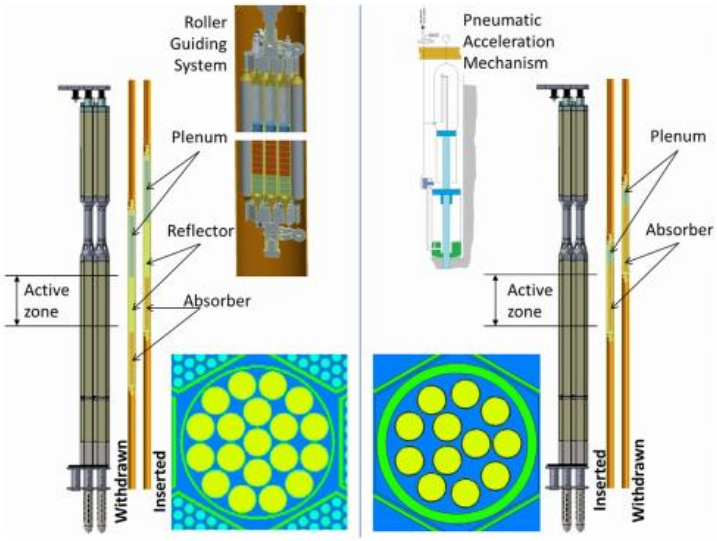

Figure 2.3 ALFRED CR (left) and SR (right) design.

Both shutdown systems were similarly conceived (B_4C pin bundles cooled by the primary lead, see Fig. 2.3). The main difference (for the diversity requirement in case of scram) arises from their mechanism of insertion relying on different physical phenomena.

- The CRs' fully withdrawn position is below the core: they are actuated by motors during reactor operation, while for emergency shutdown they are provided with an electromagnetic connection whose release allows for a rapid insertion into the core by buoyancy.
- The SRs stay still atop the core in reactor operation and their actuation occurs only for scram through the unlocking of an electromagnet. By the unlocking, the resistance to a pneumatic system is simultaneously lost and the SRs are passively pushed rapidly into the core. To face the failure of the pneumatic system, a tungsten ballast is added atop the SRs providing a sufficient weight to counteract the buoyancy and ensuring their insertion into the core, even if at a reduced speed.

2.2 Core conditions examined

The "reference" core models developed with ECCO/ERANOS (§3) and Serpent (§4) refer to the full power (300 MW) conditions at BoL (*i.e.*, fresh fuel everywhere) with the CRs completely withdrawn 4 cm below the fissile zone and the SRs completely withdrawn 12 cm above it. Therefore, the core examined is over-critical (*i.e.*, the layout of 57 + 114 FA of Fig. 2.2 was defined for the criticality at the equilibrium of the 5-year fuel cycle [6] and not at BoL when a lower number of fresh FA will be loaded), but this over-critical condition does not represent a limitation for the current study since the fundamental requirement for the neutronic codes benchmark is the full consistency between the ERANOS and Serpent models, and the simplicity of the model is preferred to avoid any influence of burnup modules on the actual benchmark.

In both codes, a cold geometry model (*i.e.*, 20 °C) was considered while the nuclear data were evaluated at the average working temperatures at full power reported in Table 2.1 for the fuel, absorbers, structures and coolant. Differently from the solid materials, the coolant density was correctly reproduced at its working temperature. As a main consequence, the fuel Doppler effect is taken into account whereas the thermal dilatation of solid materials (*e.g.*, fuel axial expansion) is neglected. The main reason for this choice is due to the fact that Serpent is not endowed with an *ad hoc* routine for the thermal dilatation as ECCO is, instead.

Besides the over-critical core model (*i.e.* full power BoL conditions with CRs and SRs completely withdrawn, representing the simplest configuration to be simulated), the calculations with both codes were extended to include the case of complete insertion of the shutdown systems, in order to compare their reactivity worth values. The complete withdrawn and fully inserted positions are sketched in Fig. 2.4 for both systems, where "CROD" and "SROD" are the absorbing bundles of the CRs and SRs, respectively (see also Fig. 2.5).

Table 2.1 Average working temperatures of the core materials/zones in the ECCO model.

Material	T [°C]	Zone	T [°C]
Fuel	900	**Inlet**	400
Clad	460	**Core**	440
CR & SR pins	450	**Outlet**	480

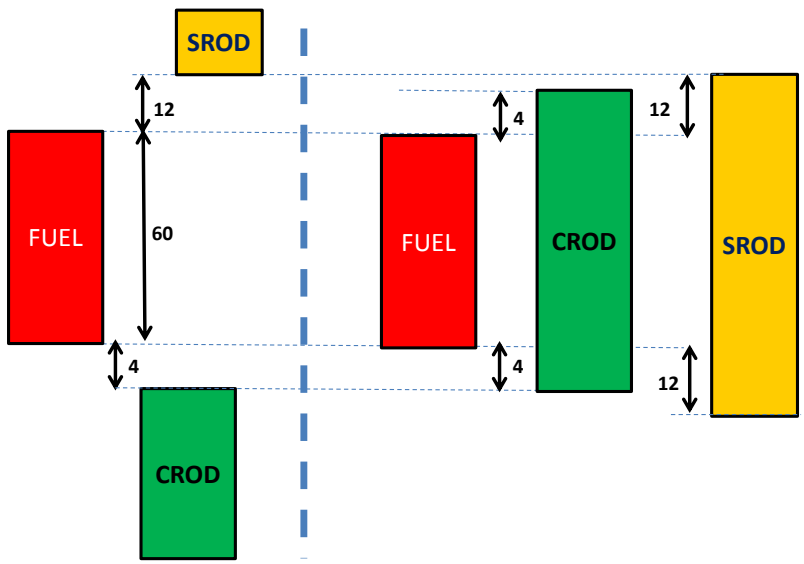

Figure 2.4 ALFRED CRs' and SRs' absorbing bundle positions when fully withdrawn (left) and inserted (right; figure not in scale, dimensions in cm).

2.3 The ALFRED core model with ECCO/ERANOS

Fig. 2.5 depicts the ERANOS axial model of the core assemblies (FA, CR, SR and dummy, §2.1). All the axial zones (*i.e.*, hexagonal slices of a certain thickness) of these elements were characterised with the ECCO cell code to obtain the corresponding (homogeneous equivalent) macroscopic cross-sections. A list of all the zones - together with their brief description and acronyms used in Fig. 2.5 - is provided in the following.

- In the FA (see also Fig. 2.1): the bottom reflector (BREF), the bottom plug of the fuel pins (BPLG), the plenum (PLEN, *i.e.*, voided pin clads containing a thin cylindrical tube in 15-15/Ti SS as support for the fuel pellets), the bottom thermal insulator (BINS, *i.e.*, pin clads filled with YSZ pellets), the fissile zone (FINN and FOUT for the inner and outer FA, respectively), the top insulator (TINS), the spring (SPRN, *i.e.*, plena with a 15-15/Ti SS spring), the top plug (TPLG) and the top reflector (TREF).
- In the dummy: the reflector region (DUMM) that is identical to the BINS and TINS ones. It is however necessary to evaluate different cross-sections to take into account their different temperatures in operating conditions (see Table 2.1). The other zones (below and above the DUMM region) are identical to the FA ones.
- In the CR: the absorbing part (CROD, made of B_4C pellets in T91 FMS clads) and its follower (FROD, *i.e.*, clads with YSZ pellets). For the sake of simplicity, the other zones were assumed identical to the FA ones in order to have a unique data set of cross-sections[2]. Nevertheless, such approximation is acceptable since it does not introduce significant biases in the resulting cross-sections, as well as in the full-core features here examined (*i.e.*, core reactivity, flux distributions, CRs and SRs reactivity worth).
- In the SR: the absorbing part (SROD) made of B_4C pellets in T91 FMS clads as the CR but with different dimensions (resulting in a lower B_4C volume fraction; see Fig. 2.3). As for the CR, the other zones were assumed identical to the FA ones to simplify the core modelling without penalising the calculations accuracy.

All the core regions shown Fig. 2.5 were modelled with ECCO by adopting a 2D heterogeneous geometry, with the exception of the axial reflectors (BREF and TREF), the external lead in the down-comer (Ext Pb), the inner vessel and the surrounding lead, which were described with homogeneous models. Table 2.2 reports the materials volume fractions in them with the density values representing the materials mix. The densities of the solid ones were considered at room temperature, while the lead density values were obtained from an extrapolation of its linear behaviour with temperature in the liquid phase [11] down to 20 °C. The inner vessel (or barrel made of 316L SS) was modelled with 72 assemblies, which represent a homogeneous mix of steel and lead to simulate it and the surrounding coolant in a hexagonal position of the core lattice. Other rings of “virtual” assemblies made by lead only were introduced in the ERANOS 3D hexagonal core model to simulate the down-comer outside the inner vessel.

Due to the ECCO cell code limitations, the CR and SR bundles (Fig. 2.3) were modelled as the FA, with the pins arranged in triangular lattices (by preserving the materials volume fractions) and the surrounding SS tube described with a hexagonal wrap having an equivalent volume.

Table 2.3 reports the materials density (at 20°C), their volume fraction in the FA, CR, SR and dummy clads, and the corresponding filling densities. The MOX density is computed from the theoretical one by assuming a 5% porosity. The filling density represents the “effective” density of the materials (MOX, YSZ, B_4C and 15-15/Ti SS) diluted in the corresponding clads. This dilution is usually adopted in deterministic codes because of their difficulty in simulating regions with “voids” or with materials having a very low density, such as the gap between fuel pellets and clads filled by He gas [6].

[2] As an example, the material/geometrical features of the SPRN zone of the FA were assumed also for the SPRN regions of the CR and SR.

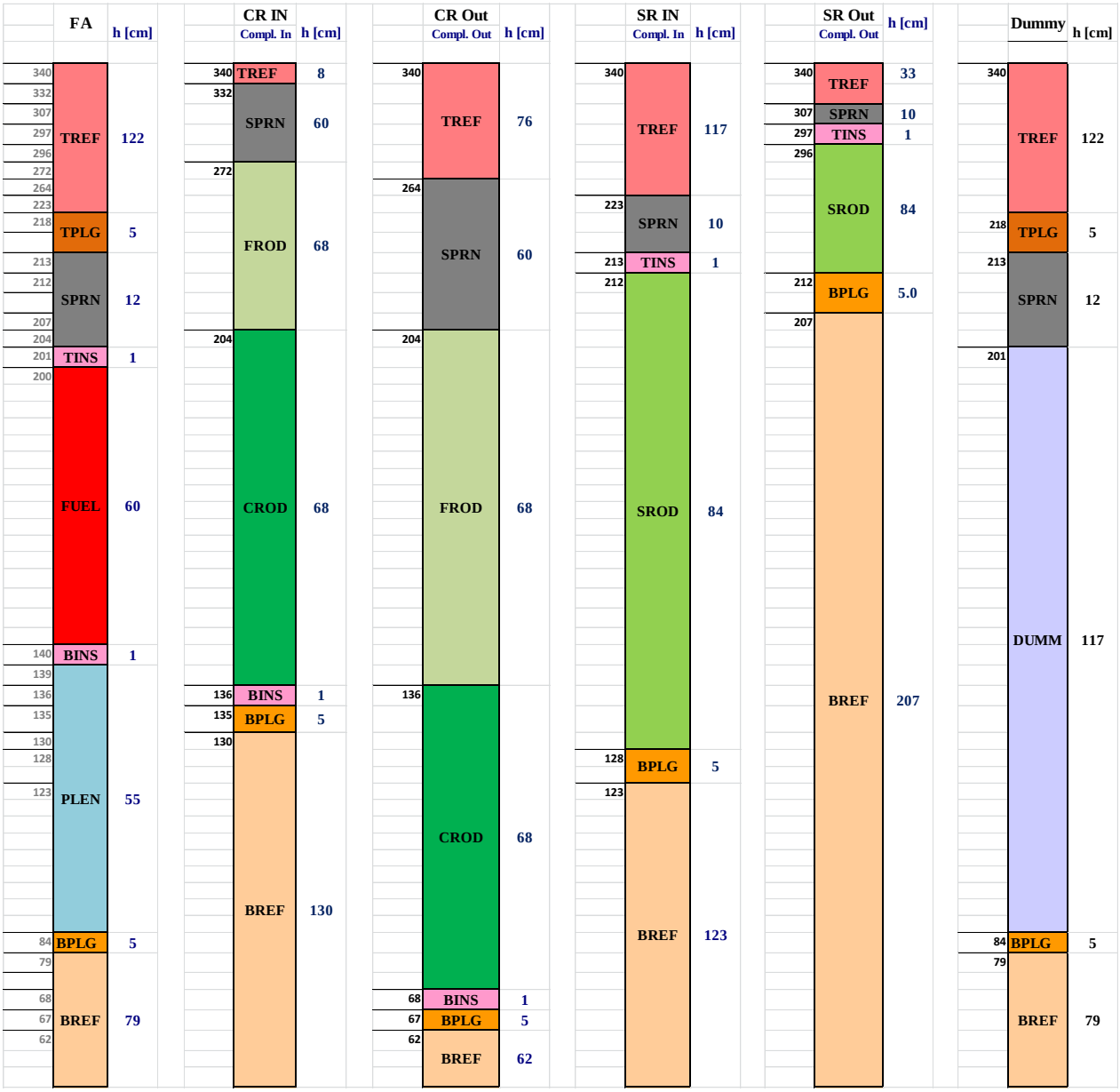

Figure 2.5 The ERANOS axial model of the ALFRED core assemblies (not in scale).

Table 2.2 ECCO models of homogeneous core zones: materials volume fraction and density (at 20°C).

Zone	15-15/Ti SS [vol. %]	Pb [vol. %]	Density** [g cm^{-3}]
BREF	12.0	88.0	10.649
TREF	20.0	80.0	10.404
Barrel*	33.8	66.2	9.980
Ext Pb		100.0	11.017

* actually, the ECCO cell for the barrel is made of 316L SS (instead of 15-15/Ti) and surrounding coolant
** of the materials mix

Table 2.3 Materials density (at 20°C) and their corresponding filling density in the FA, CR, SR and dummy clads.

Material	Density [g cm^{-3}]	ZONE	Fraction in clad [vol. %]	Filling density in clad [g cm^{-3}]
MOX (FINN)	10.494	**FINN**	89.028	9.3426
MOX (FOUT)	10.513	**FOUT**	89.028	9.3595
YSZ	6.0	**BINS, TINS, DUMM**	93.652	5.6191
		FROD	94.703	5.6822
15-15/Ti SS	7.95	**PLEN**	7.559**	0.6009**
		SPRN	7.594	0.6037
B_4C	2.2	**CROD, SROD**	94.703	2.0835
FMS T91	7.736	FA wrap, CR and SR tubes*		
Pb	11.017	Everywhere		

* modelled as equivalent hexagonal layers
** these values represent the filling density of the thin cylindrical tube supporting the pellets

3 The ECCO/ERANOS system code

3.1 Brief description of the ECCO/ERANOS system code

The European Reactor ANalysis Optimised System (ERANOS) was developed by CEA for the core design of Sodium Fast Reactors [1]. It is a modular system and consists of data libraries, deterministic codes and calculation procedures: the different modules perform several functions to analyse the core reactivity, flux distributions, burn-up and reaction rates, etc. of a nuclear system that can be modelled by 1D, 2D and 3D geometries. The cross-sections of the core regions are usually produced in a 1968 energy-group structure and condensed to the standard one at few groups (*e.g.*, 33) by the European Cell COde (ECCO) [3].

The ERANOS system code has been widely used by ENEA in the last 20 years for the core design of the LFR and Accelerator Driven Systems, *e.g.* [9], [12] and [13]. As mentioned in §1, the nuclear data suitable for ECCO in different energy structures are based on evaluated data: specifically, the JEFF-3.1 library [4] was adopted in this study. The multi-group macroscopic cross-sections (or macroscopic-group constants) obtained by ECCO are then used for the ERANOS full-core calculations. In the 3D hexagonal geometry model of the ALFRED core, they were carried out with the TGV module [14] adopting the variational-nodal method [15, 16].

Since the ECCO cell code was developed for the analysis of fast reactors, it considers correctly the peculiarities of this kind of systems like the neutron slowing down, the self-shielding effect, the inelastic and/or non-isotropic scattering events, etc. In the “reference” cell calculation option, a 2D heterogeneous geometry model was adopted to reproduce the spatial self-shielding effect (§2.3) and approached with the collision probability method for the flux solution [3] to take into account the cells heterogeneity. Successively, the cross-sections were homogenised (with the flux times volume weighting method) to obtain homogeneous equivalent values to consider (at some extent) the heterogeneity of the cell.

3.2 The ECCO calculation reference route

The ECCO model of the ALFRED core assemblies (Fig. 2.5) relies on an accurate 2D geometry description of them [17], while the axial leakages were taken into account by tuning opportunely the buckling value (identical for each energy group). More specifically [3]:

- in the fissile zone of the FA, the bucking value is calculated by ECCO in order to yield a unitary multiplication factor (k_{eff}) so as to reproduce the critical core condition;
- in the non-fissile zones the ECCO calculation procedures foresee the introduction of an external source, having the (flux and current) spectrum of the (nearest) fissile region and uniformly distributed in space within the zone. The bucking value is fixed by a semi-empirical relation depending on the (radial or axial) thickness of the zone examined (see Appendix A).

The method recommended by the ECCO developers - called *reference route* [3] - was used to create the macroscopic cross-sections of the core regions. Fig. 3.1 summarises this route, which foresees at least four steps in which the calculations:

- start with a homogeneous geometry description of the cell and a broad energy structure, usually at 172 or 33 groups (172 were chosen as reference);
- introduce the heterogeneous geometry description of the cell by maintaining the broad energy structure;
- refine the energy grid at 1968 groups for the nuclides included in the evaluated library (the most important ones for ALFRED are available) by maintaining the heterogeneous model;
- end with the spatial homogenisation of the cell and the energy collapsing in a broad energy structure at 33 groups. For the codes benchmark, the same energy grid was adopted to create the cross-sections with Serpent (§4).

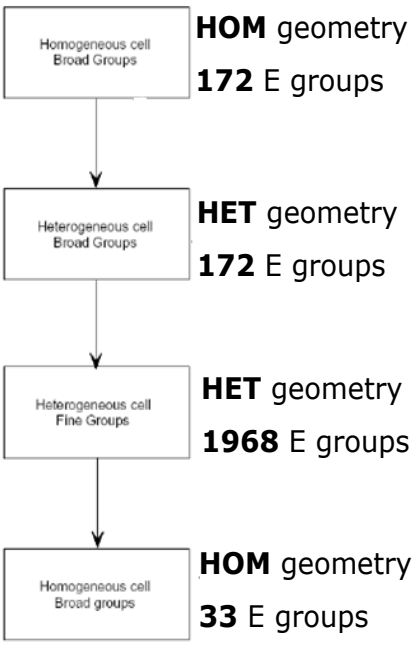

Figure 3.1 Reference route for the ECCO calculations [3].

As a net result, the macroscopic cross-section "x" (x=total, fission, capture, elastic, inelastic, etc.) was evaluated at the P_1 order of the transport equation in a broad energy-group-structure:

$$\Sigma_{x,g} = \frac{\int_V \int_{\mathrm{Eg}}^{Eg+1} \phi(\mathbf{r},\mathrm{E})\Sigma_{\mathrm{x}}(\mathbf{r},\mathrm{E})\mathrm{dE}}{\int_V \int_{\mathrm{Eg}}^{Eg+1} \phi(\mathbf{r},\mathrm{E})\mathrm{dE}} \tag{3.1}$$

where:

- "g" (1-33) is the energy (E) group considered;
- the neutron flux "$\phi(\mathbf{r},\mathrm{E})$" is used as weighting function in the integrals, in order to keep the reaction rates constant *e.g.*, during the condensation process from 1968 down to 33 groups;
- "**r**" is the position within the cell and, trivially, the final homogeneous equivalent values of the macroscopic cross-sections obtained by integrating over the volume "V" do not vary with **r**.

The multi-group constants of the non-fissile zones modelled by a heterogeneous geometry in ECCO (see §2.3) were obtained with the four-step calculation procedure of Fig. 3.1 and are usually named Heterogeneous Homogenised (HH) cross-sections (Σ_{HH}). For the fissile zones, the last step was divided in two by treating the energy collapsing and the spatial homogenisation separately. An additional sixth step can be added by imposing the buckling at zero, in order to make the leakage term vanish and to evaluate the k-infinite (k_{inf}) parameter of the fuel cells.

The mathematical basis of the ECCO cell analyses - producing the macroscopic cross-sections (vectors and matrices) for ERANOS - is described in detail in Appendix A, together with the different calculation methodologies adopted. The cross-section behaviours with energy produced by the different ECCO methods were compared, as well as their impact on the main ERANOS full-core quantities. The ECCO calculation options examined in this work deal with:

- the initial energy refinement, *i.e.*, by starting with 33 energy groups (instead of 172) for both fissile and non-fissile zones;
- the final energy refinement, *i.e.,* by a final collapsing in a structure at 80 groups (instead of 33) for both fissile and non-fissile zones;

- the homogeneous geometry models of the ECCO cells describing the fissile zone of the FA and the absorbing regions of shutdown systems, which are the most important zones for neutronics;
- the adoption of the (flux and current) fuel spectrum generated by Serpent (at 33 energy groups) as weighting function in Eq. (3.1) to obtain the HH cross-sections for the non-multiplying media. The Serpent fuel spectrum was introduced as an “external source” in ECCO and, to verify the congruence of this calculation option, the same method was used also by inserting “externally” the “internal” spectrum evaluated by ECCO itself.

The macroscopic cross-sections were created with a 33-group structure (the reference one, see Table 3.1 reporting its upper energy limits) and the more refined one at 80 groups (see Table 3.2). The latter reports in the last column also the upper energy limits in correspondence with the structure at 1968 groups (to be used in the ECCO CONDENSE instruction; see Appendix D).

Table 3.1 The 33-energy-group structure (Group / Energy [MeV]).

1	1.9640E+01
2	1.0000E+01
3	6.0653E+00
4	3.6788E+00
5	2.2313E+00
6	1.3534E+00
7	8.2085E-01
8	4.9787E-01
9	3.0197E-01
10	1.8316E-01
11	1.1109E-01
12	6.7380E-02
13	4.0868E-02
14	2.4788E-02
15	1.5034E-02
16	9.1188E-03
17	5.5308E-03
18	3.3546E-03
19	2.0347E-03
20	1.2341E-03
21	7.4852E-04
22	4.5400E-04
23	3.0433E-04
24	1.4863E-04
25	9.1661E-05
26	6.7904E-05
27	4.0169E-05
28	2.2603E-05
29	1.3710E-05
30	8.3153E-06
31	4.0000E-06
32	5.4000E-07
33	1.0000E-07

Table 3.2 The 80-energy-group structure (Group / Energy [MeV] / Group in 1968 grid).

1	1.9640E+07	1
2	1.6905E+07	19
3	1.4918E+07	34
4	1.3499E+07	46
5	1.1912E+07	61
6	1.0000E+07	82
7	7.7880E+06	112
8	6.0653E+06	142
9	4.7237E+06	172
10	3.6788E+06	202
11	2.8650E+06	232
12	2.2313E+06	262
13	1.7377E+06	292
14	1.3534E+06	322
15	1.1943E+06	337
16	1.0540E+06	352
17	9.3014E+05	367
18	8.2085E+05	382
19	7.2440E+05	397
20	6.3928E+05	412
21	5.6416E+05	427
22	4.9787E+05	442
23	4.3937E+05	457
24	3.8774E+05	472
25	3.0197E+05	502
26	2.3518E+05	534
27	1.8316E+05	564
28	1.4264E+05	594
29	1.1109E+05	624
30	8.6517E+04	654
31	6.7379E+04	686
32	5.2475E+04	716
33	4.0868E+04	746
34	3.1828E+04	776
35	2.8088E+04	792
36	2.6058E+04	802
37	2.4788E+04	808
38	2.1875E+04	823
39	1.9305E+04	838
40	1.7036E+04	853
41	1.5034E+04	868
42	1.3268E+04	883
43	1.1709E+04	898
44	1.0333E+04	913
45	9.1188E+03	928
46	8.0473E+03	943
47	7.1017E+03	958
48	6.2673E+03	973

49	5.5308E+03	988
50	4.8810E+03	1003
51	4.3074E+03	1018
52	3.8013E+03	1033
53	3.3546E+03	1048
54	2.9604E+03	1063
55	2.6126E+03	1078
56	2.3056E+03	1093
57	2.0347E+03	1108
58	1.7956E+03	1123
59	1.5846E+03	1138
60	1.3984E+03	1153
61	1.2341E+03	1168
62	1.0891E+03	1183
63	9.6112E+02	1198
64	7.4852E+02	1228
65	5.8295E+02	1258
66	4.5400E+02	1288
67	3.5358E+02	1318
68	2.7536E+02	1348
69	1.6702E+02	1408
70	1.0130E+02	1468
71	6.1442E+01	1528
72	3.7267E+01	1588
73	2.2603E+01	1648
74	1.3710E+01	1708
75	8.3153E+00	1768
76	5.0435E+00	1828
77	3.0590E+00	1848
78	1.1230E+00	1892
79	4.1399E-01	1927
80	1.5303E-01	1947

4 The SERPENT code and its ALFRED core model

4.1 Brief description of the SERPENT code

Serpent ([2], [10], and [18]) is a MC code written in C language and developed at VTT Technical Research Centre of Finland. Its original purpose was to fill the gap left by MCNP (developed by LANL [19]) for the multi-group cross-section energy collapsing and spatial homogenisation.

Since 2004, both the code capabilities and its user community have steadily grown, and nowadays Serpent is a reference tool for fission reactor physics research and development. With the latest code version (2.1.31), the users can now perform: cross-section homogenisation at the assembly level, burn-up calculations, coupled neutron-photon transport calculations, uncertainty evaluation and multi-physics simulations in coupling with the OpenFOAM toolbox [20].

The spatial homogenisation of the multi-group constants can be carried out in many ways. Thanks to the code flexibility, the user can decide to collapse the constants over arbitrary energy grids and to compute them for different reactor regions without too much effort.

Serpent 2 employs a 3D Constructive Solid Geometry (CSG) routine which enables the user to easily nest different universes (*i.e.*, sets of surfaces and cells for a detailed representation of each reactor spatial scale, from the fuel pin up to the FA/core level). This routine can thus be used to generate both 3D objects and 2D systems, like the traditional cells defined for lattice calculations. According to the geometrical model adopted, the stochastic transport of neutrons inside the core may require very different computational times as well as it can provide different levels of statistical accuracy.

Once the system is geometrically defined, the code reads the continuous-energy data (cross-sections, angular distributions, fission emission spectra, and so on) from the selected nuclear data library and evaluates them over a unionized energy grid, in order to reduce the memory consumption. After these preliminary steps, the code performs a bunch of “inactive” cycles in order to initialise the fission source[3]. At the end of the inactive cycles, the statistical scoring begins.

The effective HH cross-section for a certain reaction “x” over a group “g” is usually evaluate preserving the associated reaction rate:

$$\Sigma_{x,g} = \frac{\langle \Sigma_x(\boldsymbol{r},E) | \phi(\boldsymbol{r},E) \rangle_{V,g}}{\langle \phi(\boldsymbol{r},E) \rangle_{V,g}} \tag{4.1}$$

where the bracket notation indicates an integration over the volume “V” for each energy group “g”, while the other variables have the usual meaning (see §3.2).

While deterministic codes usually rely on application data libraries evaluated on a limited number of groups (*e.g.*, 33, 172, 175 and 1968 in ECCO), MC codes allow reading the continuous-energy data, avoiding any data pre-processing. Thanks to this energy management, Serpent 2 implicitly takes into account all the self-shielding effects, without any approximation. In addition, also the unresolved resonance region is treated more accurately, as the user can force the code to sample the data from the probability tables (the so-called p-table) in the A Compact ENDF (ACE) format specification files [21]. This option (available also in ECCO in a multi-energy-group form; §3.1) is particularly important for fast systems, where the flux in the unresolved resonance region assumes relevant values.

Another significant difference with respect to the ECCO cell code is the number of steps employed to evaluate equation (4.1) (identical to (3.1)). If the reference calculation route is

[3] In each cycle, a certain number of neutron histories is simulated: once the initial position, energy and flying direction of a particle are sampled, the particle starts moving and colliding with the medium, and its history ends when the particle leaks from the domain or it is absorbed.

employed, ECCO computes the integral in 4-5 steps (§3.2) while Serpent 2 firstly evaluates the effective cross-section on an intermediate group structure called *fine grid* (the WIMS-69 grid is the default choice, but the user can change it) and then it condenses the Σ_x over the *few-group grid* required by the user (33 in this study; see Table 3.1). If the number of energy groups required is larger than 69 (as for the 80 groups case, see Table 3.2), the *fine grid* coincides with the *few-group grid.*

The reason for this two-steps calculation is simplifying the implementation of the spatial homogenisation, which can be carried out by the code in two ways: the infinite-lattice procedure, which is always performed, and the leakage-corrected calculation, that has to be switched on by the user. The first routine does not introduce any correction to the code output, which thus strongly depends on the flux distribution in the geometry considered, while the leakage-corrected mode, known as B_1 calculation, applies a correction that takes into account the fact that the cells defined are usually sub- or super-critical. The main hypotheses made in Serpent 2 are that the flux can be factorised in angle, space and energy, so that an eigenvalue problem for the material buckling can be retrieved. This problem is solved iteratively until a spatial buckling providing a critical system is reached. The fundamental eigenfunction found to solve this problem is then employed to collapse the effective constants over the few-group structure instead of the non-corrected flux. Since the homogenisation is performed in two steps, the B_1 calculation mode does not take full advantage of the continuous-energy MC capabilities, as the leakage-corrected flux is evaluated over the few-group grid. Thanks to the options available in the code, however, the user can make the few-group and the fine-group structures overlap, to minimise the condensation errors.

The other, straightforward face of the medal is that Serpent, as an MC code, is affected by the statistical noise of its results, which – although subject to due management by the experienced user, to the price of increasing the computational burden – is inherent to its stochastic nature.

4.2 The Serpent models of the ALFRED core and calculation options adopted

The Serpent core model is based on the ERANOS one described in §2.2 (see Figs. 2.3 and 2.5) and it is shown in Figs 4.1 and 4.2.

As mentioned in §4.1, the quality of the (leakage) non-corrected calculation, which is the default one, improves with the reactor geometrical model: therefore, the most accurate set of multi-group constants would be evaluated scoring them over each assembly family with a 3D FC model, since the flux used to weight the cross-sections would be the most representative of a certain core region. However, the computational time of a full-core calculation would be too much for design calculation purposes. On the other hand, cell calculations, that are radially and axially infinite thanks to the reflective boundary conditions, are suitable for design but the results quality suffers from the geometrical simplification. This issue can be tackled for multiplying regions employing a B_1 calculation, but an alternative treatment for inactive regions like CRs, SRs or dummy reflector assemblies is needed.

The most intuitive option would be to simulate a mini-core made of one or more non-fissile assemblies in the centre (for which the homogenised and collapsed data are desired) surrounded by some rings of FA. This solution, however, would require a criticality calculation for each different inactive region, making the computational time comparable with the one of a FC calculation but much less accurate. Moreover, sensitivity studies would be required to assess the impact of the number of assemblies for both the active and inactive regions on the overall leakage effect.

To preserve the cell calculation main features (*i.e.,* a good compromise between computational speed and accuracy) also for non-fissile assemblies and, at the same time, to properly consider the leakage effects, the following strategy has been devised. The inactive region is studied

considering an isotropic source of particles with the same energy spectrum of the fuel and spatially distributed across a radially infinite cell with finite height, equal to the active height of the fuel rods. Since this approach can induce strong modifications in the flux energy spectrum due to the absence of the axial reflectors, the cell was surrounded by a top and a bottom layer of lead. This precaution allows obtaining a flux which is closer to the physical one and, at the same time, to increase the statistics of the groups at the lowest energies.

To sum up, the following models have been employed by Serpent (used as a cell code; §3) to carry out the spatial homogenisation and the energy collapsing.

1. The 3D FC heterogeneous model (see Fig. 4.1) with homogeneous core assemblies (FA, CR, SR, dummy) and barrel (SS and lead homogenised over a hexagonal area; see §2.3). Outside an external lead layer surrounding the barrel, void boundary conditions are imposed.
2. The most accurate 3D FC heterogeneous model with heterogeneous core assemblies (only the barrel and external lead were assumed homogeneous; see Fig. 4.2). Outside the external lead layer, void boundary conditions are imposed.
3. The 3D axially and radially infinite cells with heterogeneous core assemblies (see Fig. 4.3), with the B_1 calculation mode for FA and the source calculation one for non-fissile regions. The “cell” is built with a limited number of assemblies, but the imposition of reflective boundary conditions forces the particles to move in the system as if it were infinite.
4. The 3D radially infinite but axially finite cells with homogeneous core assemblies (see Fig. 4.4), with the B_1 calculation mode for FA and the source calculation one for non-fissile regions. The void boundary conditions are imposed axially, while reflective conditions are set radially.
5. The 3D radially infinite but axially finite cell with heterogeneous core assemblies (see Fig. 4.5), with the B_1 calculation mode for FA and the source calculation one for non-fissile zones. As before, void and reflective boundary conditions were settled axially and radially, respectively.

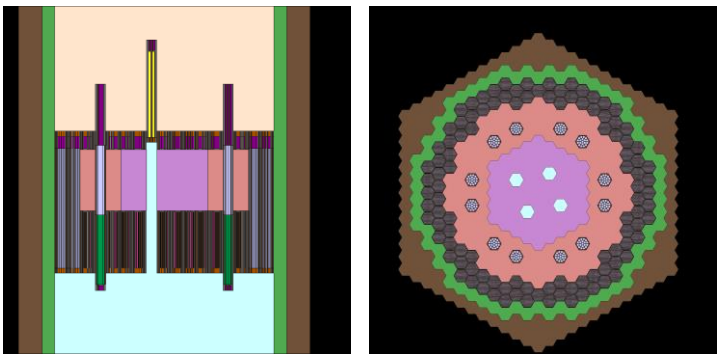

Figure 4.1 The 3D FC model with homogeneous core and barrel.

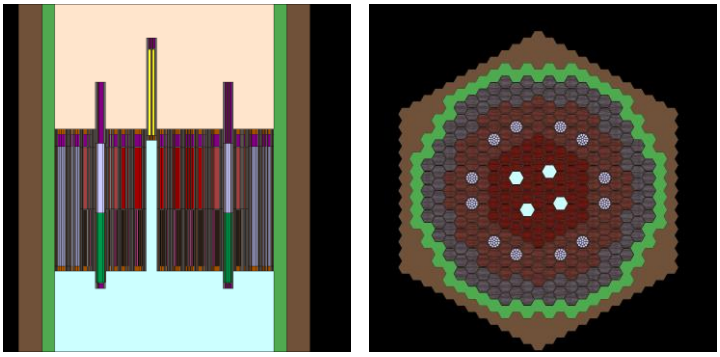

Figure 4.2 The 3D FC model with heterogeneous core assemblies (reference).

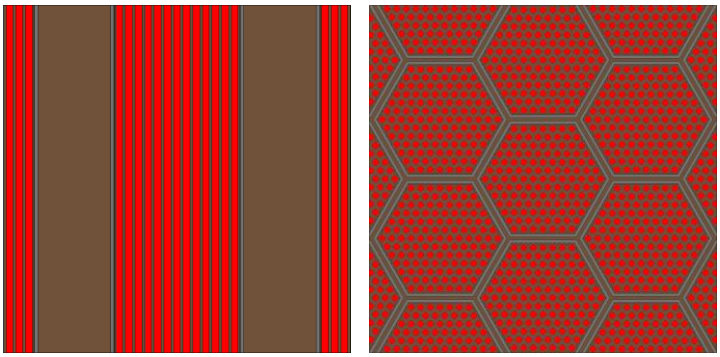

Figure 4.3 Axially and radially infinite model with heterogeneous assembly geometries.

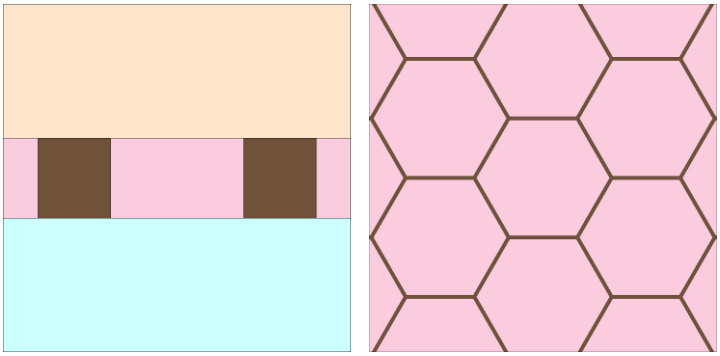

Figure 4.4 Axially finite and radially infinite model with homogeneous assembly geometries.

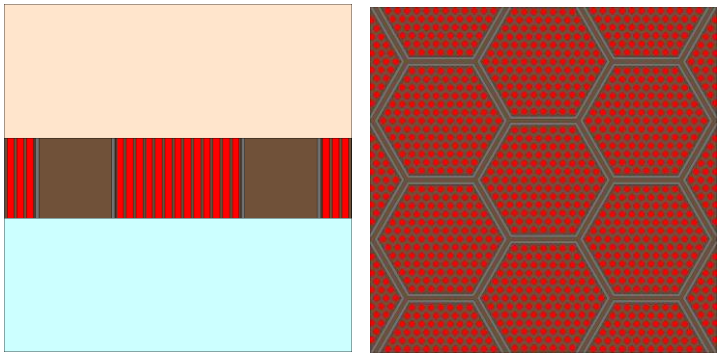

Figure 4.5 Axially finite and radially infinite cell model with heterogeneous assembly geometries.

The first model, in which the core assemblies are assumed to be spatially homogeneous (see Fig. 4.1), is an approximation of the second one (see Fig. 4.2), which can be assumed as a reference since it accurately represents the whole ALFRED core geometry. The other three models are the closest to the ECCO ones, since they represent a single region within a cell. However, there are some intrinsic differences between the stochastic and the deterministic approaches for cell calculations, in addition to the ones already mentioned.

The first difference is due to the neutron spectrum. In a fast reactor, the particles mean free path is longer than in moderated systems: therefore, in principle the cell dimensions can have a detrimental effect on the cross-sections accuracy, as the reflective boundary conditions would force the particles to collide within the cell itself, increasing artificially the reaction rate inside the region. However, since the ALFRED core composition can be roughly divided into three rings characterised by the same kind of assemblies (inner fuel, outer fuel and dummy elements), the error induced by considering an infinite cell is negligible, as shown in the results section (§5.2).

The second difference between deterministic and stochastic cell calculations is related to statistics. Since the presence of thermal particles inside the FA cell of a fast reactor is a rare event, the statistical error on the effective cross-sections can be significantly high at low energies. In principle there are many ways to reduce the statistical noise, like simulating a huge number of particles or employing some variance reduction techniques. However, the first approach could increase too much the computational time for design-oriented calculations, while the second is currently not possible in Serpent 2, as there are no variance reduction techniques available in the cross-sections generation based on flux-engeinvalue calculations. An alternative strategy could be “helping” the thermal population to increase, surrounding the cells axially with a layer of lead, so that more particles are slowed down and reflected back into the cell. This approach (*i.e.*, simulating an axially limited cell) would change the cell spectrum making it closer to the one of the FC (where the presence of the axial reflectors and of the other components, like pin insulators and plugs, softens the flux spectrum) by enhancing the calculation accuracy of its thermal component.

5 Comparison between ECCO and SERPENT cross-sections data

5.1 The most significant ECCO multi-group cross-section results

The macroscopic cross-section vectors (3.1) representing the most significant core zones are reported in the following graphs. They were obtained by ECCO at 33 energy groups by adopting the reference route described in §3.2 (and explained in more detail in §A.8). Fig. 5.1 shows the main cross-section results for the fuel inner (top) and outer (bottom) zones. It is evident that the elastic, capture and fission values are dominant over the whole spectrum, with the exception of the inelastic and (n,xn) threshold reactions above 0.1 and 2 MeV, respectively. Fig. 5.2 shows the CR (top) and SR (bottom) absorbing bundle (B_4C) cross-sections: the elastic and capture values are dominant over the whole spectrum, with the exception of the inelastic and (n,xn) threshold reactions at high energies.

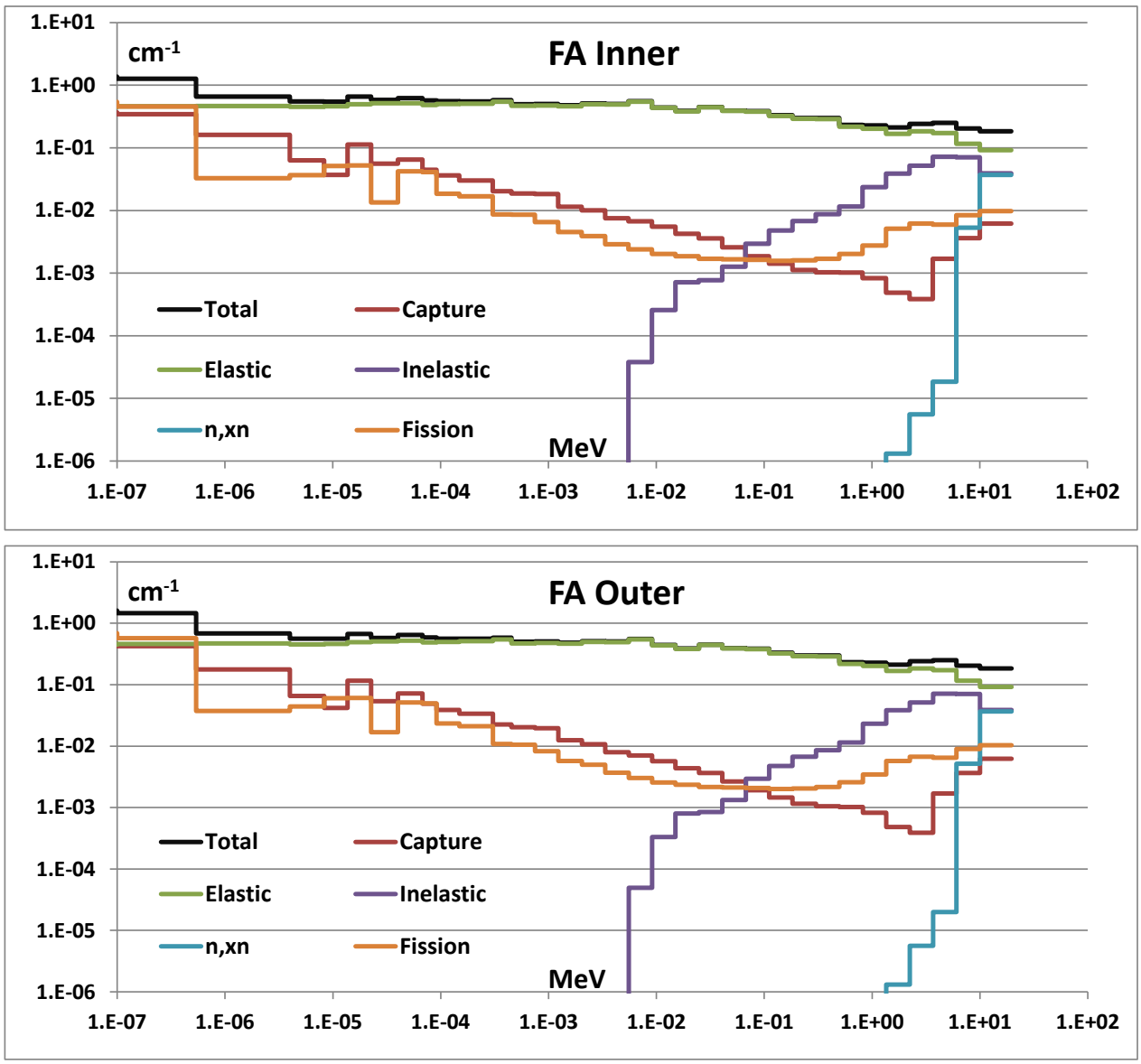

Figure 5.1 Fuel inner (top) and outer (bottom) macroscopic cross-sections (ECCO results: P_1 order, heterogeneous geometry, 33 energy groups).

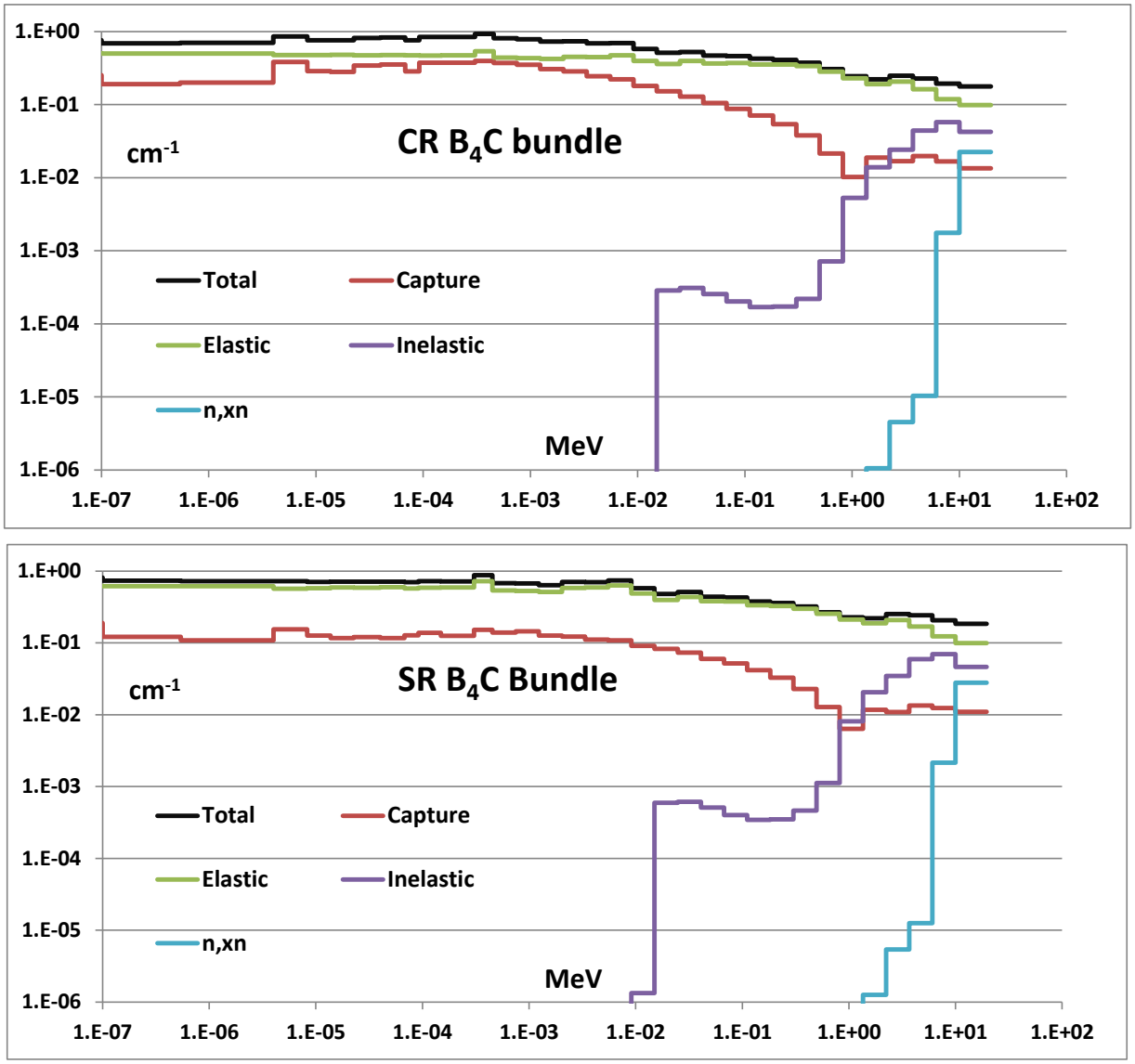

Figure 5.2 CR (top) and SR (bottom) absorbing bundles macroscopic cross-sections (ECCO results: P_1 order, heterogeneous geometry, 33 energy groups).

Fig. 5.3 shows the FA plena (left) and the pure lead (external to the barrel; right) cross-sections: it is evident that the elastic values are dominant over the whole spectrum, with the exception of the inelastic and (n,xn) threshold reactions at high energies.

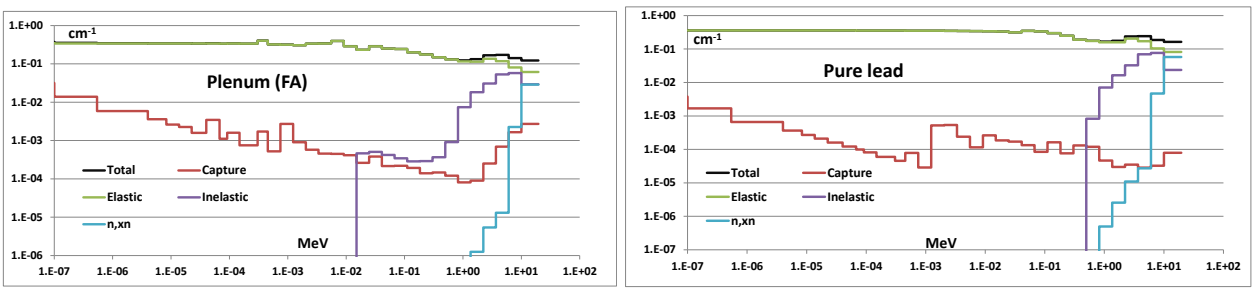

Figure 5.3 FA plena (left) and pure lead (right) macroscopic cross-sections (ECCO results: P_1 order, 33 energy groups).

5.2 Impact of different SERPENT models on multi-group cross-sections

This section reports some comparisons between the ECCO "reference" multi-group constants at 33 energy groups (§3.2) and the Serpent ones in the same energy grid obtained with different geometrical models and calculation options (§4.2). The results here reported are the most interesting and relevant ones obtained in this study. The analysis concerned mainly the transport cross-section (which is directly linked to the diffusion coefficient), the capture and the fission cross-sections. The scattering matrix comparison has been left for future evaluations.

While the multi-group constants reported in Figs. 5.1-5.3 are depicted in their "correct" histogram form, for easiness in the following graphs they are reported in a "punctual form" (with the multigroup cross-section values in correspondence of the upper energy limits) as they come out from the codes output. The complete set of the relative differences between the ECCO and Serpent cross-section results at 33 groups is reported in Appendix B.

5.2.1 Main comparisons for multi-group constants of fissile zones

Figs. 5.4, 5.5 and 5.6 show the transport, capture and fission cross-sections, respectively, scored on the ECCO-33 energy grid, for the inner fuel region. In all the three graphs, the lowest energy point in the green curve (Serpent B_1 option with a heterogeneous 3D cell axially infinite) is missing because of poor statistics.

An inspection of the data represented in these plots suggests that the Serpent models that provide the closest results to the ECCO "reference" HH cross-sections (light blue curve, §3.2) are the 3D FC and the axially limited infinite cell models (brown and purple curves, respectively), where both the inner and outer fuel regions are considered as spatially homogeneous.

The multi-group constants evaluated with Serpent usually come out with a Relative Standard Deviation (RSD) less than 1%, by the exception of the spectrum tails (first thermal and last fast groups, respectively), where it can reach values up to 30%.

For energies above 100 eV there is a good general agreement between the two codes with a relative error approximately below 10%, while at lower energies significant discrepancies (that can reach even 100% in the thermal region) appear. These larger differences are mainly due to Serpent statistical noise at low energies. Similar trends can be found also for the outer fuel region: they were omitted for the sake of conciseness.

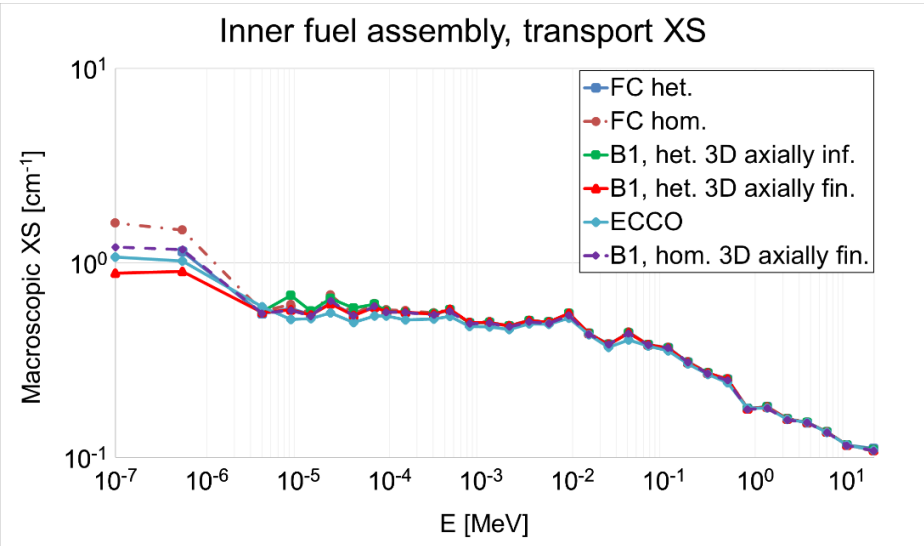

Figure 5.4 Transport macroscopic cross-sections at 33 energy groups of the inner fuel with the ECCO "reference" and different Serpent models.

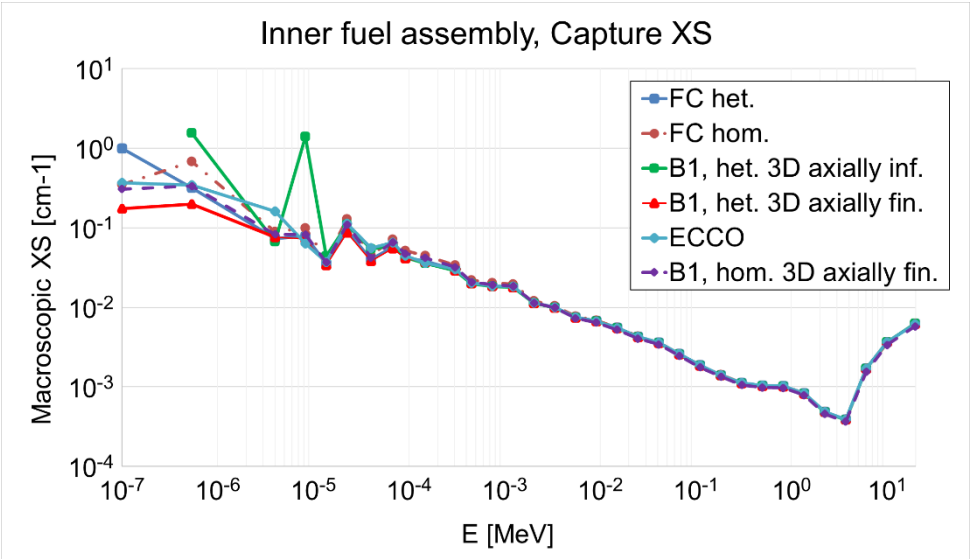

Figure 5.5 Capture macroscopic cross-sections at 33 energy groups of the inner fuel with the ECCO "reference" and different Serpent models.

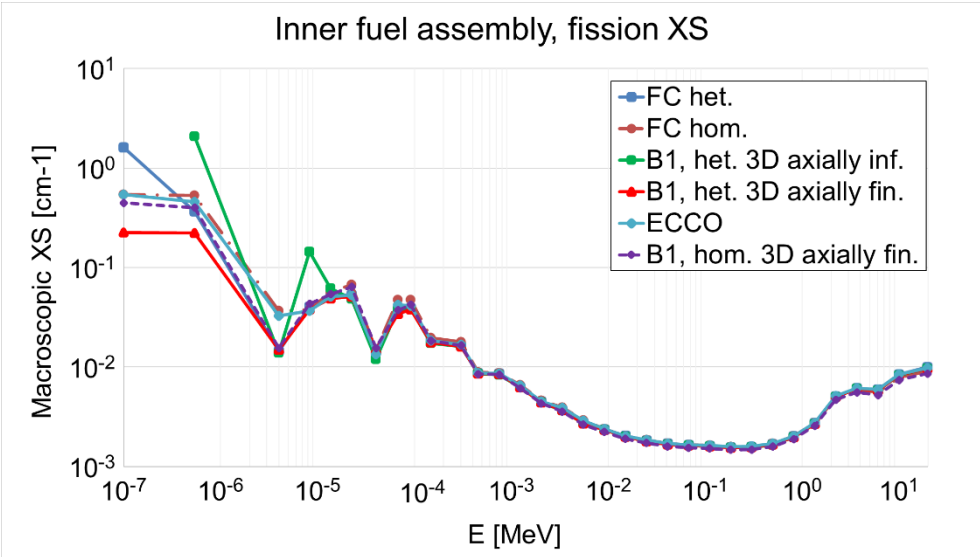

Figure 5.6 Fission macroscopic cross-sections at 33 energy groups of the inner fuel with the ECCO "reference" and different Serpent models different models.

Continuing to refer to the inner fuel zone, Fig. 5.7 shows the comparison between the transport, fission and capture multi-group constants on the more refined energy grid at 80 groups computed with the most accurate geometry models in ECCO (2D reference) and Serpent (3D FC with heterogeneous core assemblies, §4.2). As expected, the resonances region results to be described more accurately by both codes with respect to the 33-group results. Except for the first thermal and the last fast groups, the agreement between the codes for the fuel cross-sections results to be very good (0.1 ÷ 2%) and, in the light of the previous observations on Figs. 5.4-5.6, it is expected to improve if the Serpent 3D FC homogeneous model would be employed.

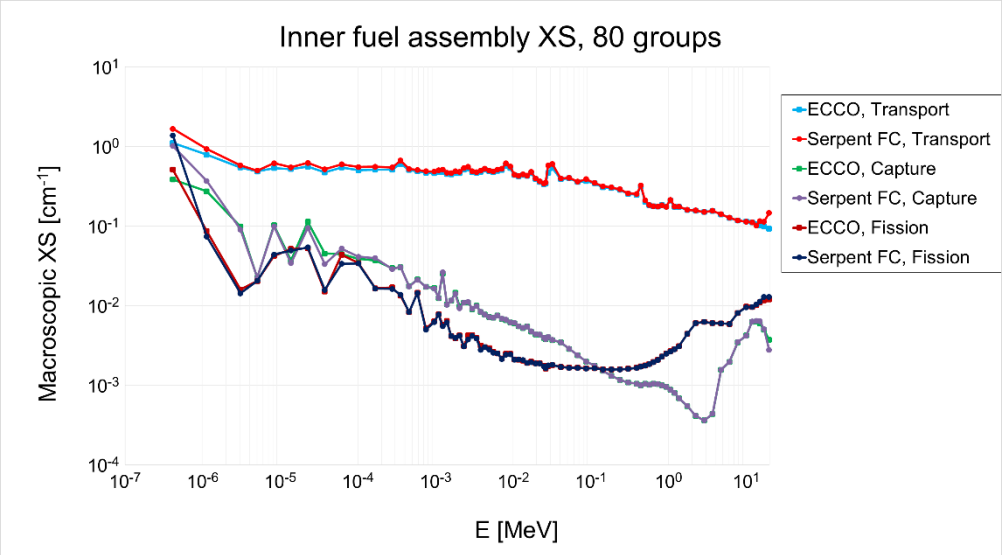

Figure 5.7 Inner fuel assembly multi-group constants (transport, capture and fission) scored on 80 energy groups with the ECCO (2D) and Serpent (3D FC) heterogeneous models.

5.2.2 Main comparisons for multi-group constants of non-fissile zones

Figs. 5.8 and 5.9 show the 33-group transport and capture cross-sections, respectively, for the SR absorbing region obtained with different Serpent models (§4.2) and the ECCO 2D reference one (§3.2). The lowest energy point in the Serpent brown curves (3D cell axially infinite) is missing because of poor statistics.

It can be observed that, for the transport cross-section (Fig. 5.8), the Serpent results with the 3D FC and the axially finite cell models are very similar among them and to the ECCO results. Differently, for the capture cross-sections (Fig. 5.9), the Serpent models axially finite and infinite differ significantly from the ECCO and the Serpent FC ones from thermal energies up to 10 eV. The behaviour of the latter two (that are the references for the code comparison analyses) is very similar, even if the ECCO values are greater than the Serpent FC ones over a large part of the spectrum. These discrepancies (that reach 40-50% in some energy groups, see Table 5.1 in §5.3) could be explained by the fact that Serpent samples the neutron flying directions without introducing any approximation in the transport process, while ECCO uses the P_1 approach. The P_1 model is a good transport approximation for scattering-dominated systems, while it may distort the physics in strong absorbing media as the SR absorbing bundles [22]. The discrepancies are less evident for higher energies above 10-100 keV, where the interaction between neutrons and the medium is weaker.

Fig. 5.10 shows the results for the transport and capture cross-sections at 80 groups obtained by the most accurate geometry models in ECCO (2D reference) and Serpent (3D FC with heterogeneous core assemblies, §4.2): also in this case there is a very good agreement for the transport values, whereas ECCO overestimates Serpent from thermal energies up to 10-100 keV for the capture ones (as in the 33-group case with 40-50% differences in some energy groups). Similar trends were found also for the CR absorbing region: they were omitted for the sake of conciseness.

It can be finally noticed that, with respect to ECCO that assumes an empirical value for the bucking factor (§3.2), Serpent does not allow to use the B_1 model for the non-fissile zones since they are non-multiplying media. As mentioned above, the axially limited cells with an active zone 60 cm thick were surrounded by top and bottom layers of lead to increase the statistics in the thermal region.

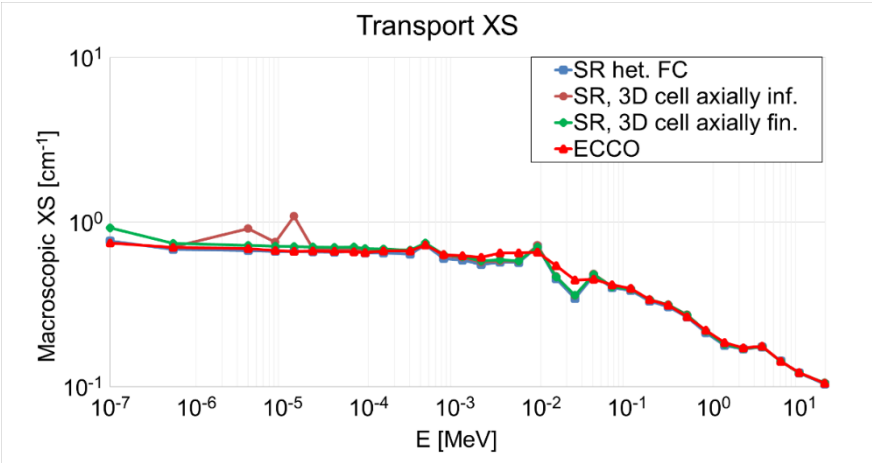

Figure 5.8 SR absorbing bundles transport cross-sections calculated at 33 energy groups with ECCO (2D) and different Serpent models.

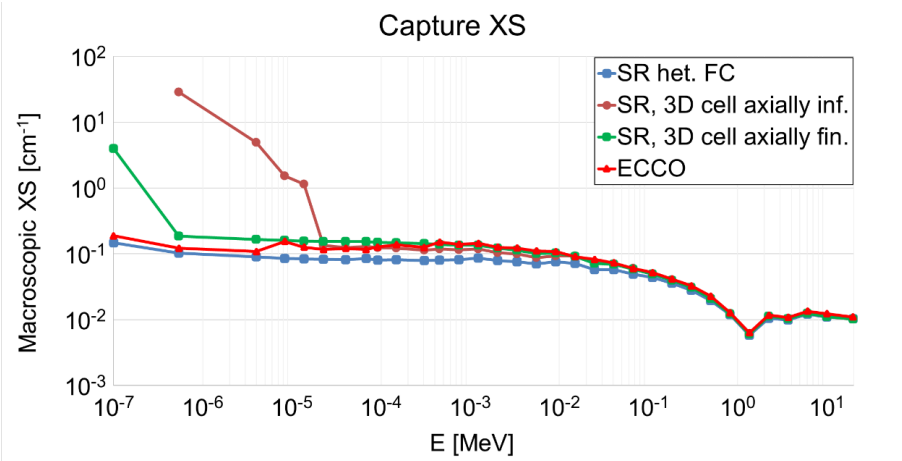

Figure 5.9 SR absorbing bundles capture cross-sections calculated at 33 energy groups with ECCO (2D) and different Serpent models.

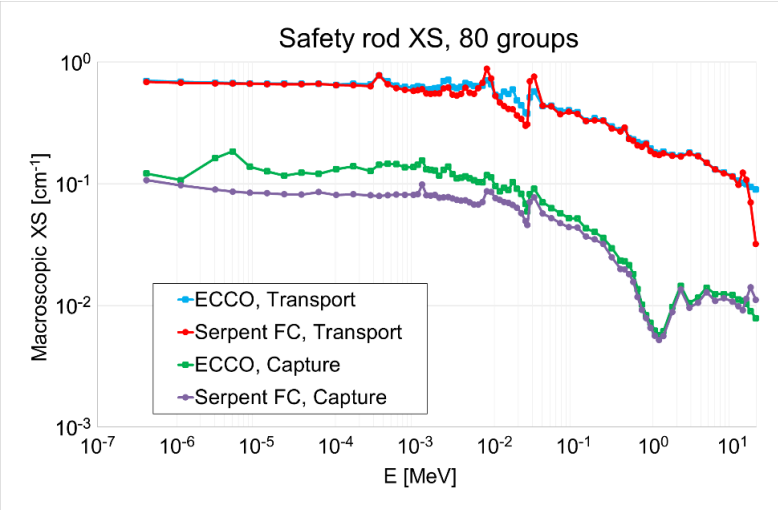

Figure 5.10 SR absorbing bundles macroscopic cross-sections (transport and capture) calculated at 80 groups with ECCO (2D) and Serpent (3D FC) heterogeneous models.

5.3 Discussion

An assessment of the different calculation options in Serpent for the multi-group constants generation has been reported previously (§5.2): a similar study was carried out also with ECCO and is reported in Appendix A, together with the description of the background mathematical theory. However, some general conclusions can be here drawn for the code benchmark in the cross-sections generation.

1. The poor statistics in the lowest energy groups is the major responsible for the discrepancies between ECCO and Serpent in the thermal region. This issue for fast systems has already been observed in [18] for the B_1 calculation mode, where it is suggested to merge the lowest energy groups in order to enhance the statistics.
2. The discrepancies between ECCO and Serpent tend to increase when the incident neutron energy decreases. Since at low energies the absorptions are more likely, the effect of the different angular approximations (P_1 vs. continuous directions) could explain such difference.
3. The highest discrepancies between ECCO and Serpent occur in the CR and SR absorbing regions. As shown in Fig. 5.11 the Serpent capture cross-sections are significantly lower than the ECCO ones in the 1 eV ÷ 10 keV range for both 33 and 80 energy-group-structure, thereby impacting on the reactivity worth evaluation by the two codes as reported in §6.
4. Generally, the agreement between the data computed with the different Serpent (and ECCO, §A.8) models is quite good but deserves more investigations (*e.g.*, a sensitivity analysis in order to quantify the impact of the multi-group constants computed with the different calculation modes on the main neutronics and thermal-hydraulics output parameters).

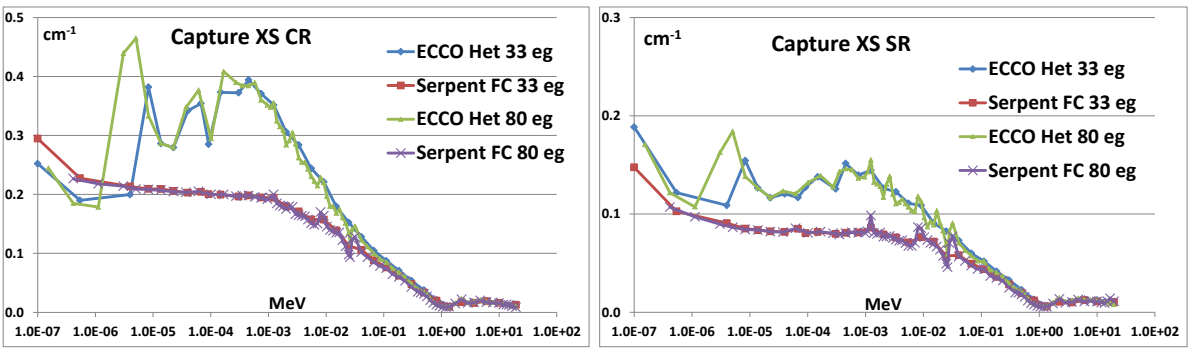

Figure 5.11 CR (left) and SR (right) absorbing bundles capture cross-sections at 33 and 80 energy groups calculated with ECCO (2D) and Serpent (3D FC) heterogeneous models.

The complete comparison between the "reference" cross-section results obtained by the two codes is reported in Appendix B, through the relative error between the 33-group values evaluated with Serpent (3D FC heterogeneous) and ECCO (2D heterogeneous) models. Table 5.1 summarises the results for the fuel inner, CR and SR absorbing bundle regions. As mentioned in §5.2.2, the fuel cross-sections differ significantly only at low energies (where the Serpent statistics is poor) while for the CR and SR absorbing bundles:

- the highest relative difference for the total cross-sections reaches 27% for the SR at 20 keV (group 14) and 23% for the CR at 0.5 keV (group 22);
- the highest relative difference for the capture cross-sections for the SR / CR reaches 47 / 50%, respectively, around 0.5 keV.

Table 5.1 Relative error [%] between the 33-group cross-sections evaluated with Serpent (3D FC heterogeneous model) and ECCO (2D reference model) for the fuel inner, CR and SR absorbing bundle regions (data ordered from the upper to the lower energy boundary).

(Serpent – ECCO) / ECCO

Energy group	Inner fuel				Safety rod B_4C			Control rod B_4C		
	Total	Transport	Capture	Fission	Total	Transport	Capture	Total	Transport	Capture
1	0.11%	2.21%	1.28%	1.65%	1.87%	-1.52%	-6.26%	0.11%	-0.97%	-4.48%
2	0.11%	0.04%	0.57%	-0.21%	-0.24%	-0.65%	-11.70%	0.28%	0.01%	-4.24%
3	0.05%	0.32%	0.39%	0.00%	0.24%	0.21%	-9.25%	0.82%	0.78%	-4.49%
4	-0.07%	-0.13%	0.22%	-0.19%	-1.26%	-1.30%	-8.62%	-0.57%	-0.68%	-5.94%
5	0.11%	0.54%	0.27%	-0.12%	-2.44%	-1.46%	-10.16%	-1.12%	-0.82%	-7.56%
6	-0.68%	1.27%	0.25%	-0.33%	-4.49%	-3.46%	-8.04%	-2.62%	-1.30%	-6.21%
7	-1.43%	0.09%	0.08%	-0.57%	-6.46%	-3.48%	-7.53%	-4.85%	-1.87%	-6.69%
8	-0.15%	4.17%	-0.02%	-0.65%	-7.20%	-0.52%	-15.01%	-5.79%	0.44%	-11.65%
9	-0.11%	1.91%	0.11%	-0.50%	-6.98%	-2.06%	-13.76%	-4.89%	-0.75%	-11.19%
10	-0.10%	2.18%	0.05%	-0.55%	-7.09%	-2.38%	-13.79%	-4.92%	-1.97%	-12.35%
11	0.08%	3.25%	0.09%	-0.55%	-6.76%	-3.05%	-15.63%	-3.90%	-1.27%	-12.82%
12	0.17%	1.46%	0.25%	-0.62%	-5.78%	-4.08%	-17.50%	-3.86%	-2.27%	-15.52%
13	0.11%	8.53%	0.32%	-0.11%	-4.61%	5.31%	-20.45%	-4.41%	0.71%	-17.30%
14	0.18%	3.76%	0.55%	-1.34%	-27.10%	-22.66%	-30.54%	-14.08%	-11.52%	-25.90%
15	0.11%	1.60%	0.52%	0.55%	-20.36%	-16.96%	-20.86%	-10.64%	-8.68%	-22.64%
16	0.07%	4.88%	0.57%	-1.26%	-2.52%	8.24%	-29.76%	-5.74%	-1.77%	-28.96%
17	0.12%	2.50%	-0.07%	-4.86%	-18.31%	-12.50%	-35.87%	-14.44%	-10.95%	-35.43%
18	0.23%	3.87%	-0.03%	-4.69%	-18.24%	-12.14%	-37.82%	-17.42%	-11.81%	-39.69%
19	0.09%	4.26%	-1.04%	-0.65%	-12.59%	-9.21%	-37.26%	-17.46%	-9.89%	-41.23%
20	0.00%	4.98%	-1.54%	-2.40%	-11.95%	-5.98%	-40.43%	-19.66%	-8.25%	-44.77%
21	0.24%	3.86%	0.18%	0.69%	-10.47%	-5.14%	-41.80%	-20.61%	-6.75%	-47.45%
22	0.73%	8.16%	-0.47%	0.52%	-16.48%	-0.08%	-46.57%	-22.72%	-5.84%	-49.69%
23	-0.46%	5.79%	-1.53%	-3.03%	-10.54%	-4.48%	-36.51%	-20.77%	-4.67%	-47.27%
24	1.40%	9.31%	4.86%	-0.29%	-10.07%	-2.77%	-40.67%	-19.61%	-3.84%	-46.47%
25	-0.62%	5.35%	-5.87%	-4.96%	-6.81%	-0.48%	-36.69%	-10.15%	-1.88%	-29.70%
26	-3.47%	11.17%	-11.80%	-14.81%	-6.37%	0.29%	-27.21%	-17.14%	5.99%	-42.34%
27	-6.10%	9.28%	-27.83%	8.34%	-6.73%	-0.83%	-32.24%	-15.70%	-0.02%	-40.64%
28	-4.95%	12.50%	-18.65%	1.94%	-6.43%	-1.19%	-29.38%	-8.72%	0.46%	-26.31%
29	0.21%	4.87%	-3.83%	1.52%	-5.30%	-0.40%	-33.81%	-8.51%	1.52%	-26.91%
30	6.03%	13.69%	24.15%	10.92%	-7.44%	-0.69%	-44.82%	-18.67%	0.96%	-45.17%
31	-15.97%	-7.72%	-54.29%	-55.52%	-6.43%	-2.58%	-16.67%	0.55%	4.75%	6.90%
32	-7.07%	12.54%	-7.75%	-19.90%	-6.71%	-2.86%	-15.63%	4.17%	5.90%	19.82%
33	117.3%	-100.0%	170.5%	197.6%	-7.12%	2.91%	-21.78%	5.02%	10.04%	16.87%

6 Comparison between ERANOS and SERPENT full-core analyses

6.1 ERANOS k_{eff} and reactivity worth value of shutdown systems

The ERANOS full-core calculations were carried out with the variational nodal method by adopting the multi-group constants evaluated by ECCO at the P_1 order. In the reference case:

- the macroscopic cross-sections were calculated with the P_1 consistent option, by adopting a 33 energy-group structure (starting from 172 groups and collapsing at 33 after the step through 1968 groups) and a 2D heterogeneous geometry model for almost all zones with few exceptions (see Table 2.2 and Fig. 2.5);
- the ERANOS calculations were performed with the P_1 order cross-sections and the P_3 order for the angular flux (in the TGV module, §3.1) at 33 energy groups.

Besides the reference case, the ECCO/ERANOS analyses were carried out also by adopting:

- a more refined 80 energy-group structure;
- a homogeneous description of the ECCO cells representing the fuel and the absorbing bundles of the shutdown systems;
- the P_1 order of the flux in ERANOS (instead of P_3).

Table 6.1 reports the values of the k_{inf} parameter for the fuel inner and outer regions evaluated by ECCO at 33 and 80 energy groups with homogeneous and heterogeneous cell geometry models. It appears evident that:

- the less accurate homogeneous model of the fuel cells yields a reactivity ~0.6-0.7% lower than the heterogeneous case for both energy structures;
- the more accurate energy refinement at 80 groups yields fuel cells reactivity ~0.3% lower than the 33-group case for both geometry models.

The ERANOS spatial calculations were performed at BoL with the CRs and SRs completely withdrawn and inserted. Table 6.2 reports the k_{eff} values with different ECCO cell calculation options in which the reference one is marked by a red box. As mentioned in §3, among the ECCO calculation options the cross-sections were generated by 2D heterogeneous geometry models of the cells starting from 172 groups (reference) and from 33 groups. Additionally, the flux and current spectra of the fuel calculated by Serpent (and condensed down to 33 groups) were used as weighting functions by ECCO in (3.1) to compute the cross-section constants of non-multiplying media. Even whether the Serpent fuel spectra are significantly different from the ECCO ones (see Figs A.1 and A.2 in §A.8), the cross-section values are not significantly different (see §A.8) and, as shown in Table 6.2, the impact on k_{eff} is almost negligible.

Table 6.1 ECCO k_{inf} values for the fuel inner and outer zones evaluated at 33 and 80 energy groups with homogeneous and heterogeneous cell geometry models.

Energy groups	k_{inf}	ECCO P_1		Hom -Het (pcm)	Hom -Het (%)
		Het	Hom		
33	Fuel Inn	1.34464	1.33483	-981	-0.73
	Fuel Out	1.53358	1.52465	-893	-0.58
80	Fuel Inn	1.34146	1.33163	-983	-0.73
	Fuel Out	1.52815	1.51923	-892	-0.58
80 -33 (pcm)	Fuel Inn	-318	-320		
	Fuel Out	-543	-542		
80 -33 (%)	Fuel Inn	-0.24	-0.24		
	Fuel Out	-0.35	-0.36		

Table 6.2 ERANOS k_{eff} values (P_3 flux moment, 33 energy groups) with different ECCO cell calculation options (and related P_1 cross-sections used in ERANOS).

k_{eff}	CR position	SR position	ERANOS P_3 33 eg , ECCO P_1 XS Het calcs from			Δk_{eff} (pcm)	
			172 eg*	33 eg**	Serpent 33 eg***	ERANOS 33 - 172	Serpent 33 - 172
CR & SR Out	Out	Out	1.07746	1.0771	1.07648	-36	-98
CR Inserted	In	Out	0.98148	0.98149	0.98115	1	-33
SR Inserted	Out	In	1.03763	1.03741	1.03682	-22	-81
CR & SR Ins	In	In	0.90121	0.90155	0.90126	34	5

* **REFERENCE**: all macroscopic cross-sections (XS) calculations in ECCO start with 172 energy groups (eg)

** All XS calculations in ECCO start with 33 eg

*** XS calculations of non-fissile zones start with flux & current spectra of fissile zone calculated by Serpent at 33 eg

Table 6.3 reports the k_{eff} values obtained with the P_1 order flux development in ERANOS. The comparison with the P_3 reference case (of Table 6.2) indicates that the P_1 order yields k_{eff} levels ~400-1000 per cent mille (pcm) lower in dependence of the CRs and SRs positions. The discrepancies between the P_N approximations increase when the CRs and SRs are fully inserted: this reasonably means that, when the system becomes less diffusive, the difference between the P_1 and P_3 flux orders increases.

Table 6.4 reports the ERANOS reference results (P_1 cross-sections, P_3 flux moment, 33 energy groups) for the CRs and SRs reactivity worth, together with the ERANOS P_1 (flux moment) ones obtained with the same ECCO heterogeneous geometry model and calculation options. Tables 6.3 and 6.4 show clearly that, in comparison with the reference P_3 results, the ERANOS P_1 approximation underestimates the k_{eff} level (from 400 up to 995 pcm) and overestimates the shutdown system anti-reactivity worth (from 172 up to 595 pcm).

Table 6.3 ERANOS k_{eff} values with P_1 (and P_3) flux moments at 33 energy groups.

k_{eff}	CR position	SR position	ECCO P_1 XS Het, ERANOS flux		Δk_{eff} (pcm)
			P_3	P_1	P_1 - P_3
CR & SR Out	Out	Out	1.07746	1.07346	-400
CR Inserted	In	Out	0.98148	0.97576	-572
SR Inserted	Out	In	1.03763	1.03212	-551
CR & SR In	In	In	0.90121	0.89126	-995

Table 6.4 ERANOS CRs and SRs reactivity worth results (P_3 and P_1 flux moments, 33 energy groups).

CR & SR worth	CR position	SR position	ECCO P_1 XS Het, ERANOS P_3 33 eg		ECCO P_1 XS Het, ERANOS P_1 33 eg		P_1 - P_3
			k_{eff}	Δk_{eff} (pcm)	k_{eff}	Δk_{eff} (pcm)	$\Delta(\Delta k_{eff})$ (pcm)
CR & SR Out	Out	Out	1.07746		1.07346		
CR Inserted	In	Out	0.98148	-9598	0.97576	-9770	-172
SR Inserted	Out	In	1.03763	-3983	1.03212	-4134	-151
CR & SR Ins	In	In	0.90121	-17625	0.89126	-18220	-595

Table 6.5 reports the ERANOS k_{eff} values obtained with the ECCO cells representing the fuel and the CR and SR absorbing bundle described with a homogeneous geometry. The results indicate that the spatial self-shielding effect (taken into account, to some extent, in the reference ECCO heterogeneous geometry models) for the fuel weights 743 pcm on the core reactivity. This effect for the CR and SR absorbing bundles is limited to 102 pcm since the calculations were carried out with both shutdown systems completely withdrawn.

Table 6.5 ERANOS k_{eff} values (P_3 flux moment, 33 energy groups) obtained with the fuel and absorbing bundle cells described with ECCO heterogeneous and homogeneous geometry models.

CR & SR Out	ECCO P_1 XS Het, ERANOS P_3 33 eg			
Fuel model	Het	Hom	Het	Hom
CR & SR model	Het	Het	Hom	Hom
k_{eff}	1.07746	1.07003	1.07644	1.06903
Δk_{eff} (pcm)		-743	-102	-843
Hom - Het		Δfuel	ΔCR&SR	Δfuel,CR&SR

Table 6.6 reports the ERANOS k_{eff} values and the reactivity worth of CR and SR: differently from Table 6.4, the macroscopic cross-sections of the absorbing bundles were created with the ECCO homogeneous cell geometry models. The comparison with the reference case (in which the CR and SR bundles are described in ECCO with 2D heterogeneous models) indicates that the CR and SR ECCO homogeneous models (not describing spatial self-shielding effects) yield:

- a decrease of ~100-660 pcm for the k_{eff} values;
- an increase of ~160-560 pcm for the shutdown systems performances;

in dependence of the CR and SR position. As shown in §A.8, the higher anti-reactivity obtained with ECCO homogeneous models of the CR and SR absorbing bundles is due to the higher values of the capture cross-sections at low energies: the difference steadily increases with decreasing energy up to the last thermal group, where the homogeneous results are two order of magnitudes greater than the heterogeneous ones (see Fig. A.13).

Table 6.6 ERANOS results (P_3 flux moment, 33 energy groups) for the reactivity worth of CR and SR (with ECCO homogeneous and heterogeneous cell models of absorbing bundles).

CR & SR worth	CR position	SR position	ERANOS P_3 33 eg , ECCO P_1 XS			Δ(CR&SR) worth
			All Het	CR & SR Hom	Hom - Het	
			k_{eff}		Δk_{eff} (pcm)	$\Delta(\Delta k_{eff})$ (pcm)
CR & SR Out	Out	Out	1.07746	1.07644	-102	
CR Inserted	In	Out	0.98148	0.97884	-264	-162
SR Inserted	Out	In	1.03763	1.03256	-507	-405
CR & SR Ins	In	In	0.90121	0.89461	-660	-558

Table 6.7 reports the ERANOS k_{eff} values obtained with 80 energy groups. The comparison with the reference ones at 33 groups indicates that the impact of the energy refinement on the core reactivity is almost negligible (< 100 pcm) for each position of the CRs and SRs.

Table 6.7 ERANOS k_{eff} values (P_3 flux moment) obtained with 80 energy groups.

k_{eff}	CR position	SR position	ECCO P_1 XS Het, ERANOS P_3 flux		Δk_{eff} (pcm)
			33 eg	80 eg	80 - 33
CR & SR Out	Out	Out	1.07746	1.07801	55
CR Inserted	In	Out	0.98148	0.98172	24
SR Inserted	Out	In	1.03763	1.03852	89
CR & SR In	In	In	0.90121	0.90163	42

Table 6.8 compares the ERANOS k_{eff} values obtained with the P_1 and P_3 flux moments at 80 energy groups. As in the 33 groups case (see Table 6.3), the P_1 values are ~400-1000 pcm lower than the P_3 ones in dependence of the CRs and SRs positions, meaning that the energy and the angular effects are loosely coupled.

Table 6.8 ERANOS k_{eff} values obtained with P_1 (and P_3) flux moments at 80 energy groups.

k_{eff}	CR position	SR position	ECCO P_1 XS Het, ERANOS 80 eg		Δk_{eff} (pcm)
			P_3	P_1	P_1 - P_3
CR & SR Out	Out	Out	1.07801	1.07399	-402
CR Inserted	In	Out	0.98172	0.97602	-570
SR Inserted	Out	In	1.03852	1.03301	-551
CR & SR In	In	In	0.90163	0.89171	-992

Table 6.9 reports the ERANOS k_{eff} values obtained with 80 energy groups by the ECCO cells of the fuel and absorbing bundles described with homogeneous geometries. As in the 33 groups case (see Table 6.5), the spatial self-shielding effect of the fuel weights ~740 pcm on the core reactivity and is limited to ~100 pcm for the CRs and SRs (in completely withdrawn position). The same impact is obtained with the P_1 flux moment used in ERANOS, shown in Table 6.10.

Table 6.11 reports the ERANOS results for the k_{eff} and reactivity worth values of CRs and SRs in which the cross-sections of the absorbing bundles were generated with the ECCO homogeneous geometry models. As in the 33 groups case (see Table 6.6), the k_{eff} values decreases by ~100-660 pcm and the shutdown systems performances increase by ~150-550 pcm (due to the spatial self-shielding not taken into account by the homogeneous models). The same effect is obtained with the P_1 flux development in ERANOS, as shown in Table 6.12.

Table 6.9 ERANOS k_{eff} values (P_3 flux moment, 80 energy groups) obtained with the fuel and absorbing bundle cells described by ECCO heterogeneous and homogeneous geometry models.

CR & SR Out	ECCO P_1 XS Het, ERANOS P_3 80 eg			
Fuel model	Het	Hom	Het	Hom
CR & SR model	Het	Het	Hom	Hom
k_{eff}	1.07801	1.07055	1.07695	1.06951
Δk_{eff} (pcm)		-746	-106	-850
Hom - Het		Δfuel	ΔCR&SR	Δfuel,CR&SR

Table 6.10 ERANOS k_{eff} values (P_1 flux moment, 80 energy groups) obtained with the fuel and absorbing bundle cells described by an ECCO heterogeneous and homogeneous geometry models.

CR & SR Out	ECCO P_1 XS Het, ERANOS P_1 80 eg			
Fuel model	Het	Hom	Het	Hom
CR & SR model	Het	Het	Hom	Hom
k_{eff}	1.07399	1.06659	1.07289	1.06551
Δk_{eff} (pcm)		-740	-110	-848
Hom - Het		Δfuel	ΔCR&SR	Δfuel,CR&SR

Table 6.11 ERANOS results (P_3 flux moment, 80 energy groups) for the reactivity worth of CR and SR (with ECCO homogeneous and heterogeneous cell models of absorbing bundles).

CR & SR worth	CR position	SR position	ERANOS P_3 80 eg , ECCO P_1 XS			Δ(CR&SR) worth
			All Het	CR & SR Hom	Hom - Het	
			k_{eff}		Δk_{eff} (pcm)	$\Delta(\Delta k_{eff})$ (pcm)
CR & SR Out	**Out**	**Out**	1.07801	1.07695	**-106**	
CR Inserted	**In**	**Out**	0.98172	0.979	**-272**	**-166**
SR Inserted	**Out**	**In**	1.03852	1.03611	**-241**	**-135**
CR & SR Ins	**In**	**In**	0.90163	0.89493	**-670**	**-564**

Table 6.12 ERANOS results (P_1 flux moment, 80 energy groups) for the reactivity worth of CR and SR (with ECCO homogeneous and heterogeneous cell models of absorbing bundles).

CR & SR worth	CR position	SR position	ERANOS P_1 80 eg , ECCO P_1 XS			Δ(CR&SR) worth
			All Het	CR & SR Hom	Hom - Het	
			k_{eff}		Δk_{eff} (pcm)	$\Delta(\Delta k_{eff})$ (pcm)
CR & SR Out	**Out**	**Out**	1.07399	1.07289	**-110**	
CR Inserted	**In**	**Out**	0.97602	0.97326	**-276**	**-166**
SR Inserted	**Out**	**In**	1.03301	1.03052	**-249**	**-139**
CR & SR Ins	**In**	**In**	0.89171	0.88478	**-693**	**-583**

6.2 Serpent k_{eff} and reactivity worth values of shutdown systems

Tables 6.13 and 6.14 report the k_{eff} and the shutdown systems reactivity worth values, respectively, obtained with two different Serpent FC models (§4.2): the reference (in which each core assembly is described with a heterogeneous geometry) and a simplified one where the fuel regions (both inner and outer) were approximated as spatially homogeneous. The homogeneous description of the fuel has an important impact over the k_{eff} value, leading to an underestimation of about 750-800 pcm (as in ECCO/ERANOS, §6.1). On the contrary, the influence of the fuel homogeneous model is quite limited on the estimation of the CRs and SRs worth.

Table 6.13 Serpent k_{eff} results with the 3D FC models with heterogeneous and homogeneous descriptions of the fuel region.

k_{eff}	CR position	SR position	All Het.	Fuel Hom.	Δk_{eff} (pcm)
CR & SR Out	**Out**	**Out**	1.07534	1.06746	**-788**
CR Inserted	**In**	**Out**	0.9866	0.97936	**-724**
SR Inserted	**Out**	**In**	1.04008	1.03204	**-804**
CR & SR In	**In**	**In**	0.91859	0.9112	**-739**

Table 6.14 Serpent results (3D FC heterogeneous model vs. 3D FC with homogeneous description of the fuel region) for the CR and SR reactivity worth.

Δk_{eff} (pcm)	CR position	SR position	All Het.	Fuel Hom.	$\Delta\Delta k_{eff}$ (pcm)
CR & SR Out	**Out**	**Out**			
CR Inserted	**In**	**Out**	-8874	-8810	**64**
SR Inserted	**Out**	**In**	-3526	-3542	**-16**
CR & SR In	**In**	**In**	-15675	-15626	**49**

6.3 Significant comparisons between ERANOS and Serpent reactivity results

Tables 6.15-6.18 show the comparison between the k_{eff}, CRs and SRs reactivity worth values obtained with:

- the Serpent 3D FC heterogeneous model;
- the ERANOS code by adopting different ECCO calculation options using a heterogeneous geometry description of the cells (that takes into account the self-shielding effect; §6.1).

Tables 6.19-6.22 show the same comparison (k_{eff}, CRs and SRs worth values) between the Serpent 3D FC heterogeneous model with a homogeneous geometry description of the fuel and the different ECCO/ERANOS calculation options. In Tables 6.20 and 6.22 the differences refer to the Serpent 3D FC model with homogeneous fuel (assumed as reference in them).

Tables 6.18 and 6.22 highlight a significant discrepancy (~400-1900 pcm) between the Serpent and ERANOS results for the CRs and SRs reactivity worth, with the deterministic values higher than the MC ones and the highest difference occurs with both CRs and SRs inserted. A further inspection indicates that, as expected (and similarly to the ECCO / ERANOS results; §6.1), the homogeneous fuel model in Serpent underscores the k_{eff} eigenvalue for each CRs and SRs position in comparison with the heterogeneous fuel model.

Table 6.15 k_{eff} values computed with the Serpent FC heterogeneous model and ERANOS with different ECCO calculation options (see Table 6.2 for the meaning of the asterisks).

k_{eff}					
CR position	SR position	SERPENT	ECCO P_1 XS Het, ERANOS P_3 flux		
			from 172 eg*	from 33 eg**	from Serpent 33 eg***
Out	Out	1.07534	1.07746	1.0771	1.07648
In	Out	0.986603	0.98148	0.98149	0.98115
Out	In	1.04008	1.03763	1.03741	1.03682
In	In	0.91859	0.90121	0.90155	0.90126

Table 6.16 Differences between the k_{eff} values computed with the Serpent FC heterogeneous model (assumed as reference) and ERANOS with different ECCO calculation options.

Δk_{eff} (pcm)					
CR position	SR position	SERPENT	ECCO P_1 XS Het, ERANOS P_3 flux		
			from 172 eg*	from 33 eg**	from Serpent 33 eg***
Out	Out	REF	212	176	114
In	Out		-512	-511	-545
Out	In		-245	-267	-326
In	In		-1738	-1704	-1733

Table 6.17 CRs and SRs reactivity worth computed with the Serpent FC heterogeneous model (assumed as reference) and ERANOS with different ECCO calculation options.

CR & SR worth (pcm)					
CR position	SR position	SERPENT	ECCO P_1 XS Het, ERANOS P_3 flux		
			from 172 eg*	from 33 eg**	from Serpent 33 eg***
Out	Out	REF			
In	Out	-8874	-9598	-9561	-9533
Out	In	-3526	-3983	-3969	-3966
In	In	-15675	-17625	-17555	-17522
CR+SR worth		-12400	-13581	-13530	-13499

Table 6.18 Difference between the CRs and SRs worth computed with the Serpent FC heterogeneous model (assumed as reference) and ERANOS with different ECCO options.

ΔWorth (pcm)					
CR position	SR position	SERPENT	ECCO P_1 XS Het, ERANOS P_3 flux		
			from 172 eg*	from 33 eg**	from Serpent 33 eg***
Out	Out	REF			
In	Out		-724	-687	-659
Out	In		-457	-443	-440
In	In		-1950	-1880	-1847
CR+SR worth			-1181	-1130	-1099

Table 6.19 k_{eff} values computed with the Serpent 3D FC model with homogeneous fuel and ERANOS with different ECCO calculation options.

k_{eff}					
CR position	SR position	SERPENT	ECCO P_1 XS Het, ERANOS P_3 flux		
			from 172 eg*	from 33 eg**	from Serpent 33 eg***
Out	Out	1.06746	1.07746	1.0771	1.07648
In	Out	0.979361	0.98148	0.98149	0.98115
Out	In	1.03204	1.03763	1.03741	1.03682
In	In	0.91120	0.90121	0.90155	0.90126

Table 6.20 Differences between k_{eff} values computed with the Serpent 3D FC model with homogeneous fuel (assumed as reference) and ERANOS with different ECCO options.

Δk_{eff} [pcm]					
CR position	SR position	SERPENT	ECCO P_1 XS Het, ERANOS P_3 flux		
			from 172 eg*	from 33 eg**	from Serpent 33 eg***
Out	Out	REF	1000	964	902
In	Out		212	213	179
Out	In		559	537	478
In	In		-999	-965	-994

Table 6.21 CRs and SRs reactivity worth computed with the Serpent 3D FC model with homogeneous fuel and ERANOS with different ECCO calculation options.

CR & SR worth (pcm)					
CR position	SR position	SERPENT	ECCO P_1 XS Het, ERANOS P_3 flux		
			from 172 eg*	from 33 eg**	from Serpent 33 eg***
Out	Out			REF	
In	Out	-8810	-9598	-9561	-9533
Out	In	-3542	-3983	-3969	-3966
In	In	-15626	-17625	-17555	-17522
CR+SR worth		-12352	-13581	-13530	-13499

Table 6.22 Difference between the CRs and SRs worth computed with the Serpent FC with homogeneous fuel (assumed as reference) and ERANOS with different ECCO options.

ΔWorth (pcm)					
CR position	SR position	SERPENT	ECCO P_1 XS Het, ERANOS P_3 flux		
			from 172 eg*	from 33 eg**	from Serpent 33 eg***
Out	Out	REF		REF	
In	Out		-788	-751	-723
Out	In		-441	-427	-424
In	In		-1999	-1929	-1896
CR+SR worth			-1229	-1178	-1147

The observed discrepancy between the worth of the absorbers as estimated by the two codes is mainly due to the differences in the capture cross-section values (§5.3), with ECCO/ERANOS overscoring Serpent even up to 40-50% (see Table 5.1 in §5.3).

6.4 Radial and axial flux traverses (ERANOS vs Serpent)

As shown in §6.3 (Tables 6.18 and 6.22), a significant discrepancy between the ERANOS and Serpent results was found for the CRs and SRs reactivity worth, which is credited as a direct consequence of the difference between the macroscopic cross-section values of their absorbing regions generated by the two codes (§5.3).

Additionally, the energy-integrated flux distributions within the core were compared along the couple of directions shown in Fig. 6.1 with both shutdown systems fully withdrawn and inserted. The flux is calculated/sampled by ERANOS/Serpent over all the length of the FA, CR, SR, dummy and barrel (homogenised with lead) assemblies lying along the directions named “Cut 1” and “Cut 2”. In the following graphs the two radial traverses at the core mid-plane are shown together with some significant axial traverses in the assemblies along them: the complete set of the axial traverses is reported in Appendix C.

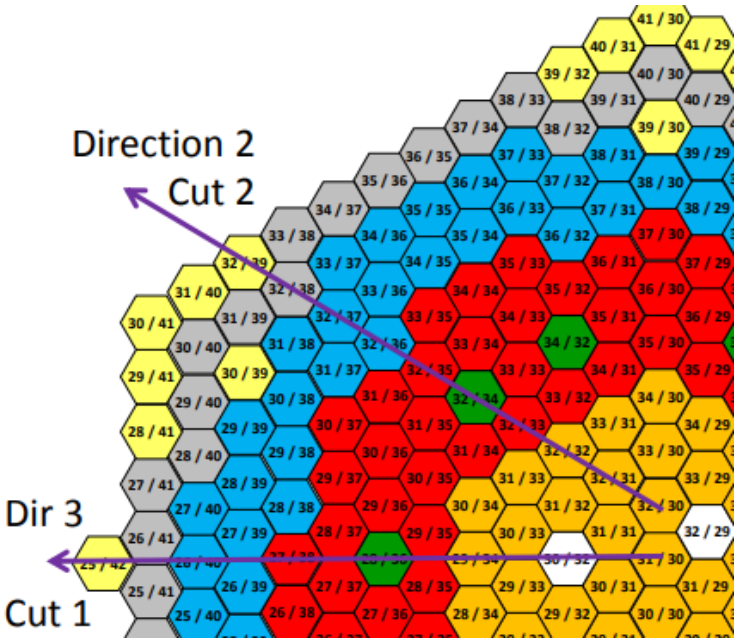

Figure 6.1 Radial directions (“Cut 1” and “Cut 2”) investigated in the ALFRED core (fuel inner/outer: orange/red; CR/SR: red/white; dummy/pure lead: blue/yellow; barrel homogenised with lead: grey).

Fig. 6.2 shows the ERANOS and Serpent radial flux traverses calculated at core mid-plane along the Cut 1 (top) and Cut 2 (bottom) directions with both CRs and SRs completely withdrawn. Fig. 6.3 reports the flux traverses in the same directions (Cut 1 on the left, Cut 2 on the right) with the CRs completely inserted and the SRs withdrawn. In Fig. 6.4 the flux traverses refer to the SRs completely inserted and the CRs withdrawn, while in Fig. 6.5 both shutdown systems are completely inserted. In these radial flux profiles (Figs. 6.2-6.5), the black vertical lines represent the boundary between the different kind of assemblies (inner and outer FA, CR, SR, dummy, barrel and external lead). It appears evident that, especially in the latter case with both shutdown systems inserted, the depression of the flux computed with ERANOS is decisively more pronounced than the Serpent one, thus reflecting the ≅10% higher anti-reactivity calculated for the shutdown systems insertion.

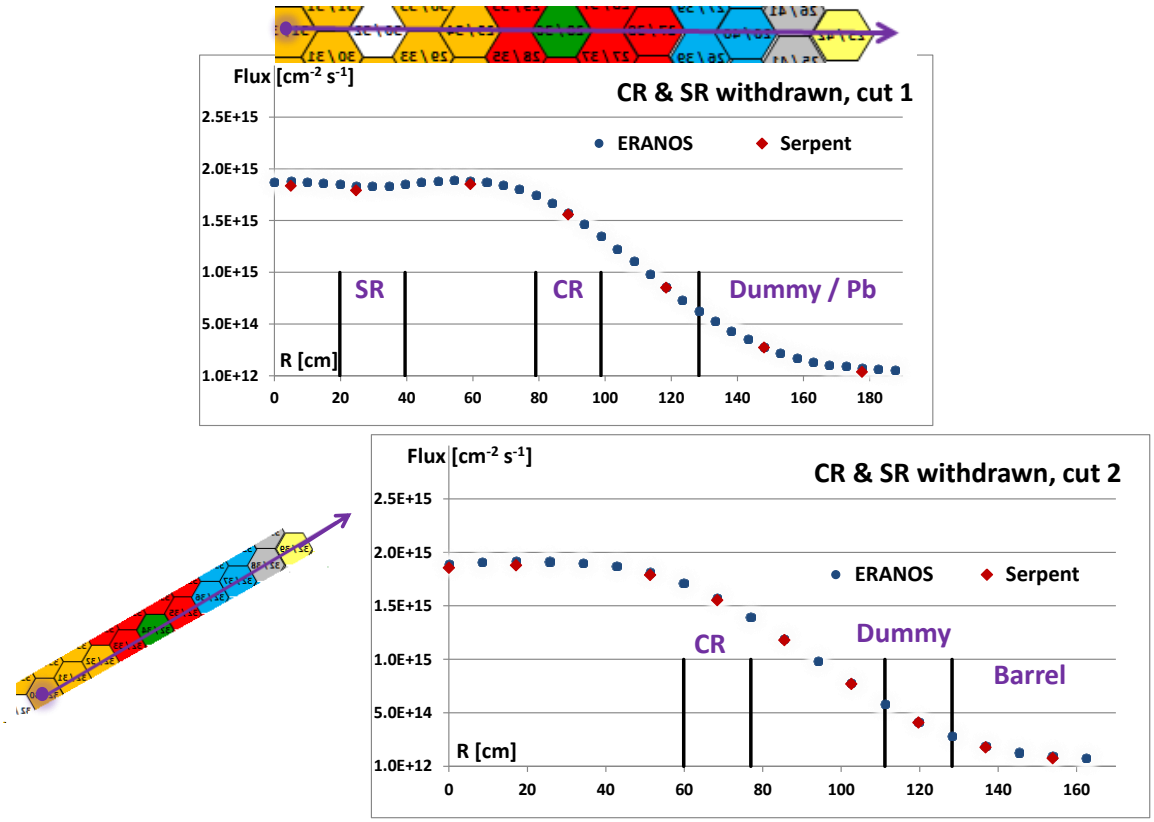

Figure 6.2 ERANOS and Serpent radial flux traverses at core mid-plane along Cut 1 (top) and Cut 2 (bottom) with both CRs and SRs completely withdrawn.

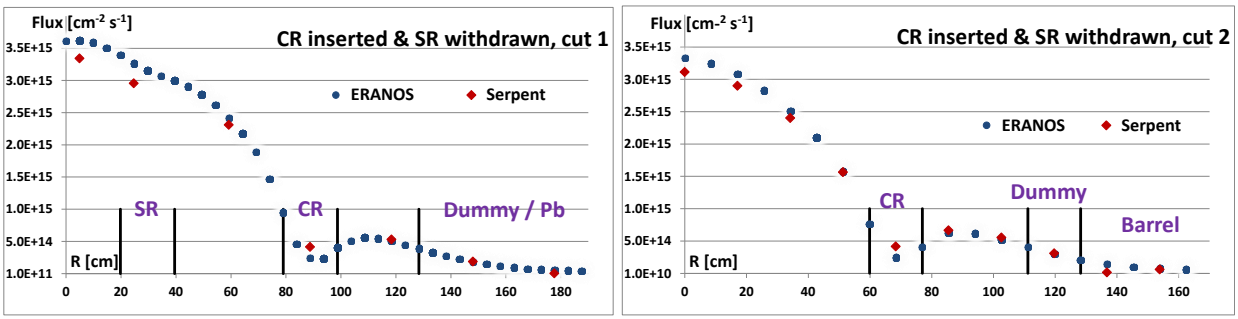

Figure 6.3 ERANOS and Serpent radial flux traverses at core mid-plane along Cut 1 (left) and Cut 2 (right) with CRs completely inserted and SRs completely withdrawn.

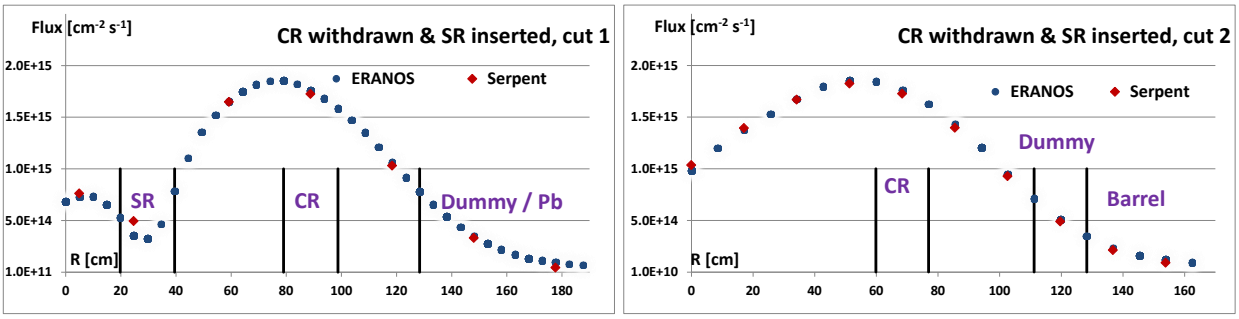

Figure 6.4 ERANOS and Serpent radial flux traverses at core mid-plane along Cut 1 (left) and Cut 2 (right) with SRs completely inserted and CRs completely withdrawn.

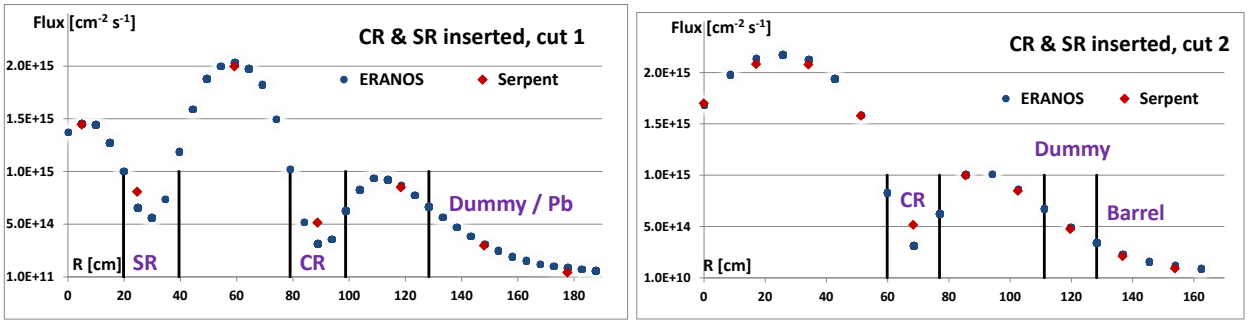

Figure 6.5 ERANOS and Serpent radial flux traverses at core mid-plane along Cut 1 (left) and Cut 2 (right) with both CRs and SRs completely inserted.

As shown in Figs. 6.6 (for the core configuration with the SRs inserted and the CRs withdrawn) and 6.7-6.8 (for both CRs and SRs inserted), the difference between the ERANOS and Serpent flux shapes is even more evident by considering the axial traverses. The graph in Fig. 6.6 refers to the flux traverses calculated/sampled by ERANOS/Serpent in the fuel inner and SR assemblies along Cut 1. Figs. 6.7 and 6.8 refer to the values in the fuel, CR and SR assemblies along Cut 1and Cut 2, respectively.

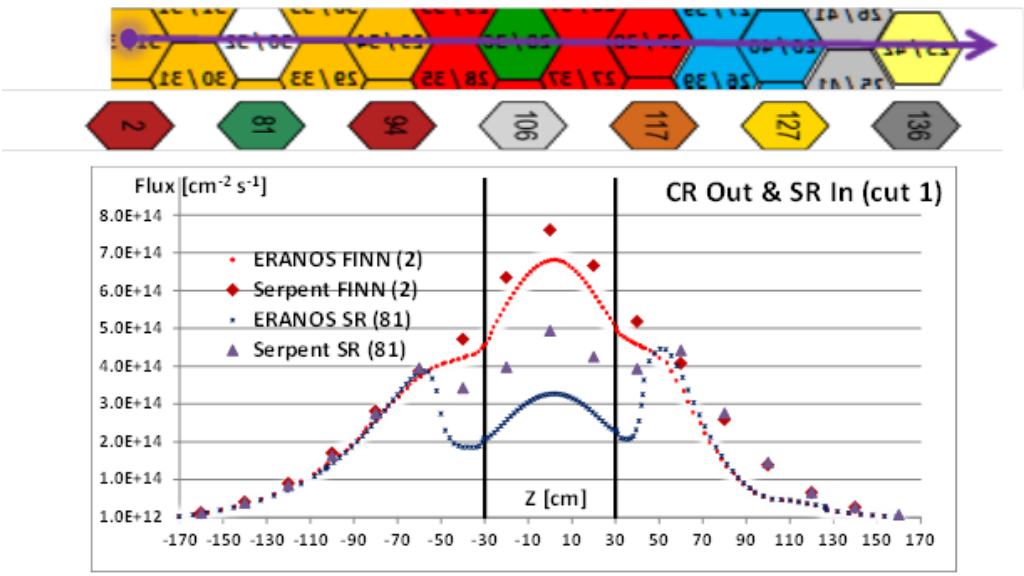

Figure 6.6 ERANOS and Serpent axial flux traverses in fuel inner and SR positions along Cut 1 with the SRs inserted and the CRs withdrawn (black vertical lines represent the fissile length boundaries).

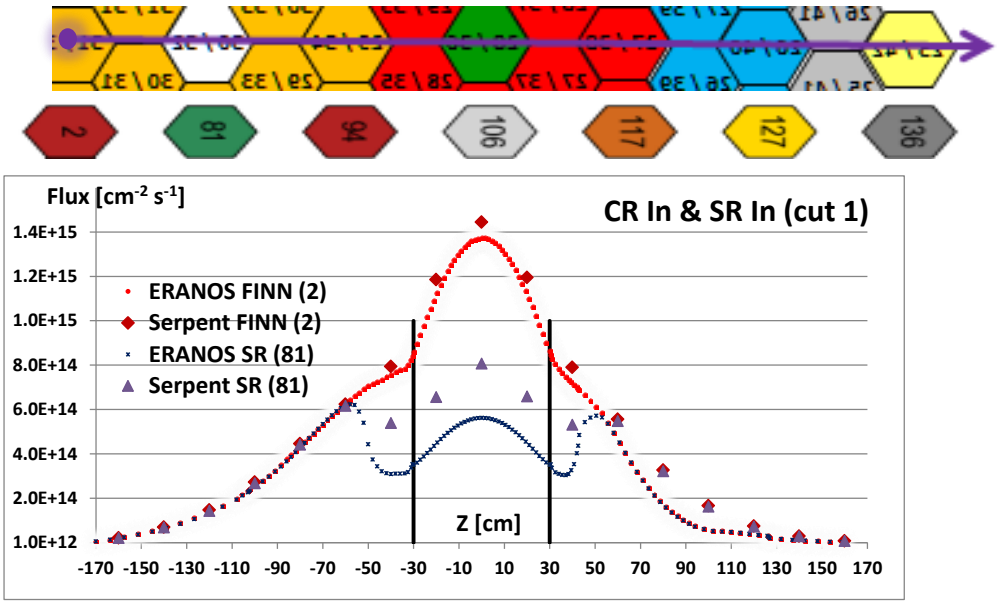

Figure 6.7 ERANOS and Serpent axial flux traverses in fuel inner and SR positions along Cut 1 with both CRs and SRs completely inserted (black vertical lines represent the fissile length boundaries).

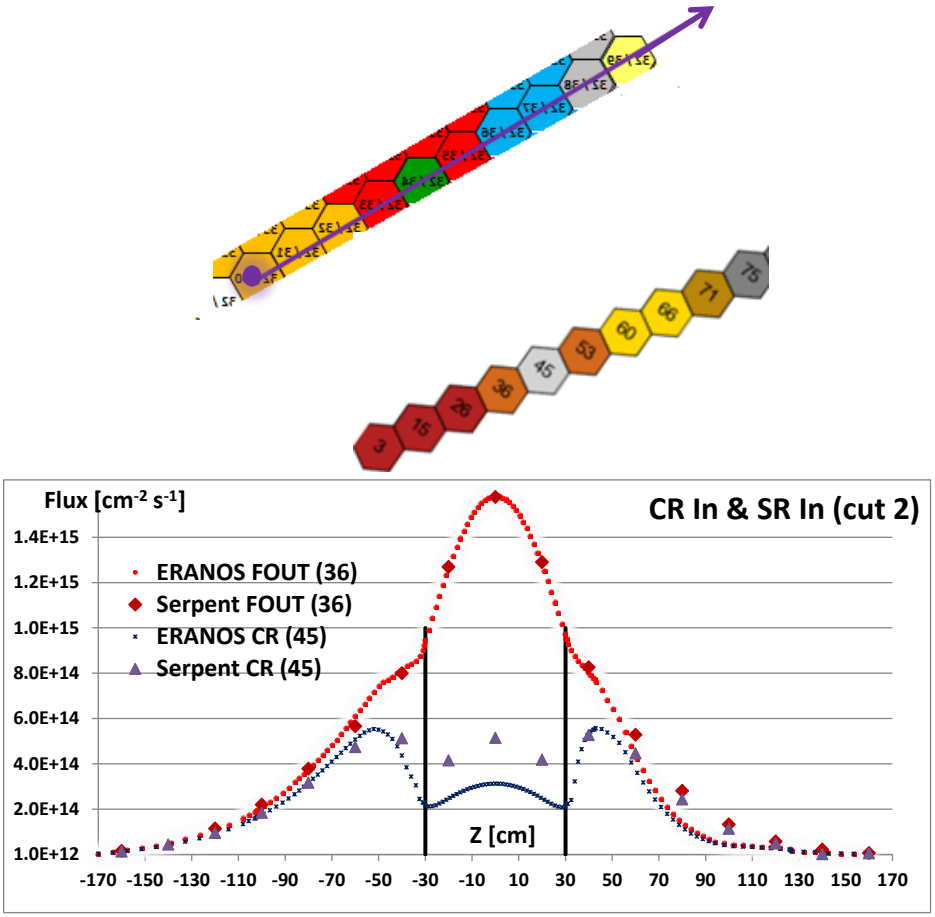

Figure 6.8 ERANOS and Serpent axial flux traverses in fuel outer and CR positions along Cut 2 with both CRs and SRs completely inserted (black vertical lines represent the fissile length boundaries).

7 Concluding remarks

An extensive and accurate comparison between the deterministic ECCO/ERANOS code and the Serpent MC code was performed through the neutronic analyses of the ALFRED (LEADER version) core. The core models were accurately compared, and their consistency verified in detail. The comparison was limited to the full power (300 MW) BoL (fresh fuel) conditions with the shutdown systems completely withdrawn (*i.e.*, over-critical core) and inserted.

By adopting the JEFF-3.1 nuclear data library, some fundamental physical quantities produced by deterministic and MC methods were compared:

- the macroscopic cross-sections - produced by the ECCO cell code in the ERANOS system and by Serpent used as a “cell code” - representative of every core region;
- the core reactivity, by obtaining only ~100 pcm difference between the two codes when both shutdown systems are completely withdrawn;
- the reactivity worth of the shutdown systems and the impact of their insertion on the spatial flux distribution within the core.

The energy behaviour of the ECCO and Serpent macroscopic cross-sections was evaluated referring to different models and calculation options, the most significant of which dealing with:

- the energy refinement of the homogenised cross-section values (at 33 and 80 groups);
- the homogeneous and heterogeneous cell geometry models of the most important core regions, as the fuel and the absorbing bundles of the CRs and SRs;
- other simplified geometry models available in Serpent used as a “cell code”. The evaluation of the multi-group constants was performed with radially infinite and both axially infinite or finite geometries, besides the reference (and more accurate) values obtained with a 3D FC heterogeneous model.

An overall agreement between the two codes was found for the most part of the 33-group results in both fissile and non-fissile zones, with the exception of the first fast group and the ones at low energies, where the Serpent RSD is quite large. The largest discrepancies appear in:

- the fuel spectra (used in ECCO as weighting function to evaluate multi-group constants of non-fissile regions) at epithermal and thermal energies;
- the capture cross-section values of CR and SR absorbers (B_4C pin bundles) below 10 keV;
- even in a smaller amount, relevant differences were found also in the fuel pins plugs, the axial reflectors and the core barrel (made of SS and the surrounding lead in the ERANOS and Serpent 3D hexagonal models). A significant contribution to this discrepancy could be due to the spectrum “softening” occurring in these regions (far from the active zone) that is correctly reproduced by the Serpent 3D FC model and not by the 2D ECCO ones.

The difference between the fuel spectra evaluated by the two codes has a negligible impact on the main features investigated here at the core level (k_{eff}, CRs and SRs worth). In fact, the fuel spectra calculated by Serpent were also loaded in ECCO as weighting functions to evaluate the cross-sections of non-multiplying media, but their impact on the results was found negligible.

The poor statistics of Serpent cross-section results in the lowest energy groups should be the major responsible of the high discrepancies with ECCO in the thermal and epithermal regions. In spite of the limited Serpent RSD values, a systematic difference between the two codes was found for the CR and SR capture cross-sections in a large part of the spectrum below 10 keV. This could find a reasonable explanation in the increasing effect of captures at these energies, which enhances the impact of the approximation order for the direction of flight that is requested in deterministic codes (P_1 in ECCO vs. Serpent continuous directions).

The difference between the CR and SR capture cross-sections (that reaches up to ~50% in the energy group around 0.5 KeV) represents the primary cause for the ≅10% discrepancy between

the reactivity worth performances evaluated by the two codes. It is worth mentioning that this discrepancy turns out to be in line with the usual overestimation introduced by deterministic codes with respect to stochastic ones in fast reactors analyses.

To confirm this assertion, the focus of the study was shifted to the full-core scale. Besides the calculation of the k_{eff}, CRs and SRs reactivity worth values, the spatial distributions of the total flux within the core were evaluated and compared in a couple of radial directions (passing through CR and SR positions). Actually, when the absorbers are inserted, the comparison between the (radial and axial) flux traverses shows a more pronounced flux depression predicted by the deterministic code, which supports the differences in absorbers' capture cross-sections as the main cause of the discrepancy.

The absorbers worth and flux depression overscoring obtained with deterministic methods can be explained also by the different angular treatment adopted, *i.e.*, continuous sampling in Serpent vs. P_1 in ECCO/ERANOS. Even though at full-core level a P_3 order of the flux was used in ERANOS, it inherited the physical information generated by ECCO, where cross-sections were calculated at the P_1 order. It is in fact well known that the P_1 approximation is acceptable for scattering-dominated (*i.e.*, non-absorbing) media, which is not the case for the absorbers or the other structures at the core boundary mentioned before. The ERANOS calculations were performed also at the P_1 order of the flux: the discrepancy with the reference P_3 flux order increases when the CR and/or SR are inserted, confirming that the angular treatment becomes fundamental when the system is less diffusive.

An intra-comparison among the ECCO cross-sections of the CR and SR absorbing bundles was performed calculating them with both 2D heterogeneous (reference) and homogeneous cell geometry models. The significant differences appearing at low energies demonstrated that the heterogeneous description is fundamental to properly take into account the spatial self-shielding effects. In the ALFRED fast spectrum core this discrepancy yields and increase of the shutdown systems performances of ~0.15÷0.55 % only in dependence of the CR and SR position.

The impact on the cross-sections of the energy treatment employed by MC and deterministic codes (continuous vs. multi-group) resulted to be very limited. However, it can be noticed that:

- the cross-sections values at 80 groups are surely more accurate for the description of the unresolved resonance region (in comparison with the 33-group ones);
- due to the continuous energy treatment, actually there are no significant differences between the Serpent results at 33 and 80 groups outside the unresolved resonance region;
- the ECCO cross-sections at 80 groups are slightly closer to the Serpent ones (than the 33-group values) *e.g.*, for the fuel fission cross-sections at low energies;
- the energy and the angular effects are loosely coupled;
- the impact of the ECCO and Serpent geometry models (heterogeneous vs. homogeneous) in the less diffusive regions is decisively higher than the one due to energy refinement[4].

It can be finally noticed that, in spite of significant differences in the computational burden associated to the two codes (about 12 hours for a fuel cell calculation and 1-2 hours for a non-fissile one in Serpent vs. less than 1 hour in ECCO for both), Serpent can be profitably employed as "cell code" for producing multi-group constants, provided that enough computational power is available. In addition to the higher model accuracy with respect to ECCO, Serpent also allows an easy and independent update of the nuclear data libraries, which can be produced converting the ENDF-6 format into the ACE one without too much effort.

[4] In the fuel, the cross-sections at 80 groups yield a cell reactivity ~0.3% lower than the 33-group case, but the k_{eff} values are almost identical. Otherwise, a fuel cell homogeneous model yield k_{eff} value ~0.7% lower.

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Appendix A: Theoretical background for determistic analyses

A.1 Aim and rationale

This appendix describes the theoretical basis (from [23] and [24]) for the steady-state neutronic analyses carried out with deterministic methods. The major part of the mathematical equations discussed is focused on the calculation methods adopted for the creation of the macroscopic cross-sections representing every fissile and non-fissile core region. Afterwards, the exact relationship between these multi-group constants – here created by the ECCO cell code (§3) – and the ones used by ERANOS in full-core spatial calculations is examined in detail.

Several approximated methods have been developed to solve the Boltzmann transport equation, notably to what concerns the direction of neutron motion. The most popular and practical approach is represented by the S_N discrete ordinate method where the angular flux is discretised for the angle variable according to a finite number of directions. An alternative approach is the P_N method, which exploits a Legendre moments expansion for the angular flux. In both cases, the space and energy dependencies of the neutron flux are managed by discrete meshes.

In the ERANOS system, the multi-group constants at the P_N order are calculated with ECCO by solving the neutron transport equation for each cell with iterative methods, starting from the nuclear data evaluated in multi-group energy structures (*e.g.,* JEFF-3.1 library in this work) such as: the microscopic cross-sections, the scattering function (§A.2) and their variations with energy for all the isotopes and neutron reactions of interest. Then, the energy dependence of the neutron flux (and its angular Legendre components) can be calculated in order to evaluate the energy condensed and spatially homogenised macroscopic cross-sections.

In the following subsections, the calculation methodologies adopted by deterministic codes are described starting from the time-independent neutron transport equation in its P_N representation, where the neutron flux "$\phi(\boldsymbol{r},\boldsymbol{\Omega},E)$" has to be evaluated (§A.2). Then, the multi-energy-group transport equation is introduced (§A.3) – based on the multi-group flux "$\phi_g(\boldsymbol{r},\boldsymbol{\Omega})$" – that is successively limited to the P_1 approximation adopted in this work (§A.4). The multi-group P_1 transport equations are described in detail for both fissile and non-fissile zones, together with their diffusion approximation and a brief recall of the one-group theory for homogeneous media.

As mentioned before, the analysis is focused on the mathematical basis adopted by cell codes to evaluate the multi-group constants of every core region (§A.5), in which the main goal is an accurate modelling of the cell geometry heterogeneity ("$\boldsymbol{r}$") and of its energy ("E") representation (1968 groups for most of the nuclides in ECCO). As described in §3.2, the cross-sections are then homogenised in space and collapsed to 33 (or 80) energy groups before being used by ERANOS for the full-core analyses, here carried out with the variational nodal method [14-16].

For easiness, even if the "reference" cross-sections were calculated with heterogeneous geometry models for the most important core regions, the solution in fundamental mode of the multi-group diffusion equation is shown, together with the buckling definition for both fissile and non-fissile zones (§A.6). The adoption of the homogeneous geometry model allows an easier description of the ECCO equations at the first order, that can be solved with P_N and B_N calculation methodologies using consistent and inconsistent approximations (§A.7). The impact of the different methods on the cross-section values was examined and resulted to be almost negligible. Differently, the multi-group constants evaluated in the non-scattering-dominated media (*e.g.*, CR and SR absorbing bundles) at low and intermediate energies with the "reference" heterogeneous cell geometry models differ significantly from the ones calculated with homogeneous models (§A.8). This result points out the importance of the correct simulation of the self-shielding effects that are not taken into account by homogeneous cell models, as well as the significant role of the angular flux distribution in less-diffusive media.

Finally, after a brief description of the P_N equations solved by ERANOS in the full-core analyses[5] (§A.9), the relationship between the multi-group constants – calculated with ECCO and used by ERANOS – is examined in detail (§A.10). While the vectors and matrices are produced by ECCO at the P_1 order, the ERANOS cross-sections are retrieved in the P_0 transport (P_0), P_0 consistent (P_0 total) and P_1 approximations. In the "reference" full-core calculations, the P_1 order was used for the cross-sections and the P_3 moments for the energy-spatial distribution of the flux (see §6.1).

A.2 The time-independent transport equation

A.2.1 The P_N approximation

The time-independent transport equation in its integro-differential form for a one-dimensional (x) slab geometry can be written as:

$$\mu \frac{\mathrm{d}\phi(x,\mu,E)}{\mathrm{d}x} + \Sigma(x,E)\phi(x,\mu,E) = \\ = \int \Sigma(x,E')f(x;E' \to E,\mu' \to \mu)\,\phi(x,\mu',E')\mathrm{d}E'\mathrm{d}\mu' + Q(x,\mu,E) \quad \text{(A.1)}$$

where:

- $(\mathrm{d}x,\mathrm{d}\mu,\mathrm{d}E)$ is the infinitesimal control volume centred around (x,μ,E);
- "$\phi(x,\mu,E)$" is the energy-dependent angular flux in position "x";
- the first term represents the neutron leakage;
- the last term "Q" is the source, that can be internal in fissile zones (*i.e.*, fissions) or external for not multiplying media;
- "μ" and "μ'" are the incoming and exiting directions (actually in a more general 2D or 3D geometry) of the neutrons (with energy "E'" and "E", respectively) whose interactions with the nuclei is represented by the scattering function "f";
- the total macroscopic cross-section "$\Sigma(x,E)$" can be calculated from the microscopic ones "$\sigma^i(T(x),E)$" (in units of barn) depending on the temperature "T" of each nuclide "i" as:

$$\Sigma(x,E) = \sum_i N_i\,\sigma^i(T(x),E) \qquad [\mathrm{cm}^{-1}] \quad \text{(A.2)}$$

where "N_i" is the atomic density of the nuclides in the medium (in units of barn^{-1} cm^{-1}).

By assuming that the angular variation of the scattering function depends only on the scattering angle (*i.e.*, isotropic medium with azimuthal symmetry in more general 2D and 3D geometries), "Σf" in (A.1) can expanded in a set of Legendre polynomials[6] "P_n" depending only on the cosine of the scattering angle "μ". In a 1D slab geometry it can be written as:

$$\Sigma(x,E')f(x;E' \to E,\mu) = \sum_{n=0}^{\infty} \frac{2n+1}{2}\Sigma_{sn}(x,E' \to E)P_n(\mu) \quad \text{(A.3.a)}$$

where the expansion coefficients "Σ_{sn}" (with n = 0, 1, 2…) are:

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[5] In which the main objective is the accurate description of the spatial "$\boldsymbol{r}$" and angular "$\boldsymbol{\Omega}$" distribution of the flux within the core by adopting a broad energy structure (33 or 80 groups).

[6] Spherical harmonics symmetrical around the rotation axis.

$$\Sigma_{sn}(x, E' \to E) = \int_{-1}^{1} \Sigma(x, E') f(x; E' \to E, \mu)\, P_n(\mu) d\mu. \qquad \text{(A.3.b)}$$

The first term "Σ_{s0}" in (A.3.a) represents the isotropic events (as the inelastic scattering from heavy nuclides), while from the second one "Σ_{s1}" the angular dependence of the interaction events is taken into account (*e.g.*, elastic scattering).

The angular distribution of the neutron flux "ϕ" and source "Q" can also be expressed as an expansion on Legendre polynomials:

$$\phi(x, \mu, E) = \sum_{n=0}^{\infty} \frac{2n+1}{2} \phi_n(x, E) P_n(\mu) = \frac{1}{2}\phi_0 + \frac{3}{2}\mu\phi_1(x, E) + \cdots \qquad \text{(A.3.c)}$$

$$Q(x, \mu, E) = \sum_{n=0}^{\infty} \frac{2n+1}{2} Q_n(x, E) P_n(\mu) = \frac{1}{2}Q_0 + \frac{3}{2}\mu Q_1(x, E) + \cdots \qquad \text{(A.3.d)}$$

where the nth moment of the flux and source are given by:

$$\phi_n(x, E) = \int_{-1}^{1} \phi\,(x, \mu, E)\, P_n(\mu) \mathrm{d}\mu \qquad \text{(A.3.e)}$$

$$Q_n(x, E) = \int_{-1}^{1} Q\,(x, \mu, E)\, P_n(\mu) \mathrm{d}\mu. \qquad \text{(A.3.f)}$$

By using the property of orthogonality of Legendre polynomials, the energy-dependent transport equation at the Nth order can be expressed by set of N+1 differential equations (for n = 0, 1, 2…, N) that is still equivalent to (A.1):

$$(n+1)\frac{\mathrm{d}\phi_{n+1}(x, E)}{\mathrm{d}x} + n\frac{\mathrm{d}\phi_{n-1}(x, E)}{\mathrm{d}x} + (2n+1)\Sigma(x, E)\phi_n(x, E) =$$
$$= (2n+1)\int \Sigma_{sn}(x; E' \to E)\, \phi_n(x, E')\mathrm{d}E' + (2n+1)Q_n(x, E) \qquad \text{(A.4)}$$

where the terms with n>0 in the integral (for neutrons entering in collisions with energy E' and exiting with energy E) act as anisotropic terms (as the source terms Q_1, Q_2 ...).

A.2.2 The P_1 approximation

The P_1 order approximation is obtained by considering n = 0 and 1 in (A.4) by imposing:

$$\phi_2(x, E) = 0 \qquad \text{(A.5.a)}$$

Therefore, the system (A.4) is limited to a couple of equations:

$$\frac{\mathrm{d}\phi_1(x,E)}{\mathrm{d}x} + \Sigma(x, E)\phi_0(x, E) = \int \Sigma_{s0}(x, E' \to E)\, \phi_0(x, E')\mathrm{d}E' + Q_0(x, E) \qquad \text{(A.5.b)}$$

$$\frac{\mathrm{d}\phi_0(x,E)}{\mathrm{d}x} + 3\Sigma(x, E)\phi_1(x, E) = 3\int \Sigma_{s1}(x, E' \to E)\, \phi_1(x, E')\mathrm{d}E' + 3Q_1(x, E) \qquad \text{(A.5.c)}$$

The P_1 approximation is valid for large systems (>> neutron mean free path) in which the angular flux is not significantly anisotropic and can be represented by the first two terms of Legendre polynomials.

A.2.3 The energy-dependent diffusion approximation

The P_1 order equations (A.5) can be approximated in a form leading to the energy-dependent diffusion theory[7] by expressing the neutron current "ϕ_1" through the Fick's law involving the diffusion coefficient "D" and the spatial gradient of the flux "ϕ_0":

$$\phi_1(x,E) = -D(x,E)\frac{\mathrm{d}\phi_0(x,E)}{\mathrm{d}x} \tag{A.6.a}$$

The equation (A.6.a) is equivalent to (A.5.c), assuming an energy-dependent diffusion coefficient defined as:

$$D(x,E) = \frac{1}{3\,\Sigma_{tr}(x,E)} = \frac{1}{3\left[\Sigma(x,E) - \frac{\int \Sigma_{s1}(x;E'\to E)\phi_1(x,E')dE'}{\phi_1(x,E)}\right]} \tag{A.6.b}$$

whose denominator in square brackets represents the energy-dependent transport cross-section "$\Sigma_{tr}(x,E)$", that is the total cross-section "Σ" with the so-called transport correction in which the scattering term of the first order is subtracted. Afterwards, the P_0 equation (A.5.b) can be written as:

$$\begin{aligned} -\frac{\mathrm{d}}{\mathrm{d}x}\left[D(x,E)\frac{\mathrm{d}\phi_0(x,E)}{\mathrm{d}x}\right] + \Sigma(x,E)\phi_0(x,E) = \\ = \int \Sigma_{s0}(x,E'\to E)\,\phi_0(x,E')\mathrm{d}E' + Q_0(x,E) \end{aligned} \tag{A.6.c}$$

For the sake of easiness, the first moment of the source "Q_1" has been neglected. Similar but a little more intricate equations can be retrieved by adding the term "$\frac{Q_1(x,E)}{\Sigma_{tr}(x,E)}$" on the right side of the Fick's law approximation (A.6.a). In this case, the equation (A.6.c) could be written at the P_1 order through an energy-dependent diffusion coefficient involving the first moment of the source.

A.3 The multi-group transport equation

The energy-dependent equations in the linear system (A.4) can be expressed in a multi-group form – with "G" energy groups – without implying any restrictions on the energy-dependent cross-sections. For each energy group g ($E_g < E < E_{g-1}$), the macroscopic constants are represented by multi-group vectors (*e.g.*, $\Sigma_{c,g}(x)$ for capture events) and matrices for the differential cross-sections (*i.e.*; $E_{g'} \rightarrow E_g$ in scattering events). By replacing the integral over E' with a sum over all the energy groups g', the system (A.4) can be written at N^{th} order thorough the G(N+1) multi-group equations:

$$\begin{aligned} (n+1)\frac{\mathrm{d}\phi_{n+1,g}(x)}{\mathrm{d}x} + n\frac{\mathrm{d}\phi_{n-1,g}(x)}{\mathrm{d}x} + (2n+1)\Sigma_{n,g}(x)\phi_{n,g}(x) = \\ = (2n+1)\sum_{g'=1}^{G}\Sigma_{sn,g'\to g}(x)\phi_{n,g'}(x) + (2n+1)Q_{n,g}(x) \end{aligned} \tag{A.7.a}$$

[7] The diffusion theory is equivalent to the P_1 approximation only for time-independent problems with isotropic sources (fissions or external neutrons) and scattering events (*i.e.*, $Q_n = \Sigma_{sn} = 0$ for n>0).

where the nth moments of the neutron flux "$\phi_{n,g}$" and of the source "$Q_{n,g}$" are given by the expansion coefficients (A.3.c) and (A.3.d), respectively, integrated in each energy group g:

$$\phi_{n,g}(x) = \int_g \phi_n(x,E)\mathrm{d}E \tag{A.7.b}$$

$$Q_{n,g}(x) = \int_g Q(x,E)\mathrm{d}E. \tag{A.7.c}$$

The system (A.7a) is still exact (from a theoretical point of view) and equivalent to the system (A.4) and to the transport equation (A.1). For each order "n", the moments of the multi-group cross-sections (vectors of G elements) are defined as:

$$\Sigma_{n,g}(x) = \frac{\int_g \Sigma(x,E)\phi_n(x,E)\mathrm{d}E}{\phi_{n,g}(x)} \tag{A.7.d}$$

for the total cross-section (and similarly for the other reactions "Σ_x"). Otherwise, the moments of the differential cross-sections (matrices of G x G elements) are defined as:

$$\Sigma_{sn,g'\to g}(x) = \frac{\int_{g'} \phi_n(x,E') \int_g \Sigma_{sn}(x,E'\to E)\mathrm{d}E\mathrm{d}E'}{\phi_{n,g}(x)}. \tag{A.7.e}$$

where "$\Sigma_{sn,g'\to g}$" are the nth order terms of the flux-averaged transfer cross-sections between group g' and g including the diagonal terms g' = g.

A.4 The multi-group P_1 approximation

In the multi-group form, the system of P_N equations (A.7.a) at the first order (P_1) becomes a system of 2G equations:

$$\frac{\mathrm{d}\phi_{1,g}(x)}{\mathrm{d}x} + \Sigma_{0,g}(x)\phi_{0,g}(x) = \sum_{g'=1}^{G} \Sigma_{s0,g'\to g}(x)\,\phi_{0,g'}(x) + Q_{0,g}(x) \tag{A.8.a}$$

$$\frac{\mathrm{d}\phi_{0,g}(x)}{\mathrm{d}x} + 3\,\Sigma_{1,g}(x)\phi_{1,g}(x) = 3\sum_{g'=1}^{G} \Sigma_{s1,g'\to g}(x)\,\phi_{1,g'}(x) + 3Q_{1,g}(x) \tag{A.8.b}$$

A.4.1 The multi-group P_1 approximation for fissile zones

In case of <u>fissile zones</u>, the source term "Q" due to fission neutrons can be assumed isotropic and included it in the 0th order term of the transfer cross-section (A.7.e) by defining:

$$\Sigma_{s0,g'\to g}(x) = \Sigma_{s0,g'\to g}(x) + \upsilon\Sigma_{f,g'\to g}(x) \tag{A.9.a}$$

where "$\upsilon\Sigma_{f,g'\to g}(x)$" is the rate at which fission neutrons appear in group g as a result of fissions brought by neutrons of the group g'. The cross-section "$\Sigma_{s0,g'\to g}(x)$" accounts for all other transfers from group g' to group g, in which the subscript "s" suggests scattering but it includes also the (n, xn) reactions.

By adopting the definition (A.9.a), the multi-group P_1 equations (A.8) for fissile media become:

$$\frac{\mathrm{d}\phi_{1,g}(x)}{\mathrm{d}x} + \Sigma_{0,g}(x)\phi_{0,g}(x) = \sum_{g'=1}^{G} \Sigma_{s0,g'\to g}(x)\,\phi_{0,g'}(x) + \frac{1}{k}\sum_{g'=1}^{G} \nu\Sigma_{f,g'\to g}(x)\phi_{0,g'} \tag{A.9.b}$$

$$\frac{\mathrm{d}\phi_{0.g}(x)}{\mathrm{d}x} + 3\Sigma_{1,g}(x)\phi_{1,g}(x) = 3\sum_{g'=1}^{G}\Sigma_{s1,g'\to g}(x)\phi_{1,g'}(x) \qquad \text{(A.9.c)}$$

where:

- as usual, an auxiliary reactivity eigenvalue "k" is introduced (*i.e.*, "ν/k" instead of "ν");
- the scattering term at the first order "$\Sigma_{s1,g'\to g}(x)$" remains identical (as well as for n>1), that is by assuming an isotropic angular distribution of fission neutrons.

A.4.2 The multi-group P_1 approximation for non-fissile zones

In case of <u>non-multiplying media</u>, the "$\Sigma_{sn,g'\to g}(x)$" terms maintain their original meaning for every "n", that are the moments of the differential cross-section accounting for all transfers from g' to g (*i.e.*, elastic / inelastic scattering and (n, xn) reactions). The multi-group P_1 equations in presence of an external source "Q" (the nearest fissile region in ECCO calculations [3]) remain formally identical to (A.8):

$$\frac{\mathrm{d}\phi_{1,g}(x)}{\mathrm{d}x} + \Sigma_{0,g}(x)\phi_{0,g}(x) = \sum_{g'=1}^{G}\Sigma_{s0,g'\to g}(x)\,\phi_{0,g'}(x) + Q_{0,g}(x) \qquad \text{(A.10.a)}$$

$$\frac{\mathrm{d}\phi_{0.g}(x)}{\mathrm{d}x} + 3\Sigma_{1,g}(x)\phi_{1,g}(x) = 3\sum_{g'=1}^{G}\Sigma_{s1,g'\to g}(x)\phi_{1,g'}(x) + Q_{1,g}(x). \qquad \text{(A.10.b)}$$

A.4.3 The multi-group diffusion approximation

Similarly to §A.2, the multi-group-energy P_1 equations can be approximated in a form leading to a multi-group diffusion theory. In this case, the multi-group neutron current "$\phi_{1,g}$" is expressed in the form of a Fick's law through a multi-group diffusion coefficient "D_g":

$$\phi_{1,g}(x) = -D_g(x)\frac{\mathrm{d}\phi_{0,g}(x)}{\mathrm{d}x}. \qquad \text{(A.11.a)}$$

Equation (A.11.a) is still equivalent to (A.9.c) and (A.10.b) P_1 equations for the fissile and non-fissile zones, respectively, by defining a multi-group diffusion coefficient:

$$D_g(x) = \frac{1}{3\left[\Sigma_{1,g}(x) - \frac{\sum_{g'=1}^{G}\Sigma_{s1,g'\to g}(x)\phi_{1,g'}(x)}{\phi_{1,g}(x)}\right]}. \qquad \text{(A.11.b)}$$

It must be noticed that:

- for easiness, as in §A.2 the external source in non-multiplying media is assumed isotropic ($Q_{1,g}$ = 0);
- the terms "$\Sigma_{s1,g'\to g}(x)$" are identical for both fissile and non-fissile zones;
- the multi-group transport cross section is defined as:

$$\Sigma_{tr,g}(x) = \Sigma_{1,g}(x) - \frac{\sum_{g'=1}^{G}\Sigma_{s1,g'\to g}(x)\phi_{1,g'}(x)}{\phi_{1,g}(x)}. \qquad \text{(A.11.c)}$$

By substituting the Fick's law approximation (A.11.a) in the P_0 equation (A.9.b), the multi-group diffusion equation for the fissile zones can be written as:

$$-\frac{\mathrm{d}}{\mathrm{d}x}\left[D_g(x)\frac{\mathrm{d}\phi_{0,g}(x)}{\mathrm{d}x}\right]+\Sigma_{0,g}(x)\phi_0(x)=$$

$$=\sum_{g'=1}^{G}\Sigma_{s0,g'\to g}(x)\,\phi_{0,g'}(x)+\frac{1}{k}\sum_{g'=1}^{G}\nu\Sigma_{f,g'\to g}(x)\phi_{0,g'}(x) \qquad \text{(A.11.d)}$$

Similarly, by substituting it in the P_0 equation (A.10.a), the multi-group diffusion equation for the non-fissile zones with an isotropic external source becomes:

$$-\frac{\mathrm{d}}{\mathrm{d}x}\left[D_g(x)\frac{\mathrm{d}\phi_{0,g}(x)}{\mathrm{d}x}\right]+\Sigma_{0,g}(x)\phi_0(x)=\sum_{g'=1}^{G}\Sigma_{s0,g'\to g}(x)\,\phi_{0,g'}(x)+Q_{0,g}(x) \qquad \text{(A.11.e)}$$

A.4.4 The one-group diffusion approximation in homogeneous fissile media

By assuming a one-group approximation (*i.e.*, cross-sections behaviour constant with energy), the multi-group diffusion equations (A.11.d) in a homogeneous fissile medium reduce to:

$$-D\frac{\mathrm{d}^2\phi_0}{\mathrm{d}x^2}+\Sigma_0\phi_0=\Sigma_{s0}\phi_0+\frac{1}{k}\upsilon\Sigma_f\phi_0 \qquad \text{(A.12.a)}$$

where the diffusion coefficient does not vary with "x" (*i.e.*, homogeneous). Adopting the definition of the absorption cross-section, that is the total minus the scattering one at the 0th order:

$$\Sigma_a=\Sigma_0-\Sigma_{s0} \qquad \text{(A.12.b)}$$

equation (A.12.a) becomes:

$$D\frac{\mathrm{d}^2\phi_0}{\mathrm{d}x}-\Sigma_a\phi_0+\frac{1}{k}\upsilon\Sigma_f\phi_0=0 \qquad \text{(A.12.c)}$$

With the definition of the material bucking "B^2":

$$B^2=\frac{1}{D}\left(\frac{\upsilon}{k}\Sigma_f-\Sigma_a\right) \qquad \text{(A.12.d)}$$

equation (A.12.c) can be rewritten as an eigenvalue problem:

$$\nabla^2\phi=-B^2\phi \qquad \text{(A.12.e)}$$

where the buckling represents the eigenvalue of the wave equation with the boundary condition of zero flux at the extrapolated boundary of the system. This equation can be solved for the constant "k" (*i.e.*, multiplication coefficient) yielding:

$$k=\frac{\upsilon\Sigma_f}{DB^2+\Sigma_a} \qquad \text{(A.12.f)}$$

where "$D\,B^2$" is the leakage term. The equation (A.12.e) is solved by ECCO iterating on the "B^2" buckling value expressed by (A.12.d) (equal for all energy groups in the multi-group case) in order to obtain the criticality condition (*i.e.*, k = 1 expressing the equivalence between the geometrical and material buckling). From (A.12.f) it can be clearly seen that the criticality represents the equilibrium between the neutrons production (numerator) and their disappearance by absorption and leakage (denominator). Consequently, the macroscopic cross-sections representing the fuel cell are calculated not in an infinite lattice (as described by the ECCO 2D heterogeneous geometry models), but in a condition simulating a critical reactor.

A.5 Evaluation of the P_N multi-group cross-sections by cell codes

A.5.1 Cross-sections evaluation in the multi-group P_N approximation

The main problem for the treatment of realistic, energy-dependent situations by means of multi-group methods is represented by the consistent determination of the multi-group constants, as done by the ECCO cell code [3]. It has become a common practice to adopt the spherical harmonics method by introducing the expansion of the scattering cross-sections in Legendre polynomials. Once this has been done, the group constants are similar to those used in the multi-group treatment described in §A.3-4.

Starting from the general transport equation (A.1) and replacing both the cross-section and flux values with their expansion coefficients (A.3.a) and (A.3.c) only in the right side, the energy-dependent transport equation in plane geometry becomes:

$$\mu \frac{\mathrm{d}\phi(x,\mu,E)}{\mathrm{d}x} + \Sigma(x,E)\phi(x,\mu,E) =$$
$$= \sum_n \frac{2n+1}{2} P_n(\mu) \int \phi_n(x,E')\Sigma_{sn}(x,E' \to E)\mathrm{d}E' \quad + Q(x,\mu,E) \qquad \text{(A.13.a)}$$

By expanding the angular flux in the second term on the left side of (A.13.a) as a sum of Legendre polynomials (A.3.c) and by integrating them in each energy group g (with $E_{g-1} < E < E_g$), equation (A.13.a) for each group becomes:

$$\mu \frac{\mathrm{d}\phi_g(x,\mu)}{\mathrm{d}x} + \sum_n \frac{2n+1}{2} P_n(\mu)\phi_{n,g}(x)\Sigma_{n,g}(x) =$$
$$\sum_n \frac{2n+1}{2} P_n(\mu) \sum_{g'=1}^{G} \Sigma_{sn,g'\to g}(x)\phi_{n,g'}(x) + Q_g(x,\mu) \qquad \text{(A.13.b)}$$

where:

- "$\Sigma_{n,g}(x)$" and "$\Sigma_{sn,g'\to g}(x)$" are the moments of flux-averaged total and differential cross-sections defined in (A.7.d) and (A.7.e), respectively;
- the multi-group angular flux in each group:

$$\phi_g(x,\mu) = \int_g \phi(x,\mu,E)\mathrm{d}E \qquad \text{(A.13.c)}$$

  was also expanded in a series of Legendre polynomials with coefficients "$\phi_{n,g}(x)$":

$$\phi_g(x) = \sum_{n=0}^{\infty} \frac{2n+1}{2} \phi_{n,g}(x,\mu) P_n(\mu) \qquad \text{(A.13.d)}$$

  by the exception of the leakage term (*i.e.*, the first one on the left side of (A.13.b) with the spatial derivate of the multi-group flux).

Now, by moving on the right side the second term of the left one, the multi-group transport equation (A.13.b) becomes:

$$\mu \frac{\mathrm{d}\phi_g(x,\mu)}{\mathrm{d}x} = \sum_n \frac{2n+1}{2} P_n(\mu) \sum_{g'} \phi_{n,g'}(x)\left[\Sigma_{n,g'\to g}(x) - \Sigma_{n,g}(x)\delta_{g,g'}\right] \quad + Q_g(x,\mu) \qquad \text{(A.14)}$$

where "$\delta_{g,g'}$" is the Kronecker delta.

Then, if the product "$\Sigma_g(x)\ \phi_g(x,\mu)$" is added to both sides of (A.14) with "$\phi_g(x,\mu)$" expanded as a sum of Legendre polynomials (A.13.d) only on the right side, the latter equation becomes:

$$\mu \frac{\mathrm{d}\phi_g(x,\mu)}{\mathrm{d}x} + \Sigma_g(x)\phi_g(x,\mu) =$$
$$\sum_n \frac{2n+1}{2} P_n(\mu) \sum_{g'} \phi_{n,g'}(x)\{\Sigma_{sn,g'\to g}(x) + [\Sigma_g(x) - \Sigma_{n,g}(x)]\delta_{g,g'}\} + Q_g(x,\mu) \qquad \text{(A.15)}$$

Provided that estimates of "$\phi_{n,g}(x)$" are available, and using them to evaluate "$\Sigma_{n,g}(x)$" and "$\Sigma_{sn,g'\to g}(x)$" with (A.7.d) and (A.7.e), all the terms in equation (A.15) become known, by the exception of the multi-group total cross-section "$\Sigma_g(x)$" which is still undetermined (and for this reason here written in red).

It results evident that the form of equation (A.15) is identical to (A.14): therefore, the group constants can be chosen so that the corresponding terms in the two equations are equal. The transfer cross-sections "$\Sigma_{sn,g'\to g}(x)$" result to be equal for g' ≠ g, while for g' = g the only necessary constraint is that the diagonal elements of the transfer matrix become:

$$\Sigma^*_{sn,g\to g}(x) = \Sigma_{sn,g\to g}(x) + \Sigma_g(x) - \Sigma_{n,g}(x) \qquad \text{(A.16)}$$

that are the transport-corrected self-scattering cross-sections. As mentioned before, by solving equation (A.15) the terms "$\Sigma_{sn,g\to g}(x)$" and "$\Sigma_{n,g}(x)$" are known, but the multi-group total cross-section "$\Sigma_g(x)$" is still unknown. Nevertheless, a univocal solution can be obtained provided the latter is chosen to satisfy equation (A.16).

A.5.2 The consistent P_N approximation

Actually, the sum over "n" in equation (A.15) will be terminated after some finite number, *i.e.*, N+1 in the P_N approximation. Consequently, there are only G(N+1) equations for determining the G(N+1) values of the transfer cross-section "$\Sigma_{sn,g'\to g}(x)$" and the G values of the total cross-section "$\Sigma_g(x)$". Therefore, G extra conditions must be imposed.

The default option in the ECCO cell code developed for fast reactor analyses is the <u>consistent P_N approximation</u> in which it is imposed that the unknown "$\Sigma_g(x)$" coincides with the flux-averaged total cross-section given by (A.7.d) at the 0th order:

$$\Sigma_g(x) = \Sigma_{0,g}(x) = \frac{\int_g \Sigma(x,E)\phi_0(x,E)\mathrm{d}E}{\phi_{0,g}(x)} \qquad \text{(A.17)}$$

The name consistent P_N approximation is used since, by the choice expressed in (A.17), the integral in equation (A.15) over all angles (through their Legendre polynomials series) results identical to the first term of the multi-group P_N equations. Therefore, the definition (A.17) for "Σ_g" is consistent with the P_N equations and for this reason is called the consistent P_N approximation.

To determine the cross-section constants from the multi-group transport equations, the values of "$\Sigma_{n,g}$" and "$\Sigma_{sn,g'\to g}(x)$" are obtained from equations (A.7.d) and (A.7.e). Consequently, the P_N consistent approximation applied to equation (A.15) for cell calculations yields:

$$\mu \frac{\mathrm{d}\phi_g(x,\mu)}{\mathrm{d}x} + \Sigma_{0,g}(x)\phi_g(x,\mu) =$$
$$\sum_n \frac{2n+1}{2} P_n(\mu) \sum_{g'} \phi_{n,g'}(x)\{\Sigma_{sn,g'\to g}(x) + [\Sigma_{0,g}(x) - \Sigma_{n,g}(x)]\delta_{g,g'}\} + Q_g(x,\mu) \qquad \text{(A.18)}$$

in which the G(N+1) unknown "$\Sigma_{sn,g'\to g}(x)$" of equation (A.16) can be derived from the system (A.18) of G(N+1) equations.

A.5.3 The consistent P1 approximation

By expanding in (A.18) also the flux "$\phi_g(x,\mu)$" on the left side and the source "$Q_g(x,\mu)$" on the right one as sum of Legendre polynomials function of "μ", the system of equations (A.18) at the P_1 order becomes:

$$\frac{\mathrm{d}\phi_1(g)}{\mathrm{d}x}+\Sigma_0(g)\phi_0(g)=\sum_{g'=1}^{G}\Sigma_{s0}(g'\to g)\,\phi_0(g')+Q_0(g) \qquad \text{(A.19.a)}$$

$$\frac{\mathrm{d}\phi_0(g)}{\mathrm{d}x}+3\Sigma_0(g)\phi_1(g)=3\sum_{g'=1}^{G}\phi_1(g')\left\{\Sigma_{s1}(g'\to g)+[\Sigma_0(g)-\Sigma_1(g)]\delta_{g,g'}\right\}+3Q_1(g) \qquad \text{(A.19.b)}$$

where the dependence from the spatial coordinate "x" was assumed implicit, while the dependence from the energy group was made explicit putting it in round brackets.

A.5.4 The consistent P_1 approximation for fissile zones

By adopting the definition used in §A.4, the P_1 transport equations as solved by cell codes for fissile zones (*i.e.*, isotropic fissions) become:

$$\frac{\mathrm{d}\phi_1(g)}{\mathrm{d}x}+\Sigma_0(g)\phi_0(g)=\sum_{g'=1}^{G}\left[\Sigma_{s0}(g'\to g)+\frac{\upsilon}{k}\Sigma_f(g'\to g)\right]\phi_0(g') \qquad \text{(A.20.a)}$$

$$\frac{\mathrm{d}\phi_0(g)}{\mathrm{d}x}+3\Sigma_0(g)\phi_1(g)=3\sum_{g'=1}^{G}\phi_1(g')\left\{\Sigma_{s1}(g'\to g)+[\Sigma_0(g)-\Sigma_1(g)]\delta_{g,g'}\right\} \qquad \text{(A.20.b)}$$

where an eingenvalue search for k equal to 1 is usually adopted to simulate the fuel cell in a reactor.

A.5.5 The consistent P_1 approximation for non-fissile zones

Otherwise, the P_1 transport equations solved by ECCO for non-multiplying media with an anisotropic external source (*i.e.*, $Q_1 \neq 0$) become:

$$\frac{\mathrm{d}\phi_1(g)}{\mathrm{d}x}+\Sigma_0(g)\phi_0(g)=\sum_{g'=1}^{G}\Sigma_{s0}(g'\to g)\phi_0(g)+Q_0(g) \qquad \text{(A.21.a)}$$

$$\frac{\mathrm{d}\phi_0(g)}{\mathrm{d}x}+3\Sigma_0(g)\phi_1(g)=3\sum_{g'=1}^{G}\phi_1(g')\left\{\Sigma_{s1}(g'\to g)+[\Sigma_0(g)-\Sigma_1(g)]\delta_{g,g'}\right\}+3Q_1(g) \qquad \text{(A.21.b)}$$

In both fissile (A.20) and non-fissile (A.21) equations, the 0th and 1st terms "$\Sigma_{s0}(g'\to g)$" and "$\Sigma_{s1}(g'\to g)$" represent the isotropic and anisotropic components of the transfer matrix, respectively, that takes into account the (elastic and inelastic) scattering and (n,xn) reactions.

A.6 The fundamental mode in the multi-group diffusion equation

For calculations aimed to describe physical phenomena with a fine group energy spectrum, a spatial trend for the flux of exponential type (for non-multiplying media) or sinusoidal one (for multiplying media) may roughly represent the effect of leakages in homogeneous media. In both cases it can be assumed that the angular flux (and hence the multi-group flux moments) can be described in fundamental mode by:

$$\phi_n(x,g)=\mathrm{Re}[\phi_n(g)\mathrm{e}^{-iBx}] \qquad \text{(A.23.a)}$$

where "Re" means the real part, the term "B" is the square root of the geometrical bucking "B^2" and it was assumed that the spatial variation of the flux moments is independent from energy (and hence from the group "g").

To easily understand the "B^2" physical meaning, it is useful to recall the multi-group diffusion equations (A.11.d) and (A.11.e) (for fissile and non-fissile zones, respectively) which contain the first order flux term (describing the leakage). In fundamental mode the latter can be written as:

$$-\frac{\mathrm{d}}{\mathrm{d}x}\left[D(g)\frac{\mathrm{d}\phi_0(g)}{\mathrm{d}x}\right] = -\frac{\mathrm{d}D(g)}{\mathrm{d}x}\frac{\mathrm{d}\phi_0(g)}{\mathrm{d}x} - D(g)\frac{\mathrm{d}^2\phi_0(g)}{\mathrm{d}x^2} = D(g)B^2\phi_0(g)\mathrm{e}^{-iBx} \qquad \text{(A.23.b)}$$

where:

- as in §A.5, and differently from (A.11.d) and (A.11.e), the flux "ϕ_0" dependence from the spatial coordinate "x" was assumed implicit (and it was assumed explicit in brackets the dependence from the energy group);
- for the <u>fissile zones</u>: the buckling "B^2" is positive, its square root is real and the exponent in (A.23.b) is imaginary yielding a flux sinusoidal behaviour with x;
- for the <u>non-fissile zones</u>: the buckling "B^2" is negative, its square root is imaginary and the exponent in (A.23.b) is negative yielding a flux exponential behaviour with x.

By assuming the fundamental mode (A.23.a) and dividing each term by "e^{-iBx}" the multi-group diffusion equation (A.11.d) for <u>fissile zones</u> becomes:

$$D(g)B^2\phi_0(g) + \Sigma_0(g)\phi_0(g) =$$
$$= \sum_{g'=1}^{G}\Sigma_{s0}(g' \to g)\phi_0(g) \quad + \frac{1}{k}\sum_{g'=1}^{G}\upsilon\Sigma_f(g' \to g)\phi_0(g) \qquad \text{(A.24.a)}$$

In case of <u>non-multiplying media,</u> the multi-group diffusion equation (A.11.e) in fundamental mode becomes:

$$D(g)B^2\phi_0(g) + \Sigma_0(g)\phi_0(g) = \sum_{g'=1}^{G}\Sigma_{s0}(g' \to g)\phi_0(g) \quad + Q_0(g) \qquad \text{(A.24.b)}$$

Differently from the fissile zones (see §A.4.4), the bucking is imposed by the ECCO code through a semi-empirical formula [3]:

$$B^2 = \frac{5}{8}\left(\frac{\pi}{h}\right)^2 \qquad \text{(A.24.c)}$$

where "h" is the typical dimension of the cell considered (*i.e.*, the height, for axial regions above and below the fuel, and the thickness for the radial zones). By assuming the fundamental mode (A.23.a) for the flux and by extending the previous concepts to the ECCO P_1 multi-group approximation, equations (A.20) and (A.21) correspond to a system of 2G equations in which:

- for the <u>fissile zones</u>, in (A.20) there is a buckling "B^2" search in order to obtain k = 1 (for a critical reactor, or lower for an Acceleration Driven System);
- for the <u>non-fissile zones</u>, in (A.21) the buckling "B^2" is imposed through the geometrical dimension of the cell by equation (A.24.c).

For the fuel cell zones, the <u>average fission spectrum</u> in its multi-group form "$\chi(g)$" (*i.e.*, fraction of fission neutrons in the group g) is obtained from the one "$\chi(g)_i$" of each fissionable nuclide "i" with the following relation:

$$\chi(g) = \frac{\sum_i \chi(g)_i \sum_{g'=1}^{G}\nu\sigma_{f,i}(g')N_i\phi_0(g')}{\sum_{g'=1}^{G}\nu\Sigma_f(g')\phi_0(g')} \qquad \text{(A.25)}$$

where "$\phi_0(g)$" is the multi-group flux of the cell calculations (A.24.a) stored for every medium, "N_i" is the atomic density of the nuclide "i", "$\sigma_{f,i}(g')$" its mult-group microscopic fission cross-section and "$\nu(g)$" the number of neutrons with energy E_g emitted by fission. The macroscopic fission term "Σ_f" in denominator is derived from the microscopic one through the relation (A.2).

A.7 The ECCO P_N solutions for homogeneous media

A.7.1 The P_N consistent solution

By adopting the fundamental mode for the multi-group flux:

$$\phi_g(x,\mu) = \mathrm{Re}\left[\phi_g(\mu)\mathrm{e}^{-iBx}\right] \tag{A.26.a}$$

the transport equation (A.1) to be solved in 1D geometries for each energy group g can be written as:

$$[\Sigma - iB\mu]\phi_g(\mu) = \int \Sigma_{s,g'\to g}(\mu' \to \mu)\phi_g(\mu')\mathrm{d}\mu' + Q_g(\mu) \tag{A.26.b}$$

By expanding the angular flux "$\phi_g(\mu)$" and the scattering functions in series of Legendre polynomials, and projecting the resulting equations on each polynomial, the orthogonality rule leads to an infinite system of algebraic equations. By the P_1 consistent approximation it reduces to a couple of equations for each group g:

$$\Sigma_{0,g}\phi_{0,g} - iB\phi_{1,g} = \sum_{g'=1}^{G}\Sigma_{s0,g'\to g}\phi_{0,g'} + Q_{0,g} \tag{A.27.a}$$

$$\Sigma_{1,g}\phi_{1,g} - \frac{iB}{3}\phi_{0,g} = \sum_{g'=1}^{G}\Sigma_{s1,g'\to g}\phi_{1,g'} + Q_{1,g} \tag{A.27.b}$$

It has to be remarked that:

- in the non-fissile zones, the two source terms "$Q_{1-2,g}$" are obtained from the flux and current spectra coming from the nearest fissile zone (loaded with the "SUBCRITICAL FLUXB" instruction in ECCO; §D.2);
- in fissile zones, the source term "Q_0" is included in the scattering one (as done in (A.9.a)) and then both the "Q_0" and "Q_1" terms vanish (*i.e.*, isotropic fissions).

It can be further noticed that at higher orders in fissile zones, the flux moments are obtained with the recurrence relation:

$$\phi_{n,g} = -\frac{n}{2n+1}\, i\, \frac{B}{A_{n,g}}\phi_{n-1,g} \qquad \text{(for n >1)} \tag{A.27.c}$$

in which the transport-like cross-sections "A_n" are given by the continued fraction:

$$A_{n,g} = b_{n-1,g} + \frac{a_n}{b_{n,g} + \frac{a_{n+1}}{b_{n+1,g} + \cdots}} \tag{A.27.d}$$

and the coefficients "a" and "b" are:

$$a_n = \frac{(n+1)^2 B^2}{(2n+1)(2n+3)} \tag{A.27.e}$$

$$b_{0,g} = \Sigma_{1,g} \tag{A.27.f}$$

$$b_{n,g} = \Sigma_{1,g} - \Sigma_{s*,n+1,g} \tag{A.27.g}$$

being "$\Sigma_{s*,n+1}$" the transport-corrected self-scattering cross-section as in (A.16):

$$\Sigma^*_{sn,g\to g} = \Sigma_{sn,g\to g} + \Sigma_{1,g} - \Sigma_{n,g} \tag{A.27.h}$$

where the "$\Sigma_{sn,g\to g}$" terms are the within group scattering terms at nth order, "Σ_1" is the current-weighed total cross-section (*i.e.*, first order) and "Σ_n" is the nth flux moment "ϕ_n" weighed one.

A.7.2 The P_N inconsistent solution

The faster inconsistent solution is obtained with the further assumption of extended transport approximation:

$$\sum_{g'=1}^{G} \Sigma_{sn,g'\to g}\phi_{n,g'} = \Sigma_{sn,g}\phi_{n,g} \qquad \text{(A.28.a)}$$

that simplifies the system of equations (A.27.a-b) yielding the P_1 inconsistent solving method.

In fissile zones the terms with n>1 are identical to the continued fractions (A.27.d) by the exception of the coefficient "b_0" containing a scattering diagonal term for the current weighted total cross-section:

$$b_{0,g} = \Sigma_1 - \Sigma^*_{s0,g\to g} + 1 \qquad \text{(A.28.b)}$$

with "$\Sigma^*_{s0,g\to g}$" expressed through equation (A.27.h).

A.7.3 The B_N method

The B_N method is quite similar to the P_N one. It consists again in an expansion in Legendre polynomials, but the general equation (A.26.b) is first divided by the term "$\Sigma - iB\mu$" before being projected. By performing the scalar product on "$P_n(\mu)$" and dividing both sides by "$\Sigma - iB\mu$", (A.26.b) can be rewritten as:

$$\phi(E,\mu) = \frac{1}{\Sigma(E)-iB\mu}\sum_n \frac{2n+1}{4\pi} P_n(\mu)\int \Sigma_{sn}(E'\to E)\phi_n(E')\mathrm{d}E' + \frac{1}{4\pi}\frac{Q_0(E)}{\Sigma(E)-iB\mu} \qquad \text{(A.29.a)}$$

By introducing the coefficients "$A_{l,n}(z)$" (that are new functions to be calculated depending on the Legendre polynomials):

$$A_{l,n}(z) = \frac{1}{2}\int_{-1}^{1}\frac{P_l(\mu)P_n(\mu)}{1-iz\mu}\mathrm{d}\mu \qquad \text{(A.29.b)}$$

after some passages the previous equations (A.29.a) become:

$$\Sigma(E)\phi_l(E) = \sum_{n=0}^{\infty}(2n+1)A_{l,n}\left(\frac{B}{\Sigma(E)}\right)\int \Sigma_{sn}(E'\to E)\phi_n(E')\mathrm{d}E' + A_{l,0}\left(\frac{B}{\Sigma(E)}\right)\mathrm{Q}_0(E) \qquad \text{(A.29.c)}$$

The functions "$A_{l,n}$" satisfy the recurrence condition:

$$\frac{1}{iz}(2n+1)A_{l,n}(z) - (n+1)A_{l,n+1}(z) - lA_{l,n-1}(z) = \frac{\delta_{l,n}}{iz} \qquad \text{(A.29.d)}$$

and it is:

$$A_{l,n}(z) = A_{n,l}(z) \qquad A_{0,0}(z) = \frac{1}{z}arctg(z) \qquad \text{(A.29.e)}$$

$$A_{0,1}(z) = A_{1,0}(z) = \frac{1}{iz}\left[A_{0,0}(z) - 1\right] \qquad A_{1,1}(z) = \frac{1}{iz}A_{1,0}(z) \qquad \text{(A.29.f)}$$

The B_N method approximation consists in truncating the system of equations at the Nth order (and beyond) by imposing the scattering source vanishes. The resulting consistent B_1 system is quite similar to (A.27.a) and (A.27.b). In the latter, the current-weighted total cross-section "Σ_1" for each energy group g is replaced by "$\gamma\Sigma_1$", where:

$$\gamma = \frac{\frac{B}{\Sigma_1} arctg\left(\frac{B}{\Sigma_1}\right)}{3\left[1 - \frac{\Sigma_1}{B} arctg\left(\frac{\Sigma_1}{B}\right)\right]} \qquad \text{(A.29.h)}$$

In <u>fissile zones</u>, the coefficients "b_n" at the Nth order of equations (A.27.f-g) are now defined as:

$$b_n = \Sigma_1 - \frac{2}{3}|B|\ \mathrm{Rleg}(\Sigma_1, B^2, N) \qquad \text{(n=0 and N=1)} \qquad \text{(A.29.i)}$$

$$b_n = \Sigma_1 - \Sigma_{s*,n+1} \qquad \text{(n < N-1)} \qquad \text{(A.29.l)}$$

$$b_n = \Sigma_1 - \Sigma_{s*,n+1} - \frac{N+1}{2N+1}\mathrm{Rleg}(\Sigma_1, B^2, N) \qquad \text{(n= N-1)} \qquad \text{(A.29.m)}$$

where "Rleg" are the ratios of the Legendre functions of the second kind. Similarly to the P_N case, by applying the extended transport approximation (A.28.a) the simplified and faster <u>inconsistent B_N</u> solution is obtained.

As in the P_N case, the B_N (consistent and inconsistent) approximations consist again in truncating at "n = N" the system of infinite equations thus obtained. It can be noted that:

- this occurs putting $\Sigma_{sn}(E' \to E)$ = 0 for n > N;
- the B_N equations converge more rapidly than the corresponding P_N ones. For instance, in the case of isotropic scattering, an "exact" expression is obtained for "ϕ_0" and also the higher order coefficients can be obtained exactly;
- it is foreseeable that also for anisotropic scattering the process converges more rapidly.

A.8 Impact of the different ECCO calculation options in the ALFRED case

The ECCO calculation route briefly described in §3.2 was adopted to produce the "reference" macroscopic cross-sections. The homogenised multi-group constants are derived as shown in the previous sections of this appendix, by generalising the equation of homogeneous media for the ECCO 2D heterogeneous geometry models with weighted averages on the different volumes of the cell regions. The main features of the ECCO calculation methodology (whose input decks are reported in Appendix D) can be summarised as follows.

- For fissile zones, there is a buckling "B^2" search in order to obtain a unitary k value (see (A.12.f)) for the cell (ECCO instruction "BSEARCH 1.0", so to simulate a critical reactor).
- For both fissile and non-fissile zones:
  - it starts with a 172 energy-group structure and proceeds with the calculation scheme indicated in Fig. 3.1 by collapsing the computed cross-sections in a 33 energy-group one after the passage through 1968 groups for most of the nuclides;
  - it computes the cross-sections at the first order of the Legendre polynomials for the scattering angle (*i.e.*, isotropic media) with the P_1 consistent calculation option.
- For the non-fissile zones:
  - it calculates the cross-sections starting with the flux and current spectra of the nearest fissile region and spatial-uniformly distributed within the zone;
  - it simulates accurately the spatial self-shielding effect by introducing an additional term to the computed cross-sections to consider the neutrons coming from fuel and not shielded in the region examined. The so-called self-shielding "DB^2" term is added, where "D" is the diffusion coefficient and "B^2" the value of the geometrical buckling driving the leakage, estimated by the semi-empirical formula (A.24.c) involving a representative dimension of the zone examined. As reported in Appendix D, this calculation method is indicated by the "SELF SHIELDING DBBSH" instruction in ECCO.

One of the goals of this work was also to verify whether different ECCO calculation options could produce significant differences in the values of the cross-sections created. For this purpose:

- in all zones (fissile and non-fissile):
  - an alternative route to the one indicated in Fig. 3.1 was explored, by starting with 33 energy groups (instead of 172) and then, as in the reference case, the cross-sections are collapsed at 33 groups after the passage through 1968 groups;
  - another alternative route was implemented starting from the usual 172 energy-group structure and collapsing the computed cross-sections in an 80 energy-group structure after the passage through 1968 groups;
  - the B_1 calculation option was adopted, with the reference 172-1968-33 energy groups treatment (as described in §A.7, while in the P_N method the *n*+1 moment of the flux ϕ_n is imposed equal to zero, in the B_N method all the scattering sources are assumed to be zero above the nth moment, leading to a simplified relationship between ϕ_n and ϕ_{n+1} through a Legendre function of the second kind).
- in the non-fissile zones (see §D.2):
  - the additional spatial self-shielding term was not added to the computed cross-sections (*i.e.*, SELF SHIELDING NODBBSH instruction in ECCO);
  - instead of the utilisation of the (flux and current) spectrum evaluated by ECCO in the (nearest) fissile region, the fuel spectrum evaluated by Serpent at 33 energy groups in the same zone was introduced "externally";

- in the fuel and the absorbing parts of CR and SR bundles (*i.e.*, B_4C pins), a homogeneous cell description was adopted in order to verify the impact of self-shielding effects (that should be reproduced by the ECCO 2D heterogeneous geometry model of the cells).

Here in the following it is shown an intra-comparison among the ECCO cross-sections obtained with different calculation methods (anyway, most of them led to very similar values) and, in some cases, their confrontation with the Serpent results obtained with the most accurate 3D FC heterogeneous model. Differently from Figs 5.1-5.3 where the values were reported in their "correct" histogram form, for easiness the following graphs are reported in a "punctual form" - with the multigroup cross-section values in correspondence of the upper energy limits - as they come from the codes output.

Figs. A.1 and A.2 show the normalised flux and current spectra evaluated by ECCO in the inner (FINN) and outer (FOUT) fuel cells, respectively, compared with the corresponding Serpent ones obtained with the 3D FC heterogeneous model (see §4.2). The ECCO values were evaluated with a 2D heterogeneous geometry in three different ways: two at 33 energy groups, obtained starting from 172 groups (reference) and 33 groups (and then collapsing to 33 after the passage through 1968 groups) and one at 80 groups (starting from 172, and then collapsing to 80 after the passage through 1968 groups). It results evident that the three ECCO options lead almost to the same fuel spectra (with an improved resonance description with the 80-group grid), while the Serpent 33-group spectra appear significantly higher below 1 keV energy, especially for the flux.

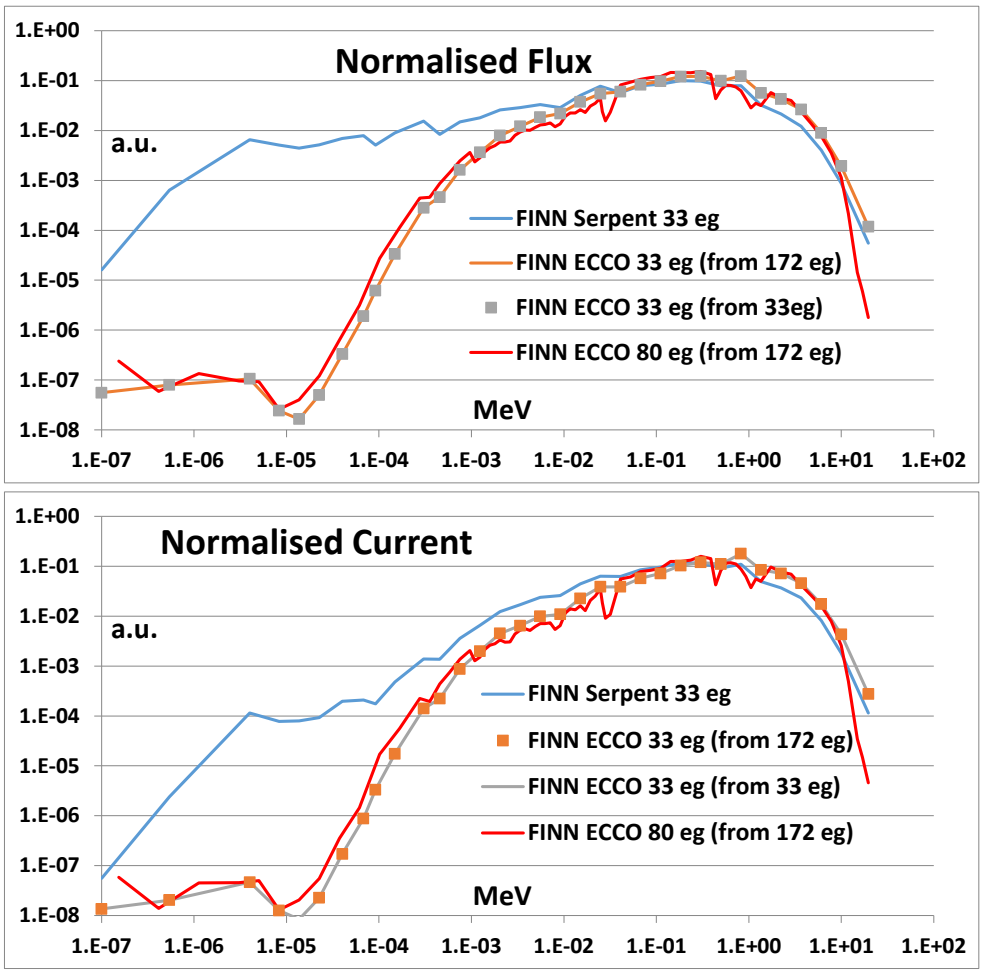

Figure A.1 Normalised flux (top) and current (bottom) spectra at 33 energy groups evaluated by ECCO (with different calculation options) and Serpent (3D FC model) in the fuel inner zone.

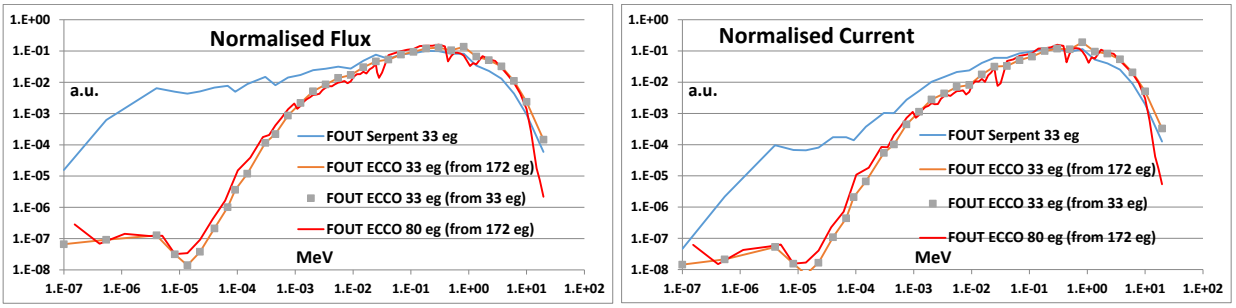

Figure A.2 Normalised flux (left) and current (right) spectra at 33 energy groups evaluated by ECCO (with different calculation options) and Serpent (3D FC model) in the fuel outer zone.

The flux and current in the fuel zones are used by ECCO (as external source Q, see §A.3-7) to evaluate the cross-sections of non-multiplying media. Because of the significant difference between the fuel spectra computed by the two codes (Figs. A.1-2), the flux and current terms coming out from Serpent at 33 groups were introduced "externally" in ECCO (SUBCRITICAL SOURCE instruction; see §D.2). To verify the congruence of this calculation option, the same instruction was used also by inserting "externally" the "internal" ECCO source. Figs. A.3 and A.4 show the results obtained in the CR and SR absorbing bundle regions, respectively, for the total (left) and capture (right) cross-sections. It appears evident that all the ECCO options (a, b, d, e) yield very similar results for both cross-sections. Furthermore, the congruence of the external source calculation option is respected since the b) and e) behaviours are practically equivalent.

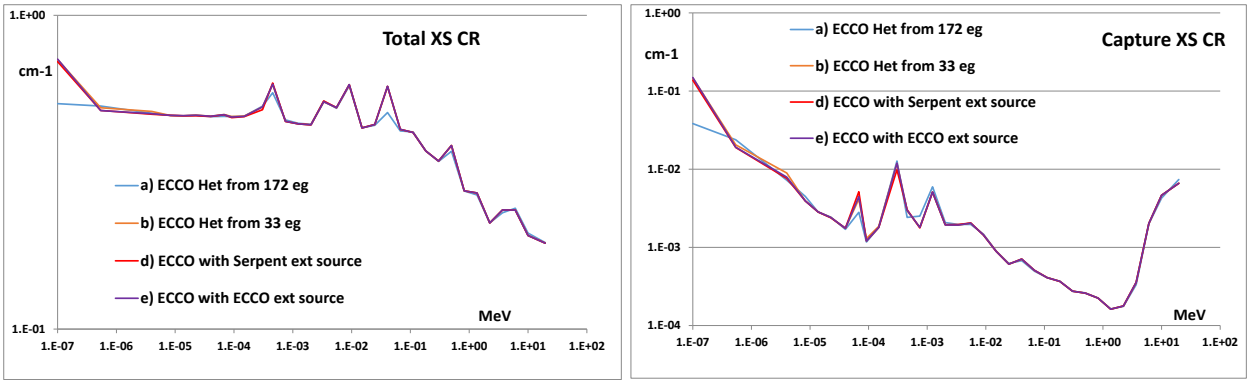

Figure A.3 CR total (left) and capture (right) cross-sections at 33 energy groups evaluated by ECCO (with different options) and Serpent (3D FC model).

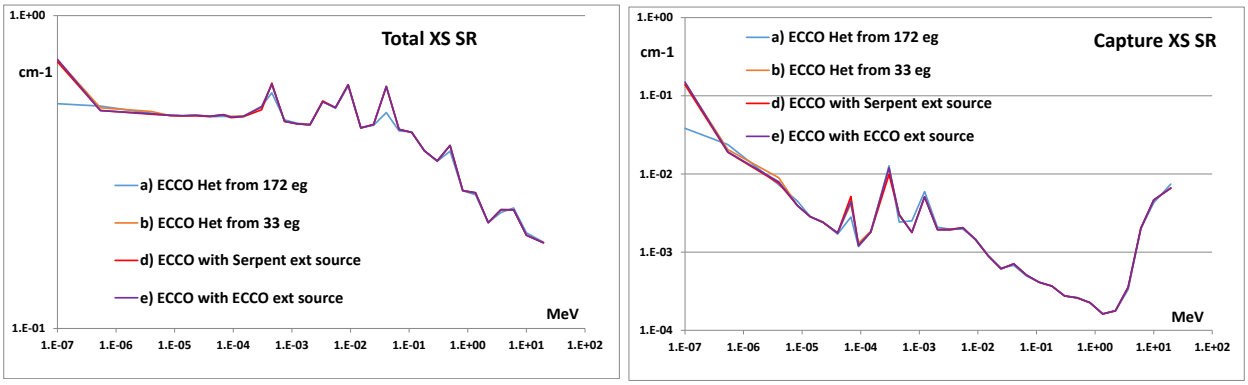

Figure A.4 SR total (left) and capture (right) cross-sections evaluated at 33 energy groups by ECCO (with different options) and Serpent (3D FC model).

The 33-group ECCO calculations were carried out also by adopting (see §A.7 and Appendix D):

- the P_1 inconsistent, the B_1 consistent and inconsistent options (to be compared with the reference P_1 consistent);
- without the additional self-shielding term for not multiplying media (NODBBSH instruction, to be compared with the DBBSH reference one).

The impact of these calculation options on the cross-section values resulted to be negligible. As examples:

- Fig. A.5 reports the total cross-sections of the inner (FINN) and outer (FOUT) fuel zones, where the consistent P_1 (reference) and B_1 methods were compared. The graph shows also that the fuel inner and outer cross-sections differ significantly only at low energies;
- Fig. A.6 reports the total cross-sections of the CR absorbing bundle, where the NODBBSH and DBBSH (reference) calculation options, combined with the P_1 and B_1 consistent methods, were compared.

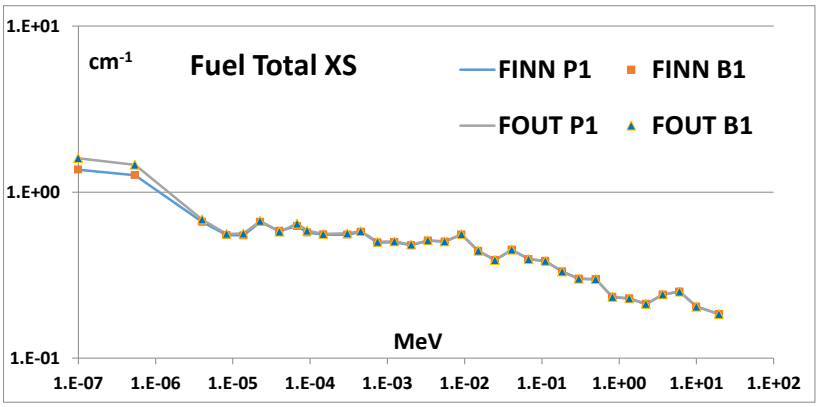

Figure A.5 Fuel inner and outer total cross-sections evaluated by ECCO with P_1 (reference) and B_1 consistent calculation options at 33 energy groups.

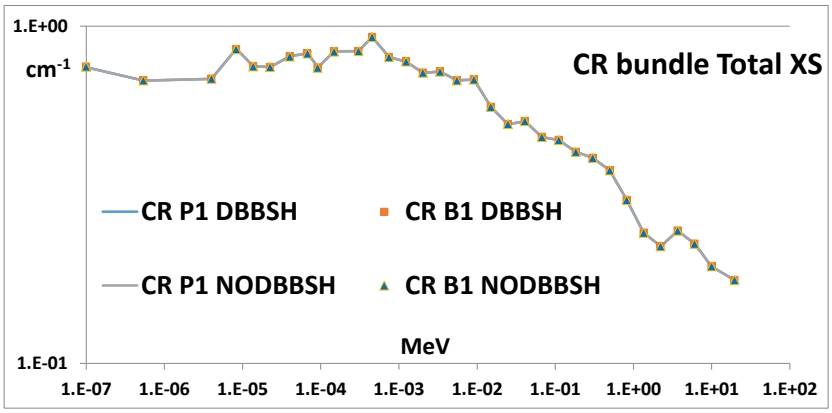

Figure A.6 CR absorbing bundle total cross-section evaluated by ECCO with NODBBSH and DBBSH (reference) calculation options at 33 energy groups.

Besides the "reference" ECCO calculations at 33 energy groups adopting 2D heterogeneous geometry models, the cross-sections were evaluated also at 80 groups. Furthermore, the most important regions for core neutronics (*i.e.*, fuel and shutdown systems absorbing bundles) were described with homogeneous cell geometries in both energy-group structures.

Figs. A.7 and A.8 show the results obtained for the total and capture cross-sections with these four different calculation options in the fuel inner and outer zones, respectively. In the same

graphs they are also compared with the 33-group values of the Serpent 3D FC heterogeneous model. Fig. A.9 shows the inner (left) and outer (right) fuel elastic cross-sections, evaluated by ECCO with the four above mentioned options. It appears evident that:

- the 33 and 80 energy group structures yield very similar results, for both the ECCO intra-comparison and the confrontation with the Serpent values (Figs. A.7 and A.8);
- the increased energy refinement at 80 groups yields a better description of the resonances (that is evident in Fig. A.9 for the elastic cross-section).

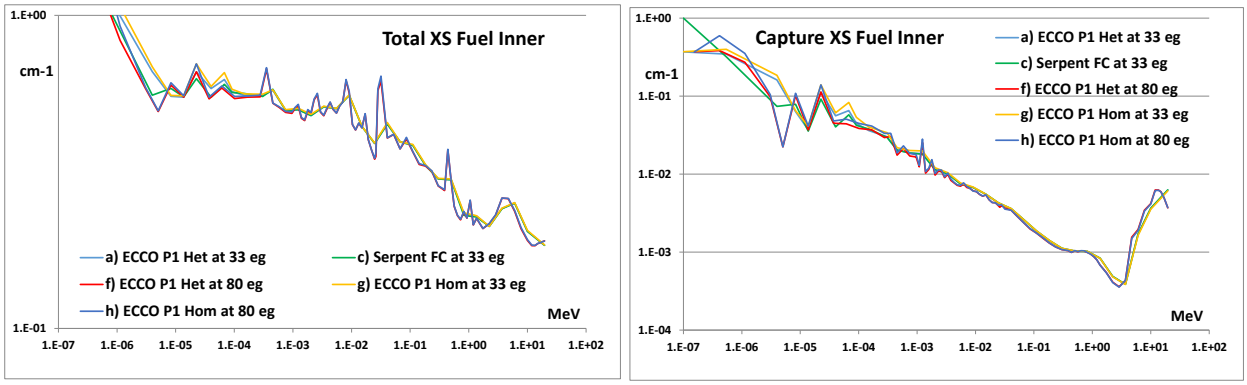

Figure A.7 Fuel Inner total (left) and capture (right) cross-sections evaluated by ECCO with 33 and 80 groups (heterogeneous and homogeneous geometry models) and by Serpent (3D FC model) at 33 groups.

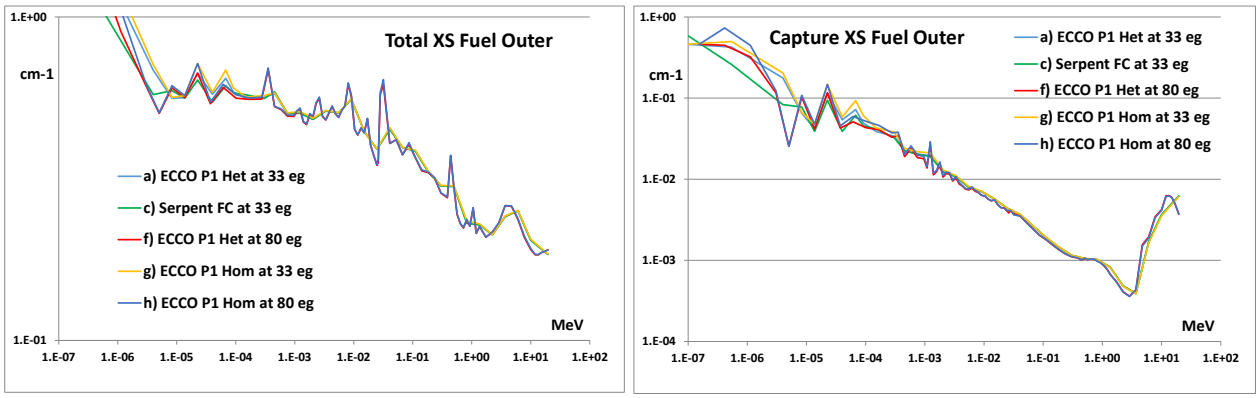

Figure A.8 Fuel outer total (left) and capture (right) cross-sections evaluated by ECCO with 33 and 80 groups (heterogeneous and homogeneous geometry models) and by Serpent (3D FC model) at 33 groups.

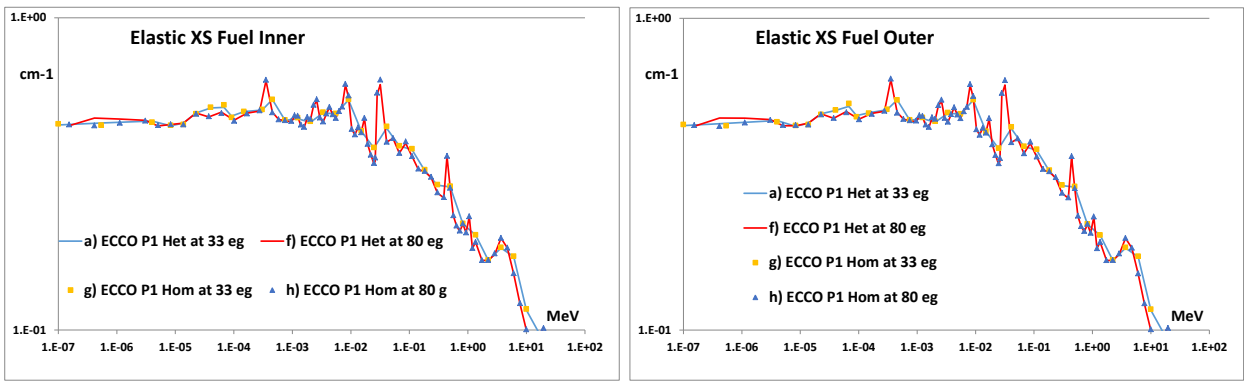

Figure A.9 Fuel inner (left) and outer (right) elastic cross-sections evaluated by ECCO at 33 and 80 groups with heterogeneous and homogeneous geometry models.

Fig. A.10 compares the fission cross-sections obtained with the four abovementioned ECCO options together with the Serpent (3D FC model) results at 33 groups. It appears evident that there is a good and general agreement above 10 eV (besides the better description of the resonances by the 80-group structure). At lower energies, the ECCO results at 80 groups are the closest to the Serpent values at 33 (and 80, here not shown) energy groups.

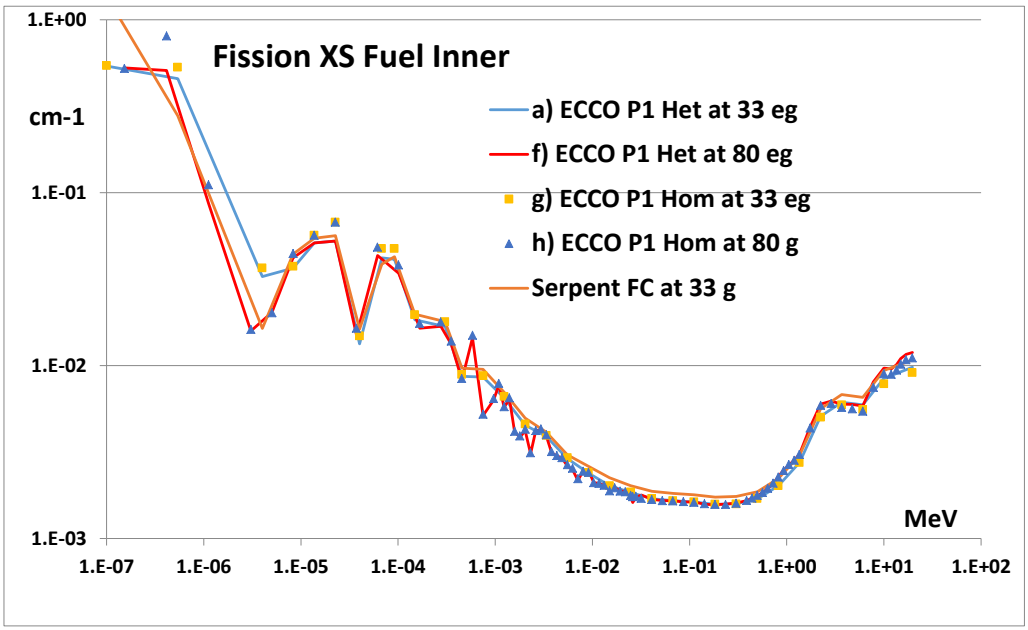

Figure A.10 Fuel fission cross-section evaluated by ECCO at 33 and 80 energy groups (heterogeneous and homogeneous geometries) and Serpent (3D FC model) at 80 groups.

Figs. A.11 and A.12 show the ECCO and Serpent multi-group constants of the CR and SR absorbing zones, respectively, for the total (left) and transport (right) cross-sections calculated at 33 and 80 groups. The ECCO results refer to the heterogeneous cell geometry models and the Serpent ones refer to the 3D FC heterogeneous model. It appears evident that, especially for the CR having a high B_4C volume fraction and in spite of the energy structure adopted, the ECCO total cross-sections are higher than the Serpent ones, while the difference is less evident for the transport cross-sections. As discussed in §5.3 (see Fig. 5.11), the main contribution to the difference between the total cross-sections is due to the capture constants over a large part of the spectrum.

Fig. A.13 shows the ECCO and Serpent capture cross-section values calculated at 33 and 80 groups by heterogeneous models (as in Fig. 5.11) compared with the ECCO ones obtained by homogeneous cell geometries (at 33 groups). It appears evident that at low energies the latter homogeneous values are significantly higher than the heterogeneous ones, reaching two order of magnitude difference in the thermal groups. It can be therefore deduced that in absorbing regions the self-shielding effect (treated by ECCO with 2D heterogeneous geometry models) has a large impact on the cross-section values. Nevertheless, since the larger differences appear only below 1 keV, the impact on the corresponding shutdown systems worth in the ALFRED fast spectrum core resulted to be limited (~150-560 pcm anti-reactivity in dependence of the CR and SR position; see §6.1).

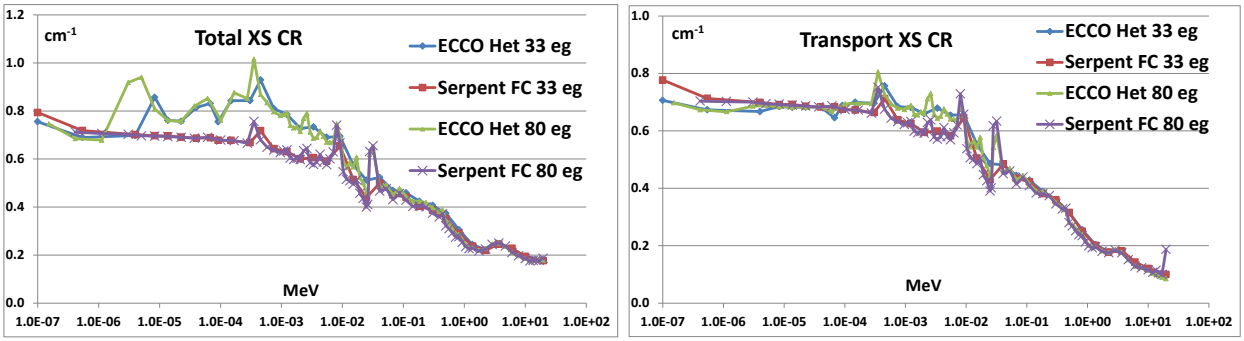

Figure A.11 CR total (left) and transport (right) cross-sections at 33 and 80 groups evaluated by ECCO (heterogeneous cell geometry) and Serpent (3D FC model).

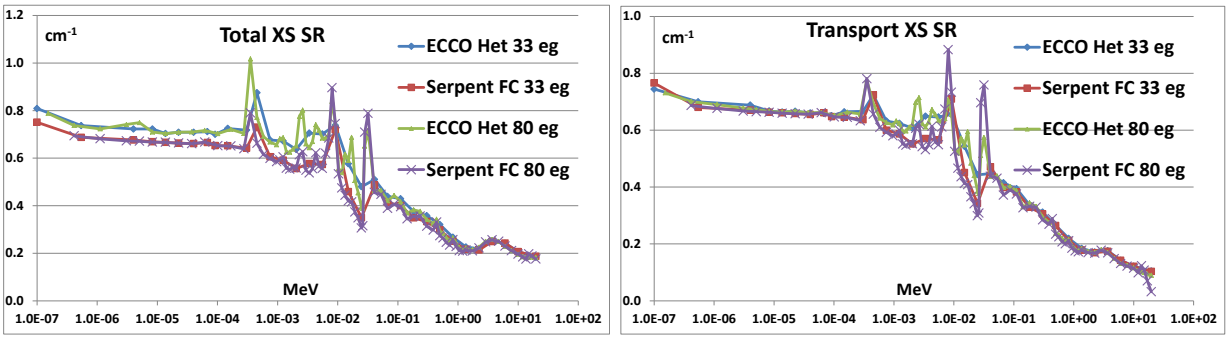

Figure A.12 SR total (left) and transport (right) cross-sections at 33 and 80 groups evaluated by ECCO (heterogeneous cell geometry) and Serpent (3D FC model).

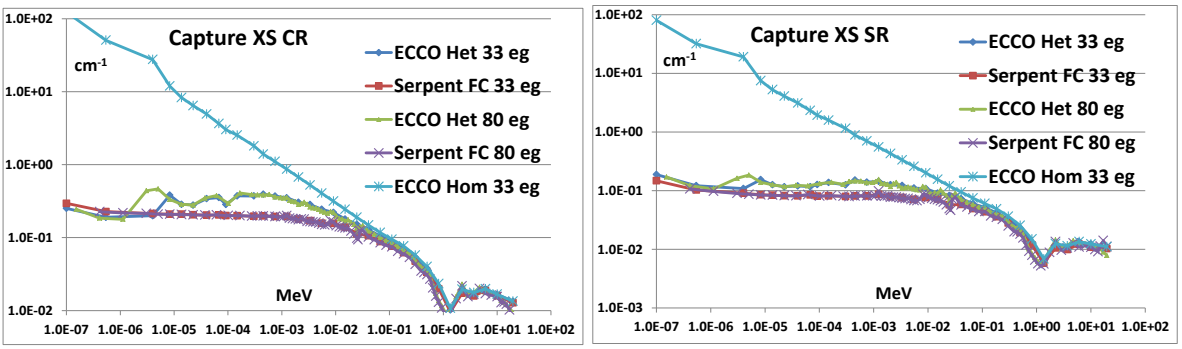

Figure A.13 CR (left) and SR (right) capture cross-sections at 33 and 80 groups evaluated by ECCO (heterogeneous and homogeneous cell geometries) and Serpent (3D FC model).

For the other core regions, the impact of the self-shielding effects and the energy refinement on the cross-section values results to be decisively lower or negligible. As examples:

- Fig. A.14 shows the total cross-sections for the dummy (*i.e.*, YSZ bundle) and pure lead regions obtained with heterogeneous and homogeneous geometry cell models, respectively, treated at 33 and 80 energy groups;
- Fig. A.15. shows the total, elastic and capture cross-sections of the FA plenum obtained with a heterogeneous geometry model at 33 and 80 energy groups;
- Fig. A.16 and A.17 show the FA plenum and dummy total cross-sections, respectively, obtained with heterogeneous and homogeneous geometry models at 33 and 80 groups. Differently from the previous graphs, the values are not reported in a logarithmic scale to make evident the improvement obtained by the 80 group-structure in the resonances region.

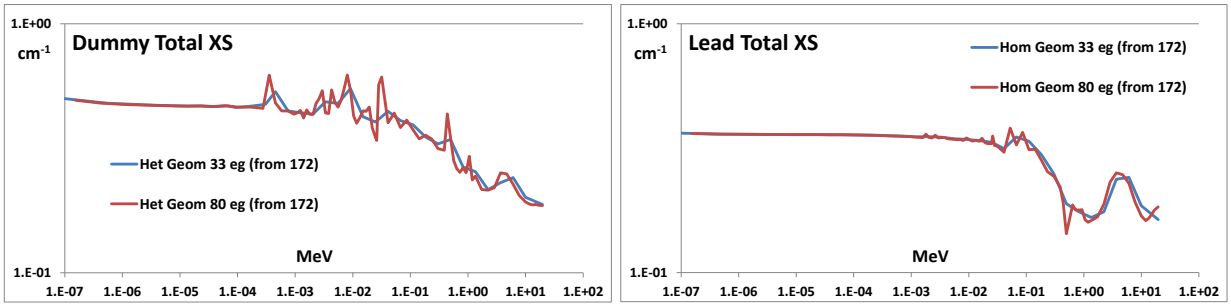

Figure A.14 Dummy (heterogeneous model, left) and pure lead (homogeneous model, right) total cross-sections evaluated with ECCO at 33 and 80 energy groups.

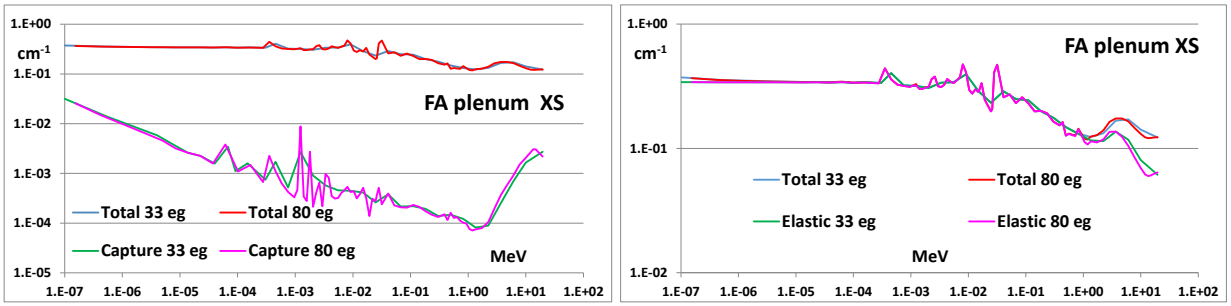

Figure A.15 FA plena total, capture (left) and elastic (right) cross-sections at 33 and 80 energy groups evaluated with the ECCO heterogeneous geometry model.

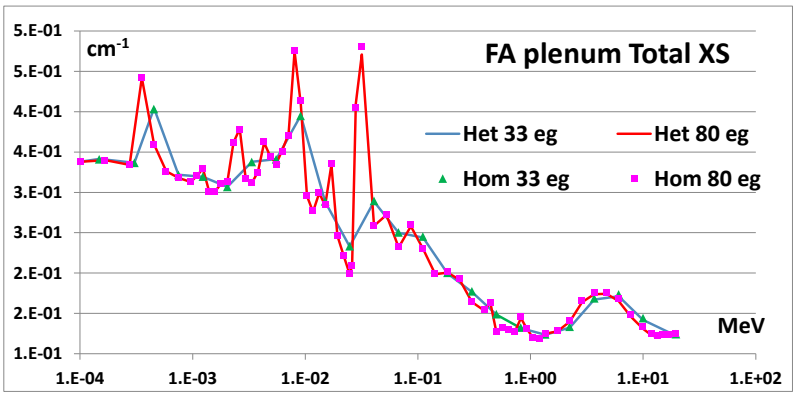

Figure A.16 FA plenum total cross-sections evaluated at 33 and 80 energy groups with heterogeneous and homogeneous ECCO geometry models.

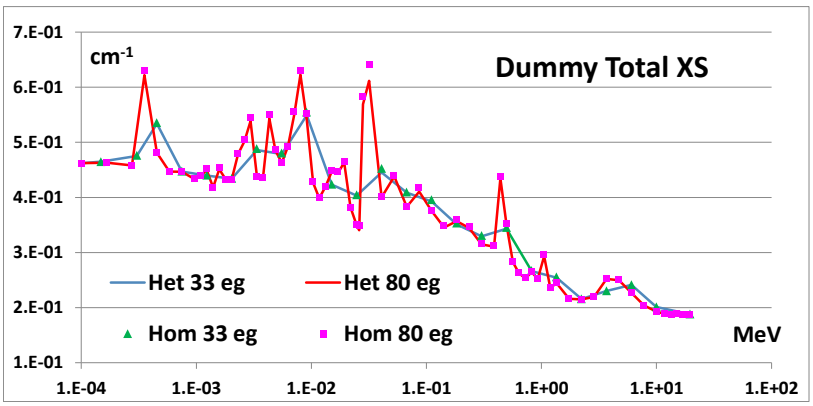

Figure A.17 Dummy total cross-sections evaluated at 33 and 80 energy groups with heterogeneous and homogeneous ECCO geometry models.

A.9 Cross-sections for ERANOS full-core calculations

The ERANOS full-core calculations can be carried out by adopting either the S_N discrete ordinate method or the variational nodal one (§A.1). The latter was used since by this option it is possible to reproduce a realistic 3D hexagonal geometry model of the ALFRED core. In any case, the code solves the following equations for both the discrete ordinates and variational nodal methods:

$$\mu \frac{\partial}{\partial x}\phi_g(x,\mu) + \Sigma_g^*(x)\phi_g(x,\mu) = \sum_{n=0}^{N}\frac{2n+1}{2}P_n(\mu)\sum_{g'=1}^{G}\Sigma_{sn,g'\to g}^*(x)\phi_{ng}(x)\,\mathrm{d}E' + \mathrm{Q}_g(x,\mu) \qquad \text{(A.30)}$$

where the "$\Sigma_{g,x}^*(x)$, $\Sigma_{sn,g'\to g}^*$" cross-sections for the "x" reaction have to be evaluated starting from the corresponding ECCO ones "$\Sigma_{g,x}(x)$, $\Sigma_{sn,g'\to g}$" (see §A.5). In some cases they are identical (*e.g.*, for fission $\Sigma_{g,f}^* = \Sigma_{g,f}$), but for the most part of vectors and matrices their values differ in dependence of the different P_N order chosen for the ERANOS cross-sections.

By comparing equations (A.30) with the ECCO ones (A.15), it can be seen that the expressions are equivalent by imposing that:

$$\Sigma_{sn,g'\to g}^*(x) = \Sigma_{n,g'\to g}(x) \qquad (g' \neq g) \qquad \text{(A.31.a)}$$

$$\Sigma_{sn,g\to g}^*(x) = \Sigma_{n,g\to g} + \Sigma_g^* - \Sigma_{n,g} \qquad (g' = g) \qquad \text{(A.31.b)}$$

Note that "Σ_g^*" in (A.30) is not determined and can be chosen to improve the convergence of the ERANOS calculation. Each choice of "Σ_g^*" gives rise to a given transport approximation, and, as shown in the following, the correspondence between the ECCO and ERANOS cross-sections varies according to the approximation chosen.

The easiest approximations used for the ERANOS cross-sections are essentially three: <u>P_0 transport, P_0 total and P_1</u>. On the other hand, the P_3 approximation was used to describe the anisotropy of the flux within the core.

A.9.1 The transport approximation (P_0)

With this approximation, the ERANOS total cross-section results identical to the transport one calculated by ECCO:

$$\Sigma_g^*(x) = \Sigma_{P0,g}^*(x) = \Sigma_{tr,g}(x). \qquad \text{(A.32.a)}$$

As it is clearly indicated in (A.11.c), the transport cross-section takes into account the anisotropy through the scattering term at the first order "Σ_{s1}".

A.9.2 The consistent P_0 approximation (P_0 total)

With this approximation, the ERANOS total cross-section is identical to the ECCO one calculated at the 0th order:

$$\Sigma_g^*(x) = \Sigma_{P0tot,g}^*(x) = \Sigma_{0,g}(x) \qquad \text{(A.32.b)}$$

With (A.32.b), the equations solved by ERANOS consist in a "pure" P_0 system since all the scattering events (as well as fissions or the external source terms) are assumed isotropic.

A.9.3 The consistent P_1 approximation (P_1)

With this approximation, the ERANOS total cross-section results identical to the total one calculated by ECCO at the first order:

$$\Sigma_g^*(x) = \Sigma_{P1,g}^*(x) = \Sigma_{1,g}(x) \qquad \text{(A.32.c)}$$

Actually, the ECCO code does not provide in output these multi-group values, since the total cross-section is represented by the 0th term "$\Sigma_{0,g}$" for both consistent (§A.7.2) and inconsistent (§A.7.3) solutions. Nevertheless, as shown in §A.10, it can be retrieved from the ECCO output through the transport cross-section and the scattering matrices at the first order "Σ_{s1}".

A.10 Correspondence between ECCO and ERANOS cross-sections

A.10.1 The ECCO cross-sections

Table A.1 summarises the macroscopic cross-sections (vectors Σ) and GxG matrices (M) given in output by the ECCO cell code at the P_1 order. The dependence from the spatial coordinate (x) is assumed implicit while in brackets the energy group g (and g' for the scattering and (n,xn) matrices) is specified. As mentioned in §A.9.3, despite the P_1 approximation the ECCO total cross-section is identical to the term at the 0th order "$\Sigma_0(g)$".

Table A.1 ECCO cross-sections and matrices (P_1 approximation).

Cross-sections / Matrices	Notation	
TOTAL	$\Sigma_0(g)$	
TRANSPORT	$\Sigma_{tr}(g)$	
CAPTURE	$\Sigma_c(g)$	
FISSION	$\Sigma_f(g)$	
PRODUCTION	$\nu\,\Sigma_f(g)$	
N,XN	$\Sigma_{n,xn}(g)$	
ELASTIC SCATTERING	$\Sigma_{el}(g)$	
INELASTIC SCATTERING	$\Sigma_{in}(g)$	
ELASTIC SCATTERING MATRIX	$\mathbf{M}_{el,0}(g, g')$	$\mathbf{M}_{el,1}(g, g')$
INELASTIC SCATTERING MATRIX	$\mathbf{M}_{in,0}(g, g')$	$\mathbf{M}_{in,1}(g, g')$
n,xn MATRIX	$\mathbf{M}_{n,xn,0}(g, g')$	$\mathbf{M}_{n,xn,1}(g, g')$

The total cross-section (at the 0th order) can be retrieved also by applying the relation between the cross-section vectors:

$$\Sigma_0(g) = \Sigma_c(g) + \Sigma_f(g) + \Sigma_{s,0}(g) =$$
$$= \Sigma_c(g) + \Sigma_f(g) + \Sigma_{el}(g) + \Sigma_{in}(g) + \Sigma_{n,xn}(g) \qquad \text{(A.33)}$$

The transfer (or total scattering) cross-sections "Σ_s" at the P_0 and P_1 orders result from the sum of elements of the corresponding matrices (M_{el}, M_{in} and $M_{n,xn}$; see Table A.1) that can be included in unique transfer matrices "TM*" (as done in ERANOS; see §A.10.2) summing the elastic, inelastic and n,xn ones at different orders. That is:

$$\Sigma_{s0}(g) = \Sigma_{n,xn}(g) + \Sigma_{el}(g) + \Sigma_{in}(g) = \sum_j \mathbf{TM_0^*}(g,j) =$$
$$= \sum_j \mathbf{M_{el,0}}(g,j) + \sum_j \mathbf{M_{in,0}}(g,j) + \sum_j \mathbf{M_{n,xn,0}}(g,j) \qquad \text{(A.34.a)}$$

$$3\,\Sigma_{s1}(g) = 3\sum_j \mathbf{TM_1^*}(g,j) =$$
$$= 3\sum_j \mathbf{M_{el,1}}(g,j) + 3\sum_j \mathbf{M_{in,1}}(g,j) + 3\sum_j \mathbf{M_{n,xn,1}}(g,j) \qquad \text{(A.34.b)}$$

where:

$$\Sigma_{el}(g) = \sum_j \mathbf{M_{el,0}}(g,j) \qquad \text{(A.34.c)}$$

$$\Sigma_{in}(g) = \sum_j \mathbf{M_{in,0}}(g,j) \qquad \text{(A.34.d)}$$

The absorption term "Σ_a" and the total cross-section at the first order "Σ_1" are not listed in the ECCO output but they can be retrieved by the following relations:

$$\Sigma_a(g) = \Sigma_0(g) - \Sigma_{s0}(g) = \Sigma_0(g) - \Sigma_{el}(g) - \Sigma_{in}(g) - \Sigma_{n,xn}(g) = \Sigma_c(g) + \Sigma_f(g) \qquad \text{(A.35.a)}$$

$$\Sigma_1(g) = \Sigma_{tr}(g) + \Sigma_{S1}(g) = \Sigma_{tr}(g) + \frac{1}{3}\sum_j \mathbf{TM_1^*}(g,j) \qquad \text{(A.35.b)}$$

A.10.2 The ERANOS cross-sections

Table A.2 summarises the macroscopic cross-section vectors "Σ^*" and GxG transfer matrices "TM^*" (A.34) used by ERANOS in the P_0 transport, P_0 total and P_1 approximations (§A.9.1-A.9.3). The ERANOS vectors identical to the ECCO ones are written in red (as in Table A.1) while, besides the asterisk, the other ERANOS cross-sections are reported in blue in order to distinguish even more easily them from the ECCO ones. As mentioned in §A.10.1, the ERANOS P_1 total cross-section "$\boldsymbol{\Sigma_{P1}^*(g)}$" values can be derived from the ECCO P_1 results through the relation (A.35.b) as they are not present explicitly in the ECCO output.

Besides the cross-sections, Table A.2 reports also the fission spectrum defined in (A.25) and the diffusion coefficient D that is:

$$\mathbf{D}^*(g) = \mathbf{1} / (\mathbf{3}\,\Sigma_{tr}(g)) \qquad \text{(A.36.a)}$$

The ERANOS capture cross-section results to be:

$$\boldsymbol{\Sigma_c^*(g)} = \Sigma_c(g) \qquad \text{(with UP-SCATTERING)} \qquad \text{(A.36.b)}$$

$$\boldsymbol{\Sigma_c^*(g)} = \Sigma_c(g) - \frac{\sum_{j=g+1}^{G} M_{el,0}(g,j)\phi_j}{\phi_g} \qquad \text{(without UP-SCATTERING)} \qquad \text{(A.36.c)}$$

In this work the <u>up-scattering option</u> (A.36.b) was adopted: it has to be specified in the ECCO / ERANOS interface in ERANOS (BASIC_EDL_CREATION_STARTING_FROM_ECCO_FILE; see §D.3).

Table A.2 ERANOS cross-sections and matrices at the P_N order ($P_N = P_0$ transport, P_0 total and P_1).

Cross-sections / Matrices	Notation	
TOTAL	$\Sigma^*_{PN}(g)$	
FISSION SPECTRUM	$\chi^*(g)$	
DIFFUSION COEFFICIENT	$D^*(g)$	
CAPTURE	$\Sigma^*_c(g)$	
FISSION	$\Sigma_f(g)$	
PRODUCTION	$\nu\,\Sigma_f(g)$	
N,XN	$\Sigma_{n,xn}(g)$[8]	
DISAPPEARANCE	$\Sigma^*_{dis}(g)$	
ELASTIC G → G	$\Sigma^*_{el,g}(g)$	
ELASTIC G → G+	$\Sigma^*_{el,g+}(g)$	
INELASTIC G → G	$\Sigma^*_{in,g}(g)$	
ELASTIC SCATTERING	$\Sigma_{el}(g)$	
INELASTIC SCATTERING	$\Sigma_{in}(g)$	
TRANSFER MATRIX	$TM^*_0(g,g')$	$TM^*_1(g,g')$

The ERANOS in-scattering inelastic cross-section (INELASTIC G → G) is actually related with the diagonal terms of the ECCO scattering matrices by the following relation including the (n,xn) reactions:

$$\Sigma^*_{in,g}(g) = M_{in,0}(g,g) + M_{n,xn,0}(g,g) \qquad \text{(A.37)}$$

while the in-scattering elastic cross-sections (ELASTIC G → G) relation with the ECCO values depends on the approximation (A.32.a-c) chosen:

$$\Sigma^*_{el,g}(g) = M_{el,0}(g,g) + \Sigma^*_{PN}(g) - \Sigma_0(g) + \Sigma^*_c(g) - \Sigma_c(g) \qquad \text{(A.38.a)}$$

With the up-scattering option (A.36.b) (here used), the ERANOS in-scattering elastic cross-section in the P_0 transport, P_0 total and P_1 approximations result:

[8] In the package identifier record, there is an integer IDUM1 which is described as an unused variable. If IDUM1 value is zero (<u>not</u> our case), the (n,xn) cross-section does not exist in the ECCO output file and is included in the corresponding inelastic values for vectors (as for matrices): $\Sigma^*_{in}(g) = \Sigma_{in}(g) + \Sigma_{n,xn}(g)$.

P_0 transport) $$\Sigma^*_{el,g}(g) = M_{el,0}(g,g) + \Sigma_{tr}(g) - \Sigma_0(g) \quad \text{(A.38.b)}$$

P_0 total) $$\Sigma^*_{el,g}(g) = M_{el,0}(g,g) \quad \text{(A.38.c)}$$

P_1) $$\Sigma^*_{el,g}(g) = M_{el,0}(g,g) + \Sigma^*_{P1}(g) - \Sigma_0(g) \quad \text{(A.38.d)}$$

By using relation (A.35.b), the in-scattering elastic cross-section in the P_1 approximation (A.38.d) can be rewritten also as:

P_1) $$\Sigma^*_{el,g}(g) = M_{el,0}(g,g) + \Sigma_{tr} + \Sigma_{S1} - \Sigma_0 = M_{el,0}(g,g) + \Sigma_{tr}(g) + \frac{1}{3}\sum_j TM^*_1(g,j) - \Sigma_0(g) \quad \text{(A.38.e)}$$

The ERANOS transfer (or total scattering) cross-section matrices are related with the elastic, inelastic and (n,xn) ones generated by ECCO as indicated in (A.34.a) and (A.34.b). Only the diagonal elements at the 0th order depend on the approximation (A.32.a-c) chosen:

$$TM^*_0(g,j) = M_{el,0}(g,j) + M_{in,0}(g,j) + M_{n,xn,0}(g,j) \qquad \text{(with } j \neq g\text{)} \quad \text{(A.39.a)}$$

$$TM^*_0(g,g) = M_{el,0}(g,g) + M_{in,0}(g,g) + M_{n,xn,0}(g,g) + \Sigma^*_{PN}(g) - \Sigma_0(g) + \Sigma^*_c(g) - \Sigma_c(g) \quad \text{(A.39.b)}$$

With the up-scattering option (A.36.b) the three approximations yield for the P_0 diagonal terms:

P_0 transport) $$TM^*_0(g,g) = M_{el,0}(g,g) + M_{in,0}(g,g) + M_{n,xn,0}(g,g) + \Sigma_{tr}(g) - \Sigma_0(g) \quad \text{(A.39.c)}$$

P_0 total) $$TM^*_0(g,g) = M_{el,0}(g,g) + M_{in,0}(g,g) + M_{n,xn,0}(g,g) \quad \text{(A.39.d)}$$

P_1) $$TM^*_0(g,g) = M_{el,0}(g,g) + M_{in,0}(g,g) + M_{n,xn,0}(g,g) + \Sigma^*_{P1}(g) - \Sigma_0(g) \quad \text{(A.39.e)}$$

Using equation (A.35.b), the diagonal elements in the P_1 approximation (A.39.e) can be expressed similarly to (A.38.e).

The relation between the transfer matrix at the first order (used only in P_0 transport and P_1 approximations) can be easily deduced from (A.35.b):

$$TM^*_1(g,j) = 3\,(\,M_{el,1}(g,j) + M_{in,1}(g,j) + M_{n,xn,1}(g,j)\,) \quad \text{(A.40)}$$

for each value of j.

The ERANOS down-scattering elastic cross-section (ELASTIC G → G+, which actually involves all the groups j > G) is related with the ECCO scattering matrices by the relation:

$$\Sigma^*_{el,g+}(g) = \sum_{j=g+1}^{G} M_{el,0}(g,j) \quad \text{(A.41)}$$

for each ERANOS approximation (*i.e.*, down-scattering because the energy intervals of groups j are below the energy limits of group g).

The disappearance cross-section (from the group g) "$\Sigma^*_{dis}(g)$" is defined in ERANOS as:

$$\Sigma^*_{dis}(g) = \Sigma^*_c(g) + \Sigma_f(g) + \Sigma_{el}(g) + \Sigma_{in}(g) + \Sigma_{n,xn}(g) - M_{el,0}(g,g) - M_{in,0}(g,g) - M_{n,xn,0}(g,g) \quad \text{(A.42.a)}$$

that, with the up-scattering option (A.36.b), becomes (for every ERANOS approximation):

$$\Sigma^*_{dis}(g) = \Sigma_c(g) + \Sigma_f(g) + \Sigma_{el}(g) + \Sigma_{in}(g) + \Sigma_{n,xn}(g) - M_{el,0}(g,g) - M_{in,0}(g,g) - M_{n,xn,0}(g,g) \quad \text{(A.42.b)}$$

By comparing (A.42.b) with the total cross-section at the 0th order (A.33), the disappearance cross-section can be written as:

$$\Sigma_0(g) = \Sigma^*_{dis}(g) + M_{el,0}(g,g) + M_{in,0}(g,g) + M_{n,xn,0}(g,g) \quad \text{(A.43)}$$

that makes clear the meaning of disappearance from the group g.

Table A.3 summarises the whole cross-sections set used by ERANOS in full-core calculations. The ECCO P_1 input cross-sections can be used in ERANOS with the P_0 (transport), P_0 total and P_1 approximation orders, as they were retrieved with previous formulae. It can be again pointed out that, in this work, the reference full-core calculations exploit the P_3 order for the flux moments even if the ECCO cross-sections and matrices were evaluated (and used in ERANOS) in the P_1 order approximation.

Table A.3 Relation between the ERANOS cross-sections - at the P_0 transport (P_0 tra), P_0 total (P_0 tot) and P_1 orders - and the ECCO cross-sections and matrices (calculated at the P_1 order).

Macroscopic cross-section	P_N	ERANOS	Equation	ECCO
Total	P_0 tra	$\Sigma^*_{P0}(g)$	(A.32.a)	$\Sigma_{tr}(g)$
	P_0 tot	$\Sigma^*_{P0tot}(g)$	(A.32.b)	$\Sigma_0(g)$
	P_1	$\Sigma^*_{P1}(g)$	(A.32.c) (A.35.b)	$\Sigma_{tr}(g) + \Sigma_{S1}(g) = \Sigma_{tr}(g) + \frac{1}{3}\sum_j TM^*_1(g,g)$
Diffusion coeff.	All	$D^*(g)$	(A.36.a)	$1 / (3\,\Sigma_{tr}(g))$
Capture	All	$\Sigma^*_c(g)$	(A.36.b)	$\Sigma_c(g)$ (with up scattering)
			(A.36.c)	$\Sigma_c(g) - \frac{\sum_{j=g+1}^{G} M_{el,0}(g,j)\Phi_j}{\phi_g}$ (without up scattering)
Fission	All	$\Sigma^*_f(g)$		$\Sigma_f(g)$
Production	All	$\nu\,\Sigma^*_f(g)$		$\nu\,\Sigma_f(g)$
n,xn	All	$\Sigma^*_{n,xn}(g)$		$\Sigma_{n,xn}(g)$ (with IDUM1 ≠ 0[b])
Inelastic g→g	All	$\Sigma^*_{in,g}(g)$	(A.37)	$M_{in,0}(g,g) + M_{n,xn,0}(g)$
Elastic g→g	P_0 tra	$\Sigma^*_{el,g}(g)$	(A.38.b)	$M_{el,0}(g,g) + \Sigma_{tr}(g) - \Sigma_0(g)$
	P_0 tot		(A.38.c)	$M_{el,0}(g,g)$
	P_1		(A.38.d) (A.38.e)	$M_{el,0}(g,g) + \Sigma_{P1}(g) - \Sigma_0(g) = M_{el,0}(g,g) + \Sigma_{tr}(g) + \Sigma_{S1}(g) - \Sigma_0(g) =$ $= M_{el,0}(g,g) + \Sigma_{tr}(g) + \frac{1}{3}\sum_j TM^*_0(g,j) - \Sigma_0(g)$

Elastic g→g+ (down-scatt.)	**All**	$\Sigma^*_{el,g+}(g)$	(A.41)	$\sum_{j=g+1}^{G} M_{el,0}(g,j)$
Elastic	**All**	$\Sigma^*_{el}(g)$	(A.34.a)	$\Sigma_{el}(g) = \sum_j M_{el,0}(g,j)$
Inelastic	**All**	$\Sigma^*_{in}(g)$	(A.34.a)	$\Sigma_{in}(g) = \sum_j M_{in,0}(g,j)$
Transfer Matrix at 0th order	**All**	$TM^*_0(g,g)$	(A.39.a)	$M_{el,0}(g,j) + M_{in,0}(g,j) + M_{n,xn,0}(g,j)$ (with $j \neq g$)
	P_0 tra		(A.39.c)	$M_{el,0}(g,g) + M_{in,0}(g,g) + M_{n,xn,0}(g,g) + \Sigma_{tr}(g) - \Sigma_0(g)$
	P_0 tot		(A.39.d)	$M_{el,0}(g,g) + M_{in,0}(g,g) + M_{n,xn,0}(g,g)$
	P_1		(A.39.e)	$M_{el,0}(g,g) + M_{in,0}(g,g) + M_{n,xn,0}(g,g) + \Sigma^*_{P1}(g) - \Sigma_0(g)$
Transfer Matrix at 1th order	**P_0 tra[a], P_1**	$TM^*_1(g,g)$	(A.40)	**3 (** $M_{el,1}(g,j) + M_{in,1}(g,j) + M_{n,xn,1}(g,j)$ **)** (for each j)
Disappearance	**All**	$\Sigma^*_{dis}(g)$	(A.42.a)	$\Sigma^*_c(g) + \Sigma_f(g) + \Sigma_{el}(g) + \Sigma_{in}(g) + \Sigma_{n,xn}(g) - M_{el,0}(g,g) - M_{in,0}(g,g) - M_{n,xn,0}(g,g)$

[a] The P_0 transport approximation adopts the transfer matrix at the first order through the transport cross-section

[b] Differently, with IDUM1 = 0 the (n,xn) ECCO cross-sections and matrices are included in the inelastic cross-sections

Appendix B: Comparison between multi-group constants (full data set of Serpent-ERANOS relative differences)

The following tables report the values of:

- the relative difference [%] between the Serpent (3D FC heterogeneous model) macroscopic cross-sections at 33 energy groups and the ECCO "reference" ones:

  (Serpent – ECCO) / ECCO

- the Relative Standard Deviation (RSD) of the Serpent results.

In both cases, the results were coloured according to their values: green if they are lower than 1%, orange if they are within the interval 1-10%, red if they are above 10%. The data are ordered from the upper to the lower energy groups (see Table 3.1 for the energy grid values).

It results evident the overall agreement between ECCO and Serpent for the great majority of the groups in the fissile (see Table B.1 in §B.1) and non-fissile (see Tables B.3, B.5, B.7 and B.9 in §B.2) zones, by the exception of the first (fastest) group and the thermal region of the spectrum where the Serpent RSD is also quite high for the MC Statistics (see Tables B.2, B.4, B.6, B.8 and B.10).

It can be then deduced that the poor statistics in the lowest energy groups is the major responsible of the code discrepancies in the thermal region. Furthermore, at lower energies the neutron absorptions are more likely and the effect of the different angular approximations (P_1 vs. continuous directions) will increase. Such effect should explain the relative difference between Serpent and ECCO capture cross-sections of the CR and SR absorbing bundle zones, which reaches up to ~50% around 0.5 keV (Table B.7), in spite of limited Serpent RSD (Table B.8), because of their "less diffusive" behaviour.

Significant differences (even if smaller than for CRs and SRs) were found also in the fuel pins plug (top and bottom) and axial reflector (top and bottom), as well as in the core barrel. All these zones (made of SS and lead only) are relatively far from the fissile region: therefore, also the spectrum "softening" in them (correctly reproduced by the Serpent 3D FC model and not by the 2D ECCO ones) could contribute to these discrepancies.

B.1 Fissile zones

Table B.1 Relative difference [%] between Serpent and ECCO macroscopic cross-sections at 33 energy groups for the fuel inner and outer zones.

(Serpent - ECCO) / ECCO

Inner fuel				Outer fuel			
Total	Transport	Capture	Fission	Total	Transport	Capture	Fission
0.1%	2.2%	1.3%	1.6%	0.1%	0.5%	0.3%	-0.8%
0.1%	0.0%	0.6%	-0.2%	0.1%	-0.3%	0.4%	-0.1%
0.1%	0.3%	0.4%	0.0%	0.1%	0.2%	0.4%	-0.2%
-0.1%	-0.1%	0.2%	-0.2%	-0.1%	0.0%	0.3%	-0.1%
0.1%	0.5%	0.3%	-0.1%	0.1%	0.5%	0.2%	-0.2%
-0.7%	1.3%	0.2%	-0.3%	-0.7%	1.2%	0.2%	-0.3%
-1.4%	0.1%	0.1%	-0.6%	-1.4%	0.1%	0.2%	-0.4%
-0.1%	4.2%	0.0%	-0.7%	-0.1%	4.3%	0.1%	-0.4%
-0.1%	1.9%	0.1%	-0.5%	-0.1%	1.9%	0.2%	-0.3%
-0.1%	2.2%	0.0%	-0.5%	-0.1%	2.2%	0.1%	-0.4%
0.1%	3.3%	0.1%	-0.6%	0.1%	3.2%	0.2%	-0.4%
0.2%	1.5%	0.3%	-0.6%	0.2%	1.4%	0.4%	-0.4%
0.1%	8.5%	0.3%	-0.1%	0.1%	8.5%	0.4%	0.0%
0.2%	3.8%	0.6%	-1.3%	0.2%	3.8%	0.5%	-1.3%
0.1%	1.6%	0.5%	0.6%	0.1%	1.5%	0.4%	0.5%
0.1%	4.9%	0.6%	-1.3%	0.1%	4.8%	0.6%	-1.2%
0.1%	2.5%	-0.1%	-4.9%	0.1%	2.4%	0.1%	-4.8%
0.2%	3.9%	0.0%	-4.7%	0.3%	3.8%	0.1%	-4.7%
0.1%	4.3%	-1.0%	-0.7%	0.0%	4.0%	-1.2%	-0.4%
0.0%	5.0%	-1.5%	-2.4%	-0.1%	4.8%	-2.3%	-2.7%
0.2%	3.9%	0.2%	0.7%	0.4%	4.2%	-0.1%	1.6%
0.7%	8.2%	-0.5%	0.5%	1.2%	8.7%	-0.6%	0.5%
-0.5%	5.8%	-1.5%	-3.0%	-0.8%	5.5%	-3.7%	-4.5%
1.4%	9.3%	4.9%	-0.3%	2.7%	11.2%	7.6%	-5.0%
-0.6%	5.4%	-5.9%	-5.0%	-0.6%	4.9%	-7.5%	-7.9%
-3.5%	11.2%	-11.8%	-14.8%	-5.1%	11.3%	-15.1%	-18.3%
-6.1%	9.3%	-27.8%	8.3%	-5.7%	8.4%	-27.8%	7.1%
-5.0%	12.5%	-18.6%	1.9%	-4.8%	12.3%	-18.7%	-3.7%
0.2%	4.9%	-3.8%	1.5%	-0.3%	4.4%	-7.1%	-3.8%
6.0%	13.7%	24.2%	10.9%	5.7%	12.1%	18.7%	6.6%
-16.0%	-7.7%	-54.3%	-55.5%	-15.9%	-6.2%	-52.9%	-51.2%
-7.1%	12.5%	-7.8%	-19.9%	-27.7%	-4.0%	-38.8%	-47.3%
117.3%	-100.0%	170.5%	197.6%	22.3%	-2.4%	27.7%	22.9%

Table B.2 RSD of the Serpent macroscopic cross-sections at 33 energy groups for the fuel inner and outer zones.

Inner fuel				Outer fuel			
Total	Transport	Capture	Fission	Total	Transport	Capture	Fission
0.14%	0.92%	0.90%	1.27%	0.07%	0.45%	0.40%	0.53%
0.05%	0.22%	0.28%	0.45%	0.02%	0.08%	0.13%	0.15%
0.02%	0.11%	0.16%	0.12%	0.01%	0.03%	0.07%	0.06%
0.01%	0.06%	0.09%	0.10%	0.00%	0.03%	0.04%	0.04%
0.01%	0.03%	0.06%	0.08%	0.01%	0.02%	0.03%	0.04%
0.02%	0.03%	0.06%	0.06%	0.01%	0.02%	0.03%	0.03%
0.01%	0.02%	0.04%	0.04%	0.00%	0.01%	0.02%	0.02%
0.02%	0.02%	0.03%	0.04%	0.01%	0.01%	0.02%	0.02%
0.01%	0.02%	0.04%	0.04%	0.00%	0.01%	0.02%	0.02%
0.01%	0.02%	0.02%	0.03%	0.00%	0.01%	0.02%	0.02%
0.01%	0.02%	0.04%	0.05%	0.00%	0.01%	0.02%	0.02%
0.01%	0.02%	0.04%	0.04%	0.00%	0.01%	0.02%	0.02%
0.02%	0.02%	0.04%	0.04%	0.01%	0.01%	0.02%	0.02%
0.02%	0.02%	0.05%	0.05%	0.01%	0.01%	0.02%	0.03%
0.01%	0.02%	0.04%	0.05%	0.01%	0.01%	0.03%	0.03%
0.02%	0.04%	0.08%	0.08%	0.01%	0.01%	0.03%	0.04%
0.02%	0.04%	0.07%	0.07%	0.01%	0.02%	0.04%	0.05%
0.02%	0.04%	0.09%	0.08%	0.02%	0.02%	0.06%	0.05%
0.02%	0.05%	0.17%	0.15%	0.01%	0.02%	0.06%	0.06%
0.04%	0.07%	0.23%	0.19%	0.02%	0.03%	0.10%	0.09%
0.05%	0.09%	0.24%	0.28%	0.03%	0.05%	0.12%	0.12%
0.11%	0.16%	0.35%	0.30%	0.06%	0.08%	0.16%	0.17%
0.12%	0.15%	0.46%	0.48%	0.06%	0.07%	0.24%	0.28%
0.21%	0.26%	0.85%	0.68%	0.09%	0.11%	0.40%	0.41%
0.38%	0.49%	1.59%	1.58%	0.20%	0.30%	0.92%	0.73%
0.39%	0.52%	1.54%	1.46%	0.16%	0.21%	0.65%	0.54%
0.43%	0.57%	1.74%	1.91%	0.18%	0.20%	1.04%	0.81%
0.64%	0.81%	2.25%	3.04%	0.21%	0.28%	0.97%	0.96%
0.49%	0.82%	2.31%	2.24%	0.31%	0.43%	1.26%	1.07%
0.87%	1.01%	3.31%	3.31%	0.29%	0.40%	1.16%	1.20%
0.65%	0.91%	3.11%	1.88%	0.22%	0.33%	0.93%	0.51%
10.78%	11.09%	16.82%	18.97%	2.69%	2.80%	4.47%	4.79%
9.60%	0.00%	8.52%	12.14%	15.81%	18.83%	21.74%	25.25%

B.2 Non-fissile zones

Table B.3 Relative difference [%] between Serpent and ECCO macroscopic cross-sections at 33 energy groups for the fuel pin insulators, spring and top plug zones.

(Serpent - ECCO) / ECCO

Top insulator			Bottom insulator			Spring			Top plug		
Total	Transport	Capture	Total	Transport	Capture	Total	Transport	Capture	Total	Transport	Capture
0.03%	3.62%	-8.32%	1.91%	18.51%	21.61%	11.04%	10.43%	21.71%	6.15%	-13.36%	-12.47%
-1.31%	2.02%	-3.18%	-0.52%	7.24%	0.77%	0.94%	2.72%	-8.42%	1.01%	16.13%	-27.44%
-0.52%	0.30%	-3.29%	-0.82%	0.11%	-1.71%	0.46%	1.93%	-13.57%	0.64%	2.71%	-44.22%
-1.71%	-0.02%	-1.08%	-1.74%	-0.05%	-2.20%	-0.53%	1.87%	-13.39%	-0.49%	1.27%	-47.86%
-1.46%	-0.95%	-1.48%	-1.11%	-0.13%	-1.51%	-2.06%	1.19%	-10.13%	-2.44%	-0.37%	-36.15%
-5.04%	0.19%	-0.91%	-5.68%	-1.15%	-2.66%	-3.71%	-0.35%	-3.60%	-5.67%	-5.27%	-16.59%
-5.09%	-2.43%	-4.88%	-5.14%	-2.39%	-4.55%	-6.17%	-1.12%	-4.00%	-8.89%	-5.64%	-14.08%
-7.18%	0.19%	-3.90%	-7.16%	0.02%	-3.52%	-4.77%	2.76%	-3.84%	-8.45%	-3.35%	-13.13%
-4.51%	-0.77%	-6.06%	-4.53%	-0.91%	-5.94%	-3.91%	2.15%	-6.21%	-10.59%	-5.45%	-20.64%
-5.73%	-2.31%	-8.09%	-5.72%	-2.31%	-8.99%	-3.61%	3.60%	-6.92%	-12.24%	-4.61%	-23.01%
-7.81%	-2.77%	-5.55%	-7.75%	-2.90%	-6.02%	-2.97%	6.23%	-3.05%	-9.87%	-2.84%	-12.84%
-3.91%	0.06%	-17.31%	-3.83%	0.04%	-16.45%	-1.06%	4.27%	-5.30%	-5.04%	-2.85%	-22.82%
-10.36%	2.13%	-11.60%	-10.32%	2.21%	-10.77%	-1.66%	16.05%	-4.57%	-8.18%	12.70%	-15.23%
-9.65%	-1.54%	-11.20%	-9.48%	-1.52%	-11.51%	-6.99%	-0.66%	-3.07%	-34.08%	-25.14%	-20.11%
-2.61%	0.33%	-11.14%	-2.76%	0.19%	-10.05%	-3.18%	0.31%	-7.78%	-18.86%	-15.57%	-35.88%
-7.22%	1.92%	-14.28%	-6.82%	1.98%	-14.05%	-0.88%	9.46%	-3.38%	-1.10%	5.53%	-10.68%
-4.22%	1.34%	-17.82%	-4.31%	0.80%	-20.69%	-2.72%	2.41%	0.86%	-13.57%	-10.09%	-15.40%
-7.30%	0.30%	-22.10%	-7.36%	0.05%	-21.97%	-2.25%	3.45%	-5.26%	-12.84%	-8.46%	-22.06%
-3.04%	-0.05%	-19.35%	-3.28%	-0.74%	-18.43%	-1.54%	3.64%	-4.95%	-5.71%	-3.96%	-17.64%
-3.23%	-0.05%	-47.67%	-2.83%	0.06%	-46.67%	-1.38%	5.47%	-9.52%	-4.13%	-0.57%	-8.07%
-3.23%	0.20%	-46.00%	-3.05%	0.01%	-48.75%	-1.08%	5.14%	-0.96%	-1.69%	0.15%	-14.25%
-6.17%	2.82%	-14.61%	-6.16%	3.43%	-15.66%	-1.81%	11.39%	-4.88%	-9.94%	4.07%	-25.44%
-7.32%	0.09%	-49.70%	-6.82%	0.48%	-50.98%	-2.18%	4.66%	-9.57%	-3.80%	-0.73%	-25.94%
-2.88%	-0.23%	-15.39%	-2.27%	1.36%	-16.10%	-0.97%	6.17%	-13.85%	-1.86%	1.17%	-33.80%
-2.56%	1.93%	-5.23%	-1.72%	2.81%	0.73%	-1.42%	6.05%	-0.20%	0.22%	3.32%	-8.47%
-1.25%	1.94%	19.47%	-1.25%	1.72%	19.54%	-1.55%	6.52%	32.18%	0.51%	3.43%	32.07%
-1.31%	1.38%	-1.48%	-2.44%	1.84%	-7.15%	-1.70%	5.63%	-3.99%	0.37%	2.71%	-15.40%
-1.12%	3.03%	-3.53%	-3.18%	0.92%	-8.68%	-2.96%	4.60%	-8.14%	-0.64%	3.13%	-22.65%
-1.83%	3.87%	-5.31%	-1.84%	0.58%	-6.34%	-1.24%	6.63%	-2.82%	-0.19%	2.73%	-10.58%
-2.52%	1.29%	-19.58%	-3.13%	1.08%	-20.52%	0.53%	7.53%	-9.21%	0.28%	1.61%	-26.70%
-5.03%	1.08%	-23.94%	-2.61%	-0.32%	-18.99%	0.50%	6.71%	-31.75%	-1.77%	-0.41%	-42.43%
-7.41%	-6.76%	-40.51%	-0.29%	19.10%	-28.07%	2.57%	11.13%	-11.77%	-1.35%	5.32%	-18.10%
-100.0%	-100.0%	-100.0%	3.7%	106.3%	6.7%	93.75%	168.4%	125.6%	2.87%	23.76%	-0.93%

Table B.4 RSD of the Serpent macroscopic cross-sections at 33 energy groups for the fuel pin insulators, spring and top plug zones.

Top insulator			Bottom insulator			Spring			Top plug		
Total	Transport	Capture	Total	Transport	Capture	Total	Transport	Capture	Total	Transport	Capture
1.79%	13.96%	12.26%	1.94%	15.34%	11.63%	6.45%	11.95%	13.29%	3.79%	17.86%	15.87%
0.68%	3.00%	2.76%	0.66%	3.49%	3.62%	1.55%	2.40%	3.17%	0.91%	4.54%	4.19%
0.25%	1.23%	1.91%	0.20%	1.57%	1.79%	0.79%	1.30%	1.34%	0.23%	1.72%	2.25%
0.17%	0.67%	1.03%	0.13%	0.52%	0.91%	0.41%	0.46%	0.71%	0.14%	0.77%	1.03%
0.11%	0.48%	0.51%	0.12%	0.55%	0.57%	0.24%	0.28%	0.36%	0.14%	0.39%	0.47%
0.22%	0.32%	0.44%	0.20%	0.30%	0.30%	0.16%	0.24%	0.21%	0.10%	0.28%	0.27%
0.10%	0.20%	0.36%	0.12%	0.28%	0.57%	0.10%	0.14%	0.32%	0.07%	0.16%	0.33%
0.18%	0.23%	0.64%	0.13%	0.23%	0.72%	0.09%	0.11%	0.39%	0.11%	0.12%	0.45%
0.07%	0.14%	0.58%	0.08%	0.18%	0.53%	0.10%	0.13%	0.31%	0.05%	0.10%	0.41%
0.07%	0.15%	0.51%	0.09%	0.16%	0.62%	0.11%	0.11%	0.33%	0.06%	0.10%	0.41%
0.07%	0.14%	0.66%	0.08%	0.14%	0.97%	0.13%	0.14%	0.42%	0.08%	0.10%	0.75%
0.05%	0.15%	0.87%	0.05%	0.13%	0.90%	0.08%	0.09%	0.38%	0.03%	0.08%	0.69%
0.17%	0.22%	1.14%	0.14%	0.21%	0.91%	0.14%	0.15%	0.49%	0.09%	0.13%	0.83%
0.15%	0.19%	1.15%	0.12%	0.18%	1.30%	0.13%	0.14%	0.60%	0.06%	0.12%	1.19%
0.09%	0.22%	0.92%	0.08%	0.17%	1.09%	0.15%	0.17%	0.42%	0.05%	0.11%	0.62%
0.18%	0.24%	0.95%	0.18%	0.21%	1.07%	0.14%	0.15%	0.25%	0.13%	0.14%	0.22%
0.19%	0.27%	1.90%	0.14%	0.23%	1.57%	0.14%	0.16%	0.84%	0.07%	0.11%	0.73%
0.23%	0.28%	1.66%	0.16%	0.30%	1.39%	0.18%	0.19%	0.87%	0.07%	0.13%	0.95%
0.13%	0.24%	2.20%	0.13%	0.27%	1.69%	0.18%	0.18%	0.72%	0.07%	0.13%	0.91%
0.18%	0.26%	4.45%	0.14%	0.34%	4.13%	0.22%	0.24%	1.18%	0.09%	0.15%	1.32%
0.23%	0.45%	3.12%	0.23%	0.54%	2.55%	0.25%	0.26%	0.59%	0.09%	0.15%	0.38%
0.54%	0.76%	2.19%	0.50%	0.64%	1.83%	0.38%	0.39%	0.59%	0.23%	0.23%	0.52%
0.36%	0.39%	4.49%	0.26%	0.46%	3.28%	0.31%	0.31%	0.42%	0.12%	0.18%	0.30%
0.45%	0.72%	4.56%	0.32%	0.75%	2.41%	0.36%	0.37%	0.93%	0.18%	0.23%	0.69%
0.74%	1.31%	3.59%	0.51%	1.13%	2.93%	0.70%	0.78%	0.94%	0.23%	0.36%	0.68%
0.68%	1.24%	8.57%	0.60%	1.15%	5.67%	0.57%	0.59%	1.16%	0.19%	0.32%	1.19%
0.81%	1.49%	3.47%	0.58%	1.40%	2.58%	0.60%	0.64%	0.72%	0.17%	0.31%	0.46%
1.03%	1.78%	4.29%	0.65%	1.30%	3.33%	0.70%	0.73%	1.08%	0.24%	0.40%	0.70%
1.41%	1.91%	5.73%	1.21%	1.77%	5.21%	0.91%	1.12%	1.10%	0.26%	0.49%	0.76%
1.50%	2.36%	6.84%	0.71%	1.60%	3.84%	0.90%	1.09%	1.20%	0.30%	0.53%	0.87%
1.27%	1.93%	6.23%	1.09%	1.41%	4.85%	1.09%	1.13%	1.29%	0.30%	0.53%	1.04%
10.79%	13.04%	43.44%	3.44%	6.48%	11.80%	4.10%	6.37%	5.70%	1.71%	3.67%	4.72%
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	16.59%	20.37%	34.12%	11.49%	19.88%	30.13%

Table B.5 Relative difference [%] between Serpent and ECCO macroscopic cross-sections at 33 energy groups for the FA axial reflectors, plenum and bottom plug zones.

(Serpent - ECCO) / ECCO

Bottom plug			Plenum			Top reflector			Bottom reflector		
Total	Transport	Capture	Total	Transport	Capture	Total	Transport	Capture	Total	Transport	Capture
5.42%	13.04%	3.44%	14.58%	16.05%	1.69%	4.79%	2.64%	-8.55%	-100.0%	-100.0%	-100.0%
0.22%	2.03%	-34.06%	-1.02%	-0.66%	-2.57%	4.50%	12.83%	-29.61%	4.10%	-3.86%	-30.52%
0.20%	1.84%	-49.94%	0.80%	1.38%	-2.16%	3.49%	4.10%	-56.50%	1.15%	21.96%	-50.63%
-0.83%	-1.08%	-49.25%	-0.75%	1.36%	-3.81%	2.40%	2.65%	-54.39%	0.94%	18.11%	-53.75%
-3.09%	-1.56%	-38.72%	-0.23%	2.68%	-2.12%	2.19%	3.33%	-36.12%	0.46%	2.90%	-31.01%
-6.26%	-4.86%	-18.86%	-1.96%	1.85%	-0.62%	-0.61%	-0.07%	-6.19%	-1.05%	0.42%	1.93%
-9.41%	-5.94%	-15.13%	-3.14%	2.03%	-0.49%	-1.73%	0.48%	-3.83%	-2.69%	-0.17%	0.44%
-9.11%	-3.93%	-14.93%	-0.86%	7.67%	-0.45%	1.15%	6.10%	-2.56%	2.45%	8.17%	-1.47%
-11.10%	-5.55%	-22.25%	-0.49%	5.92%	0.07%	-1.51%	0.28%	-5.57%	-0.47%	-0.92%	-0.83%
-12.45%	-4.36%	-24.33%	-0.58%	6.48%	-0.98%	-2.71%	0.11%	-10.63%	-1.28%	-0.83%	-6.06%
-10.11%	-3.10%	-15.24%	-0.21%	9.14%	-0.44%	-1.60%	2.68%	2.09%	-0.08%	3.87%	5.70%
-5.45%	-2.91%	-24.85%	0.05%	6.15%	-0.42%	-1.34%	0.10%	-9.32%	-0.47%	-0.96%	-4.43%
-9.38%	11.47%	-18.73%	0.17%	18.24%	-0.65%	4.18%	11.52%	-2.67%	4.46%	9.01%	0.77%
-34.82%	-25.37%	-20.54%	-0.40%	5.83%	0.14%	-21.07%	-18.46%	-18.63%	-13.59%	-12.05%	-13.91%
-20.12%	-16.53%	-37.20%	-0.65%	4.08%	-1.37%	-12.65%	-12.26%	-33.01%	-8.03%	-7.83%	-24.87%
-3.06%	3.81%	-13.67%	0.07%	13.03%	-0.63%	8.06%	9.08%	2.20%	6.56%	6.89%	3.51%
-15.22%	-11.58%	-16.77%	-0.60%	6.13%	0.10%	-7.07%	-6.89%	-8.17%	-4.38%	-4.26%	-3.01%
-14.36%	-9.73%	-22.28%	-0.45%	6.88%	-0.34%	-6.53%	-5.52%	-14.98%	-4.02%	-3.46%	-11.15%
-7.04%	-5.11%	-18.58%	-0.10%	6.30%	-0.91%	0.72%	0.84%	-8.89%	0.81%	-0.88%	-7.51%
-5.50%	-1.65%	-11.55%	-0.20%	7.82%	-1.01%	2.63%	3.40%	29.88%	2.09%	2.64%	31.90%
-3.12%	-1.18%	-17.50%	-0.16%	7.33%	-0.95%	4.20%	4.19%	-9.55%	3.26%	3.28%	-6.18%
-11.73%	2.60%	-27.86%	-0.37%	14.79%	-1.17%	-2.55%	3.03%	-22.14%	-1.57%	1.64%	-21.28%
-5.35%	-2.40%	-28.57%	-0.16%	7.75%	-1.18%	5.25%	5.11%	-10.79%	3.97%	3.91%	-8.75%
-3.43%	-0.17%	-35.71%	-0.29%	7.99%	-4.39%	5.11%	5.18%	-28.95%	3.92%	4.04%	-27.66%
-1.32%	1.96%	-12.25%	0.58%	8.98%	0.03%	6.94%	7.09%	-2.39%	5.13%	5.07%	0.37%
-1.07%	2.39%	25.93%	-0.16%	8.78%	-0.20%	6.90%	7.39%	-3.76%	5.15%	5.30%	-0.95%
-1.19%	0.84%	-18.05%	0.14%	8.57%	-0.58%	7.17%	7.14%	-5.02%	5.30%	5.32%	-2.60%
-2.22%	0.85%	-27.02%	0.01%	8.52%	-1.07%	6.57%	6.49%	-18.30%	4.91%	4.94%	-15.77%
-1.73%	0.73%	-15.47%	-0.25%	8.42%	-0.71%	7.30%	7.19%	0.80%	5.40%	5.34%	2.93%
-1.25%	0.67%	-29.52%	0.01%	8.66%	-0.44%	7.23%	7.29%	-7.19%	5.36%	5.18%	-4.63%
-3.46%	-0.39%	-43.32%	-0.37%	7.75%	1.70%	7.40%	6.42%	7.03%	5.51%	4.87%	10.33%
-3.06%	0.61%	-24.51%	0.15%	8.94%	-0.51%	7.37%	7.07%	5.78%	5.51%	4.55%	7.30%
0.99%	4.47%	-16.75%	25.30%	23.17%	24.80%	7.18%	5.98%	3.68%	5.53%	4.67%	5.92%

Table B.6 RSD of the Serpent macroscopic cross-sections at 33 energy groups for the FA axial reflectors, plenum and bottom plug zones.

Bottom plug			Plenum			Top reflector			Bottom reflector		
Total	Transport	Capture	Total	Transport	Capture	Total	Transport	Capture	Total	Transport	Capture
3.79%	20.13%	15.64%	-14.58%	-16.05%	-1.69%	0.17%	19.81%	1.73%	0.00%	0.00%	0.00%
0.91%	4.36%	4.07%	1.02%	0.66%	2.57%	0.40%	4.56%	1.88%	1.93%	30.42%	7.93%
0.23%	1.73%	1.41%	-0.80%	-1.38%	2.16%	0.09%	2.12%	0.97%	1.22%	14.02%	8.74%
0.14%	0.74%	1.05%	0.75%	-1.36%	3.81%	0.10%	0.76%	0.43%	0.56%	5.26%	2.95%
0.14%	0.40%	0.44%	0.23%	-2.68%	2.12%	0.07%	0.38%	0.05%	0.28%	1.40%	0.19%
0.10%	0.28%	0.30%	1.96%	-1.85%	0.62%	0.04%	0.18%	0.16%	0.12%	0.56%	0.57%
0.07%	0.17%	0.36%	3.14%	-2.03%	0.49%	0.03%	0.06%	0.15%	0.08%	0.23%	0.57%
0.11%	0.15%	0.43%	0.86%	-7.67%	0.45%	0.03%	0.05%	0.20%	0.05%	0.13%	0.36%
0.05%	0.11%	0.45%	0.49%	-5.92%	-0.07%	0.02%	0.06%	0.18%	0.03%	0.07%	0.20%
0.06%	0.09%	0.44%	0.58%	-6.48%	0.98%	0.01%	0.04%	0.21%	0.02%	0.07%	0.35%
0.08%	0.12%	0.73%	0.21%	-9.14%	0.44%	0.02%	0.03%	0.30%	0.03%	0.06%	0.35%
0.03%	0.09%	0.60%	-0.05%	-6.15%	0.42%	0.02%	0.04%	0.27%	0.03%	0.07%	0.52%
0.09%	0.13%	0.61%	-0.17%	-18.24%	0.65%	0.03%	0.05%	0.28%	0.05%	0.08%	0.57%
0.06%	0.11%	1.12%	0.40%	-5.83%	-0.14%	0.01%	0.04%	0.36%	0.01%	0.06%	0.48%
0.05%	0.09%	0.60%	0.65%	-4.08%	1.37%	0.01%	0.04%	0.35%	0.02%	0.06%	0.47%
0.13%	0.15%	0.27%	-0.07%	-13.03%	0.63%	0.02%	0.06%	0.07%	0.03%	0.06%	0.15%
0.07%	0.13%	0.89%	0.60%	-6.13%	-0.10%	0.00%	0.05%	0.52%	0.01%	0.04%	0.80%
0.07%	0.10%	0.89%	0.45%	-6.88%	0.34%	0.01%	0.05%	0.61%	0.01%	0.05%	0.67%
0.07%	0.10%	0.86%	0.10%	-6.30%	0.91%	0.00%	0.04%	0.32%	0.01%	0.06%	0.50%
0.09%	0.14%	1.11%	0.20%	-7.82%	1.01%	0.01%	0.05%	0.53%	0.01%	0.07%	0.65%
0.09%	0.17%	0.50%	0.16%	-7.33%	0.95%	0.00%	0.06%	0.14%	0.00%	0.08%	0.17%
0.23%	0.25%	0.57%	0.37%	-14.79%	1.17%	0.02%	0.07%	0.15%	0.03%	0.07%	0.20%
0.12%	0.20%	0.33%	0.16%	-7.75%	1.18%	0.00%	0.06%	0.04%	0.00%	0.06%	0.05%
0.18%	0.27%	0.53%	0.29%	-7.99%	4.39%	0.00%	0.06%	0.24%	0.00%	0.07%	0.24%
0.23%	0.29%	0.69%	-0.58%	-8.98%	-0.03%	0.00%	0.09%	0.14%	0.00%	0.10%	0.13%
0.19%	0.21%	1.32%	0.16%	-8.78%	0.20%	0.01%	0.07%	0.37%	0.01%	0.06%	0.52%
0.17%	0.32%	0.36%	-0.14%	-8.57%	0.58%	0.00%	0.09%	0.02%	0.00%	0.09%	0.02%
0.24%	0.39%	0.61%	-0.01%	-8.52%	1.07%	0.00%	0.10%	0.02%	0.00%	0.09%	0.02%
0.26%	0.43%	0.57%	0.25%	-8.42%	0.71%	0.00%	0.11%	0.02%	0.00%	0.08%	0.02%
0.30%	0.57%	0.66%	-0.01%	-8.66%	0.44%	0.00%	0.10%	0.05%	0.00%	0.11%	0.03%
0.30%	0.42%	0.97%	0.37%	-7.75%	-1.70%	0.00%	0.10%	0.18%	0.00%	0.08%	0.15%
1.71%	2.09%	3.75%	-0.15%	-8.94%	0.51%	0.02%	0.32%	0.54%	0.01%	0.23%	0.33%
11.49%	15.25%	24.77%	-25.30%	-23.17%	-24.80%	0.21%	2.83%	2.42%	0.10%	1.15%	1.49%

Table B.7 Relative difference [%] between Serpent and ECCO macroscopic cross-sections at 33 energy groups for the CR and SR absorbing bundles, the CR follower and dummy zones.

(Serpent - ECCO) / ECCO

Control rod B_4C			Control rod follower			Safety rod B_4C			Dummy		
Total	Transport	Capture	Total	Transport	Capture	Total	Transport	Capture	Total	Transport	Capture
0.11%	-0.97%	-4.48%	-0.62%	0.23%	-8.03%	1.87%	-1.52%	-6.26%	0.66%	0.67%	-0.45%
0.28%	0.01%	-4.24%	0.87%	0.09%	-13.16%	-0.24%	-0.65%	-11.70%	1.51%	1.07%	-2.68%
0.82%	0.78%	-4.49%	0.89%	0.55%	-16.90%	0.24%	0.21%	-9.25%	1.10%	1.25%	-4.44%
-0.57%	-0.68%	-5.94%	0.15%	0.52%	-29.04%	-1.26%	-1.30%	-8.62%	0.08%	0.51%	-1.05%
-1.12%	-0.82%	-7.56%	-0.85%	-0.31%	-12.29%	-2.44%	-1.46%	-10.16%	0.32%	0.81%	-0.21%
-2.62%	-1.30%	-6.21%	-2.64%	1.85%	-6.06%	-4.49%	-3.46%	-8.04%	-1.02%	1.35%	0.68%
-4.85%	-1.87%	-6.69%	-2.26%	-0.02%	-3.15%	-6.46%	-3.48%	-7.53%	-1.15%	0.34%	0.57%
-5.79%	0.44%	-11.65%	-2.03%	6.43%	-3.49%	-7.20%	-0.52%	-15.01%	-0.31%	4.72%	0.47%
-4.89%	-0.75%	-11.19%	-1.55%	1.38%	-4.98%	-6.98%	-2.06%	-13.76%	0.02%	2.38%	0.46%
-4.92%	-1.97%	-12.35%	-1.44%	0.95%	-4.92%	-7.09%	-2.38%	-13.79%	-0.16%	2.49%	0.08%
-3.90%	-1.27%	-12.82%	-0.96%	2.03%	-2.51%	-6.76%	-3.05%	-15.63%	0.34%	4.02%	0.79%
-3.86%	-2.27%	-15.52%	-0.98%	2.56%	-4.88%	-5.78%	-4.08%	-17.50%	0.59%	3.41%	0.49%
-4.41%	0.71%	-17.30%	-0.76%	4.97%	-5.65%	-4.61%	5.31%	-20.45%	0.39%	9.71%	-0.15%
-14.08%	-11.52%	-25.90%	-6.66%	-1.59%	-4.31%	-27.10%	-22.66%	-30.54%	0.52%	5.77%	2.74%
-10.64%	-8.68%	-22.64%	-5.71%	-2.84%	-9.11%	-20.36%	-16.96%	-20.86%	0.32%	2.13%	0.07%
-5.74%	-1.77%	-28.96%	-1.52%	4.51%	-1.18%	-2.52%	8.24%	-29.76%	-0.11%	5.83%	0.28%
-14.44%	-10.95%	-35.43%	-5.16%	-0.55%	-3.65%	-18.31%	-12.50%	-35.87%	0.21%	3.28%	0.33%
-17.42%	-11.81%	-39.69%	-4.63%	1.53%	-0.13%	-18.24%	-12.14%	-37.82%	0.51%	4.48%	1.55%
-17.46%	-9.89%	-41.23%	-2.43%	-0.21%	-6.43%	-12.59%	-9.21%	-37.26%	0.16%	1.75%	-4.53%
-19.66%	-8.25%	-44.77%	-2.34%	-1.17%	-2.65%	-11.95%	-5.98%	-40.43%	0.13%	1.70%	-8.05%
-20.61%	-6.75%	-47.45%	-1.92%	-0.37%	-5.57%	-10.47%	-5.14%	-41.80%	0.15%	1.78%	-5.14%
-22.72%	-5.84%	-49.69%	-6.10%	-1.35%	-23.81%	-16.48%	-0.08%	-46.57%	0.67%	7.16%	1.86%
-20.77%	-4.67%	-47.27%	-2.15%	1.33%	4.53%	-10.54%	-4.48%	-36.51%	-0.59%	2.64%	-13.31%
-19.61%	-3.84%	-46.47%	-2.34%	-1.14%	-36.52%	-10.07%	-2.77%	-40.67%	0.05%	1.74%	-4.18%
-10.15%	-1.88%	-29.70%	-1.89%	-0.91%	-23.29%	-6.81%	-0.48%	-36.69%	0.10%	1.70%	0.83%
-17.14%	5.99%	-42.34%	-2.08%	-0.93%	-25.96%	-6.37%	0.29%	-27.21%	0.19%	2.08%	7.15%
-15.70%	-0.02%	-40.64%	-1.81%	-0.82%	-23.37%	-6.73%	-0.83%	-32.24%	0.07%	1.72%	0.08%
-8.72%	0.46%	-26.31%	-2.04%	-0.98%	-30.51%	-6.43%	-1.19%	-29.38%	0.05%	1.73%	-0.60%
-8.51%	1.52%	-26.91%	-1.80%	-0.73%	-20.56%	-5.30%	-0.40%	-33.81%	0.07%	1.76%	-0.16%
-18.67%	0.96%	-45.17%	-1.80%	-0.81%	-23.47%	-7.44%	-0.69%	-44.82%	0.08%	1.78%	1.78%
0.55%	4.75%	6.90%	-1.73%	-2.36%	-17.24%	-6.43%	-2.58%	-16.67%	0.14%	0.55%	9.70%
4.17%	5.90%	19.82%	-2.31%	-2.95%	-22.08%	-6.71%	-2.86%	-15.63%	-0.03%	0.51%	2.06%
5.02%	10.04%	16.87%	-1.44%	0.37%	-16.93%	-7.12%	2.91%	-21.78%	-0.56%	0.71%	-4.08%

Table B.8 RSD of the Serpent macroscopic cross-sections at 33 energy groups for the CR and SR absorbing bundles, the CR follower and dummy zones.

Control rod B_4C			Control rod follower			Safety rod			Dummy rod		
Total	Transport	Capture	Total	Transport	Capture	Total	Transport	Capture	Total	Transport	Capture
0.20%	2.21%	1.81%	0.07%	0.63%	0.39%	1.38%	5.24%	5.45%	0.06%	0.33%	0.41%
0.11%	0.49%	0.50%	0.02%	0.10%	0.10%	0.31%	1.44%	2.08%	0.02%	0.07%	0.09%
0.04%	0.23%	0.22%	0.01%	0.05%	0.07%	0.16%	0.66%	1.09%	0.01%	0.05%	0.06%
0.01%	0.09%	0.15%	0.01%	0.02%	0.03%	0.04%	0.33%	0.68%	0.00%	0.02%	0.03%
0.02%	0.07%	0.08%	0.00%	0.02%	0.01%	0.04%	0.12%	0.28%	0.00%	0.01%	0.02%
0.02%	0.03%	0.05%	0.01%	0.01%	0.01%	0.03%	0.07%	0.18%	0.01%	0.01%	0.01%
0.02%	0.02%	0.05%	0.00%	0.01%	0.01%	0.02%	0.05%	0.08%	0.00%	0.01%	0.01%
0.02%	0.02%	0.04%	0.01%	0.01%	0.02%	0.03%	0.04%	0.10%	0.00%	0.01%	0.02%
0.01%	0.02%	0.04%	0.00%	0.00%	0.01%	0.03%	0.03%	0.08%	0.00%	0.00%	0.01%
0.01%	0.02%	0.03%	0.00%	0.01%	0.02%	0.02%	0.03%	0.07%	0.00%	0.00%	0.01%
0.01%	0.02%	0.04%	0.00%	0.01%	0.02%	0.02%	0.03%	0.08%	0.00%	0.00%	0.02%
0.01%	0.02%	0.03%	0.00%	0.00%	0.03%	0.01%	0.03%	0.08%	0.00%	0.00%	0.01%
0.02%	0.02%	0.05%	0.01%	0.01%	0.03%	0.04%	0.04%	0.12%	0.00%	0.00%	0.02%
0.02%	0.02%	0.05%	0.00%	0.01%	0.04%	0.02%	0.03%	0.08%	0.00%	0.00%	0.02%
0.03%	0.03%	0.09%	0.00%	0.01%	0.04%	0.02%	0.04%	0.13%	0.00%	0.00%	0.02%
0.04%	0.05%	0.09%	0.01%	0.01%	0.04%	0.06%	0.08%	0.17%	0.00%	0.00%	0.02%
0.03%	0.05%	0.09%	0.00%	0.01%	0.05%	0.03%	0.04%	0.16%	0.00%	0.00%	0.03%
0.04%	0.04%	0.14%	0.00%	0.01%	0.06%	0.04%	0.06%	0.22%	0.00%	0.00%	0.02%
0.04%	0.05%	0.13%	0.00%	0.01%	0.10%	0.04%	0.06%	0.22%	0.00%	0.00%	0.03%
0.05%	0.06%	0.14%	0.00%	0.01%	0.23%	0.05%	0.06%	0.24%	0.00%	0.01%	0.05%
0.09%	0.10%	0.22%	0.01%	0.01%	0.09%	0.05%	0.06%	0.20%	0.00%	0.00%	0.03%
0.08%	0.09%	0.20%	0.01%	0.02%	0.07%	0.09%	0.09%	0.35%	0.00%	0.01%	0.01%
0.05%	0.07%	0.18%	0.01%	0.02%	0.11%	0.08%	0.08%	0.27%	0.00%	0.00%	0.03%
0.10%	0.10%	0.27%	0.01%	0.03%	0.22%	0.07%	0.08%	0.30%	0.00%	0.00%	0.02%
0.13%	0.13%	0.37%	0.02%	0.05%	0.14%	0.10%	0.11%	0.38%	0.00%	0.01%	0.03%
0.10%	0.12%	0.27%	0.02%	0.05%	0.33%	0.08%	0.10%	0.32%	0.00%	0.01%	0.04%
0.12%	0.12%	0.33%	0.02%	0.06%	0.16%	0.09%	0.13%	0.34%	0.00%	0.01%	0.02%
0.14%	0.17%	0.39%	0.03%	0.07%	0.16%	0.10%	0.13%	0.40%	0.00%	0.01%	0.02%
0.12%	0.14%	0.38%	0.04%	0.08%	0.29%	0.13%	0.10%	0.51%	0.01%	0.01%	0.02%
0.18%	0.22%	0.47%	0.04%	0.07%	0.24%	0.11%	0.14%	0.52%	0.00%	0.01%	0.02%
0.13%	0.13%	0.31%	0.05%	0.06%	0.35%	0.09%	0.12%	0.37%	0.00%	0.01%	0.01%
0.69%	0.67%	1.61%	0.13%	0.24%	0.85%	0.36%	0.46%	1.33%	0.01%	0.01%	0.03%
4.49%	4.07%	10.15%	0.83%	1.10%	4.57%	2.58%	2.83%	10.88%	0.04%	0.06%	0.15%

Table B.9 Relative difference [%] between Serpent and ECCO macroscopic cross-sections at 33 energy groups for the barrel (SS and Pb mix) and external lead regions.

(Serpent - ECCO) / ECCO

Barrel			External lead		
Total	Transport	Capture	Total	Transport	Capture
5.23%	13.81%	-8.53%	-0.15%	0.97%	-4.58%
6.02%	4.07%	-35.45%	0.46%	0.39%	-2.03%
3.91%	4.17%	-58.59%	-0.09%	0.07%	-0.44%
1.55%	4.28%	-61.62%	0.73%	-0.37%	0.18%
1.86%	3.23%	-42.66%	1.58%	2.28%	-0.03%
-1.06%	-0.72%	-12.90%	-1.41%	0.33%	5.09%
-2.85%	-0.58%	-8.39%	-1.88%	2.38%	5.63%
-1.38%	3.50%	-7.44%	3.15%	10.80%	2.21%
-3.60%	-0.36%	-12.54%	-0.48%	0.60%	4.57%
-5.85%	-1.26%	-17.57%	0.23%	2.19%	6.17%
-5.23%	-0.35%	-4.03%	3.45%	7.24%	17.83%
-2.54%	-0.89%	-18.47%	0.93%	2.87%	8.72%
2.38%	14.57%	-9.58%	0.97%	1.93%	27.37%
-31.69%	-27.26%	-26.43%	0.06%	0.45%	3.50%
-19.35%	-18.52%	-40.90%	0.03%	0.13%	5.34%
7.15%	8.88%	-1.73%	0.05%	0.17%	2.86%
-12.08%	-11.80%	-12.77%	0.12%	0.26%	40.85%
-10.92%	-9.44%	-23.16%	0.08%	0.35%	7.79%
-1.33%	-1.16%	-16.04%	0.06%	0.37%	7.22%
1.27%	2.70%	10.20%	0.01%	-0.01%	0.54%
3.72%	3.74%	-11.89%	0.01%	0.03%	5.99%
-4.80%	3.95%	-22.92%	0.00%	0.00%	0.10%
4.66%	4.71%	-15.76%	0.02%	0.02%	1.87%
4.59%	4.79%	-33.87%	0.00%	0.00%	0.81%
7.27%	7.20%	-5.71%	0.00%	0.01%	0.40%
7.31%	7.83%	-1.19%	0.00%	0.01%	0.75%
7.55%	7.48%	-9.31%	0.00%	0.01%	1.22%
6.64%	6.63%	-22.70%	0.00%	-0.01%	0.79%
7.70%	7.63%	-3.51%	0.00%	0.02%	0.75%
7.61%	7.54%	-9.48%	0.00%	0.00%	0.97%
7.96%	6.97%	11.42%	0.01%	-0.32%	4.88%
7.71%	6.75%	3.94%	-0.03%	-0.34%	-4.71%
6.34%	5.54%	-5.55%	-0.08%	-0.60%	-4.50%

Table B.10 RSD of the Serpent macroscopic cross-sections at 33 energy groups for the barrel (SS and Pb mix) and external lead regions.

Barrel			External lead		
Total	Transport	Capture	Total	Transport	Capture
0.10%	3.22%	0.56%	0.02%	0.51%	0.47%
0.08%	0.66%	0.40%	0.01%	0.15%	0.03%
0.03%	0.43%	0.23%	0.00%	0.07%	0.01%
0.02%	0.13%	0.12%	0.00%	0.03%	0.00%
0.02%	0.07%	0.02%	0.00%	0.02%	0.00%
0.01%	0.05%	0.03%	0.00%	0.02%	0.03%
0.01%	0.02%	0.04%	0.00%	0.01%	0.04%
0.00%	0.01%	0.04%	0.00%	0.01%	0.04%
0.00%	0.01%	0.04%	0.00%	0.01%	0.03%
0.00%	0.01%	0.04%	0.00%	0.01%	0.04%
0.00%	0.01%	0.05%	0.00%	0.00%	0.05%
0.00%	0.01%	0.04%	0.00%	0.00%	0.06%
0.01%	0.01%	0.04%	0.00%	0.01%	0.05%
0.00%	0.01%	0.06%	0.00%	0.00%	0.10%
0.00%	0.01%	0.03%	0.00%	0.01%	0.08%
0.00%	0.00%	0.01%	0.00%	0.01%	0.05%
0.00%	0.00%	0.04%	0.00%	0.01%	0.16%
0.00%	0.01%	0.05%	0.00%	0.01%	0.10%
0.00%	0.00%	0.04%	0.00%	0.01%	0.06%
0.00%	0.00%	0.05%	0.00%	0.01%	0.00%
0.00%	0.00%	0.01%	0.00%	0.01%	0.08%
0.00%	0.01%	0.01%	0.00%	0.01%	0.00%
0.00%	0.00%	0.00%	0.00%	0.01%	0.00%
0.00%	0.01%	0.02%	0.00%	0.01%	0.00%
0.00%	0.01%	0.01%	0.00%	0.01%	0.00%
0.00%	0.01%	0.02%	0.00%	0.01%	0.00%
0.00%	0.01%	0.00%	0.00%	0.01%	0.00%
0.00%	0.01%	0.00%	0.00%	0.01%	0.00%
0.00%	0.01%	0.00%	0.00%	0.01%	0.00%
0.00%	0.01%	0.00%	0.00%	0.01%	0.01%
0.00%	0.01%	0.01%	0.00%	0.01%	0.03%
0.00%	0.02%	0.02%	0.00%	0.02%	0.05%
0.01%	0.08%	0.08%	0.01%	0.12%	0.30%

Appendix C: Axial flux distributions within core (full data set)

The following graphs (Figs. C.1-C.8) report the axial flux traverses calculated by ERANOS and Serpent along the directions Cut 1 and Cut 2 (see Fig. 6.1) with the CRs and SRs completely inserted and withdrawn. The black lines represent the boundary of the 60 cm fissile length.

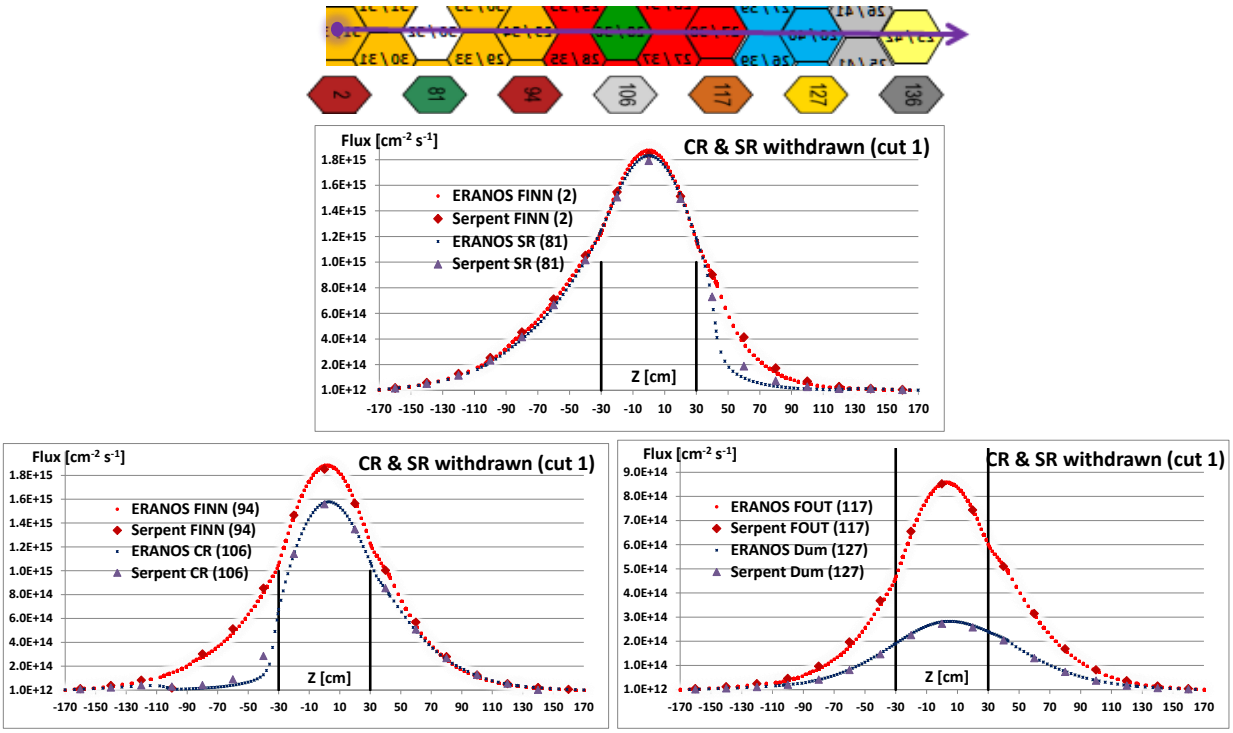

Figure C.1 ERANOS and Serpent axial flux traverses in the assembly positions along Cut 1 with both CR and SR completely withdrawn.

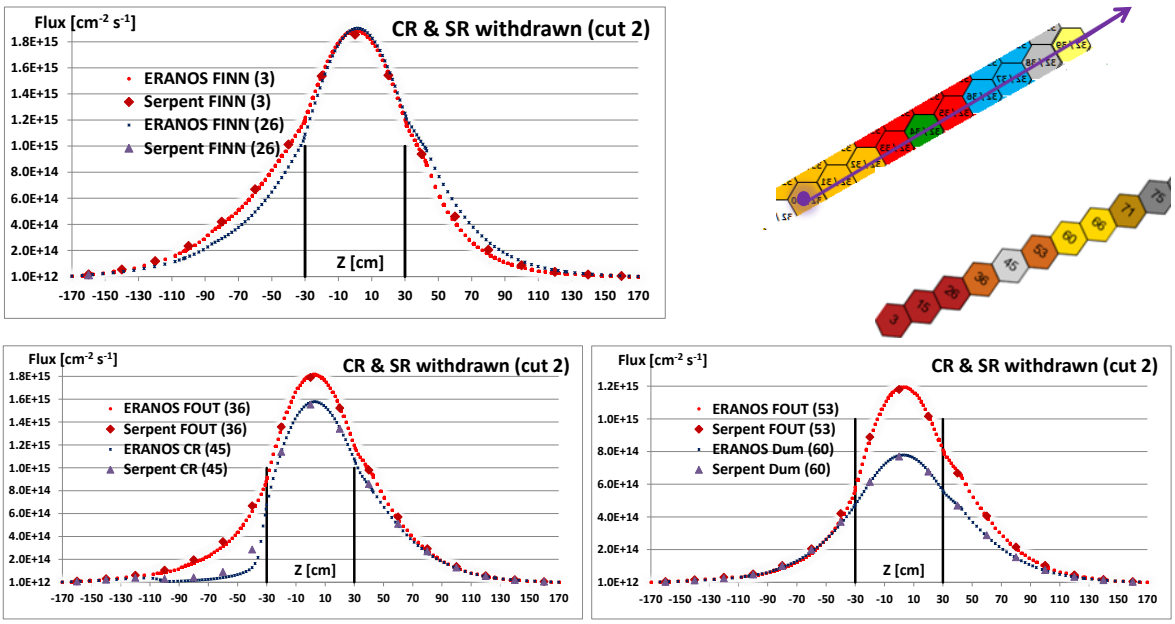

Figure C.2 ERANOS and Serpent axial flux traverses in the assembly positions along Cut 2 with both CR and SR completely withdrawn.

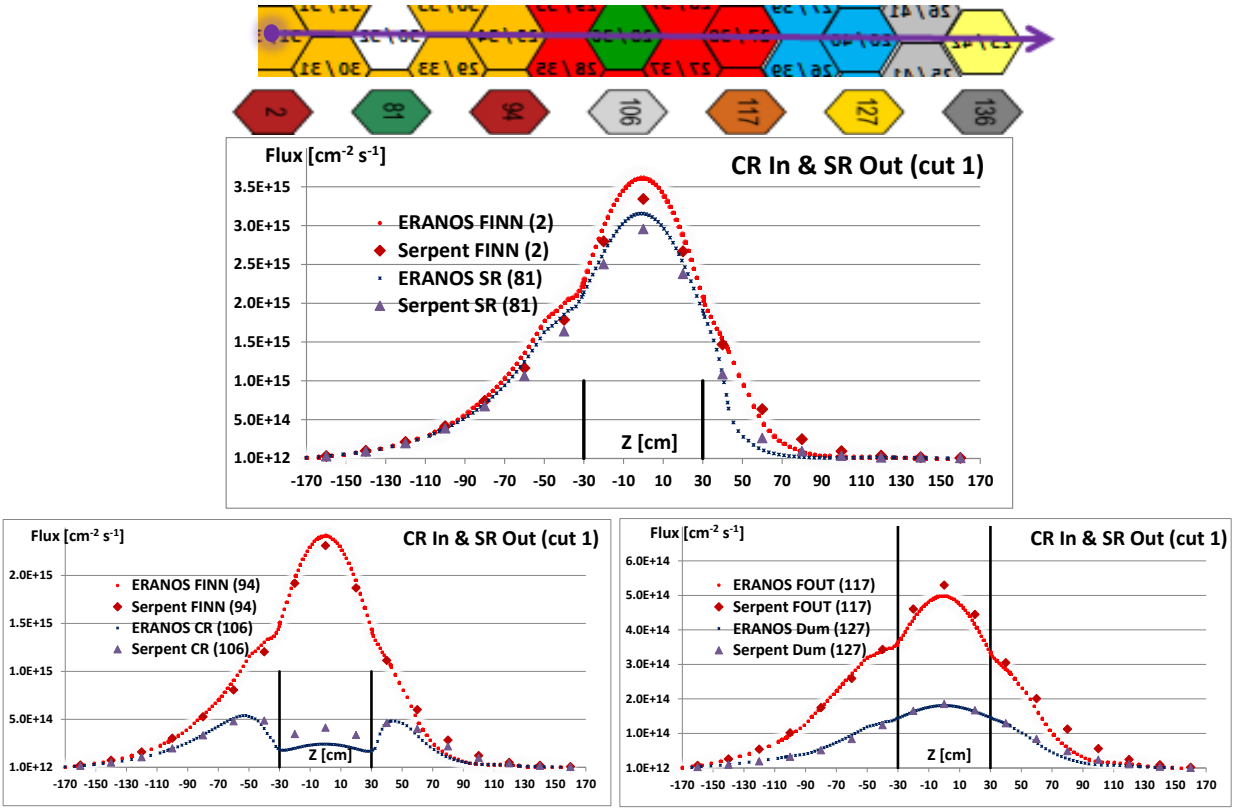

Figure C.3 ERANOS and Serpent axial flux traverses in the assembly positions along Cut 1 with the CR completely inserted and SR completely withdrawn.

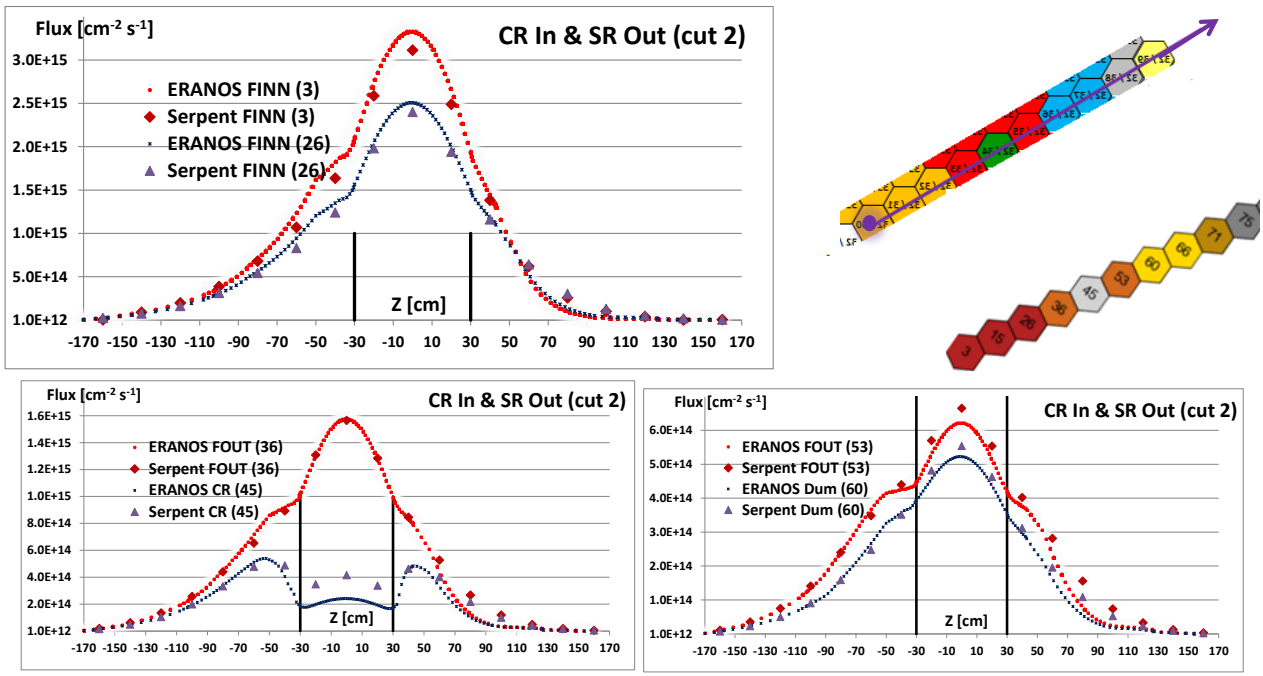

Figure C.4 ERANOS and Serpent axial flux traverses in the assembly positions along Cut 2 with the CR completely inserted and SR completely withdrawn.

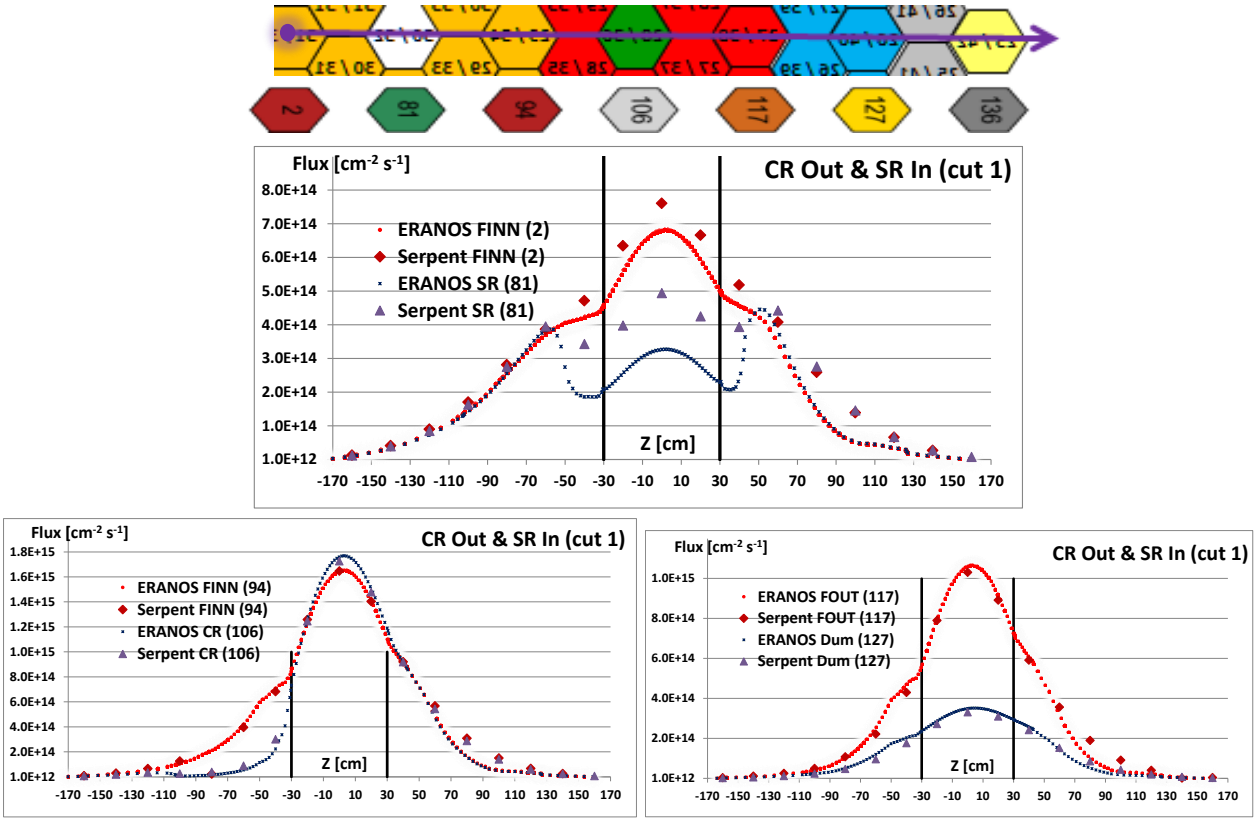

Figure C.5 ERANOS and Serpent axial flux traverses in the assembly positions along Cut 1 with the SR completely inserted and CR completely withdrawn.

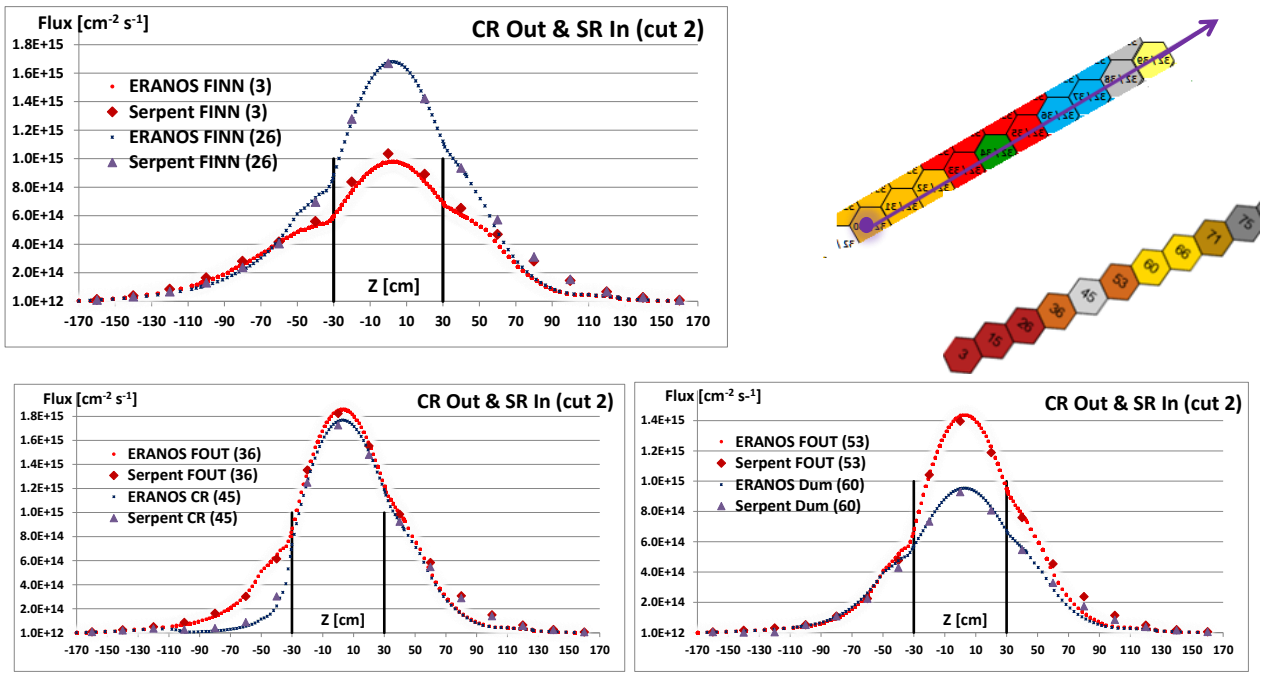

Figure C.6 ERANOS and Serpent axial flux traverses in the assembly positions along Cut 2 with the SR completely inserted and CR completely withdrawn.

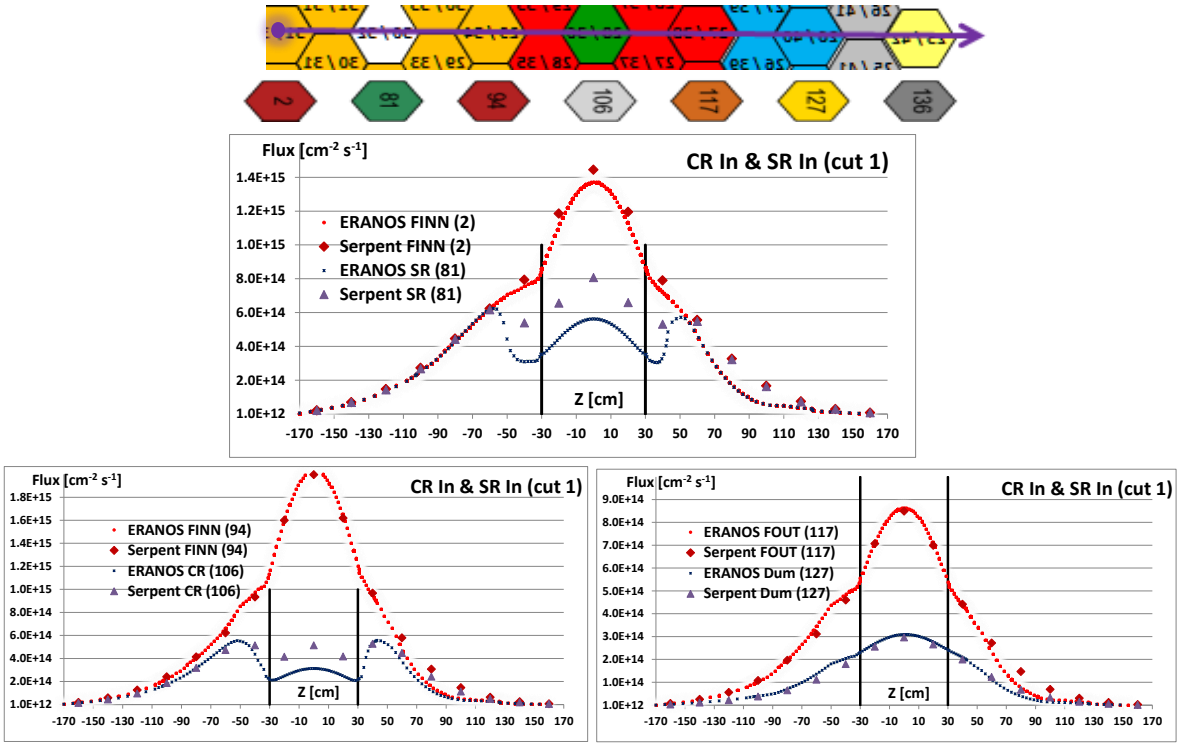

Figure C.7 ERANOS and Serpent axial flux traverses in the assembly positions along Cut 1 with both CR and SR completely inserted.

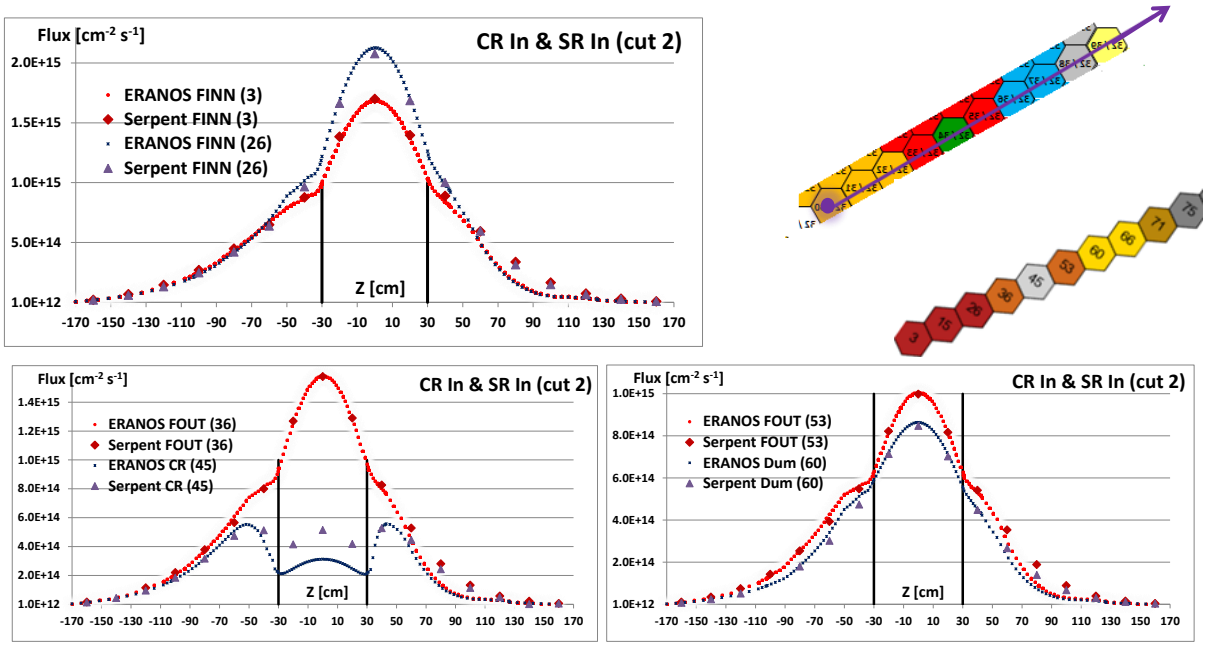

Figure C.8 ERANOS and Serpent axial flux traverses in the assembly positions along Cut 2 with both CR and SR completely inserted.

As remarked in §6.4, the depression of the flux caused by the CR and/or SR insertion results decisively higher with ERANOS, reflecting the effect of the ~10% higher calculated anti-reactivity worth of the shutdown systems in comparison with the Serpent results.

Appendix D: The ECCO / ERANOS input files

D.1 ECCO input files for fissile zones

In the following it is reported the ECCO input – written in the “Langage Utilisateur” (LU) adopted in the ERANOS system - used to create the “reference” macroscopic cross-sections of the fuel inner cell at 33 energy groups with a 2D heterogeneous geometry model. The input for the fuel outer is identical, by the exception of the lines written in red.

```
PROCEDURE ->ECCO_FUEL ;
 !============ ALLOCAZIONI PRELIMINARI ==============================
!-------------- Arricchimenti in Pu, B10 e AM -----------------------
 ->AM_SU_PU        0.013 ;
 ->ENR_INN         0.2110565 ;      !ENRICHISS INIZIALE in Pu vol.%
 ->ENR_OUT         0.2709639 ;      !ENRICHISS INIZIALE in Pu vol.%
 !
 !-------------- Geometrie varie di uso pratico -----------------------
 ->R_HOLL          0.100 ;
 ->R_FUEL          0.450 ;
 ->S_GAP           0.015 ;
 ->R_GAP          (R_FUEL+S_GAP) ;
 ->S_CLAD          0.060 ;
 ->R_CLAD         (R_GAP+S_CLAD) ;
 !
 !-------------- Densita' e porosita' per uso pratico ----------------
 ->PRACT_DENS    0.95 ;        ! Densita' pratica del combustibile
 ->FIL_DENS    ((R_FUEL**2-R_HOLL**2)/(R_GAP**2)) ; ! DensitÃ  nel gap

 !============ DEFINIZIONI DELLE CELLE ==============================

 CREATION_MILIEU ->MIL_20
 REFERENCE_UNIT 'JECCOLIB_JEFF_31.REF'
 TEMPERATURE_INITIALE 20.0

 !==================================================
 !                M A T E R I A U X
 !==================================================

 MATERIAU_SIMPLE  'PIOMBO'    CALOPORTEUR
   POURCENTAGE_EN_POIDS  11.017   !g/cm^3
    CORPS
      'Pb204'    1.42       'Pb206'   24.10       'Pb207'   22.10       'Pb208'   52.38

 MATERIAU_SIMPLE  'T91'       STRUCTURE
   POURCENTAGE_EN_POIDS   7.7359  !g/cm^3
    CORPS
      'C0'       0.1       'Si28'    (0.5*0.9187)       'Si29'    (0.5*0.0483)       'Si30'    (0.5*0.033)
      'V0'       0.2       'Cr52'    (9.0*0.837)       'Cr50'    (9.0*0.0418)       'Cr53'    (9.0*0.0967)
      'Cr54'    (9.0*0.0245)       'Mn55'     0.6       'Fe54'   (88.3*0.0565)       'Fe56'   (88.3*0.919)
      'Fe57'   (88.3*0.0216)       'Fe58'   (88.3*0.0029)       'Ni58'    (0.2*0.672)       'Ni60'    (0.2*0.2678)
      'Ni61'    (0.2*0.0118)       'Ni62'    (0.2*0.0383)       'Ni64'    (0.2*0.0101)       'Nb93'     0.1
      'Mo92'    (1.0*0.1484)       'Mo94'    (1.0*0.0925)       'Mo95'    (1.0*0.1592)
      'Mo96'    (1.0*0.1668)       'Mo97'    (1.0*0.0955)       'Mo98'    (1.0*0.2413)       'Mo100'   (1.0*0.0963)
```

```
MATERIAU_SIMPLE  '1515TI'    STRUCTURE
  POURCENTAGE_EN_POIDS   7.95    !g/cm^3
    CORPS
     'C0'      0.09       'Si28'    (0.85*0.9187)        'Si29'    (0.85*0.0483)      'Si30'    (0.85*0.033)
     'V0'      0.03       'Cr52'   (14.5*0.837)       'Cr50'   (14.5*0.0418)      'Cr53'   (14.5*0.0967)
     'Cr54'   (14.5*0.0245)      'Mn55'     1.5       'Fe54'   (65.354*0.0565)      'Fe56'   (65.354*0.919)
     'Fe57'   (65.354*0.0216)      'Fe58'   (65.354*0.0029)      'Ni58'   (15.5*0.672)      'Ni60'   (15.5*0.2678)
     'Ni61'   (15.5*0.0118)      'Ni62'   (15.5*0.0383)      'Ni64'   (15.5*0.0101)      'Nb93'     0.015
     'Mo92'    (1.5*0.1484)      'Mo94'    (1.5*0.0925)      'Mo95'    (1.5*0.1592)
     'Mo96'    (1.5*0.1668)      'Mo97'    (1.5*0.0955)      'Mo98'    (1.5*0.2413)      'Mo100'   (1.5*0.0963)
     'Ti46'    (0.4*0.0825)      'Ti47'    (0.4*0.0744)      'Ti48'    (0.4*0.7372)      'Ti49'    (0.4*0.0541)
     'Ti50'    (0.4*0.0518)      'B10'     (0.006*0.199)      'B11'     (0.006*0.801)      'P31'      0.045
     'N14'     (0.015*0.99632)      'N15'     (0.015*0.00368)      'S32'     (0.015*0.9493)
     'S33'     (0.015*0.0076)      'S34'     (0.015*0.0429)      'S36'     (0.015*0.0002)      'Al27'     0.015
     'Zr90'    (0.03*0.5145)      'Zr91'    (0.03*0.1122)      'Zr92'    (0.03*0.1715)
     'Zr94'    (0.03*0.1738)      'Zr96'    (0.03*0.0280) !      'W180'    (0.03*0.0012)
     'W182'    (0.03*0.26532)      'W183'    (0.03*0.14327)      'W184'    (0.03*0.30677)
     'W186'    (0.03*0.28464)      'Ta181'    0.015       'Cu63'    (0.03*0.6917)      'Cu65'    (0.03*0.3083)
     'Co59'     0.03       'Ca40'    (0.03*0.96945)      'Ca42'    (0.03*0.00647)      'Ca43'    (0.03*0.00135)
     'Ca44'    (0.03*0.02086)!      'Ca46'    (0.03*0.00004)      'Ca48'    (0.03*0.00187)

MATERIAU_SIMPLE  'COMB_INN'   COMBUSTIBLE
  FORMULE_MOLECULAIRE   10.494
    ELEMENT CIP 0.78299087
     'U234'     0.003000194904
     'U235'     0.404162518132
     'U236'     0.010002296764
     'U238'    99.582834990200
    ELEMENT CIP 0.21700913
     'Pu238'    2.301581154003
     'Pu239'   56.136812325802
     'Pu240'   26.650590345084
     'Pu241'    6.026944416127
     'Pu242'    7.593331097559
     'Am241'    1.290740661425
    ELEMENT CIA 1.97
     'O16'    100.0

MATERIAU_SIMPLE  'COMB_OUT'   COMBUSTIBLE
  FORMULE_MOLECULAIRE   10.513
    ELEMENT CIP 0.72203820
     'U234'     0.002999447021
     'U235'     0.403941574675
     'U236'     0.009996781937
     'U238'    99.583062196367
    ELEMENT CIP 0.27796180
     'Pu238'    2.301764074405
     'Pu239'   56.139989750890
     'Pu240'   26.646602344285
     'Pu241'    6.026447182106
     'Pu242'    7.594582799311
     'Am241'    1.290613849003
    ELEMENT CIA 1.97
     'O16'    100.0
```

```
!=================================================
!              M I L I E U X
!=================================================


 !===  Combustibile Inner ====================
 !==== diluito nel Gap (FIL_DENS) =================
 MILIEU  'M_FUEINN'
   'COMB_INN'  (100.0*(FIL_DENS))

 MILIEU  'M_FUEOUT'
   'COMB_OUT'  (100.0*(FIL_DENS))

 MILIEU 'M_PIOMB1'
   'PIOMBO'     100.0
MILIEU 'M_CALO_1'
   'PIOMBO'     100.0
MILIEU 'M_CALO_2'
   'PIOMBO'     100.0
MILIEU 'M_CLAD_1'
   '1515TI'     100.0
MILIEU 'M_WRAP_1'
   'T91'        100.0


!=====================================================
!              C E L L U L E
!=====================================================

!=======  CELLULE      ETEROGENEE ==========

!==== FUEL INNER
CELLULE 'FINN'
  RANGEMENT_COMPOSITION
    'M_FUEINN' 'M_CLAD_1'  'M_WRAP_1' 'M_CALO_1' 'M_PIOMB1'   'M_CALO_2'
  GEOMETRY DATA
    HEXAGON 3
      15.80
        HEXAGONAL LATTICE
          7  1.386
          1
            CYL 2
              0.465   REGION    1   'COMB_INN'    COMP   1   293.16
              0.525   REGION    2   'CLADDING'    COMP   2   293.16
              IN      REGION    3   'PB_AR_CL'    COMP   4   293.16
          1 1 1 1 1 1 1
        IN          REGION    4   'BB_LEADA'    COMP   6   293.16
      16.60
                  REGION    5   'SWRAPPER'    COMP   3   293.16
      17.10
                  REGION    6   'PB_FALIK'    COMP   5   293.16
    REFLECT
  END OF GEOMETRY DATA
```

```
!==== FUEL OUTER
 CELLULE 'FOUT'
  RANGEMENT_COMPOSITION
   'M_FUEOUT' 'M_CLAD_1'  'M_WRAP_1' 'M_CALO_1' 'M_PIOMB1'   'M_CALO_2'
  GEOMETRY DATA
   HEXAGON 3
    15.80
     HEXAGONAL LATTICE
      7  1.386
      1
       CYL 2
        0.465   REGION    1   'COMB_OUT'    COMP   1   293.16
        0.525   REGION    2   'CLADDING'    COMP   2   293.16
        IN      REGION    3   'PB_AR_CL'    COMP   4   293.16
      1 1 1 1 1 1 1
     IN          REGION    4   'BB_LEADA'    COMP   6   293.16
    16.60
                REGION    5   'SWRAPPER'    COMP   3   293.16
    17.10
                REGION    6   'PB_FALIK'    COMP   5   293.16
   REFLECT
  END OF GEOMETRY DATA ;

 !============ DEFINIZIONE CONDIZIONI OPERATIVE =====================
!EDITION_MILIEU (MIL_20);

 ->T_CLAD      (460.0+273.16) ;
 ->T_HOT       (450.0+273.16) ;
 ->T_MEDIA     (440.0+273.16) ;
 ->T_OUT       (480.0+273.16) ;
 ->T_FUEL      (900.0+273.16) ;
 ->T_IN        (400.0+273.16) ;

  !=====================================================================
  !           DEBUT DES CALCULS CELLULES ECCO
  !=====================================================================

 ECCO
  MILIEU (MIL_20)
  REFERENCE_UNIT 'JECCOLIB_JEFF_31.REF'

  !=========================================
  !     CELLULE FINN /FOUT HET
  !=========================================
  CELLULE 'FINN' / 'FOUT'
   EDITION MOYENNE
   'FUEL INNER HET' / 'FUEL OUTER HET'
   TEMPERATURE
     1 (T_FUEL)
     2 (T_CLAD)
     3 (T_MEDIA)
     4 (T_MEDIA)
     5 (T_MEDIA)
     6 (T_MEDIA)
```

```
STEPS 6
 STEP
  GEOMETRY HOMOGENEOUS
  GROUP STRUCTURE OTHER 172
  INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
  FLUX SOLUTION FM P1 CONSISTENT ORDER 1
  BSEARCH 1.0
  LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
  SELF SHIELDING NODBBSH
  OUTPUT LIBRARY 'FINN_172G_HOM_JEFF31'/  OUTPUT LIBRARY 'FOUT_172G_HOM_JEFF31'
    CROSS SECTIONS FLUXES
 STEP
  GEOMETRY ORIGINAL
  GROUP STRUCTURE OTHER 172
  INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
  ELEMENTS ALL
  FLUX SOLUTION CP P1 CONSISTENT ORDER 1
  BFROM 1
  LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
  SELF SHIELDING NODBBSH
  PROFILE OUTER ITERATIONS BROAD MAXIMUM NUMBER 70
  COLLISION PROBABILITIES ROTH 6
 STEP
  GEOMETRY ORIGINAL
  GROUP STRUCTURE FINE
  INPUT LIBRARY 'JECCOLIB_JEFF_31.1968'
  ELEMENTS 81
   'Fe54'  'Fe56'  'Fe57'  'Fe58'  'Cr50'  'Cr52'  'Cr53'  'Cr54'
   'Ni58'  'Ni60'  'Ni61'  'Ni62'  'Ni64'
   'Mo92'  'Mo94'  'Mo95'  'Mo96'  'Mo97'
   'Mo98'  'Mo100' 'Nb93'  'Al27'
   'Mn55'  'O16'   'N14'   'N15'   'C0'
   'Si28'  'Si29'  'Si30'  'V0'  'Zr93'  'Tc99'  'I129'
   'Ti46'  'Ti47'  'Ti48'  'Ti49'  'Ti50'
   'Ca40'  'Ca42'  'Ca43'  'Ca44'  'Ca48'
   'W182'  'W183'  'W184'  'W186'
   'Zr90'  'Zr91'  'Zr92'  'Zr94'  'Zr96'
   'B10'   'B11'  Pb204' 'Pb206' 'Pb207' 'Pb208'
   'U234'  'U235'  'U236'  'U238'
   'Pu238' 'Pu239' 'Pu240' 'Pu241' 'Pu242'  'Am241'
   'U233'  'Np237' 'Np239'  'Am243' 'Am242m'
   'Cm242' 'Cm243' 'Cm244' 'Cm245' 'Cm246' 'Cm247' 'Cm248'
  FLUX SOLUTION CP P1 CONSISTENT ORDER 1
  BFROM 1
  SELF SHIELDING NODBBSH
  LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
  PROFILE COLLISION PROBABILITIES ROTH 6
  CONDENSE 33
     1   82  142  202  262  322  382  442  502  564
   624  686  746  808  868  928  988 1048 1108 1168
   1228 1288 1336 1422 1480 1516 1579 1648 1708 1768
   1837 1919 1952
 STEP
  GEOMETRY ORIGINAL
```

```
    GROUP STRUCTURE OTHER 33
    FLUX SOLUTION CP P1 CONSISTENT ORDER 1
    BSEARCH 1.0
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING NODBBSH
    PROFILE COLLISION PROBABILITIES ROTH 6
  STEP
    HOMOGENISE
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE OTHER 33
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    BFROM 4
    OUTPUT LIBRARY 'FINN_HH_33G_JEFF31' /  OUTPUT LIBRARY 'FOUT_HH_33G_JEFF31'
      CROSS SECTIONS FLUXES
    PRINT DATA  FLUXES
      CROSS SECTIONS MACROSCOPIC VECTORS
  STEP
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE OTHER 33
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    BUCKLING 0.0
 ENDSTEPS;

FINPROC ;
```

Besides the reference input reported before, other ECCO calculation options were adopted for the fuel inner and outer cells (see §3.2 and §A.8). For the calculations with the P_1 inconsistent and B_1 consistent/inconsistent options, the instruction "FLUX SOLUTION FM/CP P1 CONSISTENT ORDER 1" for homogeneous/heterogeneous cell geometries, respectively (FM = Fundamental Mode; CP = Collision Probabilities) was replaced by;

- FLUX SOLUTION FM/CP P1 INCONSISTENT ORDER 1
- FLUX SOLUTION FM/CP B1 CONSISTENT/INCONSITENT ORDER 1

The reference macroscopic cross-sections were created with a 33 energy-group-structure (see Table 3.1), but also with the more refined structure at 80 groups (see Table 3.2). In the latter case the group numbers reported in the last column of Table 3.2 have to be replaced in the "CONDENSE" instructions of the previous ECCO input.

D.2 ECCO input files for non-fissile zones

In the following it is reported the "reference" ECCO input for the cells representing the non-fissile zones. As weighting function, the fuel inner and outer spectra at 172 groups (evaluated by a homogeneous geometry model in the first step of the ECCO routine; see §D.1) were adopted. The lines written in red abbreviate the MILIEU definitions for the media having the same materials compositions that have to be used with a different name in the different cells for the ECCO/ERANOS code programming rules.

```
PROCEDURE ->ECCO_SUB  ;

->ENR_B4C        0.900 ;        !ARRICCHIMENTO DEL BORO IN B10 at.%
!-------------- Geometrie varie di uso pratico ----------------------
 ->R_HOLL        0.100 ;
 ->R_FUEL        0.450 ;
```

```
->S_GAP          0.015 ;
->R_GAP         (R_FUEL+S_GAP) ;
->S_CLAD         0.060 ;
->R_CLAD        (R_GAP+S_CLAD) ;
!
!-------------- Densita' e porosita' per uso pratico ----------------
->PRACT_DENS    0.95 ;        ! Densita' pratica del combustibile
->FIL_DENS    ((R_FUEL**2-R_HOLL**2)/(R_GAP**2)) ; ! DensitÃ  nel gap
->THI_DENS      0.9365245 ;    ! Filling density isolante nel clad della fuel pin
->SPR_DENS      0.07594 ;      ! Filling density molla nel plenum della fuel pin
->PLE_DENS      0.07559 ;      ! Filling density tubo nel plenum della fuel pin
->ABS_DENS      0.94703 ;      ! Filling density assorbitore nel gap
->THA_DENS      0.94703 ;      ! Filling density isolante nel clad della abs pin

!============ DEFINIZIONI DELLE CELLE ==============================

CREATION_MILIEU ->MIL_20

REFERENCE_UNIT 'JECCOLIB_JEFF_31.REF'
TEMPERATURE_INITIALE 20.0

!==================================================
!              M A T E R I A U X
!==================================================

MATERIAU_SIMPLE  'PIOMBO'    CALOPORTEUR
  POURCENTAGE_EN_POIDS  11.017   !g/cm^3
    CORPS
      'Pb204'    1.42
      'Pb206'   24.10
      'Pb207'   22.10
      'Pb208'   52.38

MATERIAU_SIMPLE  'T91'       STRUCTURE (see ECCO for fuel)

MATERIAU_SIMPLE  '1515TI'    STRUCTURE (see ECCO for fuel)

MATERIAU_SIMPLE  'B4C_ARR'   ABSORBANT
  FORMULE_MOLECULAIRE    2.2
    ELEMENT CIA 4
      'B10'   (100.0*(ENR_B4C))
      'B11'   (100.0*(1-(ENR_B4C)))
    ELEMENT CIA 1
      'C0'     100.0

MATERIAU_SIMPLE  'REFL'      STRUCTURE
  POURCENTAGE_EN_POIDS   6.0
    CORPS
      'O16'     25.7226       'Y89'      4.0162       'Zr90'    35.6267       'Zr91'     7.8558
      'Zr92'    12.1398       'Zr94'    12.5705       'Zr96'     2.0683

MATERIAU_SIMPLE  'VOID'      CALOPORTEUR
  NOMBRE_D_ATOMES
    CORPS
```

```
    'Pb208'   1.0E-15  !PART/CM BARN

!==============================================
!            M I L I E U X
!==============================================

MILIEU  'M_TTHINS'
  'REFL'     (100.0*(THI_DENS))

MILIEU  'M_BTHINS'
  'REFL'     (100.0*(THI_DENS))

MILIEU  'M_SPRING'
  '1515TI'   (100.0*(SPR_DENS))

MILIEU  'M_PLENUM'
  '1515TI'   (100.0*(PLE_DENS))

MILIEU  'M_TOPLUG'
  '1515TI'     85.00
  'PIOMBO'     15.00

MILIEU  'M_BOPLUG'
  '1515TI'     90.00
  'PIOMBO'     10.00

MILIEU  'M_B4C'
  'B4C_ARR'  (100.0*(ABS_DENS))

MILIEU  'M_FOLLOW'
  'REFL'     (100.0*(THA_DENS))

MILIEU  'M_REFL'
  'REFL'     (100.0*(THI_DENS))

MILIEU  'M_TOPREF'
  '1515TI'     20.00
  'PIOMBO'     80.00

MILIEU  'M_BOTREF'
  '1515TI'     12.00
  'PIOMBO'     88.00

MILIEU  'M_BARREL'
  '1515TI'     33.80
  'PIOMBO'     66.20

MILIEU  'M_ZEXT'
  'PIOMBO'    100.0

MILIEU 'M_PIOMBO'
  'PIOMBO'    100.0

MILIEU 'M_PIOMB1' / 'M_PIOMB2 – M-PIOM26'
```

```
  'PIOMBO'    100.0

MILIEU 'M_CLAD'
  '1515TI'    100.0

MILIEU 'M_CLAD1'/ 'M_CLAD2 – M_CLAD11'
  '1515TI'    100.0

MILIEU 'M_WRAP'
  'T91'       100.0

MILIEU 'M_WRAP1' / 'M_WRAP2 – M_WRAP11'
  'T91'       100.0

MILIEU 'M_VOID'/ 'M_VOID1'
  'VOID'      100.0


!=====================================================
!              C E L L U L E
!=====================================================

!==== BOTTOM THERMAL INSULATOR
CELLULE 'BTHINS'
  RANGEMENT_COMPOSITION
    'M_BTHINS' 'M_CLAD2'  'M_WRAP2'  'M_PIOMB6' 'M_PIOMB7'
  GEOMETRY DATA
    HEXAGON 3
      15.80
        HEXAGONAL LATTICE
          7 1.386
          1
            CYL 2
              0.465   REGION    1   'BTHINS'     COMP   1   293.16
              0.525   REGION    2   'CLAD'       COMP   2   293.16
              IN      REGION    3   'CALO1'      COMP   4   293.16
          1 1 1 1 1 1 1
        IN          REGION    4   'CALO2'      COMP   4   293.16
      16.60
                  REGION    5   'WRAPPER'    COMP   3   293.16
      17.10
                  REGION    6   'PB_IA'      COMP   5   293.16
    REFLECT
  END OF GEOMETRY DATA

!==== TOP THERMAL INSULATOR
CELLULE 'TTHINS'
  RANGEMENT_COMPOSITION
    'M_TTHINS' 'M_CLAD3'  'M_WRAP3'  'M_PIOMB8' 'M_PIOMB9'
  GEOMETRY DATA
    HEXAGON 3
      15.80
        HEXAGONAL LATTICE
          7 1.386
```

```
        1
         CYL 2
          0.465   REGION    1   'TTHINS'     COMP   1   293.16
          0.525   REGION    2   'CLAD'       COMP   2   293.16
          IN      REGION    3   'CALO1'      COMP   4   293.16
        1 1 1 1 1 1 1
      IN          REGION    4   'CALO2'      COMP   4   293.16
    16.60
                REGION    5   'WRAPPER'    COMP   3   293.16
    17.10
                REGION    6   'PB_IA'      COMP   5   293.16
   REFLECT
  END OF GEOMETRY DATA

!==== SPRING
CELLULE 'SPRING'
  RANGEMENT_COMPOSITION
   'M_SPRING' 'M_CLAD4'  'M_WRAP4'  'M_PIOM10' 'M_PIOM11'
  GEOMETRY DATA
   HEXAGON 3
    15.80
     HEXAGONAL LATTICE
      7 1.386
      1
       CYL 2
        0.465   REGION    1   'SPRING'     COMP   1   293.16
        0.525   REGION    2   'CLAD'       COMP   2   293.16
        IN      REGION    3   'CALO1'      COMP   4   293.16
      1 1 1 1 1 1 1
     IN          REGION    4   'CALO2'      COMP   4   293.16
    16.60
                REGION    5   'WRAPPER'    COMP   3   293.16
    17.10
                REGION    6   'PB_IA'      COMP   5   293.16
   REFLECT
  END OF GEOMETRY DATA

!==== PLENUM
CELLULE 'PLENUM'
  RANGEMENT_COMPOSITION
   'M_VOID'   'M_PLENUM' 'M_CLAD5'  'M_WRAP5'  'M_PIOM12' 'M_PIOM13'
  GEOMETRY DATA
   HEXAGON 3
    15.80
     HEXAGONAL LATTICE
      7 1.386
      1
       CYL 3
        0.4     REGION    1   'VOID'       COMP   1   293.16
        0.465   REGION    2   'PLENUM'     COMP   2   293.16
        0.525   REGION    3   'CLAD'       COMP   3   293.16
        IN      REGION    4   'CALO1'      COMP   5   293.16
      1 1 1 1 1 1 1
     IN          REGION    5   'CALO2'      COMP   5   293.16
```

```
    16.60
              REGION    6   'WRAPPER'    COMP   4   293.16
    17.10
              REGION    7   'PB_IA'     COMP   6   293.16
  REFLECT
 END OF GEOMETRY DATA

!==== TOP PLUG
CELLULE 'TPLG'
 RANGEMENT_COMPOSITION
  'M_TOPLUG' 'M_CLAD6'  'M_WRAP6'  'M_PIOM14' 'M_PIOM15'
 GEOMETRY DATA
  HEXAGON 3
   15.80
    HEXAGONAL LATTICE
     7 1.386
     1
      CYL 2
       0.465   REGION    1   'TPLUG'     COMP   1   293.16
       0.525   REGION    2   'CLAD'      COMP   2   293.16
       IN      REGION    3   'CALO1'     COMP   4   293.16
     1 1 1 1 1 1 1
    IN          REGION    4   'CALO2'     COMP   4   293.16
   16.60
              REGION    5   'WRAPPER'    COMP   3   293.16
   17.10
              REGION    6   'PB_IA'     COMP   5   293.16
  REFLECT
END OF GEOMETRY DATA

!==== BOTTOM PLUG
CELLULE 'BPLG'
 RANGEMENT_COMPOSITION
  'M_BOPLUG' 'M_CLAD7'  'M_WRAP7'  'M_PIOM16' 'M_PIOM17'
 GEOMETRY DATA
  HEXAGON 3
   15.80
    HEXAGONAL LATTICE
     7 1.386
     1
      CYL 2
       0.465   REGION    1   'BPLUG'     COMP   1   293.16
       0.525   REGION    2   'CLAD'      COMP   2   293.16
       IN      REGION    3   'CALO1'     COMP   4   293.16
     1 1 1 1 1 1 1
    IN          REGION    4   'CALO2'     COMP   4   293.16
   16.60
              REGION    5   'WRAPPER'    COMP   3   293.16
   17.10
              REGION    6   'PB_IA'     COMP   5   293.16
  REFLECT
END OF GEOMETRY DATA

!==== CONTROL ROD B-10 90%
```

```
CELLULE 'C_ROD'
 RANGEMENT_COMPOSITION
  'M_B4C'    'M_CLAD8'  'M_WRAP8'  'M_PIOM18' 'M_PIOM19'
 GEOMETRY DATA
  HEXAGON 3
   16.04
    HEXAGONAL LATTICE
     3 3.3
     1
      CYL 2
       1.49    REGION    1   'B4C90'      COMP   1   293.16
       1.55    REGION    2   'CLAD'       COMP   3   293.16
       IN      REGION    3   'CALO5'      COMP   4   293.16
     1 1 1
    IN          REGION    4   'CALO6'      COMP   4   293.16
   16.60
              REGION    5   'WRAPPER'    COMP   2   293.16
   17.10
              REGION    6   'PB_IA'      COMP   5   293.16
  REFLECT
 END OF GEOMETRY DATA

!==== CONTROL ROD FOLLOWER
CELLULE 'F_ROD'
 RANGEMENT_COMPOSITION
  'M_FOLLOW' 'M_CLAD9'  'M_WRAP9'  'M_PIOM20' 'M_PIOM21'
 GEOMETRY DATA
  HEXAGON 3
   16.04
    HEXAGONAL LATTICE
     3 3.3
     1
      CYL 2
       1.49    REGION    1   'FOLLOW'     COMP   1   293.16
       1.55    REGION    2   'CLAD'       COMP   3   293.16
       IN      REGION    3   'CALO5'      COMP   4   293.16
     1 1 1
    IN          REGION    4   'CALO6'      COMP   4   293.16
   16.60
              REGION    5   'WRAPPER'    COMP   2   293.16
   17.10
              REGION    6   'PB_IA'      COMP   5   293.16
  REFLECT
 END OF GEOMETRY DATA

!==== SECURITY ROD B-10 90%
CELLULE 'S_ROD'
 RANGEMENT_COMPOSITION
  'M_B4C'    'M_CLAD10' 'M_WRAP10' 'M_PIOM22' 'M_PIOM23' 'M_PIOM24'
 GEOMETRY DATA
  HEXAGON 3
   14.78
    HEXAGONAL LATTICE
     2 5.25
```

```
      2
       CYL 2
        2.58   REGION   1  'B4C90I'    COMP  1   293.16
        2.64   REGION   2  'CLADI'     COMP  3   293.16
        IN     REGION   3  'CALO5'     COMP  4   293.16
       CYL 2
        1.83   REGION   4  'B4C90E'    COMP  1   293.16
        1.89   REGION   5  'CLADE'     COMP  3   293.16
        IN     REGION   6  'CALO5'     COMP  4   293.16
      1 2
    IN         REGION   7  'CALO6'     COMP  5   293.16
   16.60
             REGION   8  'WRAPP'     COMP  2   293.16
   17.10
             REGION   9  'PB_IA'     COMP  6   293.16
  REFLECT
 END OF GEOMETRY DATA

!==== DUMMY ELEMENT
CELLULE 'DUMMY'
 RANGEMENT_COMPOSITION
  'M_REFL'  'M_CLAD11' 'M_WRAP11' 'M_PIOM25' 'M_PIOM26'
 GEOMETRY DATA
  HEXAGON 3
   15.80
    HEXAGONAL LATTICE
     7 1.386
     1
      CYL 2
       0.465  REGION   1  'THIS'     COMP  1   293.16
       0.525  REGION   2  'CLAD'     COMP  2   293.16
       IN     REGION   3  'CALO1'    COMP  4   293.16
     1 1 1 1 1 1 1
    IN         REGION   4  'CALO2'    COMP  4   293.16
   16.60
             REGION   5  'WRAPPER'   COMP  3   293.16
   17.10
             REGION   6  'PB_IA'     COMP  5   293.16
  REFLECT
 END OF GEOMETRY DATA

CELLULE  'C_TOPREF'
 RANGEMENT_COMPOSITION
  'M_TOPREF'
 GEOMETRY DATA HOMOGENEOUS
  REGION   1  'TOP_FA'   COMP  1   293.16
END OF GEOMETRY DATA

CELLULE  'C_BOTREF'
 RANGEMENT_COMPOSITION
  'M_BOTREF'
 GEOMETRY DATA HOMOGENEOUS
  REGION   1  'BOT_FA'   COMP  1   293.16
END OF GEOMETRY DATA
```

```
 CELLULE  'C_BARREL'
  RANGEMENT_COMPOSITION
   'M_BARREL'
  GEOMETRY DATA HOMOGENEOUS
   REGION    1   'H_BARREL'   COMP   1   293.16
 END OF GEOMETRY DATA

 CELLULE  'C_ZEXT'
  RANGEMENT_COMPOSITION
   'M_ZEXT'
  GEOMETRY DATA HOMOGENEOUS
   REGION    1   'OUTER_PB'   COMP   1   293.16
 END OF GEOMETRY DATA;

!EDITION_MILIEU (MIL_20);

 ->T_HOT       (450.0+273.16) ;
 ->T_MEDIA     (440.0+273.16) ;
 ->T_OUT       (480.0+273.16) ;
 ->T_FUEL      (900.0+273.16) ;
 ->T_IN        (400.0+273.16) ;

  !=====================================================================
  !           DEBUT DES CALCULS CELLULES ECCO
  !=====================================================================

 ECCO
  MILIEU (MIL_20)
  REFERENCE_UNIT 'JECCOLIB_JEFF_31.REF'

  !=====================================
  !     CELLULE TINS
  !=====================================
  CELLULE 'TTHINS'
   EDITION MOYENNE
   'TOP INSULATOR HET'
   TEMPERATURE
     1 (T_OUT)       2 (T_OUT)       3 (T_OUT)       4 (T_OUT)       5 (T_OUT)       6 (T_OUT)
   STEPS 4
    STEP
     GEOMETRY HOMOGENEOUS
     GROUP STRUCTURE OTHER 172
     INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
     FLUX SOLUTION FM P1 CONSISTENT ORDER 1
     SUBCRITICAL FLUXB 'FOUT_172G_HOM_JEFF31'
     BUCKLING ((5/8)*((3.14159/1.0)**2))
     LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
     SELF SHIELDING DBBSH
    STEP
     GEOMETRY ORIGINAL
     GROUP STRUCTURE OTHER 172
     INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
     ELEMENTS ALL
```

```
    FLUX SOLUTION CP P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    PROFILE OUTER ITERATIONS BROAD MAXIMUM NUMBER 70
    COLLISION PROBABILITIES ROTH 6
  STEP
    GEOMETRY ORIGINAL
    GROUP STRUCTURE FINE
    INPUT LIBRARY 'JECCOLIB_JEFF_31.1968'
    ELEMENTS 56
     'Fe54'  'Fe56'  'Fe57'  'Fe58'
     'Cr50'  'Cr52'  'Cr53'  'Cr54'
     'Ni58'  'Ni60'  'Ni61'  'Ni62'  'Ni64'
     'Mo92'  'Mo94'  'Mo95'  'Mo96'  'Mo97'
     'Mo98'  'Mo100' 'Nb93'  'Al27'
     'Mn55'  'O16'   'N14'   'N15'   'C0'
     'Si28'  'Si29'  'Si30'  'V0'
     'Ti46'  'Ti47'  'Ti48'  'Ti49'  'Ti50'
     'Ca40'  'Ca42'  'Ca43'  'Ca44'  'Ca48'
     'W182'  'W183'  'W184'  'W186'
     'Zr90'  'Zr91'  'Zr92'  'Zr94'  'Zr96'
     'B10'   'B11'   'Pb204' 'Pb206' 'Pb207' 'Pb208'
    FLUX SOLUTION CP P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    PROFILE COLLISION PROBABILITIES ROTH 6
    CONDENSE 33
        1   82  142  202  262  322  382  442  502  564
      624  686  746  808  868  928  988 1048 1108 1168
     1228 1288 1336 1422 1480 1516 1579 1648 1708 1768
     1837 1919 1952
  STEP
    HOMOGENISE
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE OTHER 33
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    OUTPUT LIBRARY 'TINS_HH_33G_JEFF31'
      CROSS SECTIONS FLUXES
    PRINT DATA  FLUXES
      CROSS SECTIONS MACROSCOPIC VECTORS
 ENDSTEPS

!=====================================
!    CELLULE SPRN
!=====================================
CELLULE 'SPRING'
```

```
EDITION MOYENNE
'SPRING HET'
TEMPERATURE
  1 (T_OUT)      2 (T_OUT)      3 (T_OUT)      4 (T_OUT)      5 (T_OUT)      6 (T_OUT)
STEPS 4
 STEP
   GEOMETRY HOMOGENEOUS
   GROUP STRUCTURE OTHER 172
   INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
   FLUX SOLUTION FM P1 CONSISTENT ORDER 1
   SUBCRITICAL FLUXB 'FOUT_172G_HOM_JEFF31'
   BUCKLING ((5/8)*((3.14159/12.0)**2))
   LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
   SELF SHIELDING DBBSH
 STEP
   GEOMETRY ORIGINAL
   GROUP STRUCTURE OTHER 172
   INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
   ELEMENTS ALL
   FLUX SOLUTION CP P1 CONSISTENT ORDER 1
   SUBCRITICAL FROM PREVIOUS STEP
   BFROM 1
   LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
   SELF SHIELDING DBBSH
   PROFILE OUTER ITERATIONS BROAD MAXIMUM NUMBER 70
   COLLISION PROBABILITIES ROTH 6
 STEP
   GEOMETRY ORIGINAL
   GROUP STRUCTURE FINE
   INPUT LIBRARY 'JECCOLIB_JEFF_31.1968'
   ELEMENTS 55
    'Fe54'  'Fe56'  'Fe57'  'Fe58'
    'Cr50'  'Cr52'  'Cr53'  'Cr54'
    'Ni58'  'Ni60'  'Ni61'  'Ni62'  'Ni64'
    'Mo92'  'Mo94'  'Mo95'  'Mo96'  'Mo97'
    'Mo98'  'Mo100' 'Nb93'  'Al27'
    'Mn55'  'N14'   'N15'   'C0'
    'Si28'  'Si29'  'Si30'  'V0'
    'Ti46'  'Ti47'  'Ti48'  'Ti49'  'Ti50'
    'Ca40'  'Ca42'  'Ca43'  'Ca44'  'Ca48'
    'W182'  'W183'  'W184'  'W186'
    'Zr90'  'Zr91'  'Zr92'  'Zr94'  'Zr96'
    'B10'   'B11'  'Pb204' 'Pb206' 'Pb207' 'Pb208'
   FLUX SOLUTION CP P1 CONSISTENT ORDER 1
   SUBCRITICAL FROM PREVIOUS STEP
   BFROM 1
   LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
   SELF SHIELDING DBBSH
   PROFILE COLLISION PROBABILITIES ROTH 6
   CONDENSE 33
      1   82  142  202  262  322  382  442  502  564
    624  686  746  808  868  928  988 1048 1108 1168
   1228 1288 1336 1422 1480 1516 1579 1648 1708 1768
   1837 1919 1952
```

```
   STEP
    HOMOGENISE
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE OTHER 33
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    OUTPUT LIBRARY 'SPRN_HH_33G_JEFF31'
      CROSS SECTIONS FLUXES
    PRINT DATA  FLUXES
      CROSS SECTIONS MACROSCOPIC VECTORS
  ENDSTEPS

!=====================================
!    CELLULE TPLG
!=====================================
CELLULE 'TPLG'
  EDITION MOYENNE
  'TOP PLUG HET'
  TEMPERATURE
    1 (T_OUT)      2 (T_OUT)      3 (T_OUT)      4 (T_OUT)      5 (T_OUT)      6 (T_OUT)
  STEPS 4
   STEP
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE OTHER 172
    INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    SUBCRITICAL FLUXB 'FOUT_172G_HOM_JEFF31'
    BUCKLING ((5/8)*((3.14159/5.0)**2))
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
   STEP
    GEOMETRY ORIGINAL
    GROUP STRUCTURE OTHER 172
    INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
    ELEMENTS ALL
    FLUX SOLUTION CP P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    PROFILE OUTER ITERATIONS BROAD MAXIMUM NUMBER 70
    COLLISION PROBABILITIES ROTH 6
   STEP
    GEOMETRY ORIGINAL
    GROUP STRUCTURE FINE
    INPUT LIBRARY 'JECCOLIB_JEFF_31.1968'
    ELEMENTS 55
     'Fe54'  'Fe56'  'Fe57'  'Fe58'
     'Cr50'  'Cr52'  'Cr53'  'Cr54'
     'Ni58'  'Ni60'  'Ni61'  'Ni62'  'Ni64'
     'Mo92'  'Mo94'  'Mo95'  'Mo96'  'Mo97'
```

```
      'Mo98'  'Mo100' 'Nb93'  'Al27'
      'Mn55'  'N14'   'N15'   'C0'
      'Si28'  'Si29'  'Si30'  'V0'
      'Ti46'  'Ti47'  'Ti48'  'Ti49'  'Ti50'
      'Ca40'  'Ca42'  'Ca43'  'Ca44'  'Ca48'
      'W182'  'W183'  'W184'  'W186'
      'Zr90'  'Zr91'  'Zr92'  'Zr94'  'Zr96'
      'B10'   'B11'   'Pb204' 'Pb206' 'Pb207' 'Pb208'
    FLUX SOLUTION CP P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    PROFILE COLLISION PROBABILITIES ROTH 6
    CONDENSE 33
        1   82  142  202  262  322  382  442  502  564
      624  686  746  808  868  928  988 1048 1108 1168
      1228 1288 1336 1422 1480 1516 1579 1648 1708 1768
      1837 1919 1952
   STEP
    HOMOGENISE
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE OTHER 33
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    OUTPUT LIBRARY 'TPLG_HH_33G_JEFF31'
      CROSS SECTIONS FLUXES
    PRINT DATA  FLUXES
      CROSS SECTIONS MACROSCOPIC VECTORS
  ENDSTEPS

!=====================================
!     CELLULE BINS
!=====================================
CELLULE 'BTHINS'
  EDITION MOYENNE
  'BOTTOM INSULATOR HET'
  TEMPERATURE
    1 (T_IN)       2 (T_IN)       3 (T_IN)       4 (T_IN)       5 (T_IN)       6 (T_IN)
  STEPS 4
   STEP
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE OTHER 172
    INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    SUBCRITICAL FLUXB 'FOUT_172G_HOM_JEFF31'
    BUCKLING ((5/8)*((3.14159/1.0)**2))
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
   STEP
    GEOMETRY ORIGINAL
```

```
  GROUP STRUCTURE OTHER 172
  INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
  ELEMENTS ALL
  FLUX SOLUTION CP P1 CONSISTENT ORDER 1
  SUBCRITICAL FROM PREVIOUS STEP
  BFROM 1
  LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
  SELF SHIELDING DBBSH
  PROFILE OUTER ITERATIONS BROAD MAXIMUM NUMBER 70
  COLLISION PROBABILITIES ROTH 6
 STEP
  GEOMETRY ORIGINAL
  GROUP STRUCTURE FINE
  INPUT LIBRARY 'JECCOLIB_JEFF_31.1968'
  ELEMENTS 56
   'Fe54'  'Fe56'  'Fe57'  'Fe58'
   'Cr50'  'Cr52'  'Cr53'  'Cr54'
   'Ni58'  'Ni60'  'Ni61'  'Ni62'  'Ni64'
   'Mo92'  'Mo94'  'Mo95'  'Mo96'  'Mo97'
   'Mo98'  'Mo100' 'Nb93'  'Al27'
   'Mn55'  'O16'   'N14'   'N15'   'C0'
   'Si28'  'Si29'  'Si30'  'V0'
   'Ti46'  'Ti47'  'Ti48'  'Ti49'  'Ti50'
   'Ca40'  'Ca42'  'Ca43'  'Ca44'  'Ca48'
   'W182'  'W183'  'W184'  'W186'
   'Zr90'  'Zr91'  'Zr92'  'Zr94'  'Zr96'
   'B10'   'B11'  'Pb204' 'Pb206' 'Pb207' 'Pb208'
  FLUX SOLUTION CP P1 CONSISTENT ORDER 1
  SUBCRITICAL FROM PREVIOUS STEP
  BFROM 1
  LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
  SELF SHIELDING DBBSH
  PROFILE COLLISION PROBABILITIES ROTH 6
  CONDENSE 33
      1   82  142  202  262  322  382  442  502  564
    624  686  746  808  868  928  988 1048 1108 1168
   1228 1288 1336 1422 1480 1516 1579 1648 1708 1768
   1837 1919 1952
 STEP
  HOMOGENISE
  GEOMETRY HOMOGENEOUS
  GROUP STRUCTURE OTHER 33
  FLUX SOLUTION FM P1 CONSISTENT ORDER 1
  SUBCRITICAL FROM PREVIOUS STEP
  BFROM 1
  LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
  SELF SHIELDING DBBSH
  OUTPUT LIBRARY 'BINS_HH_33G_JEFF31'
   CROSS SECTIONS FLUXES
  PRINT DATA  FLUXES
   CROSS SECTIONS MACROSCOPIC VECTORS
ENDSTEPS
```

```
!=====================================
!    CELLULE PLENUM
!=====================================
CELLULE 'PLENUM'
  EDITION MOYENNE
  'PLENUM HET'
  TEMPERATURE
    1 (T_IN)      2 (T_IN)      3 (T_IN)      4 (T_IN)      5 (T_IN)      6 (T_IN)      7 (T_IN)
  STEPS 4
   STEP
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE OTHER 172
    INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    SUBCRITICAL FLUXB 'FOUT_172G_HOM_JEFF31'
    BUCKLING ((5/8)*((3.14159/55.0)**2))
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
   STEP
    GEOMETRY ORIGINAL
    GROUP STRUCTURE OTHER 172
    INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
    ELEMENTS ALL
    FLUX SOLUTION CP P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    PROFILE OUTER ITERATIONS BROAD MAXIMUM NUMBER 70
    COLLISION PROBABILITIES ROTH 6
   STEP
    GEOMETRY ORIGINAL
    GROUP STRUCTURE FINE
    INPUT LIBRARY 'JECCOLIB_JEFF_31.1968'
    ELEMENTS 55
     'Fe54'  'Fe56'  'Fe57'  'Fe58'
     'Cr50'  'Cr52'  'Cr53'  'Cr54'
     'Ni58'  'Ni60'  'Ni61'  'Ni62'  'Ni64'
     'Mo92'  'Mo94'  'Mo95'  'Mo96'  'Mo97'
     'Mo98'  'Mo100' 'Nb93'  'Al27'
     'Mn55'  'N14'   'N15'   'C0'
     'Si28'  'Si29'  'Si30'  'V0'
     'Ti46'  'Ti47'  'Ti48'  'Ti49'  'Ti50'
     'Ca40'  'Ca42'  'Ca43'  'Ca44'  'Ca48'
     'W182'  'W183'  'W184'  'W186'
     'Zr90'  'Zr91'  'Zr92'  'Zr94'  'Zr96'
     'B10'   'B11'  'Pb204' 'Pb206' 'Pb207' 'Pb208'
    FLUX SOLUTION CP P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    PROFILE COLLISION PROBABILITIES ROTH 6
    CONDENSE 33
```

```
        1   82  142  202  262  322  382  442  502  564
      624  686  746  808  868  928  988 1048 1108 1168
     1228 1288 1336 1422 1480 1516 1579 1648 1708 1768
     1837 1919 1952
   STEP
    HOMOGENISE
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE OTHER 33
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    OUTPUT LIBRARY 'PLEN_HH_33G_JEFF31'
      CROSS SECTIONS FLUXES
    PRINT DATA  FLUXES
      CROSS SECTIONS MACROSCOPIC VECTORS
  ENDSTEPS

!=========================================
!    CELLULE BPLG
!=========================================
CELLULE 'BPLG'
  EDITION MOYENNE
  'BOTTOM PLUG HET'
  TEMPERATURE
    1 (T_IN)      2 (T_IN)      3 (T_IN)      4 (T_IN)      5 (T_IN)      6 (T_IN)
  STEPS 4
   STEP
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE OTHER 172
    INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    SUBCRITICAL FLUXB 'FOUT_172G_HOM_JEFF31'
    BUCKLING ((5/8)*((3.14159/5.0)**2))
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
   STEP
    GEOMETRY ORIGINAL
    GROUP STRUCTURE OTHER 172
    INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
    ELEMENTS ALL
    FLUX SOLUTION CP P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    PROFILE OUTER ITERATIONS BROAD MAXIMUM NUMBER 70
    COLLISION PROBABILITIES ROTH 6
   STEP
    GEOMETRY ORIGINAL
    GROUP STRUCTURE FINE
    INPUT LIBRARY 'JECCOLIB_JEFF_31.1968'
    ELEMENTS 55
```

```
      'Fe54'  'Fe56'  'Fe57'  'Fe58'
      'Cr50'  'Cr52'  'Cr53'  'Cr54'
      'Ni58'  'Ni60'  'Ni61'  'Ni62'  'Ni64'
      'Mo92'  'Mo94'  'Mo95'  'Mo96'  'Mo97'
      'Mo98'  'Mo100' 'Nb93'  'Al27'
      'Mn55'  'N14'   'N15'   'C0'
      'Si28'  'Si29'  'Si30'  'V0'
      'Ti46'  'Ti47'  'Ti48'  'Ti49'  'Ti50'
      'Ca40'  'Ca42'  'Ca43'  'Ca44'  'Ca48'
      'W182'  'W183'  'W184'  'W186'
      'Zr90'  'Zr91'  'Zr92'  'Zr94'  'Zr96'
      'B10'   'B11'  'Pb204' 'Pb206' 'Pb207' 'Pb208'
    FLUX SOLUTION CP P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    PROFILE COLLISION PROBABILITIES ROTH 6
    CONDENSE 33
        1   82  142  202  262  322  382  442  502  564
      624  686  746  808  868  928  988 1048 1108 1168
      1228 1288 1336 1422 1480 1516 1579 1648 1708 1768
      1837 1919 1952
  STEP
    HOMOGENISE
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE OTHER 33
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    OUTPUT LIBRARY 'BPLG_HH_33G_JEFF31'
      CROSS SECTIONS FLUXES
    PRINT DATA  FLUXES
      CROSS SECTIONS MACROSCOPIC VECTORS
 ENDSTEPS

!=======================================
!    CELLULE CONTROL ROD
!=======================================
CELLULE 'C_ROD'
 EDITION MOYENNE
 'B4C CONTROL ROD HET'
 TEMPERATURE
   1 (T_HOT)      2 (T_HOT)      3 (T_HOT)      4 (T_HOT)      5 (T_HOT)      6 (T_HOT)
 STEPS 4
  STEP
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE OTHER 172
    INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    SUBCRITICAL FLUXB 'FOUT_172G_HOM_JEFF31'
    BUCKLING ((5/8)*((3.14159/17.1)**2))
```

```
  LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
  SELF SHIELDING DBBSH
STEP
  GEOMETRY ORIGINAL
  GROUP STRUCTURE OTHER 172
  INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
  ELEMENTS ALL
  FLUX SOLUTION CP P1 CONSISTENT ORDER 1
  SUBCRITICAL FROM PREVIOUS STEP
  BFROM 1
  LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
  SELF SHIELDING DBBSH
  PROFILE OUTER ITERATIONS BROAD MAXIMUM NUMBER 70
  COLLISION PROBABILITIES ROTH 6
STEP
  GEOMETRY ORIGINAL
  GROUP STRUCTURE FINE
  INPUT LIBRARY 'JECCOLIB_JEFF_31.1968'
  ELEMENTS 55
   'Fe54'  'Fe56'  'Fe57'  'Fe58'
   'Cr50'  'Cr52'  'Cr53'  'Cr54'
   'Ni58'  'Ni60'  'Ni61'  'Ni62'  'Ni64'
   'Mo92'  'Mo94'  'Mo95'  'Mo96'  'Mo97'
   'Mo98'  'Mo100' 'Nb93'  'Al27'
   'Mn55'  'N14'   'N15'   'C0'
   'Si28'  'Si29'  'Si30'  'V0'
   'Ti46'  'Ti47'  'Ti48'  'Ti49'  'Ti50'
   'Ca40'  'Ca42'  'Ca43'  'Ca44'  'Ca48'
   'W182'  'W183'  'W184'  'W186'
   'Zr90'  'Zr91'  'Zr92'  'Zr94'  'Zr96'
   'B10'   'B11' 'Pb204' 'Pb206' 'Pb207' 'Pb208'
  FLUX SOLUTION CP P1 CONSISTENT ORDER 1
  SUBCRITICAL FROM PREVIOUS STEP
  BFROM 1
  LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
  SELF SHIELDING DBBSH
  PROFILE COLLISION PROBABILITIES ROTH 6
  CONDENSE 33
      1   82  142  202  262  322  382  442  502  564
    624  686  746  808  868  928  988 1048 1108 1168
   1228 1288 1336 1422 1480 1516 1579 1648 1708 1768
   1837 1919 1952
STEP
  HOMOGENISE
  GEOMETRY HOMOGENEOUS
  GROUP STRUCTURE OTHER 33
  FLUX SOLUTION FM P1 CONSISTENT ORDER 1
  SUBCRITICAL FROM PREVIOUS STEP
  BFROM 1
  LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
  SELF SHIELDING DBBSH
  OUTPUT LIBRARY 'CROD_HH_33G_JEFF31'
    CROSS SECTIONS FLUXES
  PRINT DATA
```

```
      CROSS SECTIONS MACROSCOPIC VECTORS
      FLUXES
  ENDSTEPS

!=======================================
!     CELLULE CR FOLLOWER
!=======================================
CELLULE 'F_ROD'
  EDITION MOYENNE
  'FOLLOWER CONTROL ROD'
  TEMPERATURE
    1 (T_OUT)       2 (T_OUT)       3 (T_OUT)       4 (T_OUT)       5 (T_OUT)       6 (T_OUT)
  STEPS 4
   STEP
     GEOMETRY HOMOGENEOUS
     GROUP STRUCTURE OTHER 172
     INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
     FLUX SOLUTION FM P1 CONSISTENT ORDER 1
     SUBCRITICAL FLUXB 'FOUT_172G_HOM_JEFF31'
     BUCKLING ((5/8)*((3.14159/17.1)**2))
     LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
     SELF SHIELDING DBBSH
   STEP
     GEOMETRY ORIGINAL
     GROUP STRUCTURE OTHER 172
     INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
     ELEMENTS ALL
     FLUX SOLUTION CP P1 CONSISTENT ORDER 1
     SUBCRITICAL FROM PREVIOUS STEP
     BFROM 1
     LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
     SELF SHIELDING DBBSH
     PROFILE OUTER ITERATIONS BROAD MAXIMUM NUMBER 70
     COLLISION PROBABILITIES ROTH 6
   STEP
     GEOMETRY ORIGINAL
     GROUP STRUCTURE FINE
     INPUT LIBRARY 'JECCOLIB_JEFF_31.1968'
     ELEMENTS 56
       'Fe54'  'Fe56'  'Fe57'  'Fe58'
       'Cr50'  'Cr52'  'Cr53'  'Cr54'
       'Ni58'  'Ni60'  'Ni61'  'Ni62'  'Ni64'
       'Mo92'  'Mo94'  'Mo95'  'Mo96'  'Mo97'
       'Mo98'  'Mo100' 'Nb93'  'Al27'
       'Mn55'  'O16'   'N14'   'N15'   'C0'
       'Si28'  'Si29'  'Si30'  'V0'
       'Ti46'  'Ti47'  'Ti48'  'Ti49'  'Ti50'
       'Ca40'  'Ca42'  'Ca43'  'Ca44'  'Ca48'
       'W182'  'W183'  'W184'  'W186'
       'Zr90'  'Zr91'  'Zr92'  'Zr94'  'Zr96'
       'B10'   'B11'  'Pb204' 'Pb206' 'Pb207' 'Pb208'
     FLUX SOLUTION CP P1 CONSISTENT ORDER 1
     SUBCRITICAL FROM PREVIOUS STEP
     BFROM 1
```

```
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    PROFILE COLLISION PROBABILITIES ROTH 6
    CONDENSE 33
       1   82  142  202  262  322  382  442  502  564
      624  686  746  808  868  928  988 1048 1108 1168
     1228 1288 1336 1422 1480 1516 1579 1648 1708 1768
     1837 1919 1952
  STEP
    HOMOGENISE
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE OTHER 33
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    OUTPUT LIBRARY 'FROD_HH_33G_JEFF31'
      CROSS SECTIONS FLUXES
    PRINT DATA  FLUXES
      CROSS SECTIONS MACROSCOPIC VECTORS
 ENDSTEPS

!=======================================
!    CELLULE SAFETY ROD
!=======================================
CELLULE 'S_ROD'
 EDITION MOYENNE
 'B4C SAFETY ROD'
 TEMPERATURE
   1 (T_HOT)      2 (T_HOT)      3 (T_HOT)      4 (T_HOT)      5 (T_HOT)      6 (T_HOT)
   7 (T_HOT)      8 (T_HOT)      9 (T_HOT)
 STEPS 4
  STEP
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE OTHER 172
    INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    SUBCRITICAL FLUXB 'FINN_172G_HOM_JEFF31'
    BUCKLING ((5/8)*((3.14159/17.1)**2))
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
  STEP
    GEOMETRY ORIGINAL
    GROUP STRUCTURE OTHER 172
    INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
    ELEMENTS ALL
    FLUX SOLUTION CP P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    PROFILE OUTER ITERATIONS BROAD MAXIMUM NUMBER 70
    COLLISION PROBABILITIES ROTH 6
```

```
  STEP
   GEOMETRY ORIGINAL
   GROUP STRUCTURE FINE
   INPUT LIBRARY 'JECCOLIB_JEFF_31.1968'
   ELEMENTS 55
    'Fe54'  'Fe56'  'Fe57'  'Fe58'
    'Cr50'  'Cr52'  'Cr53'  'Cr54'
    'Ni58'  'Ni60'  'Ni61'  'Ni62'  'Ni64'
    'Mo92'  'Mo94'  'Mo95'  'Mo96'  'Mo97'
    'Mo98'  'Mo100' 'Nb93'  'Al27'
    'Mn55'  'N14'   'N15'   'C0'
    'Si28'  'Si29'  'Si30'  'V0'
    'Ti46'  'Ti47'  'Ti48'  'Ti49'  'Ti50'
    'Ca40'  'Ca42'  'Ca43'  'Ca44'  'Ca48'
    'W182'  'W183'  'W184'  'W186'
    'Zr90'  'Zr91'  'Zr92'  'Zr94'  'Zr96'
    'B10'   'B11'  'Pb204' 'Pb206' 'Pb207' 'Pb208'
   FLUX SOLUTION CP P1 CONSISTENT ORDER 1
   SUBCRITICAL FROM PREVIOUS STEP
   BFROM 1
   LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
   SELF SHIELDING DBBSH
   PROFILE COLLISION PROBABILITIES ROTH 6
   CONDENSE 33
       1   82  142  202  262  322  382  442  502  564
     624  686  746  808  868  928  988 1048 1108 1168
    1228 1288 1336 1422 1480 1516 1579 1648 1708 1768
    1837 1919 1952
  STEP
   HOMOGENISE
   GEOMETRY HOMOGENEOUS
   GROUP STRUCTURE OTHER 33
   FLUX SOLUTION FM P1 CONSISTENT ORDER 1
   SUBCRITICAL FROM PREVIOUS STEP
   BFROM 1
   LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
   SELF SHIELDING DBBSH
   OUTPUT LIBRARY 'SROD_HH_33G_JEFF31'
    CROSS SECTIONS FLUXES
   PRINT DATA  FLUXES
    CROSS SECTIONS MACROSCOPIC VECTORS
 ENDSTEPS

!=====================================
!    CELLULE DUMMY
!=====================================
CELLULE 'DUMMY'
 EDITION MOYENNE
 'DUMMY ELEMENT HET'
 TEMPERATURE
   1 (T_MEDIA)      2 (T_MEDIA)      3 (T_MEDIA)      4 (T_MEDIA)      5 (T_MEDIA)      6 (T_MEDIA)
 STEPS 4
  STEP
   GEOMETRY HOMOGENEOUS
```

```
  GROUP STRUCTURE OTHER 172
  INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
  FLUX SOLUTION FM P1 CONSISTENT ORDER 1
  SUBCRITICAL FLUXB 'FOUT_172G_HOM_JEFF31'
  BUCKLING ((5/8)*((3.14159/17.1)**2))
  LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
  SELF SHIELDING DBBSH
STEP
  GEOMETRY ORIGINAL
  GROUP STRUCTURE OTHER 172
  INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
  ELEMENTS ALL
  FLUX SOLUTION CP P1 CONSISTENT ORDER 1
  SUBCRITICAL FROM PREVIOUS STEP
  BFROM 1
  LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
  SELF SHIELDING DBBSH
  PROFILE OUTER ITERATIONS BROAD MAXIMUM NUMBER 70
  COLLISION PROBABILITIES ROTH 6
STEP
  GEOMETRY ORIGINAL
  GROUP STRUCTURE FINE
  INPUT LIBRARY 'JECCOLIB_JEFF_31.1968'
  ELEMENTS 56
   'Fe54'  'Fe56'  'Fe57'  'Fe58'
   'Cr50'  'Cr52'  'Cr53'  'Cr54'
   'Ni58'  'Ni60'  'Ni61'  'Ni62'  'Ni64'
   'Mo92'  'Mo94'  'Mo95'  'Mo96'  'Mo97'
   'Mo98'  'Mo100' 'Nb93'  'Al27'
   'Mn55'  'O16'   'N14'   'N15'   'C0'
   'Si28'  'Si29'  'Si30'  'V0'
   'Ti46'  'Ti47'  'Ti48'  'Ti49'  'Ti50'
   'Ca40'  'Ca42'  'Ca43'  'Ca44'  'Ca48'
   'W182'  'W183'  'W184'  'W186'
   'Zr90'  'Zr91'  'Zr92'  'Zr94'  'Zr96'
   'B10'   'B11'  'Pb204' 'Pb206' 'Pb207' 'Pb208'
  FLUX SOLUTION CP P1 CONSISTENT ORDER 1
  SUBCRITICAL FROM PREVIOUS STEP
  BFROM 1
  LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
  SELF SHIELDING DBBSH
  PROFILE COLLISION PROBABILITIES ROTH 6
  CONDENSE 33
      1   82  142  202  262  322  382  442  502  564
    624  686  746  808  868  928  988 1048 1108 1168
   1228 1288 1336 1422 1480 1516 1579 1648 1708 1768
   1837 1919 1952
STEP
  HOMOGENISE
  GEOMETRY HOMOGENEOUS
  GROUP STRUCTURE OTHER 33
  FLUX SOLUTION FM P1 CONSISTENT ORDER 1
  SUBCRITICAL FROM PREVIOUS STEP
  BFROM 1
```

```
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    OUTPUT LIBRARY 'DUMM_HH_33G_JEFF31'
      CROSS SECTIONS FLUXES
    PRINT DATA  FLUXES
      CROSS SECTIONS MACROSCOPIC VECTORS
  ENDSTEPS

!=====================================
!    CELLULE C_TOPREF
!=====================================
CELLULE 'C_TOPREF'
  EDITION MOYENNE
  'TOP REFLECTOR HOM'
  TEMPERATURE
    1 (T_OUT)
  STEPS 2
   STEP
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE OTHER 172
    INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    SUBCRITICAL FLUXB 'FOUT_172G_HOM_JEFF31'
    BUCKLING ((5/8)*((3.14159/50.0)**2))
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
   STEP
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE FINE
    INPUT LIBRARY 'JECCOLIB_JEFF_31.1968'
    ELEMENTS 55
     'Fe54'  'Fe56'  'Fe57'  'Fe58'
     'Cr50'  'Cr52'  'Cr53'  'Cr54'
     'Ni58'  'Ni60'  'Ni61'  'Ni62'  'Ni64'
     'Mo92'  'Mo94'  'Mo95'  'Mo96'  'Mo97'
     'Mo98'  'Mo100' 'Nb93'  'Al27'
     'Mn55'  'N14'   'N15'   'C0'
     'Si28'  'Si29'  'Si30'  'V0'
     'Ti46'  'Ti47'  'Ti48'  'Ti49'  'Ti50'
     'Ca40'  'Ca42'  'Ca43'  'Ca44'  'Ca48'
     'W182'  'W183'  'W184'  'W186'
     'Zr90'  'Zr91'  'Zr92'  'Zr94'  'Zr96'
     'B10'   'B11'  'Pb204' 'Pb206' 'Pb207' 'Pb208'
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    CONDENSE 33
        1   82  142  202  262  322  382  442  502  564
      624  686  746  808  868  928  988 1048 1108 1168
     1228 1288 1336 1422 1480 1516 1579 1648 1708 1768
     1837 1919 1952
    OUTPUT LIBRARY 'TREF_HOM_33G_JEFF31'
```

```
      CROSS SECTIONS FLUXES
    PRINT DATA FLUXES
      CROSS SECTIONS MACROSCOPIC VECTORS
  ENDSTEPS

!=======================================
!     CELLULE C_BOTREF
!=======================================
CELLULE 'C_BOTREF'
  EDITION MOYENNE
  'BOTTOM REFLECTOR HOM'
  TEMPERATURE
    1 (T_IN)
  STEPS 2
   STEP
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE OTHER 172
    INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    SUBCRITICAL FLUXB 'FOUT_172G_HOM_JEFF31'
    BUCKLING ((5/8)*((3.14159/50.0)**2))
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
   STEP
    GEOMETRY HOMOGENEOUS
    GROUP STRUCTURE FINE
    INPUT LIBRARY 'JECCOLIB_JEFF_31.1968'
    ELEMENTS 55
     'Fe54'  'Fe56'  'Fe57'  'Fe58'
     'Cr50'  'Cr52'  'Cr53'  'Cr54'
     'Ni58'  'Ni60'  'Ni61'  'Ni62'  'Ni64'
     'Mo92'  'Mo94'  'Mo95'  'Mo96'  'Mo97'
     'Mo98'  'Mo100' 'Nb93'  'Al27'
     'Mn55'  'N14'   'N15'   'C0'
     'Si28'  'Si29'  'Si30'  'V0'
     'Ti46'  'Ti47'  'Ti48'  'Ti49'  'Ti50'
     'Ca40'  'Ca42'  'Ca43'  'Ca44'  'Ca48'
     'W182'  'W183'  'W184'  'W186'
     'Zr90'  'Zr91'  'Zr92'  'Zr94'  'Zr96'
     'B10'   'B11'   'Pb204' 'Pb206' 'Pb207' 'Pb208'
    FLUX SOLUTION FM P1 CONSISTENT ORDER 1
    SUBCRITICAL FROM PREVIOUS STEP
    BFROM 1
    LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
    SELF SHIELDING DBBSH
    CONDENSE 33
        1   82  142  202  262  322  382  442  502  564
      624  686  746  808  868  928  988 1048 1108 1168
     1228 1288 1336 1422 1480 1516 1579 1648 1708 1768
     1837 1919 1952
    OUTPUT LIBRARY 'BREF_HOM_33G_JEFF31'
      CROSS SECTIONS FLUXES
    PRINT DATA FLUXES
      CROSS SECTIONS MACROSCOPIC VECTORS
```

```
  ENDSTEPS

!=====================================
!     CELLULE C_BARREL
!=====================================
CELLULE 'C_BARREL'
  EDITION MOYENNE
  'BARREL HOM'
  TEMPERATURE
    1 (T_MEDIA)
  STEPS 2
   STEP
     GEOMETRY HOMOGENEOUS
     GROUP STRUCTURE OTHER 172
     INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
     FLUX SOLUTION FM P1 CONSISTENT ORDER 1
     SUBCRITICAL FLUXB 'FOUT_172G_HOM_JEFF31'
     BUCKLING ((5/8)*((3.14159/22.56)**2))
     LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
     SELF SHIELDING DBBSH
   STEP
     GEOMETRY HOMOGENEOUS
     GROUP STRUCTURE FINE
     INPUT LIBRARY 'JECCOLIB_JEFF_31.1968'
     ELEMENTS 55
      'Fe54'  'Fe56'  'Fe57'  'Fe58'
      'Cr50'  'Cr52'  'Cr53'  'Cr54'
      'Ni58'  'Ni60'  'Ni61'  'Ni62'  'Ni64'
      'Mo92'  'Mo94'  'Mo95'  'Mo96'  'Mo97'
      'Mo98'  'Mo100' 'Nb93'  'Al27'
      'Mn55'  'N14'   'N15'   'C0'
      'Si28'  'Si29'  'Si30'  'V0'
      'Ti46'  'Ti47'  'Ti48'  'Ti49'  'Ti50'
      'Ca40'  'Ca42'  'Ca43'  'Ca44'  'Ca48'
      'W182'  'W183'  'W184'  'W186'
      'Zr90'  'Zr91'  'Zr92'  'Zr94'  'Zr96'
      'B10'   'B11'
      'Pb204' 'Pb206' 'Pb207' 'Pb208'
     FLUX SOLUTION FM P1 CONSISTENT ORDER 1
     SUBCRITICAL FROM PREVIOUS STEP
     BFROM 1
     LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
     SELF SHIELDING DBBSH
     CONDENSE 33
         1   82  142  202  262  322  382  442  502  564
       624  686  746  808  868  928  988 1048 1108 1168
      1228 1288 1336 1422 1480 1516 1579 1648 1708 1768
      1837 1919 1952
     OUTPUT LIBRARY 'BARL_HOM_33G_JEFF31'
      CROSS SECTIONS FLUXES
     PRINT DATA FLUXES
      CROSS SECTIONS MACROSCOPIC VECTORS
  ENDSTEPS
```

```
!=====================================
!    CELLULE C_ZEXT
!=====================================
CELLULE 'C_ZEXT'
  EDITION MOYENNE
  'DOWNCOMER HOM'
  TEMPERATURE
    1 (T_IN)
  STEPS 2
   STEP
     GEOMETRY HOMOGENEOUS
     GROUP STRUCTURE OTHER 172
     INPUT LIBRARY 'JECCOLIB_JEFF_31.172'
     FLUX SOLUTION FM P1 CONSISTENT ORDER 1
     SUBCRITICAL FLUXB 'FOUT_172G_HOM_JEFF31'
     BUCKLING ((5/8)*((3.14159/50.0)**2))
     LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
     SELF SHIELDING DBBSH
   STEP
     GEOMETRY HOMOGENEOUS
     GROUP STRUCTURE FINE
     INPUT LIBRARY 'JECCOLIB_JEFF_31.1968'
     ELEMENTS 4
      'Pb204' 'Pb206' 'Pb207' 'Pb208'
     FLUX SOLUTION FM P1 CONSISTENT ORDER 1
     SUBCRITICAL FROM PREVIOUS STEP
     BFROM 1
     LEAKAGE NLFACT CELL BENOIST FLUXWT MEAN
     SELF SHIELDING DBBSH
     CONDENSE 33
        1   82  142  202  262  322  382  442  502  564
      624  686  746  808  868  928  988 1048 1108 1168
     1228 1288 1336 1422 1480 1516 1579 1648 1708 1768
     1837 1919 1952
     OUTPUT LIBRARY 'ZEXT_HOM_33G_JEFF31'
      CROSS SECTIONS FLUXES
     PRINT DATA FLUXES
      CROSS SECTIONS MACROSCOPIC VECTORS
  ENDSTEPS;
FINPROC ;
```

As for the fuel cells (see §D.1), the P_1 inconsistent, the B_1 consistent and inconsistent options (to be compared with the reference P_1 consistent one) were adopted. Furthermore, the additional spatial self-shielding term was not added to the computed cross-sections (with the “SELF SHIELDING NODBBSH” instruction, instead of “SELF SHIELDING DBBSH”) as alternative calculation option.

Finally, instead of the utilisation of the (flux and current) spectra evaluated by ECCO in the (nearest) fissile region at 172 (reference) and 33 groups as weighting functions in the first step of ECCO calculations, the fuel spectrum evaluated by Serpent at 33 energy groups in the fuel was introduced “externally” by means of the instruction:

“SUBCRITICAL SOURCE 64/65”

replacing: “SUBCRITICAL FLUXB 'FINN/FOUT_172G_HOM_JEFF31'”

in the first step of the ECCO procedure. The “64/65” refers to the external files “FILE64/65” containing the flux and current values of the fuel inner/outer Serpent spectra, which are reported in the following.

FILE 64 (fuel inner flux and current spectra)

3.3712E-05 5.3378E-04 2.4524E-03 7.4709E-03 1.3076E-02 1.9744E-02 4.8238E-02 4.8393E-02
5.9309E-02 6.1251E-02 5.1598E-02 4.8097E-02 3.5070E-02 4.7342E-02 3.0919E-02 1.7508E-02
2.0162E-02 1.7471E-02 1.5804E-02 1.1001E-02 9.1066E-03 5.1208E-03 9.4158E-03 5.4854E-03
3.1178E-03 4.7889E-03 4.2103E-03 3.1686E-03 2.7013E-03 3.1228E-03 4.0035E-03 3.8704E-04
9.7733E-06

3.4272E-06 5.4272E-05 2.4400E-04 6.9636E-04 1.1071E-03 1.4854E-03 3.2925E-03 2.7424E-03
3.4888E-03 3.4731E-03 2.8934E-03 2.5505E-03 1.8578E-03 1.8916E-03 1.3209E-03 7.7561E-04
7.1121E-04 5.0728E-04 3.6886E-04 1.9634E-04 1.0728E-04 4.0935E-05 4.1626E-05 1.4357E-05
5.2066E-06 6.2378E-06 5.8950E-06 2.7653E-06 2.3688E-06 2.3179E-06 3.4112E-06 7.1697E-08
1.6602E-09

FILE 65 (fuel outer flux and current spectra)

2.8880E-05 4.5636E-04 2.0901E-03 6.3585E-03 1.1093E-02 1.6597E-02 3.9869E-02 3.9617E-02
4.8201E-02 4.9326E-02 4.1135E-02 3.7962E-02 2.7365E-02 3.6839E-02 2.3730E-02 1.3264E-02
1.5273E-02 1.3189E-02 1.1893E-02 8.2782E-03 6.8999E-03 3.9066E-03 7.2451E-03 4.2469E-03
2.4205E-03 3.7235E-03 3.2764E-03 2.4678E-03 2.1033E-03 2.4324E-03 3.1183E-03 3.0179E-04
7.6140E-06

3.9479E-06 6.1950E-05 2.7758E-04 7.9182E-04 1.2558E-03 1.6666E-03 3.6234E-03 2.9813E-03
3.7605E-03 3.6997E-03 3.0409E-03 2.6375E-03 1.8926E-03 1.8936E-03 1.2960E-03 7.4570E-04
6.6946E-04 4.6339E-04 3.2399E-04 1.6497E-04 8.6612E-05 3.2249E-05 3.2430E-05 1.1769E-05
4.3722E-06 5.4149E-06 5.4243E-06 2.5301E-06 2.0713E-06 2.1253E-06 3.0363E-06 6.8588E-08
1.4429E-09

D.3 ERANOS input files (fresh fuel with CRs and SRs fully withdrawn)

In the following the ERANOS input for the full-core spatial calculations with the TGV VARIANT module is reported (see “AVNM” instruction at the end). The multi-group macroscopic cross-sections created by ECCO (at 33 and 80 groups) are loaded as external library in a binary format (see “BASIC_EDL_CREATION_STARTING_FROM_ECCO_FILE” instruction). These data are then used to create the Ensemble de Donnè LU (EDL) describing the different cells (EDL_MILIEU, EDL_MICRO and EDL_MACRO). For briefness and since the fuel depletion calculations were not performed in this work, the instruction for the creation of the evolution chain of the isotopes and the list of fission products (in any case necessary to *e.g.*, obtain the core mass balance) were not reported entirely (see lines of red dots). The calculation refers to the configuration with CRs and SRs fully withdrawn, but in the EDL “COEUR” the assemblies corresponding to their fully inserted positions are also defined (and have to be replaced in the EDL “GEOMETRIE” to simulate the other configurations).

```
PROCEDURE ->TRASPORTO ;

 ! ----------------------------------------------------------------
 !-- Calcolo in trasporto con configurazione di riferimento
 ! ----------------------------------------------------------------

 ->PN  PN_MOMENT 1  ; ! Order of ECCO XS
 ->PTH  3.0E+8 ; ! Power
```

```
 ->DILRAD  1.00  ;
 ->DILAX   1.00  ;

 ->WEIGHT  0  1  0  ;

 BASIC_EDL_CREATION_STARTING_FROM_ECCO_FILE

   MILIEU   ->EDL_MILIEU
   MICRO    ->EDL_MICRO
   MACRO    ->EDL_MACRO

   EXPANSION (DILRAD) (DILAX)
  TEMPERATURE (20+273.15)
   UP_SCATTERING YES
   REACTION_LIST STANDARD
!   DIRECTIONAL_DIFFUSION_COEFFICIENT  NO
   CONSTANT_FISSION_SPECTRUM 'FINN'

   REFERENCE_UNIT 'JECCOLIB_JEFF_31.REF'

   UNIT 'FUEL_INN'         (PN)   MEDIUM  'FINN'     FUEL
   UNIT 'FUEL_OUT'         (PN)   MEDIUM  'FOUT'     FUEL
   UNIT 'IN_VESSL'         (PN)   MEDIUM  'BARL'     STRUCTURE
   UNIT 'BOTTHINS'         (PN)   MEDIUM  'BINS'     STRUCTURE
   UNIT 'BOT_PLUG'         (PN)   MEDIUM  'BPLG'     STRUCTURE
   UNIT 'BOT_REFL'         (PN)   MEDIUM  'BREF'     STRUCTURE
   UNIT 'CR_ABSRB'         (PN)   MEDIUM  'CROD'     ABSORBER
   UNIT 'DUMMY_EL'         (PN)   MEDIUM  'DUMM'     STRUCTURE
   UNIT 'CR_FOLLW'         (PN)   MEDIUM  'FROD'     STRUCTURE
   UNIT 'GAS_PLEN'         (PN)   MEDIUM  'PLEN'     STRUCTURE
   UNIT 'GAS_SPRN'         (PN)   MEDIUM  'SPRN'     STRUCTURE
   UNIT 'SR_ABSRB'         (PN)   MEDIUM  'SROD'     ABSORBER
   UNIT 'TOPTHINS'         (PN)   MEDIUM  'TINS'     STRUCTURE
   UNIT 'TOP_PLUG'         (PN)   MEDIUM  'TPLG'     STRUCTURE
   UNIT 'TOP_REFL'         (PN)   MEDIUM  'TREF'     STRUCTURE
   UNIT 'OUTER_PB'         (PN)   MEDIUM  'ZEXT'     STRUCTURE

 SANS_EDITION   ;

 CONTROLE_COHERENCE_LISTES_DE_CORPS
   MILIEU (EDL_MILIEU)
   MICRO  (EDL_MICRO)   ;

  EDITION_MACRO  (EDL_MACRO)   ;

!=====================================================================
!                  DECAY CHAIN CREATION
!=====================================================================
  = 'TYPE DE TRACE'  0 ;

  ARCHIVE 'ARCHJEFF31' ->YIELD_SET FISSION YIELD LOWER_CASE ;

  ARCHIVE 'ARCHERAN' ->FISSION_YIELD_PROC
```

```
          FISSION_YIELD_PROVISION_FOR_DECAY_CHAIN_CREATION ;

 FISSION_YIELD_PROC;
 = 'TYPE DE TRACE' 2 ;

 CREATION_CHAINE_EVOLUTION  ->EDL_CHAINE
  MILIEU  (EDL_MILIEU)
  NOYAU_LOURD
   NL 'U233'   FIS
            N2N
            NGF  'U234'
            DAF
...................................

  PRODUIT_FISSION
   PF 'Br81'   NGF
   PF 'Kr83'   NGF  'Kr84'
   PF 'Kr84'   NGF  'Rb85'
   ..........................................................

 (FISSION_YIELD_DIRECTIVE)

  ACTIVATION_PRODUCT
   PA 'B10' NGF 'B11' ;

!======================================================================
!                  CREATION GEOMETRIE
!======================================================================

 CORE_CREATION ->EDL_CORE
  LATTICE
   CENTRE            30
   RING 'ZPB'         1  15
   RING 'ZBRL'         1  11
   RING 'ZDUMMY'       1  10
   RING 'ZINT'        1   5
   RING 'ZOUT'         6   8

   POSITION 'ZSR'     30  32
                 32  29   30  28
   POSITION 'ZSRBIS'  28  31
   POSITION 'ZCR'     36  26
                 36  28   34  32
                 32  34   28  36
                 26  36   24  34
                 24  32   26  28
                 28  26   32  24
                 34  24

   LIGNE  'ZOUT'     38  25   3   1
                 35  33   3   2
                 27  38   3   3
                 22  35   3   4
                 25  27   3   5
```

```
                33  22   3   6
  LIGNE  'ZDUMMY'    40  23   5   1
                37  33   5   2
                27  40   5   3
                20  37   5   4
                23  27   5   5
                33  20   5   6
  LIGNE  'ZBRL'      41  22   6   1
                38  33   6   2
                27  41   6   3
                19  38   6   4
                22  27   6   5
                33  19   6   6

  POSITION 'ZPB'     39  21
    39  30     30  39    21  39   21  30    30  21

  LATTICE_STEP      (17.10*(DILRAD))

 BASIC_MESH
  OZ            5   (62.00*(DILAX))
              1   (67.00*(DILAX))
              1   (68.00*(DILAX))
              2   (79.00*(DILAX))
              1   (84.00*(DILAX))
             13  (136.00*(DILAX))
              1  (139.00*(DILAX))
              1  (140.00*(DILAX))
             20  (200.00*(DILAX))
              1  (201.00*(DILAX))
              1  (204.00*(DILAX))
              1  (207.00*(DILAX))
              2  (212.00*(DILAX))
              1  (213.00*(DILAX))
              1  (218.00*(DILAX))
              9  (264.00*(DILAX))
              4  (296.00*(DILAX))
              1  (297.00*(DILAX))
              1  (307.00*(DILAX))
              3  (340.00*(DILAX))

 SUB_ASSEMBLY 'FUEL_INT' FUEL      127 (0.465*2*(DILRAD))
  MEDIUM  'BREF'          0.00            (79.00*(DILAX))    ! == FOOT ==
        'BPLG'       (79.00*(DILAX))    (84.00*(DILAX))
        'PLEN'       (84.00*(DILAX))   (139.00*(DILAX))
        'BINS'      (139.00*(DILAX))   (140.00*(DILAX))
        'FINN'      (140.00*(DILAX))   (200.00*(DILAX))
        'TINS'      (200.00*(DILAX))   (201.00*(DILAX))
        'SPRN'      (201.00*(DILAX))   (213.00*(DILAX))
        'TPLG'      (213.00*(DILAX))   (218.00*(DILAX))
        'TREF'      (218.00*(DILAX))   (340.00*(DILAX))    ! == HEAD ==
  ZONE  'ZINT'
  BURNABLE_ZONE (152.0*(DILAX)) (164.0*(DILAX)) (176.0*(DILAX))
             (188.0*(DILAX))
```

```
SUB_ASSEMBLY 'FUEL_OUT' FUEL      127 (0.465*2*(DILRAD))
  MEDIUM  'BREF'         0.00            (79.00*(DILAX))    ! == FOOT ==
        'BPLG'       (79.00*(DILAX))    (84.00*(DILAX))
        'PLEN'       (84.00*(DILAX))   (139.00*(DILAX))
        'BINS'      (139.00*(DILAX))   (140.00*(DILAX))
        'FOUT'      (140.00*(DILAX))   (200.00*(DILAX))
        'TINS'      (200.00*(DILAX))   (201.00*(DILAX))
        'SPRN'      (201.00*(DILAX))   (213.00*(DILAX))
        'TPLG'      (213.00*(DILAX))   (218.00*(DILAX))
        'TREF'      (218.00*(DILAX))   (340.00*(DILAX))    ! == HEAD ==
  ZONE  'ZOUT'
  BURNABLE_ZONE (152.0*(DILAX)) (164.0*(DILAX)) (176.0*(DILAX))
            (188.0*(DILAX))

SUB_ASSEMBLY 'CROD'     ABSORBER    1  0.00
  MEDIUM  'BREF'         0.00            (62.00*(DILAX))
        'BPLG'       (62.00*(DILAX))    (67.00*(DILAX))
        'BINS'       (67.00*(DILAX))    (68.00*(DILAX))
        'CROD'       (68.00*(DILAX))   (136.00*(DILAX))
        'FROD'      (136.00*(DILAX))   (204.00*(DILAX))
        'SPRN'      (204.00*(DILAX))   (264.00*(DILAX))
        'TREF'      (264.00*(DILAX))   (340.00*(DILAX))
  ZONE 'ZCR'

SUB_ASSEMBLY 'SROD'     ABSORBER    1  0.00
  MEDIUM  'BREF'         0.00           (207.00*(DILAX))
        'BPLG'      (207.00*(DILAX))   (212.00*(DILAX))
        'SROD'      (212.00*(DILAX))   (296.00*(DILAX))
        'TINS'      (296.00*(DILAX))   (297.00*(DILAX))
        'SPRN'      (297.00*(DILAX))   (307.00*(DILAX))
        'TREF'      (307.00*(DILAX))   (340.00*(DILAX))
  ZONE 'ZSR'

SUB_ASSEMBLY 'SRODBIS'  ABSORBER    1  0.00
  MEDIUM  'BREF'         0.00           (207.00*(DILAX))
        'BPLG'      (207.00*(DILAX))   (212.00*(DILAX))
        'SROD'      (212.00*(DILAX))   (296.00*(DILAX))
        'TINS'      (296.00*(DILAX))   (297.00*(DILAX))
        'SPRN'      (297.00*(DILAX))   (307.00*(DILAX))
        'TREF'      (307.00*(DILAX))   (340.00*(DILAX))
  ZONE 'ZSRBIS'

SUB_ASSEMBLY 'DUMMY'    STRUCTURE   1  0.00
  MEDIUM  'BREF'         0.00            (79.00*(DILAX))    ! == FOOT ==
        'BPLG'       (79.00*(DILAX))    (84.00*(DILAX))
        'DUMM'       (84.00*(DILAX))   (201.00*(DILAX))
        'SPRN'      (201.00*(DILAX))   (213.00*(DILAX))
        'TPLG'      (213.00*(DILAX))   (218.00*(DILAX))
        'TREF'      (218.00*(DILAX))   (340.00*(DILAX))    ! == HEAD ==
  ZONE 'ZDUMMY'

SUB_ASSEMBLY 'BARREL'   STRUCTURE   1  0.00
  MEDIUM  'BARL'         0.00           (340.00*(DILAX))
```

```
    ZONE 'ZBRL'

   SUB_ASSEMBLY 'DOWNCMR'  STRUCTURE   1  0.00
    MEDIUM  'ZEXT'          0.00           (340.00*(DILAX))
    ZONE 'ZPB' ;

! The directive ZONE indicates where the sub-assembly can be placed
! You can allow many sub-assembly types to be placed in a zone, but
! you choose which sub-assembly you want in this zone when you define the
! geometry (directive CONFIGURATION)

  CORE_EDITION (EDL_CORE) ;

!---> geometry of the core :
! tells where the (sub)-assemblies are actually placed, what are the control
! rod positions and the boundary conditions

  GEOMETRY_CREATION ->EDL_GEOMETRIE
   CORE   (EDL_CORE)
   MEDIUM (EDL_MILIEU)
   DESCRIPTION  H3D
   CONFIGURATION
    ZONE 'ZINT'       'FUEL_INT'
    ZONE 'ZOUT'       'FUEL_OUT'
    ZONE 'ZCR'        'CROD'
    ZONE 'ZSR'        'SROD'
    ZONE 'ZSRBIS'     'SRODBIS'
    ZONE 'ZDUMMY'     'DUMMY'
    ZONE 'ZBRL'       'BARREL'
    ZONE 'ZPB'        'DOWNCMR'
   BOUNDARY  RSUP VACUUM  ZINF VACUUM  ZSUP VACUUM  ;

!  GEOMETRY_EDITION (EDL_GEOMETRIE)
!  DECOUPAGE MILIEU ;

  CREATION_CONCENTRATION_REACTEUR ->CONC
   GEOMETRIE (EDL_GEOMETRIE)
   CHAINE (EDL_CHAINE)
   MILIEU (EDL_MILIEU) 'FINN' 'FOUT' ;

 !=====================================================================
 !                    CALCOLO A BEGINNING OF LIFE
 !=====================================================================

  AVNM ->FLUX_TGV
   GEOMETRY (EDL_GEOMETRIE)
   MACRO (EDL_MACRO)
   DIRECT_CALCULATION
    TRANSPORT
    FLUX_EXPANSION_ORDER       3
    LEAKAGE_EXPANSION_ORDER    3
    WITH_SIMPLIFIED_SPHERICAL_HARMONIC
    OUTPUT_FILE ON_6
     !GEOMETRY CROSS_SECTION
```

```
    POWER FLUX
   MAX_NUMBER_OF_OUTER_ITERATIONS 100
   REACTOR_POWER (PTH)
   SPATIAL_APPROXIMATION
    INTERIOR   4
    INTERFACE  1
    SOURCE     2
   DO_NOT_USE_SYMMETRY_FLAG
   !OMEGA_TRANSFORMATION_ACCELERATION
   RADIAL_INNER_ITERATION_FULL_MATRIX
  FLUX_STORAGE 2  ;

 NODAL_FLUX_BUILDING ->FLUX_BUILT
  NODAL_FLUX (FLUX_TGV)
  APPROXIMATION_ORDER  2
  RADIAL_REFINEMENT    2
  AXIAL_REFINEMENT     2
  NEGATIVE_FIX_UP    YES
  AVERAGE_FLUX       YES ;

 (FLUX_TGV) ON_NODAL ON_HEX_FLUX ON_HEX_CONSTANT K_EFFECTIVE ->KEFF_TGV  ;

  * '*********************************************************************';
  * ('KEFF_INIT     = '/CAR(KEFF_TGV)/' ')   ;
!    ->KEFF_INIT         ('= '/CAR(KEFF_TGV)/' ')              ;
  * '*********************************************************************';

 FINPROC ;
```

Appendix E: The Serpent 2 input files

In the following, the input files needed to reproduce the Serpent 2 code results presented throughout the report are transcribed.

E.1 Input file for nuclide specification ("eranos_jeff31.ml")

The file "eranos_jeff31.ml" contains the data specifications for all the materials defined in the calculations, that has to be included in the main input file.

```
% Material compositions for ALFRED reactor, LEADER version, JEFF-3.1 lib. %
% ------------------------------------------------------------------------%

therm gr700 grj3.16t
therm gr800 grj3.18t

%% -- MATERIAL DEFINITIONS

% --------------- Fuel ----------------------------------------------------
mat fueli -9.3428 tmp 1173 rgb 255 0 0        % Inner fuel (less enriched)  Watch Out: a more precise density is 10.4855 g/cm3
95241.09c         -2.473201787523944e-03       % Americium
92234.09c         -2.074190884639327e-05       % Uranium
92235.09c         -2.794185837408752e-03
92236.09c         -6.915108330357404e-05
92238.09c         -6.884679669571728e-01
94238.09c         -4.410083910990510e-03    % Plutonium
94239.09c         -1.075643378560574e-01
94240.09c         -5.106547709379653e-02
94241.09c         -1.154829172795752e-02
94242.09c         -1.454966176010199e-02
O-16.09c          -1.170369000768405e-01       % Oxygen

mat fuelo -9.3597  tmp 1173 rgb 255 102 102   % Outer fuel (more enriched)  Watch Out: a more precise density is 10.5128 g/cm3
95241.09c         -3.167414950041660e-03       % Americium
92234.09c         -1.912162937122751e-05       % Uranium
92235.09c         -2.575148360510205e-03
92236.09c         -6.373000015201662e-05
92238.09c         -6.348471547051961e-01
94238.09c         -5.648972344726679e-03       % Plutonium
94239.09c         -1.377783470784228e-01
94240.09c         -6.539589413076820e-02
94241.09c         -1.479006204294543e-02
94242.09c         -1.863856886120473e-02
O-16.09c          -1.170755858966608e-01       % Oxygen

% --------------- Safety rods ---------------------------------------------
mat safe -2.083466 tmp 753 rgb 255 255 51 moder gr800 6000     % Safety rod
 B-10.06c          0.72
 B-11.06c          0.08
 6000.06c          0.20

mat cont -2.083466 tmp 673 rgb 0 153 76  moder gr700 6000     % Control rod
 B-10.06c          0.72
 B-11.06c          0.08
 6000.06c          0.20

% --------------- Structural materials ------------------------------------
mat Ti1515_713 -7.95 tmp 713 rgb 166 166 166 moder gr800 6000 % Dummy rod cladding (15-15 Ti)
% --- Carbon
 6000.06c         -0.09
% --- Chromium
24050.06c         -0.6061
24052.06c         -12.1365
24053.06c         -1.40215
```

```
24054.06c          -0.35525
% --- Nickel
28058.06c          -10.416
28060.06c          -4.1509
28061.06c          -0.1829
28062.06c          -0.59365
28064.06c          -0.15655
% --- Manganese
25055.06c          -1.5
% ---Molybdenum
42092.06c          -0.2226
42094.06c          -0.13875
42095.06c          -0.2388
42096.06c          -0.2502
42097.06c          -0.14325
42098.06c          -0.36195
42100.06c          -0.14445
% --- Titanium
22046.06c          -0.033
22047.06c          -0.02976
22048.06c          -0.29488
22049.06c          -0.02164
22050.06c          -0.02072
% --- Silicon
14028.06c          -0.780895
14029.06c          -0.041055
14030.06c          -0.028050
% --- Boron
 5010.06c          -0.001194
 5011.06c          -0.004806
% --- Phosphorus
15031.06c          -0.045
% --- Nitrogen
7014.06c           -0.0149448
7015.06c           -0.0000552
% --- Sulphur
16032.06c          -0.0142395
16033.06c          -0.000114
16034.06c          -0.0006435
16036.06c          -0.000003
% --- Aluminium
13027.06c          -0.015
% --- Zirconium
40090.06c          -0.015435
40091.06c          -0.003366
40092.06c          -0.005145
40094.06c          -0.005214
40096.06c          -0.00084
% --- Vanadium
23000.06c          -0.03
% --- Tungsten
74182.06c          -0.007959599999999999
74183.06c          -0.0042981
74184.06c          -0.009203099999999999
74186.06c          -0.0085392
% --- Niobium
41093.06c          -0.015
% --- Tantalum
73181.06c          -0.015
% --- Copper
29063.06c          -0.020751
29065.06c          -0.009249
% --- Cobalt
27059.06c          -0.03
% --- Calcium
20040.06c          -0.0290835
20042.06c          -0.0001941
20043.06c          -0.0000405
20044.06c          -0.0006258
20048.06c          -0.0000561
% --- Iron
26054.06c          -3.692501
```

```
26056.06c          -60.060326
26057.06c          -1.41164640
26058.06c          -0.1895266


mat Ti1515_753 -7.95 tmp 753 rgb 166 166 166  moder gr800 6000 % Safety rod cladding
    (15-15 Ti)
% --- Carbon
6000.06c           -0.09
% --- Chromium
24050.06c          -0.6061
24052.06c          -12.1365
24053.06c          -1.40215
24054.06c          -0.35525
% --- Nickel
28058.06c          -10.416
28060.06c          -4.1509
28061.06c          -0.1829
28062.06c          -0.59365
28064.06c          -0.15655
% --- Manganese
25055.06c          -1.5
% ---Molybdenum
42092.06c          -0.2226
42094.06c          -0.13875
42095.06c             -0.2388
42096.06c             -0.2502
42097.06c          -0.14325
42098.06c             -0.36195
42100.06c          -0.14445
% --- Titanium
22046.06c       -0.033
22047.06c       -0.02976
22048.06c       -0.29488
22049.06c       -0.02164
22050.06c       -0.02072
% --- Silicon
14028.06c          -0.780895
14029.06c          -0.041055
14030.06c          -0.028050
% --- Boron
 5010.06c          -0.001194
 5011.06c          -0.004806
% --- Phosphorus
15031.06c          -0.045
% --- Nitrogen
7014.06c        -0.0149448
7015.06c        -0.0000552
% --- Sulphur
16032.06c       -0.0142395
16033.06c       -0.000114
16034.06c       -0.0006435
16036.06c       -0.000003
% --- Aluminium
13027.06c       -0.015
% --- Zirconium
40090.06c          -0.015435
40091.06c          -0.003366
40092.06c          -0.005145
40094.06c          -0.005214
40096.06c          -0.00084
% --- Vanadium
23000.06c       -0.03
% --- Tungsten
74182.06c             -0.007959599999999999
74183.06c       -0.0042981
74184.06c       -0.009203099999999999
74186.06c       -0.0085392
% --- Niobium
41093.06c       -0.015
% --- Tantalum
73181.06c          -0.015
```

```
% --- Copper
29063.06c          -0.020751
29065.06c          -0.009249
% --- Cobalt
27059.06c          -0.03
% --- Calcium
20040.06c          -0.0290835
20042.06c          -0.0001941
20043.06c          -0.0000405
20044.06c          -0.0006258
20048.06c          -0.0000561
% --- Iron
26054.06c          -3.692501
26056.06c          -60.060326
26057.06c          -1.41164640
26058.06c          -0.1895266


mat Ti1515_743 -7.95 tmp 743 rgb 166 166 166   moder gr800 6000 % Fuel rod cladding (15-15 Ti)
% --- Carbon
6000.06c              -0.09
% --- Chromium
24050.06c             -0.6061
24052.06c             -12.1365
24053.06c       -1.40215
24054.06c             -0.35525
% --- Nickel
28058.06c       -10.416
28060.06c       -4.1509
28061.06c       -0.1829
28062.06c       -0.59365
28064.06c       -0.15655
% --- Manganese
25055.06c             -1.5
% ---Molybdenum
42092.06c             -0.2226
42094.06c       -0.13875
42095.06c       -0.2388
42096.06c       -0.2502
42097.06c       -0.14325
42098.06c       -0.36195
42100.06c       -0.14445
% --- Titanium
22046.06c       -0.033
22047.06c       -0.02976
22048.06c       -0.29488
22049.06c       -0.02164
22050.06c       -0.02072
% --- Silicon
14028.06c       -0.780895
14029.06c       -0.041055
14030.06c          -0.028050
% --- Boron
 5010.06c          -0.001194
 5011.06c          -0.004806
% --- Phosphorus
15031.06c       -0.045
% --- Nitrogen
7014.06c        -0.0149448
7015.06c        -0.0000552
% --- Sulphur
16032.06c             -0.0142395
16033.06c             -0.000114
16034.06c       -0.0006435
16036.06c       -0.000003
% --- Aluminium
13027.06c       -0.015
% --- Zirconium
40090.06c          -0.015435
40091.06c          -0.003366
40092.06c          -0.005145
```

```
40094.06c          -0.005214
40096.06c          -0.00084
% --- Vanadium
23000.06c       -0.03
% --- Tungsten
74182.06c       -0.007959599999999999
74183.06c       -0.0042981
74184.06c       -0.009203099999999999
74186.06c       -0.0085392
% --- Niobium
41093.06c       -0.015
% --- Tantalum
73181.06c          -0.015
% --- Copper
29063.06c          -0.020751
29065.06c          -0.009249
% --- Cobalt
27059.06c          -0.03
% --- Calcium
20040.06c          -0.0290835
20042.06c          -0.0001941
20043.06c          -0.0000405
20044.06c          -0.0006258
20048.06c          -0.0000561
% --- Iron
26054.06c       -3.692501
26056.06c       -60.060326
26057.06c          -1.41164640
26058.06c          -0.1895266


mat Ti1515_673 -7.95 tmp 673 rgb 166 166 166    moder gr700 6000    % Cladding (15-15 Ti)
% --- Carbon
6000.06c           -0.09
% --- Chromium
24050.06c          -0.6061
24052.06c          -12.1365
24053.06c          -1.40215
24054.06c          -0.35525
% --- Nickel
28058.06c          -10.416
28060.06c          -4.1509
28061.06c             -0.1829
28062.06c          -0.59365
28064.06c          -0.15655
% --- Manganese
25055.06c          -1.5
% ---Molybdenum
42092.06c          -0.2226
42094.06c          -0.13875
42095.06c             -0.2388
42096.06c             -0.2502
42097.06c             -0.14325
42098.06c             -0.36195
42100.06c             -0.14445
% --- Titanium
22046.06c             -0.033
22047.06c             -0.02976
22048.06c          -0.29488
22049.06c             -0.02164
22050.06c             -0.02072
% --- Silicon
14028.06c             -0.780895
14029.06c             -0.041055
14030.06c             -0.028050
% --- Boron
 5010.06c          -0.001194
 5011.06c          -0.004806
% --- Phosphorus
15031.06c          -0.045
% --- Nitrogen
7014.06c           -0.0149448
```

```
7015.06c             -0.0000552
% --- Sulphur
16032.06c         -0.0142395
16033.06c         -0.000114
16034.06c         -0.0006435
16036.06c         -0.000003
% --- Aluminium
13027.06c         -0.015
% --- Zirconium
40090.06c         -0.015435
40091.06c         -0.003366
40092.06c         -0.005145
40094.06c         -0.005214
40096.06c         -0.00084
% --- Vanadium
23000.06c         -0.03
% --- Tungsten
74182.06c         -0.007959599999999999
74183.06c         -0.0042981
74184.06c         -0.009203099999999999
74186.06c         -0.0085392
% --- Niobium
41093.06c         -0.015
% --- Tantalum
73181.06c         -0.015
% --- Copper
29063.06c         -0.020751
29065.06c         -0.009249
% --- Cobalt
27059.06c         -0.03
% --- Calcium
20040.06c         -0.0290835
20042.06c         -0.0001941
20043.06c         -0.0000405
20044.06c         -0.0006258
20048.06c         -0.0000561
% --- Iron
26054.06c         -3.692501
26056.06c         -60.060326
26057.06c         -1.41164640
26058.06c         -0.1895266


mat fmst91_713 -7.7359 tmp 713 rgb 115 115 115  moder gr800 6000 % FMS T91 for the
    wrapper (according to LEADER version)
% --- Carbon
6000.06c             -0.1
% --- Silicon
14028.06c         -0.45935
14029.06c         -0.02415
14030.06c         -0.0165
% --- Vanadium
23000.06c         -0.2
% --- Chromium
24050.06c         -0.3762
24052.06c         -7.533
24053.06c         -0.8703
24054.06c            -0.2205
% --- Manganese
25055.06c         -0.6
% ---Molybdenum
42092.06c         -0.1484
42094.06c         -0.0925
42095.06c         -0.1592
42096.06c       -0.1668
42097.06c       -0.0955
42098.06c       -0.2413
42100.06c       -0.0963
% --- Nickel
28058.06c       -0.1344
28060.06c       -0.05356
28061.06c       -0.002360
```

```
28062.06c       -0.00766
28064.06c       -0.00202
% --- Niobium
41093.06c       -0.1
% --- Iron
26054.06c       -4.98895
26056.06c       -81.1477
26057.06c         -1.90728
26058.06c         -0.25607


mat fmst91_753 -7.7359 tmp 753 rgb 115 115 115   moder gr800 6000 % Safety rod wrapper (stainless steel)
% --- Carbon
6000.06c        -0.1
% --- Silicon
14028.06c         -0.45935
14029.06c       -0.02415
14030.06c       -0.0165
% --- Vanadium
23000.06c       -0.2
% --- Chromium
24050.06c             -0.3762
24052.06c       -7.533
24053.06c       -0.8703
24054.06c       -0.2205
% --- Manganese
25055.06c       -0.6
% ---Molybdenum
42092.06c       -0.1484
42094.06c       -0.0925
42095.06c       -0.1592
42096.06c       -0.1668
42097.06c       -0.0955
42098.06c       -0.2413
42100.06c       -0.0963
% --- Nickel
28058.06c             -0.1344
28060.06c       -0.05356
28061.06c       -0.002360
28062.06c             -0.00766
28064.06c       -0.00202
% --- Niobium
41093.06c       -0.1
% --- Iron
26054.06c       -4.98895
26056.06c       -81.1477
26057.06c         -1.90728
26058.06c         -0.25607

mat fmst91_673  -7.7359 tmp 673 rgb 115 115 115   moder gr700 6000 % Fuel rod wrapper (stainless steel)
% --- Carbon
6000.06c          -0.1
% --- Silicon
14028.06c         -0.45935
14029.06c         -0.02415
14030.06c         -0.0165
% --- Vanadium
23000.06c         -0.2
% --- Chromium
24050.06c         -0.3762
24052.06c         -7.533
24053.06c         -0.8703
24054.06c         -0.2205
% --- Manganese
25055.06c         -0.6
% ---Molybdenum
42092.06c         -0.1484
42094.06c         -0.0925
42095.06c         -0.1592
42096.06c         -0.1668
```

```
42097.06c          -0.0955
42098.06c          -0.2413
42100.06c          -0.0963
% --- Nickel
28058.06c          -0.1344
28060.06c          -0.05356
28061.06c          -0.002360
28062.06c          -0.00766
28064.06c          -0.00202
% --- Niobium
41093.06c          -0.1
% --- Iron
26054.06c          -4.98895
26056.06c          -81.1477
26057.06c          -1.90728
26058.06c          -0.25607


% ------------------------------------------------------------------------------------------
% --------------- Coolant ------------------------------------------------------------------
mat cool_max -11.017 tmp 753 rgb 112 81 57                % Coolant
82204.06c          -0.0142        % Lead
82206.06c          -0.2410
82207.06c          -0.2210
82208.06c          -0.5238


mat cool_avg -11.017 tmp 713 rgb 112 81 57                % Coolant
82204.06c          -0.0142        % Lead
82206.06c          -0.2410
82207.06c          -0.2210
82208.06c          -0.5238


mat cool_min -11.017 tmp 673 rgb 112 81 57                % Coolant
82204.06c          -0.0142        % Lead
82206.06c          -0.2410
82207.06c          -0.2210
82208.06c          -0.5238


% --------------- Other structural materials -----------------------------------------
mat ZrYO -6 tmp 673 rgb 204 204 255
% --- Zirconium
40090.06c          -0.356267
40091.06c          -0.078558
40092.06c          -0.121398
40094.06c          -0.125705
40096.06c          -0.020683
% --- Oxygen
 8016.06c          -0.257226
% --- Yttrium
39089.06c          -0.040162


mat foll -5.68218 tmp 673 rgb 204 204 255
% --- Zirconium
40090.06c          -0.356267
40091.06c          -0.078558
40092.06c          -0.121398
40094.06c          -0.125705
40096.06c          -0.020683
% --- Oxygen
 8016.06c          -0.257226
% --- Yttrium
39089.06c          -0.040162


mat tins  -5.619 tmp 753 rgb 192 192 192        % Insulator (same as coolant)
```

```
% --- Zirconium
40090.06c         -0.356267
40091.06c         -0.078558
40092.06c         -0.121398
40094.06c         -0.125705
40096.06c         -0.020683
% --- Oxygen
 8016.06c         -0.257226
% --- Yttrium
39089.06c         -0.040162


mat bins        -5.619 tmp 673 rgb 192 192 192  % Insulator (same as coolant)
% --- Zirconium
40090.06c         -0.356267
40091.06c         -0.078558
40092.06c         -0.121398
40094.06c         -0.125705
40096.06c         -0.020683
% --- Oxygen
 8016.06c         -0.257226
% --- Yttrium
39089.06c         -0.040162


mat spr  -0.60372 tmp 753 rgb 204 0 204                  moder gr800 6000 % Insulator (same as coolant)
% --- Carbon
6000.06c       -0.1
% --- Silicon
14028.06c      -0.45935
14029.06c      -0.02415
14030.06c        -0.0165
% --- Vanadium
23000.06c            -0.2
% --- Chromium
24050.06c      -0.3762
24052.06c      -7.533
24053.06c      -0.8703
24054.06c      -0.2205
% --- Manganese
25055.06c            -0.6
% ---Molybdenum
42092.06c      -0.1484
42094.06c      -0.0925
42095.06c      -0.1592
42096.06c      -0.1668
42097.06c      -0.0955
42098.06c            -0.2413
42100.06c      -0.0963
% --- Nickel
28058.06c      -0.1344
28060.06c      -0.05356
28061.06c      -0.002360
28062.06c      -0.00766
28064.06c      -0.00202
% --- Niobium
41093.06c            -0.1
% --- Iron
26054.06c      -4.98895
26056.06c      -81.1477
26057.06c        -1.90728
26058.06c        -0.25607


mat pln  -0.60094 tmp 673 rgb 255 102 178       moder gr700 6000   % Insulator (same as coolant)
% --- Carbon
6000.06c       -0.1
% --- Silicon
14028.06c      -0.45935
14029.06c      -0.02415
```

```
14030.06c       -0.0165
% --- Vanadium
23000.06c            -0.2
% --- Chromium
24050.06c            -0.3762
24052.06c       -7.533
24053.06c       -0.8703
24054.06c       -0.2205
% --- Manganese
25055.06c       -0.6
% ---Molybdenum
42092.06c       -0.1484
42094.06c       -0.0925
42095.06c            -0.1592
42096.06c            -0.1668
42097.06c            -0.0955
42098.06c            -0.2413
42100.06c            -0.0963
% --- Nickel
28058.06c       -0.1344
28060.06c       -0.05356
28061.06c       -0.002360
28062.06c       -0.00766
28064.06c       -0.00202
% --- Niobium
41093.06c       -0.1
% --- Iron
26054.06c            -4.98895
26056.06c       -81.1477
26057.06c         -1.90728
26058.06c         -0.25607


mat tplg  -8.41005 tmp 753 rgb 255 128 0        moder gr800 6000   % Insulator (same as coolant)
% --- Lead
82204.06c         -2.130000000000000e-03
82206.06c         -3.615000000000000e-02
82207.06c         -3.315000000000000e-02
82208.06c         -7.857000000000000e-02
% --- Carbon
6000.06c        -8.500000000000000e-04
% --- Silicon
14028.06c            -3.904474999999999e-03
14029.06c       -2.052750000000000e-04
14030.06c       -1.402500000000000e-04
% --- Vanadium
23000.06c       -1.700000000000000e-03
% --- Chromium
24050.06c       -3.197700000000000e-03
24052.06c       -6.403050000000000e-02
24053.06c       -7.397550000000000e-03
24054.06c       -1.874250000000000e-03
% --- Manganese
25055.06c       -5.100000000000000e-03
% ---Molybdenum
42092.06c       -1.261400000000000e-03
42094.06c       -7.862500000000001e-04
42095.06c       -1.353200000000000e-03
42096.06c       -1.417800000000000e-03
42097.06c            -8.117500000000000e-04
42098.06c       -2.051050000000000e-03
42100.06c       -8.185499999999999e-04
% --- Nickel
28058.06c       -1.142400000000000e-03
28060.06c       -4.552600000000000e-04
28061.06c       -2.006000000000000e-05
28062.06c       -6.511000000000001e-05
28064.06c            -1.717000000000000e-05
% --- Niobium
41093.06c       -8.500000000000000e-04
% --- Iron
```

```
692.  26054.06c       -4.240607500000000e-02
693.  26056.06c       -6.897554499999999e-01
694.  26057.06c         -1.621188000000000e-02
695.  26058.06c         -2.176595000000000e-03
696.
697.
698.  mat bplg  -8.25670 tmp 673 rgb 255 128 0        moder gr700 6000   % Insulator (same as
    coolant)
699.  % --- Lead
700.  82204.06c         -1.420000000000000e-03
701.  82206.06c         -2.410000000000000e-02
702.  82207.06c         -2.210000000000000e-02
703.  82208.06c         -5.238000000000001e-02
704.  % --- Carbon
705.  6000.06c        -9.000000000000001e-04
706.  % --- Silicon
707.  14028.06c       -4.134150000000000e-03
708.  14029.06c       -2.173500000000000e-04
709.  14030.06c       -1.485000000000000e-04
710.  % --- Vanadium
711.  23000.06c       -1.800000000000000e-03
712.  % --- Chromium
713.  24050.06c       -3.385800000000000e-03
714.  24052.06c       -6.779700000000001e-02
715.  24053.06c       -7.832700000000001e-03
716.  24054.06c       -1.984500000000000e-03
717.  % --- Manganese
718.  25055.06c       -5.400000000000000e-03
719.  % ---Molybdenum
720.  42092.06c             -1.335600000000000e-03
721.  42094.06c             -8.325000000000000e-04
722.  42095.06c             -1.432800000000000e-03
723.  42096.06c             -1.501200000000000e-03
724.  42097.06c         -8.595000000000000e-04
725.  42098.06c       -2.171700000000000e-03
726.  42100.06c             -8.667000000000000e-04
727.  % --- Nickel
728.  28058.06c       -1.209600000000000e-03
729.  28060.06c       -4.820400000000000e-04
730.  28061.06c             -2.124000000000000e-05
731.  28062.06c             -6.894000000000000e-05
732.  28064.06c             -1.818000000000000e-05
733.  % --- Niobium
734.  41093.06c             -9.000000000000001e-04
735.  % --- Iron
736.  26054.06c       -4.490055000000000e-02
737.  26056.06c             -7.303293000000001e-01
738.  26057.06c         -1.716552000000000e-02
739.  26058.06c         -2.304630000000000e-03
740.
741.
742.  mat tref -10.4040 tmp 753 rgb 255 229 204       moder gr800 6000 % Upper and lower
    reflector (same as coolant)
743.  % --- Lead
744.  82204.06c         -1.136000000000000e-02
745.  82206.06c         -1.928000000000000e-01
746.  82207.06c         -1.768000000000000e-01
747.  82208.06c         -4.190400000000001e-01
748.  % --- Carbon
749.  6000.06c              -2.000000000000000e-04
750.  % --- Silicon
751.  14028.06c       -9.186999999999999e-04
752.  14029.06c       -4.830000000000001e-05
753.  14030.06c       -3.300000000000000e-05
754.  % --- Vanadium
755.  23000.06c       -4.000000000000000e-04
756.  % --- Chromium
757.  24050.06c       -7.524000000000000e-04
758.  24052.06c       -1.506600000000000e-02
759.  24053.06c       -1.740600000000000e-03
760.  24054.06c       -4.410000000000000e-04
761.  % --- Manganese
```

```
25055.06c       -1.200000000000000e-03
% ---Molybdenum
42092.06c       -2.968000000000001e-04
42094.06c       -1.850000000000000e-04
42095.06c       -3.184000000000000e-04
42096.06c       -3.336000000000000e-04
42097.06c       -1.910000000000000e-04
42098.06c       -4.826000000000000e-04
42100.06c            -1.926000000000000e-04
% --- Nickel
28058.06c       -2.688000000000000e-04
28060.06c            -1.071200000000000e-04
28061.06c            -4.720000000000001e-06
28062.06c          -1.532000000000000e-05
28064.06c            -4.040000000000000e-06
% --- Niobium
41093.06c       -2.000000000000000e-04
% --- Iron
26054.06c       -9.977900000000001e-03
26056.06c       -1.622954000000000e-01
26057.06c          -3.814560000000000e-03
26058.06c          -5.121400000000001e-04


mat bref -10.6490 tmp 673 rgb 204 255 255       moder gr700 6000    % Upper and lower reflector (same as coolant)
% --- Lead
82204.06c          -1.249600000000000e-02
82206.06c          -2.120800000000000e-01
82207.06c          -1.944800000000000e-01
82208.06c          -4.609440000000000e-01
% --- Carbon
6000.06c        -1.200000000000000e-04
% --- Silicon
14028.06c       -5.512199999999999e-04
14029.06c       -2.898000000000000e-05
14030.06c       -1.980000000000000e-05
% --- Vanadium
23000.06c       -2.400000000000000e-04
% --- Chromium
24050.06c       -4.514400000000000e-04
24052.06c       -9.039600000000000e-03
24053.06c       -1.044360000000000e-03
24054.06c       -2.646000000000000e-04
% --- Manganese
25055.06c       -7.199999999999999e-04
% ---Molybdenum
42092.06c       -1.780800000000000e-04
42094.06c       -1.110000000000000e-04
42095.06c          -1.910400000000000e-04
42096.06c       -2.001600000000000e-04
42097.06c       -1.146000000000000e-04
42098.06c       -2.895600000000000e-04
42100.06c       -1.155600000000000e-04
% --- Nickel
28058.06c       -1.612800000000000e-04
28060.06c       -6.427200000000000e-05
28061.06c       -2.832000000000000e-06
28062.06c       -9.192000000000000e-06
28064.06c       -2.424000000000000e-06
% --- Niobium
41093.06c       -1.200000000000000e-04
% --- Iron
26054.06c       -5.986739999999999e-03
26056.06c       -9.737724000000000e-02
26057.06c          -2.288736000000000e-03
26058.06c          -3.072840000000000e-04


mat barrel -9.90799 tmp 673 rgb 80 170 80       moder gr700 6000    % Upper and lower reflector (same as coolant)
% --- Lead
```

```
82204.06c          -9.400400000000001e-03
82206.06c          -1.595420000000000e-01
82207.06c          -1.463020000000000e-01
82208.06c          -3.467556000000001e-01
% --- Carbon
6000.06c           -3.380000000000000e-04
% --- Silicon
14028.06c       -1.552603000000000e-03
14029.06c          -8.162700000000001e-05
14030.06c       -5.577000000000000e-05
% --- Vanadium
23000.06c       -6.760000000000001e-04
% --- Chromium
24050.06c       -1.271556000000000e-03
24052.06c       -2.546154000000000e-02
24053.06c       -2.941614000000000e-03
24054.06c       -7.452900000000000e-04
% --- Manganese
25055.06c       -2.028000000000000e-03
% ---Molybdenum
42092.06c       -5.015920000000000e-04
42094.06c       -3.126500000000000e-04
42095.06c       -5.380960000000001e-04
42096.06c       -5.637840000000000e-04
42097.06c       -3.227900000000000e-04
42098.06c       -8.155940000000000e-04
42100.06c       -3.254940000000000e-04
% --- Nickel
28058.06c       -4.542720000000000e-04
28060.06c          -1.810328000000000e-04
28061.06c       -7.976800000000001e-06
28062.06c       -2.589080000000000e-05
28064.06c       -6.827600000000000e-06
% --- Niobium
41093.06c       -3.380000000000000e-04
% --- Iron
26054.06c       -1.686265100000000e-02
26056.06c       -2.742792260000000e-01
26057.06c          -6.446606400000001e-03
26058.06c          -8.655166000000002e-04

% ------------------- homogenised compositions ----------------------
mix fuelihom
fueli           -0.32252
Ti1515_743      -0.07539
fmst91_713      -0.06948
cool_avg        -0.53261

mix fuelohom
fuelo           -0.32291
Ti1515_743      -0.07535
fmst91_713      -0.06944
cool_avg        -0.53230

mix safehom
safe                        -0.09409
Ti1515_753      -0.02218
fmst91_753      -0.20561
cool_max           -0.67813

mix conthom
cont                        -0.202841
Ti1515_753                  -0.063590
fmst91_753                  -0.087845
cool_min           -0.645724
```

E.2 Input files for the 3D core model

In the following, the input file “ALFRED_ECCO.ge” used to reproduce all the geometrical features of the 3D core model is reported. It should be noticed that all the CR and SR movements are controlled in the main script with the command “*trans*”.

```
% ------------------------------------------------------------------------%
% ------------------------------------------------------------------------%
% Geometry definitions for ALFRED reactor, LEADER version                 %
% ------------------------------------------------------------------------%

% ---------------------------------------- GEOMETRIC SURFACES DEFINITIONS ----------------------------------------

% ------------------------ Radial coordinate ------------------------------------------------------------------------

% Core
surf s1 cyl 0.0 0.0 233               % core external perimeter

% Hexagonal assembly
surf w1 hexyc 0.0 0.0 7.9         % wrapping inner perimeter
surf w2 hexyc 0.0 0.0 8.3         % wrapping outer perimeter

surf w3 hexyc 0.0 0.0 7.39        % wrapping inner perimeter
surf w4 hexyc 0.0 0.0 8.3         % wrapping outer perimeter

surf w5 hexyc 0.0 0.0 8.02        % wrapping inner perimeter
surf w6 hexyc 0.0 0.0 8.3         % wrapping outer perimeter

% ------------------------ Axial coordinate -------------------------------------------------------------------------
% Reactor
surf z_core_u   pz  170.0         % Core axial upper limit
surf z_core_b   pz -170.0         % Core axial lower limit

% Fuel rod (FR)
surf z_tref_fr  pz   170.0        % Fuel pin upper limit
surf z_tplg_fr  pz   48.0         % Fuel pin upper limit
surf z_sprn_fr  pz   43.0         % Fuel pin upper limit
surf z_ins_u    pz   31.0         % Insulator upper limit
surf z_fuel_u   pz   30.0         % Fuel active zone upper limit
surf z_fuel_b   pz  -30.0         % Fuel active zone lower limit
surf z_ins_b    pz  -31.0         % Insulator lower limit
surf z_plen     pz  -86.0         % Plenum fuel pin lower limit
surf z_bplg_fr  pz  -91.0         % Bottom plug
surf z_bref_fr  pz  -170.0        % Bottom reflector

% Control rod (CR)
surf z_tref_cr  pz   300.0        % Top reflector upper limit
surf z_sprn_cr  pz    94.0        % Spring upper limit
surf z_frod_u   pz    34.0        % Follower upper limit
surf z_frod_b   pz   -34.0        % Follower lower limit
surf z_crod_cr  pz  -102.0        % Control rod zone upper limit
surf z_bins_cr  pz  -103.0        % Bottom insulator zone lower limit
surf z_bplg_cr  pz  -108.0        % Bottom plug
surf z_bref_cr  pz  -300.0        % Bottom reflector

% Safety rod (SR)
surf z_tref_sr   pz   300.0       % Fuel pin upper limit
surf z_sprn_sr   pz   137.0       % Fuel pin upper limit
surf z_tins_sr   pz   127.0       % Fuel pin upper limit
surf z_srod_sr   pz   126.0   % Insulator upper limit
surf z_bplg_sr   pz    42.0       % Fuel active zone upper limit
surf z_bref_sru  pz    37.0       % Upper reflector
surf z_bref_srb  pz  -300.0       % Bottom reflector

% Dummy rod (DR)
surf z_tref_dr  pz   170.0        % Fuel pin upper limit
surf z_tplg_dr  pz    48.0        % Fuel pin upper limit
surf z_sprn_dr  pz    43.0        % Fuel pin upper limit
surf z_dumm_u   pz    31.0        % Insulator upper limit
surf z_dumm_b   pz   -86.0        % Fuel active zone upper limit
surf z_bplg_dr  pz   -91.0        % Fuel active zone upper limit
surf z_bref_dr  pz  -170.0        % Bottom reflector

% -------------------- PIN DEFINITION ---------------------------------------------------------------------------------
pin pl                                  % Plenum pin
void        0.4
pln         0.465
Ti1515_713  0.525
cool_min

pin tg                          % Top plug "pin"
tplg       0.465
Ti1515_753 0.525
cool_max

pin bg                          % Bottom plug "pin"
bplg       0.465
Ti1515_713 0.525
cool_min

pin ti                          % Top insulator "pin"
tins       0.465
```

```
87.  Ti1515_713 0.525
88.  cool_max
89.
90.  pin bi                        % Bottom insulator "pin"
91.  bins       0.465
92.  Ti1515_713 0.525
93.  cool_min
94.
95.  pin dp                        % Dummy "pin"
96.  foll       0.465
97.  Ti1515_713 0.525
98.  cool_avg
99.
100. pin sp                        % Spring "pin"
101. spr        0.465
102. Ti1515_713 0.525
103. cool_max
104.
105. pin s1                        % Safety pin
106. safe       2.58
107. Ti1515_753 2.64
108. cool_max
109.
110. pin s2                        % Safety pin
111. safe       1.83
112. Ti1515_753 1.89
113. cool_max
114.
115. pin c1                        % Control pin
116. cont       1.49
117. Ti1515_673 1.55
118. cool_min
119.
120. pin ce                        % Control pin plenum
121. foll       1.49
122. fmst91_713 1.55
123. cool_avg
124.
125. pin fp                        % Control pin follower
126. foll       1.49
127. fmst91_713 1.55
128. cool_avg
129.
130. pin ll                                  % Pure lead (empty lattice positions)
131. cool_min
132.
133. pin vv                                  % Pure lead (empty lattice positions)
134. void
135.
136. % ------------------------------- ASSEMBLY DEFINITION ------------------------------------------------------------
137. % -- Top insulator assembly
138. lat top_ins 2 0.0 0.0 15 15 1.386
139. ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
140.  ll ll ll ll ll ll ll ll ti ti ti ti ti ti ti ll
141.   ll ll ll ll ll ll ll ti ti ti ti ti ti ti ti ll
142.    ll ll ll ll ll ll ti ti ti ti ti ti ti ti ti ll
143.     ll ll ll ll ll ti ti ti ti ti ti ti ti ti ti ll
144.      ll ll ll ti ti ti ti ti ti ti ti ti ti ti ti ll
145.       ll ll ti ti ti ti ti ti ti ti ti ti ti ti ti ll
146.        ll ti ti ti ti ti ti ti ti ti ti ti ti ti ti ll
147.         ll ti ti ti ti ti ti ti ti ti ti ti ti ti ll ll
148.          ll ti ti ti ti ti ti ti ti ti ti ti ti ll ll ll
149.           ll ti ti ti ti ti ti ti ti ti ti ti ll ll ll ll
150.            ll ti ti ti ti ti ti ti ti ti ti ll ll ll ll ll
151.             ll ti ti ti ti ti ti ti ti ti ll ll ll ll ll ll
152.              ll ti ti ti ti ti ti ti ti ll ll ll ll ll ll ll
153.               ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
154.
155. % -- Spring assembly
156. lat spring 2 0.0 0.0 15 15 1.386
157. ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
158.  ll ll ll ll ll ll ll sp sp sp sp sp sp sp ll
159.   ll ll ll ll ll ll sp sp sp sp sp sp sp sp ll
160.    ll ll ll ll ll sp sp sp sp sp sp sp sp sp ll
161.     ll ll ll ll sp sp sp sp sp sp sp sp sp sp ll
162.      ll ll ll sp sp sp sp sp sp sp sp sp sp sp ll
163.       ll ll sp sp sp sp sp sp sp sp sp sp sp sp ll
164.        ll sp sp sp sp sp sp sp sp sp sp sp sp sp ll
165.         ll sp sp sp sp sp sp sp sp sp sp sp sp ll ll
166.          ll sp sp sp sp sp sp sp sp sp sp sp sp ll ll ll
167.           ll sp sp sp sp sp sp sp sp sp sp ll ll ll ll
168.            ll sp sp sp sp sp sp sp sp sp sp ll ll ll ll ll
169.             ll sp sp sp sp sp sp sp sp sp ll ll ll ll ll ll
170.              ll sp sp sp sp sp sp sp ll ll ll ll ll ll ll
171.               ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
172.
173. % -- Dummy assembly
174. lat dr_dumm 2 0.0 0.0 15 15 1.386
175. ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
176.  ll ll ll ll ll ll ll dp dp dp dp dp dp dp ll
177.   ll ll ll ll ll ll dp dp dp dp dp dp dp dp ll
178.    ll ll ll ll ll dp dp dp dp dp dp dp dp dp ll
179.     ll ll ll ll dp dp dp dp dp dp dp dp dp dp ll
180.      ll ll ll dp dp dp dp dp dp dp dp dp dp dp ll
181.       ll ll dp dp dp dp dp dp dp dp dp dp dp dp ll
182.        ll dp dp dp dp dp dp dp dp dp dp dp dp dp ll
```

```
        ll dp dp dp dp dp dp dp dp dp dp dp dp ll ll
         ll dp dp dp dp dp dp dp dp dp dp dp ll ll ll
          ll dp dp dp dp dp dp dp dp dp dp ll ll ll ll
           ll dp dp dp dp dp dp dp dp dp ll ll ll ll ll
            ll dp dp dp dp dp dp dp dp ll ll ll ll ll ll
             ll dp dp dp dp dp dp dp ll ll ll ll ll ll ll
              ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll

% -- Inactive fuel assembly
lat bot_ins 2 0.0 0.0 15 15 1.386
ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
 ll ll ll ll ll ll ll ll bi bi bi bi bi bi bi bi ll
  ll ll ll ll ll ll bi bi bi bi bi bi bi bi bi ll
   ll ll ll ll ll bi bi bi bi bi bi bi bi bi bi ll
    ll ll ll ll bi bi bi bi bi bi bi bi bi bi bi ll
     ll ll ll bi bi bi bi bi bi bi bi bi bi bi bi ll
      ll ll bi bi bi bi bi bi bi bi bi bi bi bi bi ll
       ll bi bi bi bi bi bi bi bi bi bi bi bi bi bi ll
        ll bi bi bi bi bi bi bi bi bi bi bi bi bi ll ll
         ll bi bi bi bi bi bi bi bi bi bi bi bi ll ll ll
          ll bi bi bi bi bi bi bi bi bi bi bi ll ll ll ll
           ll bi bi bi bi bi bi bi bi bi bi ll ll ll ll ll
            ll bi bi bi bi bi bi bi bi bi ll ll ll ll ll ll
             ll bi bi bi bi bi bi bi bi ll ll ll ll ll ll ll
              ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll

% -- Plenum assembly
lat plen 2 0.0 0.0 15 15 1.386
ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
 ll ll ll ll ll ll ll pl pl pl pl pl pl pl pl ll
  ll ll ll ll ll ll pl pl pl pl pl pl pl pl pl ll
   ll ll ll ll ll pl pl pl pl pl pl pl pl pl pl ll
    ll ll ll ll pl pl pl pl pl pl pl pl pl pl pl ll
     ll ll ll pl pl pl pl pl pl pl pl pl pl pl pl ll
      ll ll pl pl pl pl pl pl pl pl pl pl pl pl pl ll
       ll pl pl pl pl pl pl pl pl pl pl pl pl pl pl ll
        ll pl pl pl pl pl pl pl pl pl pl pl pl pl ll ll
         ll pl pl pl pl pl pl pl pl pl pl pl pl ll ll ll
          ll pl pl pl pl pl pl pl pl pl pl pl ll ll ll ll
           ll pl pl pl pl pl pl pl pl pl ll ll ll ll ll ll
            ll pl pl pl pl pl pl pl pl ll ll ll ll ll ll ll
             ll pl pl pl pl pl pl pl ll ll ll ll ll ll ll ll
              ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll

% -- Outer fuel assembly
lat top_plg 2 0.0 0.0 15 15 1.386
ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
 ll ll ll ll ll ll ll tg tg tg tg tg tg tg ll
  ll ll ll ll ll ll tg tg tg tg tg tg tg tg ll
   ll ll ll ll ll tg tg tg tg tg tg tg tg tg ll
    ll ll ll ll tg tg tg tg tg tg tg tg tg tg ll
     ll ll ll tg tg tg tg tg tg tg tg tg tg tg ll
      ll ll tg tg tg tg tg tg tg tg tg tg tg tg ll
       ll tg tg tg tg tg tg tg tg tg tg tg tg tg ll
        ll tg tg tg tg tg tg tg tg tg tg tg tg ll ll
         ll tg tg tg tg tg tg tg tg tg tg tg ll ll ll
          ll tg tg tg tg tg tg tg tg tg tg ll ll ll ll
           ll tg tg tg tg tg tg tg tg tg ll ll ll ll ll
            ll tg tg tg tg tg tg tg tg ll ll ll ll ll ll
             ll tg tg tg tg tg tg tg ll ll ll ll ll ll ll
              ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll

% -- Outer fuel assembly
lat bot_plg 2 0.0 0.0 15 15 1.386
ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
 ll ll ll ll ll ll ll bg bg bg bg bg bg bg ll
  ll ll ll ll ll ll bg bg bg bg bg bg bg bg ll
   ll ll ll ll ll bg bg bg bg bg bg bg bg bg ll
    ll ll ll ll bg bg bg bg bg bg bg bg bg bg ll
     ll ll ll bg bg bg bg bg bg bg bg bg bg bg ll
      ll ll bg bg bg bg bg bg bg bg bg bg bg bg ll
       ll bg bg bg bg bg bg bg bg bg bg bg bg bg ll
        ll bg bg bg bg bg bg bg bg bg bg bg bg ll ll
         ll bg bg bg bg bg bg bg bg bg bg bg ll ll ll
          ll bg bg bg bg bg bg bg bg bg bg ll ll ll ll
           ll bg bg bg bg bg bg bg bg bg ll ll ll ll ll
            ll bg bg bg bg bg bg bg bg ll ll ll ll ll ll
             ll bg bg bg bg bg bg bg ll ll ll ll ll ll ll
              ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll

% -- Void assembly
lat va 2 0.0 0.0 15 15 1.386
vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
 vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
  vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
   vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
    vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
     vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
      vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
       vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
        vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
         vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
          vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
           vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
            vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
             vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
              vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
```

```
              vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv


% -- Lead assembly
lat la 2 0.0 0.0 15 15 1.386
ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
 ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
  ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
   ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
    ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
     ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
      ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
       ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
        ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
         ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
          ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
           ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
            ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
             ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
              ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll

% -- Safety rod assembly (circular array)
lat safe2 4 0.0 0.0 2         % Active section
3 2.0 0 s1 s1 s1
9 5.5 0 s1 s1 s1 s1 s1 s1 s1 s1 s1

% -- Safety rod assembly (circular array)
lat safe1 4 0.0 0.0 2         % Active section
1 0 0 s1
6 5.25 30 s2 s2 s2 s2 s2 s2

% -- Control rod assembly (circular array)
lat cont1 4 0.0 0.0 3         % Active section
1 0.0 0 c1
6 3.3 30 c1 c1 c1 c1 c1 c1
12 6.37511 15 c1 c1 c1 c1 c1 c1 c1 c1 c1 c1 c1 c1

lat continact 4 0.0 0.0 3 % Inactive section
1 0.0 0 fp
6 3.3 30 fp fp fp fp fp fp
12 6.37511 15 fp fp fp fp fp fp fp fp fp fp fp fp


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% INNER FUEL %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Inner fuel
cell c1r0           u1fuel       fuelihom          -w1                     % filling the channel
cell c1r1           u1fuel       fuelihom           w1  -w2                 % filling the wrapper
cell c1r2           u1fuel       fuelihom           w2                       % filling the external region

cell c1r0_GCU       INN_FUEL     fuelihom          -w1                     % filling the channel
cell c1r1_GCU       INN_FUEL     fuelihom           w1 -w2                  % filling the wrapper
cell c1r2_GCU       INN_FUEL     fuelihom           w2                       % filling the external region

/*
cell u1r0           u1hom        fuelihom           -w2                     % filling the channel
cell c1r1           u1fuel       fill u1hom         -w2                      % filling the channel
cell c1r2           u1fuel       fill u1hom          w2                       % filling the external region

cell c1r0_GCU       u1homGCU     fuelihom           -w2                     % filling the channel
cell c1r1_GCU       INN_FUEL     fill u1homGCU      -w2                      % filling the channel
cell c1r2_GCU       INN_FUEL     fill u1hom          w2                       % filling the external region
*/

% Top plug
cell u1tplgr0       u1tplg       fill top_plg      -w1                     % filling the channel
cell u1tplgr1       u1tplg       fmst91_753         w1 -w2                  % filling the wrapper
cell u1tplgr2       u1tplg       cool_max           w2                       % filling the external region

cell u1tplgr0_GCU   IF_TOP_PLUG  fill top_plg      -w1                     % filling the channel
cell u1tplgr1_GCU   IF_TOP_PLUG  fmst91_753         w1 -w2                  % filling the wrapper
cell u1tplgr2_GCU   IF_TOP_PLUG  cool_max           w2                       % filling the external region

% Spring
cell u1sprnr0       u1spr        fill spring       -w1                     % filling the channel
cell u1sprnr1       u1spr        fmst91_753         w1 -w2                  % filling the wrapper
cell u1sprnr2       u1spr        cool_max           w2                       % filling the external region

cell u1sprnr0_GCU   IF_SPRING    fill spring       -w1                     % filling the channel
cell u1sprnr1_GCU   IF_SPRING    fmst91_753         w1 -w2                  % filling the wrapper
cell u1sprnr2_GCU   IF_SPRING    cool_max           w2                       % filling the external region

% Top insulator
cell u1tinsr0       u1tins       fill top_ins      -w1                     % filling the channel
cell u1tinsr1       u1tins       fmst91_753         w1 -w2                  % filling the wrapper
cell u1tinsr2       u1tins       cool_max           w2                       % filling the external region

cell u1tinsr0_GCU   IF_TOP_INS   fill top_ins      -w1                     % filling the channel
cell u1tinsr1_GCU   IF_TOP_INS   fmst91_753         w1 -w2                  % filling the wrapper
cell u1tinsr2_GCU   IF_TOP_INS   cool_max           w2                       % filling the external region

% Bottom insulator
cell u1binsr0       u1bins       fill bot_ins      -w1                     % filling the channel
cell u1binsr1       u1bins       fmst91_673         w1 -w2                  % filling the wrapper
cell u1binsr2       u1bins       cool_min           w2                       % filling the external region

cell u1binsr0_GCU   IF_BOT_INS   fill bot_ins      -w1                     % filling the channel
```

```
cell u1binsr1_GCU   IF_BOT_INS   fmst91_673         w1 -w2                  % filling the wrapper
cell u1binsr2_GCU   IF_BOT_INS   cool_min           w2                       % filling the external region

% Plenum
cell u1plnr0        u1pln        fill plen         -w1                     % filling the channel
cell u1plnr1        u1pln        fmst91_673         w1 -w2                  % filling the wrapper
cell u1plnr2        u1pln        cool_min           w2                       % filling the external region

cell u1plnr0_GCU    IF_PLEN      fill plen         -w1                     % filling the channel
cell u1plnr1_GCU    IF_PLEN      fmst91_673         w1 -w2                  % filling the wrapper
cell u1plnr2_GCU    IF_PLEN      cool_min           w2                       % filling the external region

% Bottom plug
cell u1bplgr0       u1bplg        fill bot_plg     -w1                     % filling the channel
cell u1bplgr1       u1bplg        fmst91_673        w1 -w2                  % filling the wrapper
cell u1bplgr2       u1bplg        cool_min          w2                       % filling the external region

cell u1bplgr0_GCU   IF_BOT_PLUG   fill bot_plg     -w1                     % filling the channel
cell u1bplgr1_GCU   IF_BOT_PLUG   fmst91_673        w1 -w2                  % filling the wrapper
cell u1bplgr2_GCU   IF_BOT_PLUG   cool_min          w2                       % filling the external region

% Inner fuel assembly axial scan
cell c1tref     u1ref tref       z_tplg_fr  -z_tref_fr  % upper reflector
cell c1a1       u1 fill u1ref    z_tplg_fr  -z_tref_fr  % upper reflector
cell c1a2       u1 fill u1tplg   z_sprn_fr  -z_tplg_fr  % upper plug
cell c1a3       u1 fill u1spr    z_ins_u    -z_sprn_fr  % spring
cell c1a4       u1 fill u1tins   z_fuel_u   -z_ins_u    % insulator
cell c1a5       u1 fill u1fuel   z_fuel_b   -z_fuel_u   % fuel
cell c1a6       u1 fill u1bins   z_ins_b    -z_fuel_b   % insulator
cell c1a7       u1 fill u1pln    z_plen     -z_ins_b    % plenum
cell c1a8       u1 fill u1bplg   z_bplg_fr  -z_plen     % bottom plug
cell c1ref_bo   u1ref bref       z_bref_fr  -z_bplg_fr  % bottom reflector
cell c1a9       u1 fill u1ref    z_bref_fr  -z_bplg_fr  % bottom reflector

% Inner fuel assembly axial scan (universe definition to compute group-wise constants)
cell c1tref_GCU     IF_TOP_REF tref          z_tplg_fr -z_tref_fr  % upper reflector
cell c1a1_GCU       IF fill IF_TOP_REF       z_tplg_fr -z_tref_fr  % upper reflector
cell c1a2_GCU       IF fill IF_TOP_PLUG      z_sprn_fr -z_tplg_fr  % upper plug
cell c1a3_GCU       IF fill IF_SPRING        z_ins_u   -z_sprn_fr  % spring
cell c1a4_GCU       IF fill IF_TOP_INS       z_fuel_u  -z_ins_u    % insulator
cell c1a5_GCU       IF fill INN_FUEL         z_fuel_b  -z_fuel_u   % fuel
cell c1a6_GCU       IF fill IF_BOT_INS       z_ins_b   -z_fuel_b   % insulator
cell c1a7_GCU       IF fill IF_PLEN          z_plen    -z_ins_b    % plenum
cell c1a8_GCU       IF fill IF_BOT_PLUG      z_bplg_fr -z_plen     % bottom plug
cell c1ref_bo_GCU   IF_BOT_REF bref          z_bref_fr -z_bplg_fr  % bottom reflector
cell c1a9_GCU       IF fill IF_BOT_REF       z_bref_fr -z_bplg_fr  % bottom reflector

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% OUTER FUEL %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Outer Fuel
cell c2r1           u2fuel fuelohom               -w1                     % filling the channel
cell c2r2           u2fuel fuelohom                w1 -w2                  % filling the wrapper
cell c2r3           u2fuel fuelohom                w2                       % filling the external region

cell c2r1_GCU       OUT_FUEL fuelohom             -w1                     % filling the channel
cell c2r2_GCU       OUT_FUEL fuelohom              w1 -w2                  % filling the wrapper
cell c2r3_GCU       OUT_FUEL fuelohom              w2                       % filling the external region

% Top plug
cell u2tplgr0       u2tplg       fill top_plg     -w1                     % filling the channel
cell u2tplgr1       u2tplg       fmst91_753        w1 -w2                  % filling the wrapper
cell u2tplgr2       u2tplg       cool_max          w2                       % filling the external region
cell u2tplgr0_GCU   OF_TOP_PLUG  fill top_plg     -w1                     % filling the channel
cell u2tplgr1_GCU   OF_TOP_PLUG  fmst91_753        w1 -w2                  % filling the wrapper
cell u2tplgr2_GCU   OF_TOP_PLUG  cool_max          w2                       % filling the external region

% Spring
cell u2sprnr0       u2spr        fill spring      -w1                     % filling the channel
cell u2sprnr1       u2spr        fmst91_753        w1 -w2                  % filling the wrapper
cell u2sprnr2       u2spr        cool_max          w2                       % filling the external region
cell u2sprnr0_GCU   OF_SPRING    fill spring      -w1                     % filling the channel
cell u2sprnr1_GCU   OF_SPRING    fmst91_753        w1 -w2                  % filling the wrapper
cell u2sprnr2_GCU   OF_SPRING    cool_max          w2                       % filling the external region

% Top insulator
cell u2tinsr0       u2tins       fill top_ins     -w1                     % filling the channel
cell u2tinsr1       u2tins       fmst91_753        w1 -w2                  % filling the wrapper
cell u2tinsr2       u2tins       cool_max          w2                       % filling the external region
cell u2tinsr0_GCU   OF_TOP_INS   fill top_ins     -w1                     % filling the channel
cell u2tinsr1_GCU   OF_TOP_INS   fmst91_753        w1 -w2                  % filling the wrapper
cell u2tinsr2_GCU   OF_TOP_INS   cool_max          w2                       % filling the external region

% Bottom insulator
cell u2binsr0       u2bins       fill bot_ins     -w1                     % filling the channel
cell u2binsr1       u2bins       fmst91_673        w1 -w2                  % filling the wrapper
cell u2binsr2       u2bins       cool_min          w2                       % filling the external region
cell u2binsr0_GCU   OF_BOT_INS   fill bot_ins     -w1                     % filling the channel
cell u2binsr1_GCU   OF_BOT_INS   fmst91_673        w1 -w2                  % filling the wrapper
cell u2binsr2_GCU   OF_BOT_INS   cool_min          w2                       % filling the external region

% Plenum
cell u2plnr0        u2pln        fill plen        -w1                     % filling the channel
cell u2plnr1        u2pln        fmst91_673        w1 -w2                  % filling the wrapper
cell u2plnr2        u2pln        cool_min          w2                       % filling the external region
cell u2plnr0_GCU    OF_PLEN      fill plen        -w1                     % filling the channel
cell u2plnr1_GCU    OF_PLEN      fmst91_673        w1 -w2                  % filling the wrapper
cell u2plnr2_GCU    OF_PLEN      cool_min          w2                       % filling the external region
```

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% Bottom plug
cell u2bplgr0       u2bplg        fill bot_plg    -w1                     % filling the channel
cell u2bplgr1       u2bplg        fmst91_673       w1 -w2                  % filling the wrapper
cell u2bplgr2       u2bplg        cool_min         w2                       % filling the external region
cell u2bplgr0_GCU   OF_BOT_PLUG   fill bot_plg    -w1                     % filling the channel
cell u2bplgr1_GCU   OF_BOT_PLUG   fmst91_673       w1 -w2                  % filling the wrapper
cell u2bplgr2_GCU   OF_BOT_PLUG   cool_min         w2                       % filling the external region


% Outer fuel assembly axial scan
cell c2tref     u2ref tref        z_tplg_fr -z_tref_fr  % upper reflector universe definition
cell c2a1       u2 fill u2ref     z_tplg_fr -z_tref_fr  % upper reflector
cell c2a2       u2 fill u2tplg    z_sprn_fr -z_tplg_fr  % upper plug
cell c2a3       u2 fill u2spr     z_ins_u   -z_sprn_fr  % spring
cell c2a4       u2 fill u2tins    z_fuel_u  -z_ins_u    % insulator
cell c2a5       u2 fill u2fuel    z_fuel_b  -z_fuel_u   % fuel universe definition
cell c2a6       u2 fill u2bins    z_ins_b   -z_fuel_b   % insulator
cell c2a7       u2 fill u2pln     z_plen    -z_ins_b    % plenum
cell c2a8       u2 fill u2bplg    z_bplg_fr -z_plen     % bottom plug
cell c2ref_bo   u2ref bref        z_bref_fr -z_bplg_fr  % bottom reflector universe definition
cell c2a9       u2 fill u2ref     z_bref_fr -z_bplg_fr  % bottom reflector

% Outer fuel assembly axial scan
cell c2tref_GCU     OF_TOP_REF tref       z_tplg_fr -z_tref_fr  % upper reflector universe definition
cell c2a1_GCU       OF fill OF_TOP_REF    z_tplg_fr -z_tref_fr  % upper reflector
cell c2a2_GCU       OF fill OF_TOP_PLUG   z_sprn_fr -z_tplg_fr  % upper plug
cell c2a3_GCU       OF fill OF_SPRING     z_ins_u   -z_sprn_fr  % spring
cell c2a4_GCU       OF fill OF_TOP_INS    z_fuel_u  -z_ins_u    % insulator
cell c2a5_GCU       OF fill OUT_FUEL      z_fuel_b  -z_fuel_u   % fuel universe definition
cell c2a6_GCU       OF fill OF_BOT_INS    z_ins_b   -z_fuel_b   % insulator
cell c2a7_GCU       OF fill OF_PLEN       z_plen    -z_ins_b    % plenum
cell c2a8_GCU       OF fill OF_BOT_PLUG   z_bplg_fr -z_plen     % bottom plug
cell c2ref_bo_GCU   OF_BOT_REF bref       z_bref_fr -z_bplg_fr  % bottom reflector universe definition
cell c2a9_GCU       OF fill OF_BOT_REF    z_bref_fr -z_bplg_fr  % bottom reflector

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% SAFETY ROD %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Safety rod
cell c3r1  SR_ACT fill safe1               -w3          % Filling the channel
cell c3r2  SR_ACT fmst91_753                w3 -w4       % Filling the cladding
cell c3r4  SR_ACT cool_max                  w4            % Filling the external region

% Spring
cell u3sprr0 SR_SPRING fill spring         -w3          % Filling the channel
cell u3sprr1 SR_SPRING fmst91_753           w3 -w4       % Filling the cladding
cell u3sprr2 SR_SPRING cool_max             w4            % Filling the external region

% Top insulator
cell u3tinsr0 SR_TOP_INS fill top_ins      -w3          % Filling the channel
cell u3tinsr1 SR_TOP_INS fmst91_753         w3 -w4       % Filling the cladding
cell u3tinsr2 SR_TOP_INS cool_max           w4            % Filling the external region

% Bottom plug
cell u3bplgr0 SR_BOT_PLUG fill bot_plg     -w3          % Filling the channel
cell u3bplgr1 SR_BOT_PLUG fmst91_673        w3 -w4       % Filling the cladding
cell u3bplgr2 SR_BOT_PLUG cool_min          w4            % Filling the external region

% Safety rod axial scan
cell c3tref    SR_TOP_REF tref         z_sprn_sr  -z_tref_sr  % upper reflector  universe definition
cell c3a1      SR fill SR_TOP_REF      z_sprn_sr  -z_tref_sr  % upper reflector
cell c3a2      SR fill SR_SPRING       z_tins_sr  -z_sprn_sr  % spring
cell c3a3      SR fill SR_TOP_INS      z_srod_sr  -z_tins_sr  % insulator
cell c3srod    SR fill SR_ACT          z_bplg_sr  -z_srod_sr  % safety rod universe definition
cell c3a4      SR fill SR_BOT_PLUG     z_bref_sru -z_bplg_sr  % bottom plug
cell c3ref_bo  SR_BOT_REF bref         z_bref_srb -z_bref_sru % bottom reflector universe definition
cell c3a5      SR fill SR_BOT_REF      z_bref_srb -z_bref_sru % bottom reflector

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% CONTROL ROD %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Control rod
cell c4r1  CR_ACT fill cont1                -w5          % Filling the channel
cell c4r2  CR_ACT fmst91_673                 w5 -w6       % Filling the cladding
cell c4r3  CR_ACT cool_min                   w6            % Filling the external region

% Dummy rod
cell c4r4    CR_DUMM fill continact         -w5          % Filling the channel
cell c4r5    CR_DUMM fmst91_713              w5 -w6       % Filling the cladding
cell c4r6    CR_DUMM cool_avg                w6            % Filling the external region

% Spring
cell u4sprr0 CR_SPRING fill spring          -w3          % Filling the channel
cell u4sprr1 CR_SPRING fmst91_753            w3 -w4       % Filling the cladding
cell u4sprr2 CR_SPRING cool_max              w4            % Filling the external region

% Bottom insulator
cell u4tinsr0 CR_BOT_INS fill bot_ins       -w3          % Filling the channel
cell u4tinsr1 CR_BOT_INS fmst91_673          w3 -w4       % Filling the cladding
cell u4tinsr2 CR_BOT_INS cool_min            w4            % Filling the external region

% Bottom plug
cell u4bplgr0 CR_BOT_PLUG fill spring       -w3          % Filling the channel
cell u4bplgr1 CR_BOT_PLUG fmst91_673         w3 -w4       % Filling the cladding
cell u4bplgr2 CR_BOT_PLUG cool_min           w4            % Filling the external region


```

```
% Control rod axial scan
cell c4ref_u  CR_TOP_REF tref         z_sprn_cr   -z_tref_cr   % upper reflector universe definition
cell c4a1     CR fill CR_TOP_REF      z_sprn_cr   -z_tref_cr   % upper reflector
cell c4a2     CR fill CR_SPRING       z_frod_u    -z_sprn_cr   % spring
cell c4frod   CR fill CR_DUMM         z_frod_b    -z_frod_u    % follower
cell c4crod   CR fill CR_ACT          z_crod_cr   -z_frod_b    % absorber
cell c4a3     CR fill CR_BOT_INS      z_bins_cr   -z_crod_cr   % bottom insulator
cell c4a4     CR fill CR_BOT_PLUG     z_bplg_cr   -z_bins_cr   % bottom plug
cell c4ref_b  CR_BOT_REF bref         z_bref_cr   -z_bplg_cr   % bottom reflector universe definition
cell c4a5     CR fill CR_BOT_REF      z_bref_cr   -z_bplg_cr   % bottom reflector

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% DUMMY ELEMENT %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Dummy element
cell c5r1 DR_DUMM fill dr_dumm              -w1                     % Filling the channel
cell c5r2 DR_DUMM fmst91_713                 w1 -w2                  % filling the wrapper
cell c5r3 DR_DUMM cool_avg                   w2                       % Filling the external region

% Top plug
cell u5tplgr0 DR_TOP_PLUG fill top_plg      -w1                     % Filling the channel
cell u5tplgr1 DR_TOP_PLUG fmst91_673         w1 -w2                  % filling the wrapper
cell u5tplgr2 DR_TOP_PLUG cool_max           w2                       % Filling the external region

% Spring
cell u5sprr0 DR_SPRING fill spring          -w1                     % Filling the channel
cell u5sprr1 DR_SPRING fmst91_753            w1 -w2                  % filling the wrapper
cell u5sprr2 DR_SPRING cool_max              w2                       % Filling the external region

% Bottom plug
cell u5bplgr0 DR_BOT_PLUG fill bot_plg      -w1                     % Filling the channel
cell u5bplgr1 DR_BOT_PLUG fmst91_673         w1 -w2                  % filling the wrapper
cell u5bplgr2 DR_BOT_PLUG cool_min           w2                       % Filling the external region

% Dummy rod axial scan
cell c5tref    DR_TOP_REF tref           z_tplg_dr    -z_tref_dr    % upper reflector universe definition
cell c5a1      DR fill DR_TOP_REF        z_tplg_dr    -z_tref_dr    % upper reflector
cell c5a2      DR fill DR_TOP_PLUG       z_sprn_dr    -z_tplg_dr    % top plug
cell c5a3      DR fill DR_SPRING         z_dumm_u     -z_sprn_dr    % spring
cell c5dum     DR fill DR_DUMM           z_dumm_b     -z_dumm_u     % dummy element
cell c5a4      DR fill DR_BOT_PLUG       z_bplg_dr    -z_dumm_b     % bottom plug
cell c5ref_bo  DR_BOT_REF bref           z_bref_dr    -z_bplg_dr    % bottom reflector universe definition
cell c5a5      DR fill DR_BOT_REF        z_bref_dr    -z_bplg_dr    % bottom reflector

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% BARREL ELEMENT %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Barrel element
cell c6r1 B_ass barrel  -w1          % Filling the channel
cell c6r2 B_ass barrel   w1 -w2       % Filling the wrapper
cell c6r3 B_ass barrel   w2            % Filling the external region

cell c6 BA fill B_ass z_core_b -z_core_u

%% --------------------------------------------- Core lattice loading ---------------------------------------------
lat core 3 0.0 0.0 32 32 17.1      % Core with CR and SR extracted
vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
 vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
  vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
   vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv ll ll ll ll ll ll ll ll ll ll ll ll ll vv vv vv vv
    vv vv vv vv vv vv vv vv vv vv vv vv vv vv ll ll ll ll BA BA BA BA BA BA ll ll ll ll vv vv vv vv
     vv vv vv vv vv vv vv vv vv vv vv vv vv ll ll ll BA BA DR DR DR DR DR BA BA ll ll ll vv vv vv vv
      vv vv vv vv vv vv vv vv vv vv vv vv ll ll BA BA DR DR DR DR DR DR DR DR BA BA ll ll vv vv vv vv
       vv vv vv vv vv vv vv vv vv vv vv ll BA BA DR DR DR DR u2 u2 u2 DR DR DR DR BA BA ll vv vv vv vv
        vv vv vv vv vv vv vv vv vv vv ll BA DR DR DR u2 u2 u2 u2 u2 u2 u2 u2 DR DR DR BA ll vv vv vv vv
         vv vv vv vv vv vv vv vv vv ll BA DR DR DR u2 OF u2 CR u2 CR u2 OF u2 DR DR DR BA ll vv vv vv vv
          vv vv vv vv vv vv vv vv ll BA DR DR u2 u2 u2 u2 u2 u2 u2 u2 u2 u2 u2 u2 DR DR BA ll vv vv vv vv
           vv vv vv vv vv vv vv ll BA DR DR u2 u2 CR u2 u1 u1 u1 u1 u1 u2 CR u2 u2 DR DR BA ll vv vv vv vv
            vv vv vv vv vv vv ll BA DR DR u2 u2 u2 u2 u1 u1 u1 u1 u1 u1 u2 u2 u2 u2 DR DR BA ll vv vv vv vv
             vv vv vv vv vv ll ll BA DR DR u2 CR u2 u1 u1 u1 u1 SR u1 u1 u2 CR u2 DR DR BA ll ll vv vv vv vv
              vv vv vv vv ll ll BA DR DR u2 u2 u2 u1 u1 SR u1 u1 u1 u1 u1 u2 u2 u2 DR DR BA ll ll vv vv vv vv
               vv vv vv ll ll ll BA DR u2 OF u2 u1 u1 u1 u1 IF u1 u1 u1 u1 u2 OF u2 DR BA ll ll ll vv vv vv vv
                vv vv vv ll ll BA DR DR u2 u2 u2 u1 u1 u1 u1 u1 SR u1 u1 u2 u2 u2 DR DR BA ll ll vv vv vv vv vv
                 vv vv vv ll ll BA DR DR u2 CR u2 u1 u1 SR u1 u1 u1 u1 u2 CR u2 DR DR BA ll ll vv vv vv vv vv vv
                  vv vv vv ll BA DR DR u2 u2 u2 u2 u1 u1 u1 u1 u1 u1 u2 u2 u2 u2 DR DR BA ll vv vv vv vv vv vv vv
                   vv vv vv ll BA DR DR u2 u2 CR u2 u1 u1 u1 u1 u1 u2 CR u2 u2 DR DR BA ll vv vv vv vv vv vv vv vv
                    vv vv vv ll BA DR DR u2 u2 u2 u2 u2 u2 u2 u2 u2 u2 u2 u2 DR DR BA ll vv vv vv vv vv vv vv vv vv
                     vv vv vv ll BA DR DR DR u2 OF u2 CR u2 CR u2 OF u2 DR DR DR BA ll vv vv vv vv vv vv vv vv vv vv
                      vv vv vv ll BA DR DR DR u2 u2 u2 u2 u2 u2 u2 u2 DR DR DR BA ll vv vv vv vv vv vv vv vv vv vv vv
                       vv vv vv ll BA BA DR DR DR DR u2 u2 u2 DR DR DR DR BA BA ll vv vv vv vv vv vv vv vv vv vv vv vv
                        vv vv vv ll ll BA BA DR DR DR DR DR DR DR DR BA BA ll ll vv vv vv vv vv vv vv vv vv vv vv vv vv
                         vv vv vv ll ll ll BA BA DR DR DR DR DR BA BA ll ll ll vv vv vv vv vv vv vv vv vv vv vv vv vv vv
                          vv vv vv ll ll ll ll BA BA BA BA BA BA ll ll ll ll vv vv vv vv vv vv vv vv vv vv vv vv vv vv
vv
                           vv vv vv ll ll ll ll ll ll ll ll ll ll ll ll ll vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
vv
                            vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
vv
                             vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
vv vv
                              vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
vv vv
                                                vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
vv vv vv vv vv vv vv vv

cell c100 0 fill core -s1 z_core_b -z_core_u  % Filling the cylinder with the core
cell c101 0 outside s1 z_core_b -z_core_u     % Placing the vacuum outside the reactor
cell c104 0 outside z_core_u                  % Placing the vacuum above the reactor
```

```
657. cell c105 0 outside -z_core_b                % Placing the vacuum below the reactor
```

It should be remarked that the multi-group constants computed with the 3D FC model presented throughout the report have been obtained with the geometry model described in the previous file “ALFRED_ECCO.ge” but with the SRs rotated with an angle of 60 degrees. It has been assumed that the SR orientation has a negligible impact on the values of the multi-group constants. All the other calculations regarding the core characterisation have been performed using the 3D model defined in “ALFRED_ECCO.ge” without any modification.

E.3 Input files for the assembly cell model

In the following, the input files needed to reproduce the assembly cell model are reported.

E.3.1 Inner Fuel, 3D axially finite cell

The following file refers to the definition of a 3D assembly cell which is radially infinite (*i.e.*, finite with reflective boundary conditions) and axially finite. This file can be run independently.

```
1.   %% -- EXTERNAL FILE INCLUSION
2.   include "/home/abrate/ricerca/enea_sarotto/alfred/alfred_ecco/cell_calculation/eranos_jeff31"  % materials
3.
4.   %% -- LIBRARY FOR NUCLEAR DATA
5.   set acelib "/opt/serpent/xsdata/jeff31/sss_jeff31.xsdata"
6.
7.   % ---------------------------------------- GEOMETRIC SURFACES DEFINITIONS ----------------------------------------  %-
     ----------------------------------------------------------------------------------------------------------------------
8.   % ------------------------ Radial coordinate ------------------------------------------------------------------------
9.
10.  % Core
11.  surf s1 sqc 0.0 0.0 25        % wrapping inner perimeter
12.
13.  % Hexagonal assembly
14.  surf w1 hexyc 0.0 0.0 7.9         % wrapping inner perimeter
15.  surf w2 hexyc 0.0 0.0 8.3         % wrapping outer perimeter
16.  surf wi hexyc 0.0 0.0 7.9         % wrapping inner perimeter
17.  surf wo hexyc 0.0 0.0 8.3         % wrapping outer perimeter
18.
19.  % Fuel rod (FR)
20.  surf z_tref     pz  130.0           % Upper reflector
21.  surf z_fuel_u   pz   30.0           % Fuel active zone upper limit
22.  surf z_fuel_b   pz  -30.0           % Fuel active zone lower limit
23.  surf z_bref     pz  -130.0          % Bottom reflector
24.
25.  %-----------------------------------------------------------------------------------------------------------------------
26.  % --------------------- PIN DEFINITION ---------------------------------------------------------------------------
27.
28.  pin pi          % Inner fuel pin
29.  fueli       0.465
30.  Ti1515_743  0.525
31.  cool_avg
32.
33.  pin po          % Outer fuel pin
34.  fuelo       0.465
35.  Ti1515_743  0.525
36.  cool_avg
37.
38.  pin ll          % Pure lead (empty lattice positions)
39.  cool_min
40.
41.  pin vv          % Pure lead (empty lattice positions)
42.  void
43.  %-----------------------------------------------------------------------------------------------------------------------
44.  % ------------------------------- ASSEMBLY DEFINITION ---------------------------------------------------------------
45.
46.  % -- Inner fuel assembly
47.  lat ass1 2 0.0 0.0 15 15 1.386
48.  ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
49.   ll ll ll ll ll ll ll ll pi pi pi pi pi pi pi pi ll
50.    ll ll ll ll ll ll pi pi pi pi pi pi pi pi pi ll
51.     ll ll ll ll ll pi pi pi pi pi pi pi pi pi pi ll
52.      ll ll ll ll pi pi pi pi pi pi pi pi pi pi pi ll
53.       ll ll ll pi pi pi pi pi pi pi pi pi pi pi pi ll
54.        ll ll pi pi pi pi pi pi pi pi pi pi pi pi pi ll
55.         ll pi pi pi pi pi pi pi pi pi pi pi pi pi pi ll
56.          ll pi pi pi pi pi pi pi pi pi pi pi pi pi ll ll
57.           ll pi pi pi pi pi pi pi pi pi pi pi pi ll ll ll
58.            ll pi pi pi pi pi pi pi pi pi pi pi pi ll ll ll ll
59.             ll pi pi pi pi pi pi pi pi pi pi pi ll ll ll ll ll
60.              ll pi pi pi pi pi pi pi pi pi ll ll ll ll ll ll
61.               ll pi pi pi pi pi pi pi pi ll ll ll ll ll ll ll
```

```
              ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll

% -- Outer fuel assembly
lat ass2 2 0.0 0.0 15 15 1.386
ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
 ll ll ll ll ll ll ll po po po po po po po ll
  ll ll ll ll ll ll po po po po po po po po ll
   ll ll ll ll ll po po po po po po po po po ll
    ll ll ll ll po po po po po po po po po po ll
     ll ll ll po po po po po po po po po po po ll
      ll ll po po po po po po po po po po po po ll
       ll po po po po po po po po po po po po po ll
        ll po po po po po po po po po po po po ll ll
         ll po po po po po po po po po po po ll ll ll
          ll po po po po po po po po po po ll ll ll ll
           ll po po po po po po po po po ll ll ll ll ll
            ll po po po po po po po po ll ll ll ll ll ll
             ll po po po po po po po ll ll ll ll ll ll ll
              ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll

%-------------------------------------------------------------------------------------------------------------------

% ------------------------------------------------------------------------------------------------------------------
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% INNER FUEL %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Inner fuel
cell c1r0           INN_FUEL           fill ass1         -w1                     % filling the channel
cell c1r1           INN_FUEL           fmst91_713         w1  -w2                 % filling the wrapper
cell c1r2           INN_FUEL           cool_avg           w2                       % filling the external region
% Inner fuel assembly axial scan (universe definition to compute group-wise constants)
cell c1tref_GCU     IF_TOP_REF tref          z_fuel_u  -z_tref    % upper reflector
cell c1a1_GCU       IF fill IF_TOP_REF       z_fuel_u  -z_tref    % upper reflector
cell c1a5_GCU       IF fill INN_FUEL         z_fuel_b  -z_fuel_u  % fuel
cell c1ref_bo_GCU   IF_BOT_REF bref          z_bref    -z_fuel_b  % bottom reflector
cell c1a9_GCU       IF fill IF_BOT_REF       z_bref    -z_fuel_b  % bottom reflector

%% --------------------------------------------- Core lattice loading ---------------------------------------------

lat core 3 0.0 0.0 5 5 17.1      % Core with CR and SR extracted
IF IF IF IF IF
 IF IF IF IF IF
  IF IF IF IF IF
   IF IF IF IF IF
    IF IF IF IF IF

%% ---------------------------------------------------------------------------------------------------------------------
-----------

cell c100 0 fill core -s1 z_bref -z_tref % Filling the cylinder with the core
cell c101 0 outside s1    z_bref -z_tref % Placing the vacuum outside the reactor
cell c104 0 outside       z_tref                  % Placing the vacuum above the reactor
cell c105 0 outside      -z_bref                  % Placing the vacuum below the reactor

%% -- PLOTS
plot 3 2000 2000  0
plot 3 2000 2000  48
plot 3 2000 2000  43
plot 3 2000 2000  31
plot 1 1000 1000  29.18505
plot 2 1000 1000

%% -- SIMULATION SETUP
set bc 2
set fum nj19 1 0 %[ BTCH DUMMY LIM ] B1 leakage-corrected mode
set pop 1000000 40 300

%set csw IF_src_3D
%set nps 10000000 1000
%src IF_1M_1000a_250i_3D sf src_IF_1M_1000a_250i_3D 1


set ures 1               % aggiunta il 3-09-18 per risolvere le risonanze dello spettro veloce
set his yes              % Check on fission source convergence

%% -- GROUP CONSTANT GENERATION
set micro nj19           % ECCO-33 groups
set nfg nj19


% --- Detector for tallying the flux energy spectrum

% Detector to tally flux spectrum
ene ECCO_1968 4 nj20
ene ECCO_33   4 nj19

det flx_spectrum_1968 de ECCO_1968 df IF_src_1968_1M_500a -1
det flx_spectrum_33   de ECCO_33   df IF_src_33_1M_500a   -1

set gcu INN_FUEL
        IF_TOP_REF
        IF_BOT_REF
```

E.3.2 Inner Fuel, 3D infinite cell

The following file refers to the definition of a 3D assembly cell which is infinite both radially (*i.e.*, finite with reflective boundary conditions) and axially. This file can be run independently.

```
%% -- EXTERNAL FILE INCLUSION
include "/home/abrate/ricerca/enea_sarotto/alfred/alfred_ecco/cell_calculation/eranos_jeff31.ml"  % materials

%% -- LIBRARY FOR NUCLEAR DATA
set acelib "/opt/serpent/xsdata/jeff31/sss_jeff31.xsdata"

% ---------------------------------------- GEOMETRIC SURFACES DEFINITIONS ----------------------------------------  %-
-----------------------------------------------------------------------------------------------------------------------
% ------------------------ Radial coordinate ------------------------------------------------------------------------

% Core
surf s1 sqc 0.0 0.0 25        % wrapping inner perimeter

% Hexagonal assembly
surf w1 hexyc 0.0 0.0 7.9         % wrapping inner perimeter
surf w2 hexyc 0.0 0.0 8.3         % wrapping outer perimeter
surf wi hexyc 0.0 0.0 7.9         % wrapping inner perimeter
surf wo hexyc 0.0 0.0 8.3         % wrapping outer perimeter

% Safety rod
surf cyl1 cyl 0.0 0.0 7.35        % cladding inner perimeter
surf cyl2 cyl 0.0 0.0 8.35        % cladding outer perimeter

% Control Rod
surf cyl3 cyl 0.0 0.0 8.05        % cladding inner perimeter
surf cyl4 cyl 0.0 0.0 8.35        % cladding outer perimeter

%-----------------------------------------------------------------------------------------------------------------------
% --------------------- PIN DEFINITION ---------------------------------------------------------------------------

pin pi          % Inner fuel pin
fueli       0.465
Ti1515_743  0.525
cool_avg

pin po          % Outer fuel pin
fuelo       0.465
Ti1515_743  0.525
cool_avg

pin pl          % Plenum pin
void        0.4
pln         0.465
Ti1515_713  0.525
cool_min

pin tg       % Top plug "pin"
tplg       0.465
Ti1515_753 0.525
cool_max

pin bg       % Bottom plug "pin"
bplg       0.465
Ti1515_713 0.525
cool_min

pin ti       % Top insulator "pin"
tins       0.465
Ti1515_713 0.525
cool_max

pin bi       % Bottom insulator "pin"
bins       0.465
Ti1515_713 0.525
cool_min

pin dp       % Dummy "pin"
foll       0.465
Ti1515_713 0.525
cool_avg

pin sp       % Spring "pin"
spr        0.465
Ti1515_713 0.525
cool_max

pin s1       % Safety pin
safe       2.58
Ti1515_753 2.64
cool_max

pin s2       % Safety pin
safe       1.83
Ti1515_753 1.89
cool_max

pin c1       % Control pin
cont       1.49
```

```
88.  Ti1515_673 1.55
89.  cool_min
90.
91.  pin ce       % Control pin plenum
92.  foll       1.49
93.  fmst91_713 1.55
94.  cool_avg
95.
96.  pin fp       % Control pin follower
97.  foll       1.49
98.  fmst91_713 1.55
99.  cool_avg
100.
101. pin ll          % Pure lead (empty lattice positions)
102. cool_min
103.
104. pin vv          % Pure lead (empty lattice positions)
105. void
106. %-----------------------------------------------------------------------------------------------------------------
107. % ------------------------------- ASSEMBLY DEFINITION ---------------------------------------------------------
108. % -- Top insulator assembly
109. lat top_ins 2 0.0 0.0 15 15 1.386
110. ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
111.  ll ll ll ll ll ll ll ti ti ti ti ti ti ti ll
112.   ll ll ll ll ll ll ti ti ti ti ti ti ti ti ll
113.    ll ll ll ll ll ti ti ti ti ti ti ti ti ti ll
114.     ll ll ll ll ti ti ti ti ti ti ti ti ti ti ll
115.      ll ll ll ti ti ti ti ti ti ti ti ti ti ti ll
116.       ll ll ti ti ti ti ti ti ti ti ti ti ti ti ll
117.        ll ti ti ti ti ti ti ti ti ti ti ti ti ti ll
118.         ll ti ti ti ti ti ti ti ti ti ti ti ti ll ll
119.          ll ti ti ti ti ti ti ti ti ti ti ti ti ll ll ll
120.           ll ti ti ti ti ti ti ti ti ti ti ti ll ll ll ll
121.            ll ti ti ti ti ti ti ti ti ti ti ll ll ll ll ll
122.             ll ti ti ti ti ti ti ti ti ti ll ll ll ll ll ll
123.              ll ti ti ti ti ti ti ti ti ll ll ll ll ll ll ll
124.               ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
125.
126. % -- Spring assembly
127. lat spring 2 0.0 0.0 15 15 1.386
128. ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
129.  ll ll ll ll ll ll ll sp sp sp sp sp sp sp ll
130.   ll ll ll ll ll ll sp sp sp sp sp sp sp sp ll
131.    ll ll ll ll ll sp sp sp sp sp sp sp sp sp ll
132.     ll ll ll ll sp sp sp sp sp sp sp sp sp sp ll
133.      ll ll ll sp sp sp sp sp sp sp sp sp sp sp ll
134.       ll ll sp sp sp sp sp sp sp sp sp sp sp sp ll
135.        ll sp sp sp sp sp sp sp sp sp sp sp sp sp ll
136.         ll sp sp sp sp sp sp sp sp sp sp sp sp ll ll
137.          ll sp sp sp sp sp sp sp sp sp sp sp ll ll ll
138.           ll sp sp sp sp sp sp sp sp sp sp ll ll ll ll
139.            ll sp sp sp sp sp sp sp sp sp ll ll ll ll ll
140.             ll sp sp sp sp sp sp sp sp ll ll ll ll ll ll
141.              ll sp sp sp sp sp sp sp ll ll ll ll ll ll ll
142.               ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
143.
144. % -- Inner fuel assembly
145. lat ass1 2 0.0 0.0 15 15 1.386
146. ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
147.  ll ll ll ll ll ll ll pi pi pi pi pi pi pi ll
148.   ll ll ll ll ll ll pi pi pi pi pi pi pi pi ll
149.    ll ll ll ll ll pi pi pi pi pi pi pi pi pi ll
150.     ll ll ll ll pi pi pi pi pi pi pi pi pi pi ll
151.      ll ll ll pi pi pi pi pi pi pi pi pi pi pi ll
152.       ll ll pi pi pi pi pi pi pi pi pi pi pi pi ll
153.        ll pi pi pi pi pi pi pi pi pi pi pi pi pi ll
154.         ll pi pi pi pi pi pi pi pi pi pi pi pi ll ll
155.          ll pi pi pi pi pi pi pi pi pi pi pi ll ll ll
156.           ll pi pi pi pi pi pi pi pi pi pi ll ll ll ll
157.            ll pi pi pi pi pi pi pi pi pi ll ll ll ll ll
158.             ll pi pi pi pi pi pi pi pi pi ll ll ll ll ll ll
159.              ll pi pi pi pi pi pi pi pi ll ll ll ll ll ll ll
160.               ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
161.
162. % -- Outer fuel assembly
163. lat ass2 2 0.0 0.0 15 15 1.386
164. ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
165.  ll ll ll ll ll ll ll po po po po po po po ll
166.   ll ll ll ll ll ll po po po po po po po po ll
167.    ll ll ll ll ll po po po po po po po po po ll
168.     ll ll ll ll po po po po po po po po po po ll
169.      ll ll ll po po po po po po po po po po po ll
170.       ll ll po po po po po po po po po po po po ll
171.        ll po po po po po po po po po po po po po ll
172.         ll po po po po po po po po po po po po ll ll
173.          ll po po po po po po po po po po po po ll ll ll
174.           ll po po po po po po po po po po po ll ll ll ll
175.            ll po po po po po po po po po po ll ll ll ll ll
176.             ll po po po po po po po po po ll ll ll ll ll ll
177.              ll po po po po po po po po ll ll ll ll ll ll ll
178.               ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
179.
180. % -- Dummy assembly
181. lat dr_dumm 2 0.0 0.0 15 15 1.386
182. ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
183.  ll ll ll ll ll ll ll dp dp dp dp dp dp dp ll
```

```
184.   ll ll ll ll ll ll dp dp dp dp dp dp dp dp ll
185.    ll ll ll ll ll dp dp dp dp dp dp dp dp dp ll
186.     ll ll ll ll dp dp dp dp dp dp dp dp dp dp ll
187.      ll ll ll dp dp dp dp dp dp dp dp dp dp dp ll
188.       ll ll dp dp dp dp dp dp dp dp dp dp dp dp ll
189.        ll dp dp dp dp dp dp dp dp dp dp dp dp dp ll
190.         ll dp dp dp dp dp dp dp dp dp dp dp dp ll ll
191.          ll dp dp dp dp dp dp dp dp dp dp dp ll ll ll
192.           ll dp dp dp dp dp dp dp dp dp dp ll ll ll ll
193.            ll dp dp dp dp dp dp dp dp dp ll ll ll ll ll
194.             ll dp dp dp dp dp dp dp dp ll ll ll ll ll ll
195.              ll dp dp dp dp dp dp dp ll ll ll ll ll ll ll
196.               ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
197.
198. % -- Inactive fuel assembly
199. lat bot_ins 2 0.0 0.0 15 15 1.386
200. ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
201.  ll ll ll ll ll ll ll ll bi bi bi bi bi bi bi bi ll
202.   ll ll ll ll ll ll bi bi bi bi bi bi bi bi bi ll
203.    ll ll ll ll ll bi bi bi bi bi bi bi bi bi bi ll
204.     ll ll ll ll bi bi bi bi bi bi bi bi bi bi bi ll
205.      ll ll ll bi bi bi bi bi bi bi bi bi bi bi bi ll
206.       ll ll bi bi bi bi bi bi bi bi bi bi bi bi bi ll
207.        ll bi bi bi bi bi bi bi bi bi bi bi bi bi bi ll
208.         ll bi bi bi bi bi bi bi bi bi bi bi bi bi ll ll
209.          ll bi bi bi bi bi bi bi bi bi bi bi bi ll ll ll
210.           ll bi bi bi bi bi bi bi bi bi bi bi ll ll ll ll
211.            ll bi bi bi bi bi bi bi bi bi bi ll ll ll ll ll
212.             ll bi bi bi bi bi bi bi bi bi ll ll ll ll ll ll
213.              ll bi bi bi bi bi bi bi bi ll ll ll ll ll ll ll
214.               ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
215.
216. % -- Plenum assembly
217. lat plen 2 0.0 0.0 15 15 1.386
218. ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
219.  ll ll ll ll ll ll ll pl pl pl pl pl pl pl pl ll
220.   ll ll ll ll ll ll pl pl pl pl pl pl pl pl ll
221.    ll ll ll ll ll pl pl pl pl pl pl pl pl pl ll
222.     ll ll ll ll pl pl pl pl pl pl pl pl pl pl ll
223.      ll ll ll pl pl pl pl pl pl pl pl pl pl pl ll
224.       ll ll pl pl pl pl pl pl pl pl pl pl pl pl ll
225.        ll pl pl pl pl pl pl pl pl pl pl pl pl pl ll
226.         ll pl pl pl pl pl pl pl pl pl pl pl pl ll ll
227.          ll pl pl pl pl pl pl pl pl pl pl pl ll ll ll
228.           ll pl pl pl pl pl pl pl pl pl pl ll ll ll ll
229.            ll pl pl pl pl pl pl pl pl pl pl ll ll ll ll
230.             ll pl pl pl pl pl pl pl pl ll ll ll ll ll ll
231.              ll pl pl pl pl pl pl pl ll ll ll ll ll ll ll
232.               ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
233.
234. % -- Outer fuel assembly
235. lat top_plg 2 0.0 0.0 15 15 1.386
236. ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
237.  ll ll ll ll ll ll ll tg tg tg tg tg tg tg ll
238.   ll ll ll ll ll ll tg tg tg tg tg tg tg tg ll
239.    ll ll ll ll ll tg tg tg tg tg tg tg tg tg ll
240.     ll ll ll ll tg tg tg tg tg tg tg tg tg tg ll
241.      ll ll ll tg tg tg tg tg tg tg tg tg tg tg ll
242.       ll ll tg tg tg tg tg tg tg tg tg tg tg tg ll
243.        ll tg tg tg tg tg tg tg tg tg tg tg tg tg ll
244.         ll tg tg tg tg tg tg tg tg tg tg tg tg ll ll
245.          ll tg tg tg tg tg tg tg tg tg tg tg tg ll ll ll
246.           ll tg tg tg tg tg tg tg tg tg tg tg ll ll ll ll
247.            ll tg tg tg tg tg tg tg tg tg tg ll ll ll ll ll
248.             ll tg tg tg tg tg tg tg tg tg ll ll ll ll ll ll
249.              ll tg tg tg tg tg tg tg tg ll ll ll ll ll ll ll
250.               ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
251.
252. % -- Outer fuel assembly
253. lat bot_plg 2 0.0 0.0 15 15 1.386
254. ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
255.  ll ll ll ll ll ll ll ll bg bg bg bg bg bg bg ll
256.   ll ll ll ll ll ll bg bg bg bg bg bg bg bg ll
257.    ll ll ll ll ll bg bg bg bg bg bg bg bg bg ll
258.     ll ll ll ll bg bg bg bg bg bg bg bg bg bg ll
259.      ll ll ll bg bg bg bg bg bg bg bg bg bg bg ll
260.       ll ll bg bg bg bg bg bg bg bg bg bg bg bg ll
261.        ll bg bg bg bg bg bg bg bg bg bg bg bg bg ll
262.         ll bg bg bg bg bg bg bg bg bg bg bg bg ll ll
263.          ll bg bg bg bg bg bg bg bg bg bg bg ll ll ll
264.           ll bg bg bg bg bg bg bg bg bg bg ll ll ll ll
265.            ll bg bg bg bg bg bg bg bg bg ll ll ll ll ll
266.             ll bg bg bg bg bg bg bg bg bg ll ll ll ll ll ll
267.              ll bg bg bg bg bg bg bg ll ll ll ll ll ll ll
268.               ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
269.
270. % -- Void assembly
271. lat va 2 0.0 0.0 15 15 1.386
272. vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
273.  vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
274.   vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
275.    vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
276.     vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
277.      vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
278.       vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
279.        vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
```

```
        vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
         vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
          vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
           vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
            vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
             vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv
              vv vv vv vv vv vv vv vv vv vv vv vv vv vv vv


% -- Lead assembly
lat la 2 0.0 0.0 15 15 1.386
ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
 ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
  ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
   ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
    ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
     ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
      ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
       ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
        ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
         ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
          ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
           ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
            ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
             ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll
              ll ll ll ll ll ll ll ll ll ll ll ll ll ll ll

% -- Safety rod assembly (circular array)
lat safe2 4 0.0 0.0 2     % Active section
3 2.0 0 s1 s1 s1
9 5.5 0 s1 s1 s1 s1 s1 s1 s1 s1 s1

% -- Safety rod assembly (circular array)
lat safe1 4 0.0 0.0 2     % Active section
1 0 0 s1
6 5.25 30 s2 s2 s2 s2 s2 s2

% -- Control rod assembly (circular array)
lat cont1 4 0.0 0.0 3     % Active section
1 0.0 0 c1
6 3.3 30 c1 c1 c1 c1 c1 c1
12 6.37511 15 c1 c1 c1 c1 c1 c1 c1 c1 c1 c1 c1 c1

lat continact 4 0.0 0.0 3 % Inactive section
1 0.0 0 fp
6 3.3 30 fp fp fp fp fp fp
12 6.37511 15 fp fp fp fp fp fp fp fp fp fp fp fp
%-------------------------------------------------------------------------------------------------------------------

% ------------------------------------------------------------------------------------------------------------------
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% INNER FUEL %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Inner fuel
cell c1r0           f1           fill ass1         -w1                     % filling the channel
cell c1r1           f1           fmst91_713         w1  -w2                 % filling the wrapper
cell c1r2           f1           cool_avg           w2                       % filling the external region

cell c1r0_GCU       IF           fill ass1         -wi                     % filling the channel
cell c1r1_GCU       IF           fmst91_713         wi -wo                  % filling the wrapper
cell c1r2_GCU       IF           cool_avg           wo                       % filling the external region

% Top plug
cell u1tplgr0       u1tplg       fill top_plg      -w1                     % filling the channel
cell u1tplgr1       u1tplg       fmst91_753         w1 -w2                  % filling the wrapper
cell u1tplgr2       u1tplg       cool_max           w2                       % filling the external region

cell u1tplgr0_GCU   IF_TOP_PLUG  fill top_plg      -w1                     % filling the channel
cell u1tplgr1_GCU   IF_TOP_PLUG  fmst91_753         w1 -w2                  % filling the wrapper
cell u1tplgr2_GCU   IF_TOP_PLUG  cool_max           w2                       % filling the external region
% Spring
cell u1sprnr0       u1spr        fill spring       -w1                     % filling the channel
cell u1sprnr1       u1spr        fmst91_753         w1 -w2                  % filling the wrapper
cell u1sprnr2       u1spr        cool_max           w2                       % filling the external region

cell u1sprnr0_GCU   IF_SPRING    fill spring       -w1                     % filling the channel
cell u1sprnr1_GCU   IF_SPRING    fmst91_753         w1 -w2                  % filling the wrapper
cell u1sprnr2_GCU   IF_SPRING    cool_max           w2                       % filling the external region

% Top insulator
cell u1tinsr0       u1tins       fill top_ins      -w1                     % filling the channel
cell u1tinsr1       u1tins       fmst91_753         w1 -w2                  % filling the wrapper
cell u1tinsr2       u1tins       cool_max           w2                       % filling the external region

cell u1tinsr0_GCU   IF_TOP_INS   fill top_ins      -w1                     % filling the channel
cell u1tinsr1_GCU   IF_TOP_INS   fmst91_753         w1 -w2                  % filling the wrapper
cell u1tinsr2_GCU   IF_TOP_INS   cool_max           w2                       % filling the external region

% Bottom insulator
cell u1binsr0       u1bins       fill bot_ins      -w1                     % filling the channel
cell u1binsr1       u1bins       fmst91_673         w1 -w2                  % filling the wrapper
cell u1binsr2       u1bins       cool_min           w2                       % filling the external region

cell u1binsr0_GCU   IF_BOT_INS   fill bot_ins      -w1                     % filling the channel
cell u1binsr1_GCU   IF_BOT_INS   fmst91_673         w1 -w2                  % filling the wrapper
cell u1binsr2_GCU   IF_BOT_INS   cool_min           w2                       % filling the external region

% Plenum
```

```
376. cell u1plnr0        u1pln        fill plen         -w1                      % filling the channel
377. cell u1plnr1        u1pln        fmst91_673         w1 -w2                   % filling the wrapper
378. cell u1plnr2        u1pln        cool_min           w2                        % filling the external region
379.
380. cell u1plnr0_GCU    IF_PLEN      fill plen         -w1                      % filling the channel
381. cell u1plnr1_GCU    IF_PLEN      fmst91_673         w1 -w2                   % filling the wrapper
382. cell u1plnr2_GCU    IF_PLEN      cool_min           w2                        % filling the external region
383.
384. % Bottom plug
385. cell u1bplgr0       u1bplg        fill bot_plg     -w1                      % filling the channel
386. cell u1bplgr1       u1bplg        fmst91_673         w1 -w2                   % filling the wrapper
387. cell u1bplgr2       u1bplg        cool_min           w2                        % filling the external region
388.
389. cell u1bplgr0_GCU   IF_BOT_PLUG   fill bot_plg     -w1                      % filling the channel
390. cell u1bplgr1_GCU   IF_BOT_PLUG   fmst91_673         w1 -w2                   % filling the wrapper
391. cell u1bplgr2_GCU   IF_BOT_PLUG   cool_min           w2                        % filling the external region
392.
393. %% ---------------------------------------------- Core lattice loading ----------------------------------------------
394.
395. lat core 3 0.0 0.0 5 5 17.1      % Core with CR and SR extracted
396. f1 f1 f1 f1 f1
397.  f1 f1 f1 f1 f1
398.   f1 f1 IF f1 f1
399.    f1 f1 f1 f1 f1
400.     f1 f1 f1 f1 f1
401.
402. %% ------------------------------------------------------------------------------------------------------------------------
     -----------
403.
404. cell c100 0 fill core -s1  % Filling the cylinder with the core
405. cell c101 0 outside s1     % Placing the vacuum outside the reactor
406.
407. %% -- PLOTS
408. plot 3 2000 2000  135
409. plot 3 2000 2000  48
410. plot 3 2000 2000  43
411. plot 3 2000 2000  31
412. plot 1 1000 1000 29.18505
413. plot 2 1000 1000
414.
415. %% -- SIMULATION SETUP
416. set bc 2
417. set fum nj19 %[ BTCH DUMMY LIM ] B1 leakage-corrected mode
418. set pop 1000000 1000 50
419. src OF_1M_500a_250i_2D sf src_OF_1M_500a_250i_2D 1
420.
421. set ures 1               % aggiunta il 3-09-18 per risolvere le risonanze dello spettro veloce
422.
423.
424. set his yes              % Check on fission source convergence
425.
426. %% -- GROUP CONSTANT GENERATION
427. ene 172xmas 4 nj18
428. set micro nj19           % ECCO-33 groups
429. set nfg nj19
430.
431.
432. % --- Detector for tallying the flux energy spectrum
433. %     The energy grid used for tallying will be defined later
434. %det IF_src_in_1g               ds wi -1  df if_src_500k_1g   1
435. %det IF_src_in_172g  de 172xmas ds wi -1  df if_src_500k_172g 1
436. %det IF_src_out                ds wi  1  df if_src_500k      -0.8
437.
438. % Detector to tally flux spectrum
439. ene MyEnergyGrid 3 2000 1e-11 2e1
440. det flx_spectrum de MyEnergyGrid df IF_src_1M_500a -1
```

E.3.3 Safety rod, 3D infinite cell with external source (fission spectrum)

In the following, the input file that defines a non-multiplying region cell (the absorbing bundle of the SR in this case), both axially and radially infinite (*i.e.*, finite with reflective boundary conditions) with an external neutron source. In order to simulate the behaviour of a different region, it is sufficient to change the assembly definition. The complete set of all the different assembly types is present in the *"ALFRED_ECCO.ge"* and "*ALFRED_ECCO_v2.ge*" files (§E.2). This file can be run independently.

In this case (SR), the external source is distributed in energy as the fission spectrum of the inner fuel, computed in the previous input (see §E.3.2) with the card "*det flx_spectrum de MyEnergyGrid df IF_src_1M_500a -1*".

```
1.   %% -- EXTERNAL FILE INCLUSION
2.   include "/home/abrate/ricerca/enea_sarotto/alfred/alfred_ecco/cell_calculation/eranos_jeff31.ml"  % materials
3.
4.
```

```

%% -- LIBRARY FOR NUCLEAR DATA
set acelib "/opt/serpent/xsdata/jeff31/sss_jeff31.xsdata"


% ------------------------ Radial coordinate -----------------------------------------------------------------------
% Core
surf s1 sqc 0.0 0.0 25        % wrapping inner perimeter


% Hexagonal assembly
surf w1 hexyc 0.0 0.0 7.39        % wrapping inner perimeter
surf w2 hexyc 0.0 0.0 8.3         % wrapping outer perimeter

% Safety rod
surf cyl1 cyl 0.0 0.0 7.35        % cladding inner perimeter
surf cyl2 cyl 0.0 0.0 8.35        % cladding outer perimeter

%-------------------------------------------------------------------------------------------------------------------
% --------------------- PIN DEFINITION -----------------------------------------------------------------------------
pin s1       % Safety pin
safe       2.58
Ti1515_753 2.64
cool_max

pin s2       % Safety pin
safe       1.83
Ti1515_753 1.89
cool_max

% -- Safety rod assembly (circular array)
lat safe1 4 0.0 0.0 2     % Active section
1 0     0 s1
6 5.25 30 s2 s2 s2 s2 s2 s2

%-------------------------------------------------------------------------------------------------------------------
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% SAFETY ROD %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Safety rod
cell c3r1  SR_ACT fill safe1               -w1          % Filling the channel
cell c3r2  SR_ACT fmst91_753                w1 -w2     % Filling the cladding
cell c3r4  SR_ACT cool_max                  w2            % Filling the external region

lat core 3 0.0 0.0 5 5 17.1      % Core with CR and SR extracted
SR_ACT SR_ACT SR_ACT SR_ACT SR_ACT
SR_ACT SR_ACT SR_ACT SR_ACT SR_ACT
SR_ACT SR_ACT SR_ACT SR_ACT SR_ACT
SR_ACT SR_ACT SR_ACT SR_ACT SR_ACT
SR_ACT SR_ACT SR_ACT SR_ACT SR_ACT

%% ---------------------------------------------------------------------------------------------------------------------
-----------

cell c100 0 fill core -s1  % Filling the cylinder with the core
cell c101 0 outside s1     % Placing the vacuum outside the reactor

%% -- PLOTS
plot 3 2000 2000  135
plot 3 2000 2000  48
plot 3 2000 2000  43
plot 3 2000 2000  31
plot 1 1000 1000  29.18505
plot 2 1000 1000

%% -- SIMULATION SETUP
set bc 2
set fum nj19 %[ BTCH DUMMY LIM ] B1 leakage-corrected mode
%set pop 1000000 500 250 % Population data


set nps 1000000000 5000

set ures 1                % aggiunta il 3-09-18 per risolvere le risonanze dello spettro veloce


set his yes               % Check on fission source convergence

%% -- GROUP CONSTANT GENERATION
set micro nj19           % ECCO-33 groups
set nfg nj19
set gcu        SR_ACT

ene ene_grid 4 nj19

% --- Detector for tallying the flux energy spectrum
%     The energy grid used for tallying will be defined later
det SR_ACT_FLX  du SR_ACT   de ene_grid
det SR_ACT      dr -3 void  dr -16 void du SR_ACT   de ene_grid


src IF sb 1969 2 1.000000000000000e-11  0.000000000000000e+00
                 1.505000000000000e-09  1.116070000000000e-06
                 4.000000000000000e-09  2.241170000000000e-06
                 5.950000000000000e-09  3.522260000000000e-06
                 8.450000000000000e-09  9.483829999999999e-06
                 1.250000000000000e-08  2.712730000000000e-05
                 1.750000000000000e-08  4.535580000000000e-05
```

100.	2.250000000000000e-08	6.573010000000000e-05
101.	2.750000000000000e-08	9.134400000000000e-05
102.	3.250000000000000e-08	1.217190000000000e-04
103.	3.850000000000000e-08	2.275350000000000e-04
104.	4.600000000000000e-08	3.451590000000000e-04
105.	5.400000000000000e-08	4.496570000000000e-04
106.	6.250000000000000e-08	6.405710000000000e-04
107.	7.200000000000000e-08	8.819920000000000e-04
108.	7.850000000000000e-08	3.026330000000000e-04
109.	8.750000000000000e-08	1.790750000000000e-03
110.	9.750000000000001e-08	7.015670000000000e-04
111.	1.075000000000000e-07	2.430120000000000e-03
112.	1.245000000000000e-07	3.805160000000000e-03
113.	1.370000000000000e-07	1.365080000000000e-03
114.	1.431850000000000e-07	1.534470000000000e-03
115.	1.497000000000000e-07	1.703700000000000e-03
116.	1.565150000000000e-07	1.885370000000000e-03
117.	1.648550000000000e-07	2.804500000000000e-03
118.	1.748550000000000e-07	3.185730000000000e-03
119.	1.845000000000000e-07	2.972570000000000e-03
120.	1.939050000000000e-07	3.424920000000000e-03
121.	2.039750000000000e-07	3.821360000000000e-03
122.	2.145700000000000e-07	4.238440000000000e-03
123.	2.267900000000000e-07	5.601420000000000e-03
124.	2.407900000000000e-07	6.328910000000000e-03
125.	2.557550000000000e-07	7.205970000000000e-03
126.	2.717550000000000e-07	8.101300000000001e-03
127.	2.900000000000000e-07	1.038210000000000e-02
128.	3.072500000000000e-07	7.885929999999999e-03
129.	3.172500000000000e-07	3.064600000000000e-03
130.	3.273300000000000e-07	8.364570000000000e-03
131.	3.423300000000000e-07	9.029570000000001e-03
132.	3.599650000000000e-07	1.211810000000000e-02
133.	3.804650000000000e-07	1.329390000000000e-02
134.	3.955000000000000e-07	5.798480000000000e-03
135.	4.069950000000000e-07	9.178920000000000e-03
136.	4.234950000000000e-07	1.273130000000000e-02
137.	4.413400000000000e-07	1.142320000000000e-02
138.	4.583450000000000e-07	1.209410000000000e-02
139.	4.760050000000000e-07	1.275450000000000e-02
140.	4.925000000000001e-07	1.078900000000000e-02
141.	5.098100000000000e-07	1.430810000000000e-02
142.	5.256000000000000e-07	8.822930000000000e-03
143.	5.357900000000000e-07	6.248430000000000e-03
144.	5.534800000000000e-07	2.024320000000000e-02
145.	5.811200000000000e-07	2.157160000000000e-02
146.	6.101400000000000e-07	2.293860000000000e-02
147.	6.390750000000000e-07	2.198760000000000e-02
148.	6.678550000000000e-07	2.315760000000000e-02
149.	6.937800000000000e-07	1.778190000000000e-02
150.	7.232750000000000e-07	2.914370000000000e-02
151.	7.607750000000000e-07	3.085700000000000e-02
152.	7.850000000000000e-07	8.051340000000001e-03
153.	8.047250000000000e-07	2.376620000000000e-02
154.	8.347250000000000e-07	2.468180000000000e-02
155.	8.550000000000000e-07	8.089560000000001e-03
156.	8.682130000000001e-07	1.329190000000000e-02
157.	8.932130000000000e-07	2.721640000000000e-02
158.	9.200000000000000e-07	1.623420000000000e-02
159.	9.400000000000000e-07	1.621010000000000e-02
160.	9.610000000000000e-07	1.782580000000000e-02
161.	9.790000000000001e-07	1.133440000000000e-02
162.	9.909999999999999e-07	8.090580000000000e-03
163.	1.008000000000000e-06	1.943570000000000e-02
164.	1.027500000000000e-06	1.213120000000000e-02
165.	1.040000000000000e-06	8.075060000000000e-03
166.	1.058000000000000e-06	2.097410000000000e-02
167.	1.075500000000000e-06	7.252770000000000e-03
168.	1.088500000000000e-06	1.368680000000000e-02
169.	1.103500000000000e-06	1.046060000000000e-02
170.	1.116500000000000e-06	1.043660000000000e-02
171.	1.136500000000000e-06	2.166980000000000e-02
172.	1.160000000000000e-06	1.602810000000000e-02
173.	1.186030000000000e-06	2.562850000000000e-02
174.	1.218530000000000e-06	2.625640000000000e-02
175.	1.251040000000000e-06	2.548630000000000e-02
176.	1.283540000000000e-06	2.605440000000000e-02
177.	1.318750000000000e-06	2.956970000000000e-02
178.	1.353750000000000e-06	2.552740000000000e-02
179.	1.387280000000000e-06	2.703880000000000e-02
180.	1.422280000000000e-06	2.762030000000000e-02
181.	1.457500000000000e-06	2.716180000000000e-02
182.	1.487500000000000e-06	1.931250000000000e-02
183.	1.522170000000000e-06	3.409930000000000e-02
184.	1.567170000000000e-06	3.493570000000000e-02
185.	1.609760000000000e-06	3.001860000000000e-02
186.	1.649760000000000e-06	3.058020000000000e-02
187.	1.690990000000000e-06	3.150340000000000e-02
188.	1.733490000000000e-06	3.208590000000000e-02
189.	1.776000000000000e-06	3.110350000000000e-02
190.	1.818500000000000e-06	3.162160000000000e-02
191.	1.847690000000000e-06	1.126910000000000e-02
192.	1.869930000000000e-06	2.120170000000000e-02
193.	1.907230000000000e-06	3.300640000000000e-02
194.	1.952250000000000e-06	3.199890000000000e-02
195.	1.997240000000000e-06	3.252390000000000e-02

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197.	2.079800000000000e-06	2.849260000000000e-02
198.	2.115000000000000e-06	2.102380000000000e-02
199.	2.157650000000000e-06	3.849270000000000e-02
200.	2.213680000000000e-06	3.912020000000000e-02
201.	2.271160000000000e-06	3.979090000000000e-02
202.	2.330130000000000e-06	4.040670000000000e-02
203.	2.371190000000000e-06	1.503850000000000e-02
204.	2.402040000000000e-06	2.632190000000000e-02
205.	2.453370000000000e-06	4.196520000000000e-02
206.	2.517520000000000e-06	4.264040000000000e-02
207.	2.575000000000000e-06	3.246820000000000e-02
208.	2.629660000000000e-06	3.817140000000000e-02
209.	2.689660000000000e-06	3.875900000000000e-02
210.	2.743960000000000e-06	3.037750000000000e-02
211.	2.802950000000000e-06	4.415820000000000e-02
212.	2.873910000000000e-06	4.488890000000000e-02
213.	2.946660000000000e-06	4.558960000000000e-02
214.	3.021260000000000e-06	4.627160000000000e-02
215.	3.098180000000000e-06	4.745250000000000e-02
216.	3.177480000000000e-06	4.808750000000000e-02
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219.	3.423540000000000e-06	4.947650000000000e-02
220.	3.510210000000000e-06	5.014730000000000e-02
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223.	3.783590000000000e-06	5.200770000000000e-02
224.	3.879370000000000e-06	5.267160000000000e-02
225.	3.963930000000000e-06	3.873080000000000e-02
226.	4.064630000000000e-06	6.849570000000001e-02
227.	4.181520000000000e-06	5.456390000000000e-02
228.	4.287370000000000e-06	5.515390000000000e-02
229.	4.395910000000000e-06	5.591790000000000e-02
230.	4.507190000000000e-06	5.660010000000000e-02
231.	4.621290000000000e-06	5.724620000000000e-02
232.	4.738280000000000e-06	5.795470000000000e-02
233.	4.858230000000000e-06	5.861300000000000e-02
234.	4.981220000000000e-06	5.926680000000000e-02
235.	5.064580000000000e-06	1.990100000000000e-02
236.	5.106960000000000e-06	1.994770000000000e-02
237.	5.149700000000000e-06	2.003890000000000e-02
238.	5.192790000000000e-06	2.009210000000000e-02
239.	5.236240000000000e-06	2.017880000000000e-02
240.	5.280060000000000e-06	2.024100000000000e-02
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251.	5.786940000000000e-06	2.101830000000000e-02
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253.	5.884200000000000e-06	2.117890000000000e-02
254.	5.933440000000000e-06	2.123890000000000e-02
255.	5.983090000000000e-06	2.132300000000000e-02
256.	6.033160000000000e-06	2.140110000000000e-02
257.	6.083650000000000e-06	2.146750000000000e-02
258.	6.134560000000000e-06	2.153580000000000e-02
259.	6.185890000000000e-06	2.160440000000000e-02
260.	6.237650000000000e-06	2.167090000000000e-02
261.	6.289850000000000e-06	2.176060000000000e-02
262.	6.342490000000000e-06	2.182940000000000e-02
263.	6.395560000000000e-06	2.190220000000000e-02
264.	6.449080000000000e-06	2.196580000000000e-02
265.	6.503050000000000e-06	2.203790000000000e-02
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267.	6.612340000000000e-06	2.217000000000000e-02
268.	6.667670000000000e-06	2.227240000000000e-02
269.	6.723470000000000e-06	2.233500000000000e-02
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271.	6.836470000000000e-06	2.252560000000000e-02
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273.	6.951360000000000e-06	2.266670000000000e-02
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277.	7.186980000000000e-06	2.303190000000000e-02
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280.	7.368920000000000e-06	2.325930000000000e-02
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282.	7.492760000000000e-06	2.340570000000000e-02
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284.	7.618690000000000e-06	2.351980000000000e-02
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306.	9.151679999999999e-06	2.526220000000000e-02
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489.	4.205330000000000e-05	3.851780000000000e-02
490.	4.240520000000000e-05	3.917170000000000e-02
491.	4.276010000000000e-05	4.002790000000000e-02
492.	4.311790000000000e-05	4.076470000000000e-02
493.	4.347870000000000e-05	4.059450000000000e-02
494.	4.384250000000000e-05	3.908620000000000e-02
495.	4.420940000000000e-05	3.648340000000000e-02
496.	4.457940000000000e-05	3.267800000000000e-02
497.	4.495240000000000e-05	3.197940000000000e-02
498.	4.532860000000000e-05	3.832430000000000e-02
499.	4.570790000000000e-05	4.312420000000000e-02
500.	4.609040000000000e-05	4.450110000000000e-02
501.	4.647610000000000e-05	4.493700000000000e-02
502.	4.686500000000000e-05	4.521070000000000e-02
503.	4.725720000000000e-05	4.535740000000000e-02
504.	4.765260000000000e-05	4.550410000000000e-02
505.	4.805140000000000e-05	4.567410000000000e-02
506.	4.845350000000000e-05	4.579170000000000e-02
507.	4.885900000000000e-05	4.589240000000000e-02
508.	4.926780000000000e-05	4.597130000000000e-02
509.	4.968010000000000e-05	4.601830000000000e-02
510.	5.009580000000000e-05	4.608310000000000e-02
511.	5.051500000000000e-05	4.625870000000000e-02
512.	5.093780000000000e-05	4.642930000000000e-02
513.	5.136400000000000e-05	4.648440000000000e-02
514.	5.179380000000000e-05	4.655000000000000e-02
515.	5.222720000000000e-05	4.654880000000000e-02
516.	5.266430000000000e-05	4.658430000000000e-02
517.	5.310500000000000e-05	4.671450000000000e-02
518.	5.354940000000000e-05	4.676920000000000e-02
519.	5.399750000000000e-05	4.699610000000000e-02
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522.	5.536440000000000e-05	4.724360000000000e-02
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524.	5.629490000000000e-05	4.742150000000000e-02
525.	5.676600000000000e-05	4.748270000000000e-02
526.	5.724100000000000e-05	4.751920000000000e-02
527.	5.772000000000000e-05	4.758310000000000e-02
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532.	6.017580000000000e-05	4.815410000000000e-02
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835.	7.516500000000000e-04	9.859220000000001e-02
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1483.	1.609640000000000e-01	6.550610000000000e-01
1484.	1.623110000000000e-01	6.628810000000001e-01
1485.	1.636690000000000e-01	6.688850000000000e-01
1486.	1.650390000000000e-01	6.742640000000000e-01
1487.	1.664200000000000e-01	6.556840000000000e-01
1488.	1.678130000000000e-01	6.219140000000000e-01
1489.	1.692170000000000e-01	4.296830000000000e-01
1490.	1.706330000000000e-01	4.726350000000000e-01
1491.	1.720610000000000e-01	5.605560000000001e-01
1492.	1.735010000000000e-01	5.732380000000000e-01
1493.	1.749530000000000e-01	6.678190000000001e-01
1494.	1.764170000000000e-01	7.299070000000000e-01
1495.	1.778930000000000e-01	7.581240000000000e-01
1496.	1.793820000000000e-01	7.355920000000000e-01
1497.	1.808830000000000e-01	7.112210000000000e-01
1498.	1.823960000000000e-01	7.337260000000000e-01
1499.	1.839230000000000e-01	6.859070000000000e-01
1500.	1.854620000000000e-01	5.908890000000000e-01
1501.	1.870140000000000e-01	4.407780000000000e-01
1502.	1.885790000000000e-01	3.385420000000000e-01
1503.	1.901570000000000e-01	3.690740000000000e-01
1504.	1.917480000000000e-01	4.221480000000000e-01
1505.	1.933530000000000e-01	4.508120000000000e-01
1506.	1.949710000000000e-01	4.835270000000000e-01
1507.	1.966020000000000e-01	5.055930000000000e-01
1508.	1.982470000000000e-01	5.069840000000000e-01
1509.	1.999060000000000e-01	5.461340000000000e-01
1510.	2.015790000000000e-01	5.544240000000000e-01
1511.	2.032660000000000e-01	5.780640000000000e-01
1512.	2.049670000000000e-01	5.911380000000001e-01
1513.	2.066820000000000e-01	6.740700000000000e-01
1514.	2.084120000000000e-01	5.876700000000000e-01
1515.	2.101560000000000e-01	5.482890000000000e-01
1516.	2.119140000000000e-01	6.119830000000001e-01
1517.	2.136880000000000e-01	6.335600000000000e-01
1518.	2.154760000000000e-01	6.663500000000000e-01
1519.	2.172790000000000e-01	6.713790000000000e-01
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1521.	2.209310000000000e-01	4.576650000000000e-01
1522.	2.227790000000000e-01	5.001190000000000e-01
1523.	2.246440000000000e-01	5.453630000000000e-01
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1525.	2.284190000000000e-01	6.100810000000000e-01
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1527.	2.322580000000000e-01	6.016220000000000e-01
1528.	2.342020000000000e-01	5.921320000000000e-01
1529.	2.361620000000000e-01	5.956510000000000e-01
1530.	2.381380000000000e-01	6.257630000000000e-01
1531.	2.401300000000000e-01	6.291450000000000e-01
1532.	2.421400000000000e-01	6.080760000000000e-01
1533.	2.441660000000000e-01	6.029710000000000e-01
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1535.	2.482700000000000e-01	5.764920000000000e-01
1536.	2.503470000000000e-01	5.648420000000000e-01
1537.	2.524420000000000e-01	6.273500000000000e-01
1538.	2.545550000000000e-01	6.536870000000000e-01
1539.	2.566850000000000e-01	7.046090000000000e-01
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1542.	2.631830000000000e-01	6.542950000000000e-01
1543.	2.653850000000000e-01	6.826890000000000e-01
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1557.	2.970910000000000e-01	6.510940000000000e-02
1558.	2.978500000000000e-01	3.708430000000000e-01
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1561.	3.032370000000000e-01	7.659290000000000e-01
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1570.	3.268550000000000e-01	4.885960000000000e-01
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1578.	3.493880000000000e-01	5.537620000000000e-01
1579.	3.523110000000000e-01	4.386670000000000e-01
1580.	3.552600000000000e-01	3.842250000000000e-01
1581.	3.582330000000000e-01	3.915190000000000e-01
1582.	3.612300000000000e-01	3.746790000000000e-01
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1603.	4.303140000000000e-01	3.707760000000000e-01
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1609.	4.523770000000000e-01	4.499830000000000e-01
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1614.	4.716240000000000e-01	4.332110000000000e-01
1615.	4.755710000000000e-01	5.038990000000000e-01
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1617.	4.835630000000000e-01	5.752880000000000e-01
1618.	4.876100000000000e-01	5.596170000000000e-01
1619.	4.916900000000000e-01	5.502040000000000e-01
1620.	4.958050000000000e-01	6.846330000000001e-01
1621.	4.999540000000000e-01	6.261610000000000e-01
1622.	5.041380000000000e-01	5.555100000000000e-01
1623.	5.083560000000000e-01	6.260000000000000e-01
1624.	5.126100000000000e-01	5.663880000000000e-01
1625.	5.169000000000000e-01	6.730870000000000e-01
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1627.	5.255870000000000e-01	4.526840000000000e-01
1628.	5.299850000000000e-01	4.314250000000000e-01
1629.	5.344200000000000e-01	5.230350000000000e-01
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1631.	5.434020000000001e-01	5.373870000000000e-01
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1635.	5.618210000000000e-01	5.117860000000000e-01
1636.	5.665220000000000e-01	5.353670000000000e-01
1637.	5.712630000000000e-01	5.252630000000000e-01
1638.	5.760430000000000e-01	5.102930000000000e-01
1639.	5.808630000000000e-01	5.157050000000000e-01
1640.	5.857240000000000e-01	5.863880000000000e-01
1641.	5.906260000000000e-01	5.827330000000000e-01
1642.	5.955680000000000e-01	5.801760000000000e-01
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1646.	6.157550000000001e-01	4.550910000000000e-01

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1650.	6.366260000000000e-01	4.774710000000000e-01
1651.	6.419530000000000e-01	5.553450000000000e-01
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1653.	6.527420000000000e-01	5.341490000000000e-01
1654.	6.582040000000000e-01	4.584550000000000e-01
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1657.	6.748670000000000e-01	4.060600000000000e-01
1658.	6.805140000000000e-01	4.449100000000000e-01
1659.	6.862090000000000e-01	4.465240000000000e-01
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1661.	6.977420000000000e-01	4.295830000000000e-01
1662.	7.035810000000000e-01	5.029220000000000e-01
1663.	7.094680000000000e-01	5.132780000000000e-01
1664.	7.154050000000000e-01	4.008370000000000e-01
1665.	7.213920000000000e-01	3.012920000000000e-01
1666.	7.274290000000000e-01	3.372650000000000e-01
1667.	7.335160000000000e-01	3.962160000000000e-01
1668.	7.396540000000000e-01	4.040890000000000e-01
1669.	7.458430000000000e-01	3.601280000000000e-01
1670.	7.520850000000000e-01	3.670370000000000e-01
1671.	7.583780000000000e-01	3.435940000000000e-01
1672.	7.647250000000000e-01	3.499480000000000e-01
1673.	7.711240000000000e-01	3.492970000000000e-01
1674.	7.775770000000000e-01	3.416050000000000e-01
1675.	7.840840000000000e-01	3.514010000000000e-01
1676.	7.906450000000000e-01	3.177140000000000e-01
1677.	7.972610000000000e-01	3.606560000000000e-01
1678.	8.039330000000000e-01	3.653180000000000e-01
1679.	8.106600000000001e-01	3.539260000000000e-01
1680.	8.174440000000000e-01	2.507760000000000e-01
1681.	8.242840000000000e-01	2.895540000000000e-01
1682.	8.311820000000000e-01	2.981060000000000e-01
1683.	8.381380000000001e-01	3.015490000000000e-01
1684.	8.451510000000000e-01	2.672430000000000e-01
1685.	8.522240000000000e-01	2.529910000000000e-01
1686.	8.593550000000000e-01	2.387610000000000e-01
1687.	8.665460000000000e-01	2.361010000000000e-01
1688.	8.737980000000000e-01	2.403070000000000e-01
1689.	8.811100000000000e-01	2.455170000000000e-01
1690.	8.884830000000000e-01	2.195190000000000e-01
1691.	8.959180000000000e-01	2.439570000000000e-01
1692.	9.034150000000000e-01	2.153320000000000e-01
1693.	9.109750000000000e-01	2.168470000000000e-01
1694.	9.185980000000000e-01	2.121510000000000e-01
1695.	9.262850000000000e-01	2.156280000000000e-01
1696.	9.340370000000000e-01	2.147560000000000e-01
1697.	9.418530000000001e-01	2.122420000000000e-01
1698.	9.497340000000000e-01	1.737050000000000e-01
1699.	9.576820000000000e-01	1.879650000000000e-01
1700.	9.656960000000000e-01	1.609330000000000e-01
1701.	9.737770000000000e-01	1.542390000000000e-01
1702.	9.819260000000000e-01	1.631640000000000e-01
1703.	9.901430000000000e-01	1.403350000000000e-01
1704.	9.984280000000000e-01	1.542420000000000e-01
1705.	1.006780000000000e+00	1.510320000000000e-01
1706.	1.015210000000000e+00	1.644210000000000e-01
1707.	1.023700000000000e+00	1.788260000000000e-01
1708.	1.032270000000000e+00	1.552920000000000e-01
1709.	1.040910000000000e+00	1.560090000000000e-01
1710.	1.049620000000000e+00	1.619800000000000e-01
1711.	1.058400000000000e+00	1.659500000000000e-01
1712.	1.067260000000000e+00	1.679220000000000e-01
1713.	1.076190000000000e+00	1.908340000000000e-01
1714.	1.085200000000000e+00	1.978020000000000e-01
1715.	1.094280000000000e+00	2.023000000000000e-01
1716.	1.103430000000000e+00	2.058620000000000e-01
1717.	1.112670000000000e+00	2.036780000000000e-01
1718.	1.121980000000000e+00	1.838590000000000e-01
1719.	1.131370000000000e+00	2.035700000000000e-01
1720.	1.140840000000000e+00	2.032150000000000e-01
1721.	1.150380000000000e+00	1.844620000000000e-01
1722.	1.160010000000000e+00	2.040900000000000e-01
1723.	1.169720000000000e+00	2.116370000000000e-01
1724.	1.179500000000000e+00	2.087920000000000e-01
1725.	1.189370000000000e+00	1.931000000000000e-01
1726.	1.199330000000000e+00	2.133530000000000e-01
1727.	1.209360000000000e+00	1.948720000000000e-01
1728.	1.219480000000000e+00	2.190090000000000e-01
1729.	1.229690000000000e+00	1.609150000000000e-01
1730.	1.239980000000000e+00	1.719370000000000e-01
1731.	1.250350000000000e+00	1.862940000000000e-01
1732.	1.260820000000000e+00	1.704270000000000e-01
1733.	1.271370000000000e+00	1.709280000000000e-01
1734.	1.282010000000000e+00	1.475260000000000e-01
1735.	1.292740000000000e+00	1.481550000000000e-01
1736.	1.303550000000000e+00	1.409540000000000e-01
1737.	1.314460000000000e+00	1.441640000000000e-01
1738.	1.325460000000000e+00	1.441760000000000e-01
1739.	1.336550000000000e+00	1.563220000000000e-01
1740.	1.347740000000000e+00	1.650990000000000e-01
1741.	1.359020000000000e+00	1.729370000000000e-01
1742.	1.370390000000000e+00	1.847590000000000e-01
1743.	1.381860000000000e+00	1.527960000000000e-01

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1746.	1.416840000000000e+00	1.558710000000000e-01
1747.	1.428690000000000e+00	1.656510000000000e-01
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1757.	1.552850000000000e+00	1.323340000000000e-01
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1761.	1.605490000000000e+00	1.402460000000000e-01
1762.	1.618920000000000e+00	1.298620000000000e-01
1763.	1.632470000000000e+00	1.442100000000000e-01
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1765.	1.659910000000000e+00	1.320060000000000e-01
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1767.	1.687800000000000e+00	1.423750000000000e-01
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1769.	1.716170000000000e+00	1.372730000000000e-01
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1773.	1.774340000000000e+00	1.316380000000000e-01
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1775.	1.804160000000000e+00	1.243800000000000e-01
1776.	1.819260000000000e+00	1.207420000000000e-01
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1779.	1.865310000000000e+00	1.118760000000000e-01
1780.	1.880920000000000e+00	1.098930000000000e-01
1781.	1.896660000000000e+00	1.136430000000000e-01
1782.	1.912530000000000e+00	9.754910000000000e-02
1783.	1.928530000000000e+00	1.020150000000000e-01
1784.	1.944670000000000e+00	1.026210000000000e-01
1785.	1.960950000000000e+00	1.059080000000000e-01
1786.	1.977360000000000e+00	1.091000000000000e-01
1787.	1.993900000000000e+00	1.102470000000000e-01
1788.	2.010590000000000e+00	1.097940000000000e-01
1789.	2.027410000000000e+00	1.095860000000000e-01
1790.	2.044380000000000e+00	1.008610000000000e-01
1791.	2.061490000000000e+00	1.018450000000000e-01
1792.	2.078740000000000e+00	1.030980000000000e-01
1793.	2.096130000000000e+00	1.128580000000000e-01
1794.	2.113670000000000e+00	1.016510000000000e-01
1795.	2.131360000000000e+00	1.085790000000000e-01
1796.	2.149200000000000e+00	1.049580000000000e-01
1797.	2.167180000000000e+00	1.062340000000000e-01
1798.	2.185320000000000e+00	1.042230000000000e-01
1799.	2.203600000000000e+00	1.066840000000000e-01
1800.	2.222040000000000e+00	1.119460000000000e-01
1801.	2.240640000000000e+00	1.129790000000000e-01
1802.	2.259390000000000e+00	1.153230000000000e-01
1803.	2.278290000000000e+00	1.074820000000000e-01
1804.	2.297360000000000e+00	1.098030000000000e-01
1805.	2.316580000000000e+00	1.093200000000000e-01
1806.	2.335970000000000e+00	1.062780000000000e-01
1807.	2.355520000000000e+00	1.116970000000000e-01
1808.	2.375230000000000e+00	1.141660000000000e-01
1809.	2.395110000000000e+00	1.006170000000000e-01
1810.	2.415150000000000e+00	9.911510000000000e-02
1811.	2.435360000000000e+00	9.264840000000001e-02
1812.	2.455740000000000e+00	9.793520000000000e-02
1813.	2.476290000000000e+00	9.598530000000000e-02
1814.	2.497010000000000e+00	8.972310000000000e-02
1815.	2.517900000000000e+00	9.145720000000000e-02
1816.	2.538970000000000e+00	8.621590000000000e-02
1817.	2.560220000000000e+00	8.983160000000000e-02
1818.	2.581650000000000e+00	9.378670000000000e-02
1819.	2.603250000000000e+00	9.180960000000001e-02
1820.	2.625030000000000e+00	8.764230000000001e-02
1821.	2.647000000000000e+00	8.749750000000001e-02
1822.	2.669150000000000e+00	8.298050000000000e-02
1823.	2.691490000000000e+00	8.312319999999999e-02
1824.	2.714010000000000e+00	8.225739999999999e-02
1825.	2.736720000000000e+00	8.037370000000001e-02
1826.	2.759620000000000e+00	7.536510000000000e-02
1827.	2.782720000000000e+00	7.322470000000000e-02
1828.	2.806000000000000e+00	7.718620000000000e-02
1829.	2.829480000000000e+00	7.494480000000001e-02
1830.	2.853160000000000e+00	6.970050000000000e-02
1831.	2.877040000000000e+00	7.239030000000001e-02
1832.	2.901110000000000e+00	7.103600000000000e-02
1833.	2.925390000000000e+00	7.044839999999999e-02
1834.	2.949870000000000e+00	6.622630000000000e-02
1835.	2.974550000000000e+00	6.744799999999999e-02
1836.	2.999440000000000e+00	6.733920000000000e-02
1837.	3.024540000000000e+00	6.399070000000000e-02
1838.	3.049850000000000e+00	6.541360000000000e-02
1839.	3.075380000000000e+00	6.333490000000000e-02
1840.	3.101110000000000e+00	6.426680000000000e-02

1841.	3.127060000000000e+00	6.028510000000000e-02
1842.	3.153230000000000e+00	5.914030000000000e-02
1843.	3.179620000000000e+00	5.856360000000000e-02
1844.	3.206220000000000e+00	5.612590000000000e-02
1845.	3.233050000000000e+00	5.449780000000000e-02
1846.	3.260110000000000e+00	5.132030000000000e-02
1847.	3.287390000000000e+00	4.909350000000000e-02
1848.	3.314900000000000e+00	4.874400000000000e-02
1849.	3.342640000000000e+00	4.799790000000000e-02
1850.	3.370610000000000e+00	4.626270000000000e-02
1851.	3.398820000000000e+00	4.627940000000000e-02
1852.	3.427260000000000e+00	4.609310000000000e-02
1853.	3.455940000000000e+00	4.483130000000000e-02
1854.	3.484860000000000e+00	4.254280000000000e-02
1855.	3.514020000000000e+00	4.386700000000000e-02
1856.	3.543430000000000e+00	4.197760000000000e-02
1857.	3.573080000000000e+00	4.158770000000000e-02
1858.	3.602980000000000e+00	4.019030000000000e-02
1859.	3.633130000000000e+00	3.988240000000000e-02
1860.	3.663530000000000e+00	3.861090000000000e-02
1861.	3.694190000000000e+00	3.840140000000000e-02
1862.	3.725100000000000e+00	3.774740000000000e-02
1863.	3.756270000000000e+00	3.472880000000000e-02
1864.	3.787710000000000e+00	3.582820000000000e-02
1865.	3.819400000000000e+00	3.712090000000000e-02
1866.	3.851360000000000e+00	3.641570000000000e-02
1867.	3.883590000000000e+00	3.628970000000000e-02
1868.	3.916090000000000e+00	3.600400000000000e-02
1869.	3.948860000000000e+00	3.487160000000000e-02
1870.	3.981910000000000e+00	3.509890000000000e-02
1871.	4.015230000000000e+00	3.475750000000000e-02
1872.	4.048830000000000e+00	3.482960000000000e-02
1873.	4.082710000000000e+00	3.531230000000000e-02
1874.	4.116870000000000e+00	3.416840000000000e-02
1875.	4.151320000000000e+00	3.178310000000000e-02
1876.	4.186060000000000e+00	3.019110000000000e-02
1877.	4.221090000000000e+00	3.098170000000000e-02
1878.	4.256410000000000e+00	3.069480000000000e-02
1879.	4.292030000000000e+00	2.900190000000000e-02
1880.	4.327950000000000e+00	2.591900000000000e-02
1881.	4.364170000000000e+00	2.606290000000000e-02
1882.	4.400690000000000e+00	2.632170000000000e-02
1883.	4.437510000000000e+00	2.662000000000000e-02
1884.	4.474650000000000e+00	2.617120000000000e-02
1885.	4.512090000000000e+00	2.591350000000000e-02
1886.	4.549850000000000e+00	2.457520000000000e-02
1887.	4.587920000000000e+00	2.510910000000000e-02
1888.	4.626310000000000e+00	2.425340000000000e-02
1889.	4.665030000000000e+00	2.496530000000000e-02
1890.	4.704070000000000e+00	2.431520000000000e-02
1891.	4.743430000000000e+00	2.462060000000000e-02
1892.	4.783120000000000e+00	2.358440000000000e-02
1893.	4.823150000000000e+00	2.161530000000000e-02
1894.	4.863510000000000e+00	2.115690000000000e-02
1895.	4.904210000000000e+00	2.168650000000000e-02
1896.	4.945250000000000e+00	2.145700000000000e-02
1897.	4.986630000000000e+00	2.118020000000000e-02
1898.	5.028360000000000e+00	2.045200000000000e-02
1899.	5.070440000000000e+00	1.919590000000000e-02
1900.	5.112870000000000e+00	1.784510000000000e-02
1901.	5.155650000000000e+00	1.801800000000000e-02
1902.	5.198800000000000e+00	1.848650000000000e-02
1903.	5.242300000000000e+00	1.840610000000000e-02
1904.	5.286170000000000e+00	1.790620000000000e-02
1905.	5.330400000000000e+00	1.701460000000000e-02
1906.	5.375010000000000e+00	1.715950000000000e-02
1907.	5.419990000000000e+00	1.698790000000000e-02
1908.	5.465340000000000e+00	1.641160000000000e-02
1909.	5.511080000000000e+00	1.596200000000000e-02
1910.	5.557200000000000e+00	1.527260000000000e-02
1911.	5.603700000000000e+00	1.429940000000000e-02
1912.	5.650590000000000e+00	1.384790000000000e-02
1913.	5.697880000000000e+00	1.380230000000000e-02
1914.	5.745560000000000e+00	1.367600000000000e-02
1915.	5.793640000000000e+00	1.345410000000000e-02
1916.	5.842120000000000e+00	1.330680000000000e-02
1917.	5.891010000000000e+00	1.286790000000000e-02
1918.	5.940310000000000e+00	1.208960000000000e-02
1919.	5.990010000000000e+00	1.236520000000000e-02
1920.	6.040140000000000e+00	1.198730000000000e-02
1921.	6.090680000000000e+00	1.173230000000000e-02
1922.	6.141650000000000e+00	1.171750000000000e-02
1923.	6.193050000000000e+00	1.143180000000000e-02
1924.	6.244870000000000e+00	1.105700000000000e-02
1925.	6.297130000000000e+00	1.082770000000000e-02
1926.	6.349820000000000e+00	1.024190000000000e-02
1927.	6.402960000000000e+00	9.650350000000000e-03
1928.	6.456540000000000e+00	1.005120000000000e-02
1929.	6.510570000000000e+00	9.847079999999999e-03
1930.	6.565050000000000e+00	9.332890000000000e-03
1931.	6.619990000000000e+00	8.954350000000000e-03
1932.	6.675390000000000e+00	8.631710000000001e-03
1933.	6.731250000000000e+00	8.368479999999999e-03
1934.	6.787580000000000e+00	7.910860000000001e-03
1935.	6.844380000000000e+00	7.800890000000000e-03
1936.	6.901650000000000e+00	7.784870000000000e-03
1937.	6.959400000000000e+00	7.577790000000000e-03

1938.	7.017640000000000e+00	7.265660000000000e-03
1939.	7.076370000000000e+00	6.934150000000000e-03
1940.	7.135580000000000e+00	6.664390000000000e-03
1941.	7.195290000000000e+00	6.123680000000000e-03
1942.	7.255500000000000e+00	6.030610000000000e-03
1943.	7.316220000000000e+00	5.850070000000000e-03
1944.	7.377440000000000e+00	5.677350000000000e-03
1945.	7.439180000000000e+00	5.543850000000000e-03
1946.	7.501430000000000e+00	5.406720000000000e-03
1947.	7.564200000000000e+00	5.220210000000000e-03
1948.	7.627500000000000e+00	5.026910000000000e-03
1949.	7.691330000000000e+00	4.806420000000000e-03
1950.	7.755690000000000e+00	4.559440000000000e-03
1951.	7.820590000000000e+00	4.329160000000000e-03
1952.	7.886040000000000e+00	4.208470000000000e-03
1953.	7.952030000000000e+00	4.179590000000000e-03
1954.	8.018570000000000e+00	4.101210000000000e-03
1955.	8.085670000000000e+00	3.905830000000000e-03
1956.	8.153340000000000e+00	3.647790000000000e-03
1957.	8.221560000000000e+00	3.446520000000000e-03
1958.	8.290360000000000e+00	3.294950000000000e-03
1959.	8.359740000000000e+00	3.187590000000000e-03
1960.	8.429690000000001e+00	3.078360000000000e-03
1961.	8.500230000000000e+00	3.003220000000000e-03
1962.	8.571370000000000e+00	2.889350000000000e-03
1963.	8.643090000000001e+00	2.737360000000000e-03
1964.	8.715420000000000e+00	2.581250000000000e-03
1965.	8.788349999999999e+00	2.485470000000000e-03
1966.	8.861890000000001e+00	2.415960000000000e-03
1967.	8.936050000000000e+00	2.337960000000000e-03
1968.	9.010830000000000e+00	2.200920000000000e-03
1969.	9.086230000000001e+00	2.094630000000000e-03
1970.	9.162270000000000e+00	2.034020000000000e-03
1971.	9.238940000000000e+00	1.945180000000000e-03
1972.	9.316250000000000e+00	1.860650000000000e-03
1973.	9.394209999999999e+00	1.746300000000000e-03
1974.	9.472820000000001e+00	1.670750000000000e-03
1975.	9.552090000000000e+00	1.580170000000000e-03
1976.	9.632030000000000e+00	1.504610000000000e-03
1977.	9.712630000000001e+00	1.433410000000000e-03
1978.	9.793910000000000e+00	1.349730000000000e-03
1979.	9.875859999999999e+00	1.297300000000000e-03
1980.	9.958510000000000e+00	1.232180000000000e-03
1981.	1.004180000000000e+01	1.170560000000000e-03
1982.	1.012590000000000e+01	1.104440000000000e-03
1983.	1.021060000000000e+01	1.049300000000000e-03
1984.	1.029610000000000e+01	9.967629999999999e-04
1985.	1.038220000000000e+01	9.387060000000000e-04
1986.	1.046910000000000e+01	9.084800000000000e-04
1987.	1.055670000000000e+01	8.635790000000000e-04
1988.	1.064500000000000e+01	8.170130000000000e-04
1989.	1.073410000000000e+01	7.792670000000001e-04
1990.	1.082390000000000e+01	7.334320000000000e-04
1991.	1.091450000000000e+01	6.947070000000000e-04
1992.	1.100580000000000e+01	6.412460000000001e-04
1993.	1.109800000000000e+01	5.924000000000000e-04
1994.	1.119080000000000e+01	5.609490000000000e-04
1995.	1.128450000000000e+01	5.254870000000001e-04
1996.	1.137890000000000e+01	4.969850000000000e-04
1997.	1.147410000000000e+01	4.696180000000000e-04
1998.	1.157010000000000e+01	4.330690000000000e-04
1999.	1.166700000000000e+01	4.177680000000000e-04
2000.	1.176460000000000e+01	3.894440000000000e-04
2001.	1.186300000000000e+01	3.643450000000000e-04
2002.	1.196230000000000e+01	3.433790000000000e-04
2003.	1.206240000000000e+01	3.220270000000000e-04
2004.	1.216330000000000e+01	3.093200000000000e-04
2005.	1.226510000000000e+01	2.880860000000000e-04
2006.	1.236780000000000e+01	2.684980000000000e-04
2007.	1.247130000000000e+01	2.517410000000000e-04
2008.	1.257560000000000e+01	2.361320000000000e-04
2009.	1.268090000000000e+01	2.167990000000000e-04
2010.	1.278700000000000e+01	2.065580000000000e-04
2011.	1.289400000000000e+01	1.911290000000000e-04
2012.	1.300190000000000e+01	1.810200000000000e-04
2013.	1.311070000000000e+01	1.659790000000000e-04
2014.	1.322040000000000e+01	1.516990000000000e-04
2015.	1.333100000000000e+01	1.426950000000000e-04
2016.	1.344260000000000e+01	1.329800000000000e-04
2017.	1.355510000000000e+01	1.272840000000000e-04
2018.	1.366850000000000e+01	1.144220000000000e-04
2019.	1.378290000000000e+01	1.066600000000000e-04
2020.	1.389820000000000e+01	9.959410000000000e-05
2021.	1.401450000000000e+01	9.105120000000001e-05
2022.	1.413180000000000e+01	8.623699999999999e-05
2023.	1.425010000000000e+01	7.894900000000001e-05
2024.	1.436930000000000e+01	7.192540000000000e-05
2025.	1.448950000000000e+01	6.945070000000000e-05
2026.	1.461080000000000e+01	6.414650000000000e-05
2027.	1.473310000000000e+01	5.820470000000000e-05
2028.	1.485630000000000e+01	5.080170000000000e-05
2029.	1.498070000000000e+01	4.602730000000000e-05
2030.	1.510600000000000e+01	4.348380000000000e-05
2031.	1.523240000000000e+01	4.082000000000000e-05
2032.	1.535990000000000e+01	3.767670000000000e-05
2033.	1.548840000000000e+01	3.413620000000000e-05
2034.	1.561800000000000e+01	3.285860000000000e-05

```
                    1.574870000000000e+01  2.851890000000000e-05
                    1.588050000000000e+01  2.736130000000000e-05
                    1.601340000000000e+01  2.418840000000000e-05
                    1.614740000000000e+01  2.237800000000000e-05
                    1.628250000000000e+01  2.035620000000000e-05
                    1.641880000000000e+01  1.787390000000000e-05
                    1.655620000000000e+01  1.732880000000000e-05
                    1.669470000000000e+01  1.613820000000000e-05
                    1.683440000000000e+01  1.400020000000000e-05
                    1.697530000000000e+01  1.317770000000000e-05
                    1.711740000000000e+01  1.203170000000000e-05
                    1.726060000000000e+01  1.125340000000000e-05
                    1.740500000000000e+01  9.941349999999999e-06
                    1.755070000000000e+01  9.948030000000001e-06
                    1.769760000000000e+01  7.985010000000000e-06
                    1.784570000000000e+01  7.041590000000000e-06
                    1.799500000000000e+01  5.705530000000000e-06
                    1.814560000000000e+01  6.062940000000000e-06
                    1.829740000000000e+01  5.288860000000000e-06
                    1.845050000000000e+01  4.709130000000000e-06
                    1.860490000000000e+01  4.795830000000000e-06
                    1.876060000000000e+01  4.181650000000000e-06
                    1.891760000000000e+01  3.391120000000000e-06
                    1.907590000000000e+01  3.353800000000000e-06
                    1.923560000000000e+01  2.414540000000000e-06
                    1.939650000000000e+01  2.701090000000000e-06
                    1.955880000000000e+01  2.384850000000000e-06
```

E.3.4 Safety rod, 3D axially finite cell with external source (fission spectrum)

In the following, the input file that defines a non-multiplying region cell (the absorbing bundle of the SR in this case) axially finite and radially infinite (*i.e.*, finite with reflective boundary conditions) with an external neutron source is defined. This file can be run independently.

Also in this case, the source is distributed in energy as the fission spectrum of the inner fuel, computed in the previous input (see §E.3.2) with the card “*det flx_spectrum de MyEnergyGrid df IF_src_1M_500a -1*”.

```
%% -- EXTERNAL FILE INCLUSION
include "/home/abrate/serpent2models/models/alfred/materials/eranos_jeff31.ml"  % materials
%% -- LIBRARY FOR NUCLEAR DATA
set acelib "/opt/serpent/xsdata/jeff31/sss_jeff31.xsdata"


% ------------------------ Radial coordinate -----------------------------------------------------------------------
% Core
surf s1 sqc 0.0 0.0 25        % wrapping inner perimeter

% Safety rod (SR)
surf z_tref     pz   80.0           % Upper reflector
surf z_safe_u   pz   30.0           % Fuel active zone upper limit
surf z_safe_b   pz  -30.0           % Fuel active zone lower limit
surf z_bref     pz  -80.0          % Bottom reflector

%-------------------------------------------------------------------------------------------------------------------
% -----------------------------------------------------------------------------------------------------------------
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% SAFETY ROD %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% safety rod assembly axial scan (universe definition to compute group-wise constants)
cell c1tref_GCU     SR_TOP_REF tref          z_safe_u  -z_tref    % upper reflector
cell c1a1_GCU       SR fill SR_TOP_REF       z_safe_u  -z_tref    % upper reflector
cell c3srod_u       AZ safehom               z_safe_b  -z_safe_u  % safety rod universe definition
cell c3srod         SR fill AZ               z_safe_b  -z_safe_u  % safety rod universe definition
cell c1ref_bo_GCU   SR_BOT_REF bref          z_bref    -z_safe_b  % bottom reflector
cell c1a9_GCU       SR fill SR_BOT_REF       z_bref    -z_safe_b  % bottom reflector
%-------------------------------------------------------------------------------------------------------------------
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% SAFETY ROD %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

lat core 3 0.0 0.0 5 5 17.1      % Core with CR and SR extracted
SR SR SR SR SR
SR SR SR SR SR
SR SR SR SR SR
SR SR SR SR SR
SR SR SR SR SR

%% ----------------------------------------------------------------------------------------------------------------------------------

cell c100 0 fill core -s1 z_bref -z_tref          % Filling the cylinder with the core
cell c101 0 outside s1    z_bref -z_tref          % Placing the vacuum outside the reactor
cell c104 0 outside       z_tref                  % Placing the vacuum above the reactor
cell c105 0 outside      -z_bref                  % Placing the vacuum below the reactor

%% -- PLOTS
plot 3 2000 2000  135
plot 3 2000 2000  48
plot 3 2000 2000  43
```

```
plot 3 2000 2000  31
plot 1 1000 1000 29.18505
plot 2 1000 1000

%% -- SIMULATION SETUP
set bc 2
%set fum nj19 %[ BTCH DUMMY LIM ] B1 leakage-corrected mode
set nps 10000000 100

set ures 1                % aggiunta il 3-09-18 per risolvere le risonanze dello spettro veloce
set his yes              % Check on fission source convergence

%% -- GROUP CONSTANT GENERATION
set micro nj19           % ECCO-33 groups
set nfg nj19
set gcu AZ

ene ECCO33 4 nj19
ene e2000 3 2000 1e-11 20

set xsplot 2000 1e-11 20

det tot     dr -1 void du AZ de ECCO33
det capt    dr -2 void du AZ de ECCO33
det flx               du AZ de ECCO33 % flux
det flxfine du AZ de e2000

src IF sb 1969 2 1.000000000000000e-11  0.000000000000000e+00
                 3.000000000000000e-09  1.116070000000000e-06
                 5.000000000000000e-09  2.241170000000000e-06
                 6.900000000000000e-09  3.522260000000000e-06
                 1.000000000000000e-08  9.483829999999999e-06
                 1.500000000000000e-08  2.712730000000000e-05
                 2.000000000000000e-08  4.535580000000000e-05
                 2.500000000000000e-08  6.573010000000000e-05
                 3.000000000000000e-08  9.134400000000000e-05
                 3.500000000000000e-08  1.217190000000000e-04
                 4.200000000000000e-08  2.275350000000000e-04
                 5.000000000000000e-08  3.451590000000000e-04
                 5.800000000000000e-08  4.496570000000000e-04
                 6.700000000000000e-08  6.405710000000000e-04
                 7.700000000000000e-08  8.819920000000000e-04
                 8.000000000000000e-08  3.026330000000000e-04
                 9.500000000000000e-08  1.790750000000000e-03
                 1.000000000000000e-07  7.015670000000000e-04
                 1.150000000000000e-07  2.430120000000000e-03
                 1.340000000000000e-07  3.805160000000000e-03
                 1.400000000000000e-07  1.365080000000000e-03
                 1.463700000000000e-07  1.534470000000000e-03
                 1.530300000000000e-07  1.703700000000000e-03
                 1.600000000000000e-07  1.885370000000000e-03
                 1.697100000000000e-07  2.804500000000000e-03
                 1.800000000000000e-07  3.185730000000000e-03
                 1.890000000000000e-07  2.972570000000000e-03
                 1.988100000000000e-07  3.424920000000000e-03
                 2.091400000000000e-07  3.821360000000000e-03
                 2.200000000000000e-07  4.238440000000000e-03
                 2.335800000000000e-07  5.601420000000000e-03
                 2.480000000000000e-07  6.328910000000000e-03
                 2.635100000000000e-07  7.205970000000000e-03
                 2.800000000000000e-07  8.101300000000001e-03
                 3.000000000000000e-07  1.038210000000000e-02
                 3.145000000000000e-07  7.885929999999999e-03
                 3.200000000000000e-07  3.064600000000000e-03
                 3.346600000000000e-07  8.364570000000000e-03
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456.	3.726650000000000e-05	3.756960000000000e-02
457.	3.757840000000000e-05	3.773340000000000e-02
458.	3.789290000000000e-05	3.782890000000000e-02
459.	3.820990000000000e-05	3.784630000000000e-02
460.	3.852970000000000e-05	3.788900000000000e-02
461.	3.885210000000000e-05	3.804580000000000e-02
462.	3.917720000000000e-05	3.820910000000000e-02
463.	3.950510000000000e-05	3.829210000000000e-02
464.	3.983560000000000e-05	3.841200000000000e-02
465.	4.016900000000000e-05	3.854920000000000e-02
466.	4.050510000000000e-05	3.866950000000000e-02
467.	4.084410000000000e-05	3.866930000000000e-02
468.	4.118590000000000e-05	3.859330000000000e-02
469.	4.153050000000000e-05	3.838010000000000e-02
470.	4.187810000000000e-05	3.824590000000000e-02
471.	4.222850000000000e-05	3.851780000000000e-02
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477.	4.439360000000000e-05	3.648340000000000e-02
478.	4.476510000000000e-05	3.267800000000000e-02
479.	4.513970000000000e-05	3.197940000000000e-02
480.	4.551740000000000e-05	3.832430000000000e-02
481.	4.589830000000000e-05	4.312420000000000e-02
482.	4.628240000000000e-05	4.450110000000000e-02
483.	4.666970000000000e-05	4.493700000000000e-02
484.	4.706030000000000e-05	4.521070000000000e-02
485.	4.745410000000000e-05	4.535740000000000e-02
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490.	4.947310000000000e-05	4.597130000000000e-02
491.	4.988710000000000e-05	4.601830000000000e-02
492.	5.030460000000000e-05	4.608310000000000e-02
493.	5.072550000000000e-05	4.625870000000000e-02
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795.	6.283490000000001e-04	9.276590000000000e-02
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807.	6.944330000000001e-04	9.462270000000000e-02
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1442.	1.334430000000000e-01	8.119770000000000e-01
1443.	1.345600000000000e-01	8.517540000000000e-01
1444.	1.356860000000000e-01	8.397930000000000e-01
1445.	1.368210000000000e-01	8.010210000000000e-01
1446.	1.379660000000000e-01	7.260690000000000e-01
1447.	1.391210000000000e-01	5.988850000000000e-01
1448.	1.402850000000000e-01	3.900140000000000e-01
1449.	1.414590000000000e-01	2.842530000000000e-01
1450.	1.426420000000000e-01	3.243430000000000e-01
1451.	1.438360000000000e-01	3.813510000000000e-01
1452.	1.450400000000000e-01	4.312850000000000e-01
1453.	1.462530000000000e-01	4.695530000000000e-01
1454.	1.474770000000000e-01	4.718070000000000e-01
1455.	1.487110000000000e-01	5.056810000000001e-01
1456.	1.499560000000000e-01	4.973990000000000e-01
1457.	1.512110000000000e-01	4.648670000000000e-01
1458.	1.524760000000000e-01	5.717520000000000e-01
1459.	1.537520000000000e-01	5.362150000000000e-01
1460.	1.550380000000000e-01	5.902100000000000e-01
1461.	1.563360000000000e-01	5.958160000000000e-01
1462.	1.576440000000000e-01	6.107640000000000e-01
1463.	1.589630000000000e-01	6.330070000000000e-01
1464.	1.602940000000000e-01	6.275640000000000e-01
1465.	1.616350000000000e-01	6.550610000000000e-01
1466.	1.629880000000000e-01	6.628810000000001e-01
1467.	1.643510000000000e-01	6.688850000000000e-01
1468.	1.657270000000000e-01	6.742640000000000e-01
1469.	1.671140000000000e-01	6.556840000000000e-01
1470.	1.685120000000000e-01	6.219140000000000e-01
1471.	1.699220000000000e-01	4.296830000000000e-01
1472.	1.713440000000000e-01	4.726350000000000e-01
1473.	1.727780000000000e-01	5.605560000000001e-01
1474.	1.742240000000000e-01	5.732380000000000e-01
1475.	1.756820000000000e-01	6.678190000000001e-01
1476.	1.771520000000000e-01	7.299070000000000e-01
1477.	1.786340000000000e-01	7.581240000000000e-01
1478.	1.801290000000000e-01	7.355920000000000e-01
1479.	1.816360000000000e-01	7.112210000000000e-01
1480.	1.831560000000000e-01	7.337260000000000e-01
1481.	1.846890000000000e-01	6.859070000000000e-01
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1492.	2.024190000000000e-01	5.544240000000000e-01
1493.	2.041130000000000e-01	5.780640000000000e-01
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1537.	2.945180000000000e-01	6.264000000000000e-01
1538.	2.969830000000000e-01	7.094850000000000e-01
1539.	2.972000000000000e-01	6.510940000000000e-02
1540.	2.985000000000000e-01	3.708430000000000e-01
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1603.	5.020370000000000e-01	6.261610000000000e-01
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1607.	5.190530000000000e-01	6.730870000000000e-01
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1609.	5.277770000000001e-01	4.526840000000000e-01
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1611.	5.366470000000000e-01	5.230350000000000e-01
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1613.	5.456660000000000e-01	5.373870000000000e-01
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1622.	5.881650000000001e-01	5.863880000000000e-01
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1627.	6.131890000000000e-01	5.084050000000000e-01
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1629.	6.234950000000000e-01	5.339240000000000e-01
1630.	6.287120000000001e-01	5.451050000000000e-01
1631.	6.339730000000000e-01	5.355720000000001e-01
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1639.	6.776790000000000e-01	4.060600000000000e-01
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1647.	7.243980000000000e-01	3.012920000000000e-01
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1651.	7.489510000000000e-01	3.601280000000000e-01
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1657.	7.873510000000000e-01	3.514010000000000e-01
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1659.	8.005830000000000e-01	3.606560000000000e-01
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1661.	8.140380000000000e-01	3.539260000000000e-01
1662.	8.208500000000000e-01	2.507760000000000e-01
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1664.	8.346460000000000e-01	2.981060000000000e-01
1665.	8.416300000000000e-01	3.015490000000000e-01
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1667.	8.557750000000000e-01	2.529910000000000e-01
1668.	8.629360000000000e-01	2.387610000000000e-01
1669.	8.701570000000000e-01	2.361010000000000e-01
1670.	8.774390000000000e-01	2.403070000000000e-01
1671.	8.847810000000000e-01	2.455170000000000e-01
1672.	8.921850000000000e-01	2.195190000000000e-01
1673.	8.996510000000000e-01	2.439570000000000e-01
1674.	9.071800000000000e-01	2.153320000000000e-01
1675.	9.147710000000000e-01	2.168470000000000e-01
1676.	9.224260000000000e-01	2.121510000000000e-01
1677.	9.301450000000000e-01	2.156280000000000e-01
1678.	9.379290000000000e-01	2.147560000000000e-01
1679.	9.457770000000000e-01	2.122420000000000e-01
1680.	9.536920000000000e-01	1.737050000000000e-01
1681.	9.616720000000000e-01	1.879650000000000e-01
1682.	9.697200000000000e-01	1.609330000000000e-01
1683.	9.778340000000000e-01	1.542390000000000e-01
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1685.	9.942680000000000e-01	1.403350000000000e-01
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1691.	1.045240000000000e+00	1.560090000000000e-01
1692.	1.053990000000000e+00	1.619800000000000e-01
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1695.	1.080670000000000e+00	1.908340000000000e-01
1696.	1.089720000000000e+00	1.978020000000000e-01

1697.	1.098840000000000e+00	2.023000000000000e-01
1698.	1.108030000000000e+00	2.058620000000000e-01
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1710.	1.224560000000000e+00	2.190090000000000e-01
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1739.	1.559320000000000e+00	1.323340000000000e-01
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1742.	1.598800000000000e+00	1.374200000000000e-01
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1764.	1.920500000000000e+00	9.754910000000000e-02
1765.	1.936570000000000e+00	1.020150000000000e-01
1766.	1.952780000000000e+00	1.026210000000000e-01
1767.	1.969120000000000e+00	1.059080000000000e-01
1768.	1.985590000000000e+00	1.091000000000000e-01
1769.	2.002210000000000e+00	1.102470000000000e-01
1770.	2.018970000000000e+00	1.097940000000000e-01
1771.	2.035860000000000e+00	1.095860000000000e-01
1772.	2.052900000000000e+00	1.008610000000000e-01
1773.	2.070080000000000e+00	1.018450000000000e-01
1774.	2.087400000000000e+00	1.030980000000000e-01
1775.	2.104870000000000e+00	1.128580000000000e-01
1776.	2.122480000000000e+00	1.016510000000000e-01
1777.	2.140240000000000e+00	1.085790000000000e-01
1778.	2.158150000000000e+00	1.049580000000000e-01
1779.	2.176210000000000e+00	1.062340000000000e-01
1780.	2.194420000000000e+00	1.042230000000000e-01
1781.	2.212780000000000e+00	1.066840000000000e-01
1782.	2.231300000000000e+00	1.119460000000000e-01
1783.	2.249970000000000e+00	1.129790000000000e-01
1784.	2.268800000000000e+00	1.153230000000000e-01
1785.	2.287790000000000e+00	1.074820000000000e-01
1786.	2.306930000000000e+00	1.098030000000000e-01
1787.	2.326240000000000e+00	1.093200000000000e-01
1788.	2.345700000000000e+00	1.062780000000000e-01
1789.	2.365330000000000e+00	1.116970000000000e-01
1790.	2.385130000000000e+00	1.141660000000000e-01
1791.	2.405090000000000e+00	1.006170000000000e-01
1792.	2.425210000000000e+00	9.911510000000000e-02
1793.	2.445500000000000e+00	9.264840000000001e-02

1794.	2.465970000000000e+00	9.793520000000000e-02
1795.	2.486600000000000e+00	9.598530000000000e-02
1796.	2.507410000000000e+00	8.972310000000000e-02
1797.	2.528400000000000e+00	9.145720000000000e-02
1798.	2.549550000000000e+00	8.621590000000000e-02
1799.	2.570890000000000e+00	8.983160000000000e-02
1800.	2.592400000000000e+00	9.378670000000000e-02
1801.	2.614100000000000e+00	9.180960000000001e-02
1802.	2.635970000000000e+00	8.764230000000001e-02
1803.	2.658030000000000e+00	8.749750000000001e-02
1804.	2.680270000000000e+00	8.298050000000000e-02
1805.	2.702700000000000e+00	8.312319999999999e-02
1806.	2.725320000000000e+00	8.225739999999999e-02
1807.	2.748120000000000e+00	8.037370000000001e-02
1808.	2.771120000000000e+00	7.536510000000000e-02
1809.	2.794310000000000e+00	7.322470000000000e-02
1810.	2.817690000000000e+00	7.718620000000000e-02
1811.	2.841270000000000e+00	7.494480000000001e-02
1812.	2.865050000000000e+00	6.970050000000000e-02
1813.	2.889020000000000e+00	7.239030000000001e-02
1814.	2.913200000000000e+00	7.103600000000000e-02
1815.	2.937580000000000e+00	7.044839999999999e-02
1816.	2.962160000000000e+00	6.622630000000000e-02
1817.	2.986950000000000e+00	6.744799999999999e-02
1818.	3.011940000000000e+00	6.733920000000000e-02
1819.	3.037150000000000e+00	6.399070000000000e-02
1820.	3.062560000000000e+00	6.541360000000000e-02
1821.	3.088190000000000e+00	6.333490000000000e-02
1822.	3.114030000000000e+00	6.426680000000000e-02
1823.	3.140090000000000e+00	6.028510000000000e-02
1824.	3.166370000000000e+00	5.914030000000000e-02
1825.	3.192860000000000e+00	5.856360000000000e-02
1826.	3.219580000000000e+00	5.612590000000000e-02
1827.	3.246530000000000e+00	5.449780000000000e-02
1828.	3.273690000000000e+00	5.132030000000000e-02
1829.	3.301090000000000e+00	4.909350000000000e-02
1830.	3.328710000000000e+00	4.874400000000000e-02
1831.	3.356570000000000e+00	4.799790000000000e-02
1832.	3.384650000000000e+00	4.626270000000000e-02
1833.	3.412980000000000e+00	4.627940000000000e-02
1834.	3.441540000000000e+00	4.609310000000000e-02
1835.	3.470340000000000e+00	4.483130000000000e-02
1836.	3.499380000000000e+00	4.254280000000000e-02
1837.	3.528660000000000e+00	4.386700000000000e-02
1838.	3.558190000000000e+00	4.197760000000000e-02
1839.	3.587970000000000e+00	4.158770000000000e-02
1840.	3.617990000000000e+00	4.019030000000000e-02
1841.	3.648260000000000e+00	3.988240000000000e-02
1842.	3.678790000000000e+00	3.861090000000000e-02
1843.	3.709580000000000e+00	3.840140000000000e-02
1844.	3.740620000000000e+00	3.774740000000000e-02
1845.	3.771920000000000e+00	3.472880000000000e-02
1846.	3.803490000000000e+00	3.582820000000000e-02
1847.	3.835320000000000e+00	3.712090000000000e-02
1848.	3.867410000000000e+00	3.641570000000000e-02
1849.	3.899770000000000e+00	3.628970000000000e-02
1850.	3.932410000000000e+00	3.600400000000000e-02
1851.	3.965310000000000e+00	3.487160000000000e-02
1852.	3.998500000000000e+00	3.509890000000000e-02
1853.	4.031960000000000e+00	3.475750000000000e-02
1854.	4.065700000000000e+00	3.482960000000000e-02
1855.	4.099720000000000e+00	3.531230000000000e-02
1856.	4.134030000000000e+00	3.416840000000000e-02
1857.	4.168620000000000e+00	3.178310000000000e-02
1858.	4.203500000000000e+00	3.019110000000000e-02
1859.	4.238680000000000e+00	3.098170000000000e-02
1860.	4.274150000000000e+00	3.069480000000000e-02
1861.	4.309920000000000e+00	2.900190000000000e-02
1862.	4.345980000000000e+00	2.591900000000000e-02
1863.	4.382350000000000e+00	2.606290000000000e-02
1864.	4.419020000000000e+00	2.632170000000000e-02
1865.	4.456000000000000e+00	2.662000000000000e-02
1866.	4.493290000000000e+00	2.617120000000000e-02
1867.	4.530890000000000e+00	2.591350000000000e-02
1868.	4.568810000000000e+00	2.457520000000000e-02
1869.	4.607040000000000e+00	2.510910000000000e-02
1870.	4.645590000000000e+00	2.425340000000000e-02
1871.	4.684470000000000e+00	2.496530000000000e-02
1872.	4.723670000000000e+00	2.431520000000000e-02
1873.	4.763190000000000e+00	2.462060000000000e-02
1874.	4.803050000000000e+00	2.358440000000000e-02
1875.	4.843250000000000e+00	2.161530000000000e-02
1876.	4.883770000000000e+00	2.115690000000000e-02
1877.	4.924640000000000e+00	2.168650000000000e-02
1878.	4.965850000000000e+00	2.145700000000000e-02
1879.	5.007410000000000e+00	2.118020000000000e-02
1880.	5.049310000000000e+00	2.045200000000000e-02
1881.	5.091560000000000e+00	1.919590000000000e-02
1882.	5.134170000000000e+00	1.784510000000000e-02
1883.	5.177130000000000e+00	1.801800000000000e-02
1884.	5.220460000000000e+00	1.848650000000000e-02
1885.	5.264140000000000e+00	1.840610000000000e-02
1886.	5.308200000000000e+00	1.790620000000000e-02
1887.	5.352610000000000e+00	1.701460000000000e-02
1888.	5.397410000000000e+00	1.715950000000000e-02
1889.	5.442570000000000e+00	1.698790000000000e-02
1890.	5.488120000000000e+00	1.641160000000000e-02

1891.	5.534040000000000e+00	1.596200000000000e-02
1892.	5.580350000000000e+00	1.527260000000000e-02
1893.	5.627050000000000e+00	1.429940000000000e-02
1894.	5.674140000000000e+00	1.384790000000000e-02
1895.	5.721620000000000e+00	1.380230000000000e-02
1896.	5.769500000000000e+00	1.367600000000000e-02
1897.	5.817780000000000e+00	1.345410000000000e-02
1898.	5.866460000000000e+00	1.330680000000000e-02
1899.	5.915550000000000e+00	1.286790000000000e-02
1900.	5.965060000000000e+00	1.208960000000000e-02
1901.	6.014970000000000e+00	1.236520000000000e-02
1902.	6.065310000000000e+00	1.198730000000000e-02
1903.	6.116060000000000e+00	1.173230000000000e-02
1904.	6.167240000000000e+00	1.171750000000000e-02
1905.	6.218850000000000e+00	1.143180000000000e-02
1906.	6.270890000000000e+00	1.105700000000000e-02
1907.	6.323370000000000e+00	1.082770000000000e-02
1908.	6.376280000000000e+00	1.024190000000000e-02
1909.	6.429640000000000e+00	9.650350000000000e-03
1910.	6.483440000000000e+00	1.005120000000000e-02
1911.	6.537700000000000e+00	9.847079999999999e-03
1912.	6.592410000000000e+00	9.332890000000000e-03
1913.	6.647570000000000e+00	8.954350000000000e-03
1914.	6.703200000000000e+00	8.631710000000001e-03
1915.	6.759290000000000e+00	8.368479999999999e-03
1916.	6.815860000000000e+00	7.910860000000001e-03
1917.	6.872890000000000e+00	7.800890000000000e-03
1918.	6.930410000000000e+00	7.784870000000000e-03
1919.	6.988400000000000e+00	7.577790000000000e-03
1920.	7.046880000000000e+00	7.265660000000000e-03
1921.	7.105850000000000e+00	6.934150000000000e-03
1922.	7.165310000000000e+00	6.664390000000000e-03
1923.	7.225270000000000e+00	6.123680000000000e-03
1924.	7.285740000000000e+00	6.030610000000000e-03
1925.	7.346700000000000e+00	5.850070000000000e-03
1926.	7.408180000000000e+00	5.677350000000000e-03
1927.	7.470180000000000e+00	5.543850000000000e-03
1928.	7.532690000000000e+00	5.406720000000000e-03
1929.	7.595720000000000e+00	5.220210000000000e-03
1930.	7.659280000000000e+00	5.026910000000000e-03
1931.	7.723380000000000e+00	4.806420000000000e-03
1932.	7.788010000000000e+00	4.559440000000000e-03
1933.	7.853180000000000e+00	4.329160000000000e-03
1934.	7.918900000000000e+00	4.208470000000000e-03
1935.	7.985160000000000e+00	4.179590000000000e-03
1936.	8.051980000000000e+00	4.101210000000000e-03
1937.	8.119360000000000e+00	3.905830000000000e-03
1938.	8.187310000000000e+00	3.647790000000000e-03
1939.	8.255820000000000e+00	3.446520000000000e-03
1940.	8.324909999999999e+00	3.294950000000000e-03
1941.	8.394570000000000e+00	3.187590000000000e-03
1942.	8.464820000000000e+00	3.078360000000000e-03
1943.	8.535650000000000e+00	3.003220000000000e-03
1944.	8.607080000000000e+00	2.889350000000000e-03
1945.	8.679100000000000e+00	2.737360000000000e-03
1946.	8.751730000000000e+00	2.581250000000000e-03
1947.	8.824970000000000e+00	2.485470000000000e-03
1948.	8.898820000000001e+00	2.415960000000000e-03
1949.	8.973280000000001e+00	2.337960000000000e-03
1950.	9.048370000000000e+00	2.200920000000000e-03
1951.	9.124090000000001e+00	2.094630000000000e-03
1952.	9.200440000000000e+00	2.034020000000000e-03
1953.	9.277440000000000e+00	1.945180000000000e-03
1954.	9.355070000000000e+00	1.860650000000000e-03
1955.	9.433350000000001e+00	1.746300000000000e-03
1956.	9.512290000000000e+00	1.670750000000000e-03
1957.	9.591889999999999e+00	1.580170000000000e-03
1958.	9.672160000000000e+00	1.504610000000000e-03
1959.	9.753100000000000e+00	1.433410000000000e-03
1960.	9.834709999999999e+00	1.349730000000000e-03
1961.	9.917009999999999e+00	1.297300000000000e-03
1962.	1.000000000000000e+01	1.232180000000000e-03
1963.	1.008370000000000e+01	1.170560000000000e-03
1964.	1.016810000000000e+01	1.104440000000000e-03
1965.	1.025310000000000e+01	1.049300000000000e-03
1966.	1.033900000000000e+01	9.967629999999999e-04
1967.	1.042550000000000e+01	9.387060000000000e-04
1968.	1.051270000000000e+01	9.084800000000000e-04
1969.	1.060070000000000e+01	8.635790000000000e-04
1970.	1.068940000000000e+01	8.170130000000000e-04
1971.	1.077880000000000e+01	7.792670000000001e-04
1972.	1.086900000000000e+01	7.334320000000000e-04
1973.	1.096000000000000e+01	6.947070000000000e-04
1974.	1.105170000000000e+01	6.412460000000001e-04
1975.	1.114420000000000e+01	5.924000000000000e-04
1976.	1.123750000000000e+01	5.609490000000000e-04
1977.	1.133150000000000e+01	5.254870000000001e-04
1978.	1.142630000000000e+01	4.969850000000000e-04
1979.	1.152190000000000e+01	4.696180000000000e-04
1980.	1.161830000000000e+01	4.330690000000000e-04
1981.	1.171560000000000e+01	4.177680000000000e-04
1982.	1.181360000000000e+01	3.894440000000000e-04
1983.	1.191250000000000e+01	3.643450000000000e-04
1984.	1.201220000000000e+01	3.433790000000000e-04
1985.	1.211270000000000e+01	3.220270000000000e-04
1986.	1.221400000000000e+01	3.093200000000000e-04
1987.	1.231620000000000e+01	2.880860000000000e-04

```
1988.                    1.241930000000000e+01  2.684980000000000e-04
1989.                    1.252320000000000e+01  2.517410000000000e-04
1990.                    1.262800000000000e+01  2.361320000000000e-04
1991.                    1.273370000000000e+01  2.167990000000000e-04
1992.                    1.284020000000000e+01  2.065580000000000e-04
1993.                    1.294770000000000e+01  1.911290000000000e-04
1994.                    1.305610000000000e+01  1.810200000000000e-04
1995.                    1.316530000000000e+01  1.659790000000000e-04
1996.                    1.327550000000000e+01  1.516990000000000e-04
1997.                    1.338660000000000e+01  1.426950000000000e-04
1998.                    1.349860000000000e+01  1.329800000000000e-04
1999.                    1.361150000000000e+01  1.272840000000000e-04
2000.                    1.372550000000000e+01  1.144220000000000e-04
2001.                    1.384030000000000e+01  1.066600000000000e-04
2002.                    1.395610000000000e+01  9.959410000000000e-05
2003.                    1.407290000000000e+01  9.105120000000001e-05
2004.                    1.419070000000000e+01  8.623699999999999e-05
2005.                    1.430940000000000e+01  7.894900000000001e-05
2006.                    1.442920000000000e+01  7.192540000000000e-05
2007.                    1.454990000000000e+01  6.945070000000000e-05
2008.                    1.467170000000000e+01  6.414650000000000e-05
2009.                    1.479440000000000e+01  5.820470000000000e-05
2010.                    1.491830000000000e+01  5.080170000000000e-05
2011.                    1.504310000000000e+01  4.602730000000000e-05
2012.                    1.516900000000000e+01  4.348380000000000e-05
2013.                    1.529590000000000e+01  4.082000000000000e-05
2014.                    1.542390000000000e+01  3.767670000000000e-05
2015.                    1.555300000000000e+01  3.413620000000000e-05
2016.                    1.568310000000000e+01  3.285860000000000e-05
2017.                    1.581440000000000e+01  2.851890000000000e-05
2018.                    1.594670000000000e+01  2.736130000000000e-05
2019.                    1.608010000000000e+01  2.418840000000000e-05
2020.                    1.621470000000000e+01  2.237800000000000e-05
2021.                    1.635040000000000e+01  2.035620000000000e-05
2022.                    1.648720000000000e+01  1.787390000000000e-05
2023.                    1.662520000000000e+01  1.732880000000000e-05
2024.                    1.676430000000000e+01  1.613820000000000e-05
2025.                    1.690460000000000e+01  1.400020000000000e-05
2026.                    1.704610000000000e+01  1.317770000000000e-05
2027.                    1.718870000000000e+01  1.203170000000000e-05
2028.                    1.733250000000000e+01  1.125340000000000e-05
2029.                    1.747760000000000e+01  9.941349999999999e-06
2030.                    1.762380000000000e+01  9.948030000000001e-06
2031.                    1.777130000000000e+01  7.985010000000000e-06
2032.                    1.792000000000000e+01  7.041590000000000e-06
2033.                    1.807000000000000e+01  5.705530000000000e-06
2034.                    1.822120000000000e+01  6.062940000000000e-06
2035.                    1.837370000000000e+01  5.288860000000000e-06
2036.                    1.852740000000000e+01  4.709130000000000e-06
2037.                    1.868250000000000e+01  4.795830000000000e-06
2038.                    1.883880000000000e+01  4.181650000000000e-06
2039.                    1.899640000000000e+01  3.391120000000000e-06
2040.                    1.915540000000000e+01  3.353800000000000e-06
2041.                    1.931570000000000e+01  2.414540000000000e-06
2042.                    1.947730000000000e+01  2.701090000000000e-06
2043.                    1.964030000000000e+01  2.384850000000000e-06
```

E.4 Input files for the core models

In the following, the main input file for the 3D core model is reported.

```
%% -- EXTERNAL FILE INCLUSION

include "eranos_jeff31.ml"  % materials
include "ALFRED_ECCO.ge"  % geometry

%% -- LIBRARY FOR NUCLEAR DATA
set acelib "/opt/serpent/xsdata/jeff31/sss_jeff31.xsdata"

%% -- SIMULATION SETUP
trans u SR 0 0 -84         % Translate Control Rod to insert/withdrawn
trans u CR 0 0 68          % Translate Control Rod to insert/withdrawn

set pop 1000000 500 100       % Population data
src ALFRED_FC_src_1M_500i sf ALFRED_FC_src_1M_500i 1  % external fisson source (scored from a previous run)

set power 300000000           % Total thermal power [W]
set ures 1                    % sample unresolved resonance region tables

set his yes              % Check on fission source convergence

%% -- GROUP CONSTANT GENERATION
set micro nj19           % ECCO-33 groups
set nfg nj19
set gcu        IF_TOP_REF
               IF_TOP_PLUG
               IF_SPRING
               IF_TOP_INS
```

```
                INN_FUEL
                IF_BOT_INS
                IF_PLEN
                IF_BOT_PLUG
                IF_BOT_REF
                OUT_FUEL
                SR_ACT
                CR_DUMM
                CR_ACT
                DR_DUMM
                BA
                ll
```

E.5 Input files for the detector definitions (“traverses.de”)

In this file, the tallies to score the flux and power values over each assembly are defined.

```
% assembly-wise power map
set cpd 1 [20 -30 30]

% power
det POW dh 3 0 0 17.1 32 32 -30 30 20 du core dr -8 void

% flux
det FLX dh 3 0 0 17.1 32 32 -170 170 17 du core
```