4th RCM meeting on « updated codes and methods to reduce the calculational uncertainties of the LMFR reactivity effects »

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European ERANOS formulaire for Fast Reactor Core Analysis

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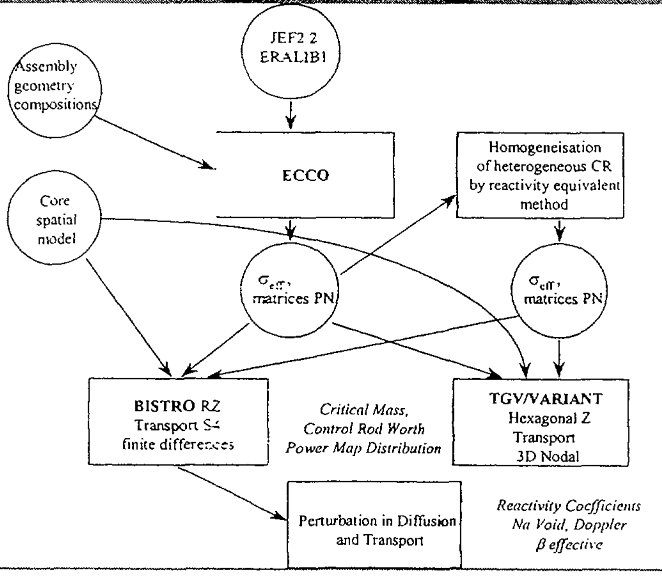
ERANOS Code Scheme

ERANOS code scheme
developed within the European collaboration on fast reactors

- Contains all the functions required to calculate a complete set of core, shielding and fuel cycle parameters for LMFR cores
- Nuclear data taken from recent evaluations (JEF2.2) and adjusted on integral experiments (ERALIB1)
- Calculational scheme uses the ECCO cell code to generate cross section data
- Whole core calculations carried out using the spatial modules BISTRO (Sn) and TGV/VARIANT (nodal)
- Validation based on integral and power reactor experiments
- Integral experiments also used for adjustment of nuclear data

ERANOS Reference Scheme for Core Calculations



JEF2.2
ERALIB1

Assembly geometry compositions

Core spatial model

ECCO

σ_{eff}, matrices PN

Homogeneisation of heterogeneous CR by reactivity equivalent method

σ_{eff}, matrices PN

BISTRO RZ
Transport S4
finite differences

Critical Mass,
Control Rod Worth
Power Map Distribution

TGV/VARIANT
Hexagonal Z
Transport
3D Nodal

Perturbation in Diffusion and Transport

Reactivity Coefficients
Na Void, Doppler
β effective

JEF2.2 Nuclear Data

- The nuclear data used for this analysis is based on the JEF2.2 nuclear data evaluation
- Clean core measurements performed in the MASURCA, ZEBRA and SNEAK facilities have been selected to assess the performance of the JEF2.2 library

	Average (C-E)/E	Standard Deviation
Critical Mass	+323 pcm	1460 pcm
Buckling	-210 pcm	1200 pcm
K-infinity	-50 pcm	2200 pcm
Spectral Indices f(Pu239)/f(U235)	+1.1 %	2.6 %
f(U238)/f(U235)	-1.0 %	3.7 %
c(U238)/F(U235)	+1.4 %	2.2 %
f(Pu240)/f(U235)	-4.0 %	8.6 %
f(Pu241)/f(U235)	-1.4 %	5.0 %
f(Pu242)/f(U235)	-5.2 %	8.0 %
c(B10)/F(U235)	-2.0 %	2.3 %

- The results are satisfactory but are associated with large uncertainties

ERANOS Validation

- Numerical validation of individual algorithms
- Analysis of clean integral experiments
- Sensitivity calculations
- Analysis of power reactor experiments (Super-Phenix startup)
- Determination of uncertainties on reactor values
- Analysis of experiments specific to safety performance
  - SNEAK 12A & B, CONRAD safety configurations
- Complementary validation for advanced reactor concepts
  - mock-up experiments in zero power reactors (e.g. MASURCA)
  - representative experiments in power reactors (e.g. PHENIX)

Experimental Data for LMFR Reactivity Effects: Pu Enrichment

- CIRANO experimental programme at the MASURCA facility dedicated to studying the physical characteristics of the CAPRA/CADRA core configurations

- replacement of fertile UO_2 blankets by steel reflectors
  - substitution at the core centre of fuels with different isotopic vectors (Pu240 content varying from 8% to 35%)
  - substitution at the core centre of fuels with increased plutonium enrichments and corresponding fuel dilution (plutonium enrichment varying from 25% to 40%)
  - Most of these physical changes are well predicted by calculation

- Substantially increased understanding of the physical characteristics associated with highly enriched steel reflected LMFR cores

ERALIB1

- An adjusted data library ERALIB1 is available for use with the ERANOS code scheme
- Adjustment based on the JEF2.2 evaluation using a least square method generalised to both integral parameters and nuclear data
- Experimental data base includes over 300 integral experiments covering a wide range of systems and applications
- Function to be minimised is :

  $$F = (\sigma - \sigma_0)^t M^{-1} (\sigma - \sigma_0) + (E - C)^t I^{-1} (E - C)$$

  - where : σ_0 is the JEF2.2 multigroup cross section with associated uncertainty,
  - E - C is the difference between calculation and experiment

    σ is the unknown true multigroup cross section value

ERALIB1

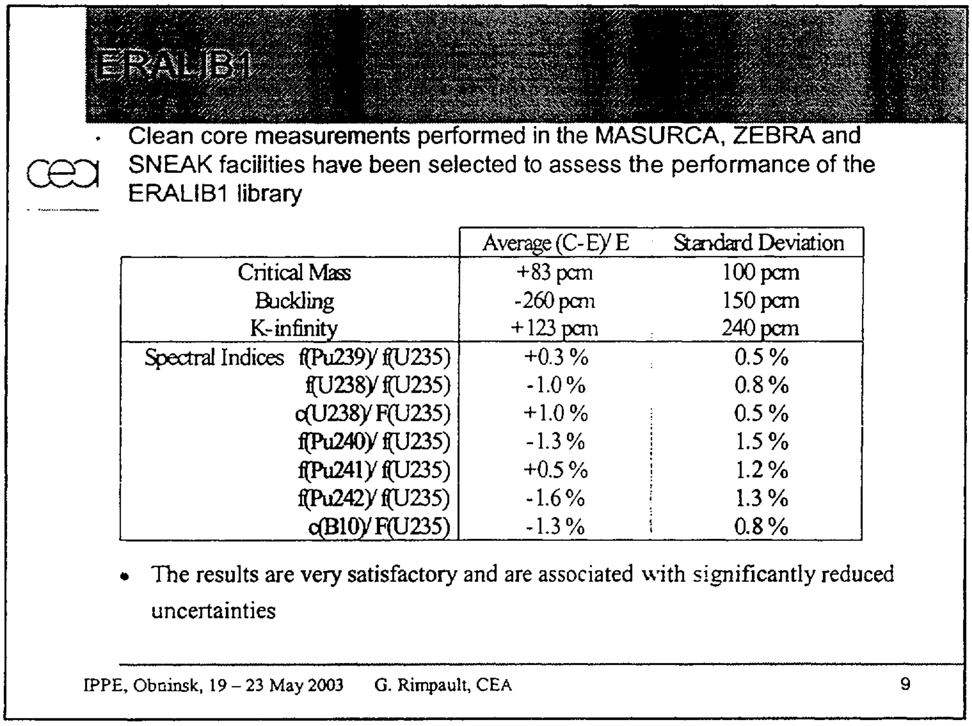
Sensitivities of the integral parameters are calculated using direct and generalised perturbation theory

$$\frac{E-C}{C} = S\frac{\sigma-\sigma_0}{\sigma_0}$$

- The quality of the adjusted s values is measured by the value χ^2

$$\chi^2 = N \pm \sqrt{2N} \; or \; \frac{\chi^2}{N} = 1 \pm \sqrt{\frac{2}{N}}$$

Where N is the number degrees of freedom of the number of integral data

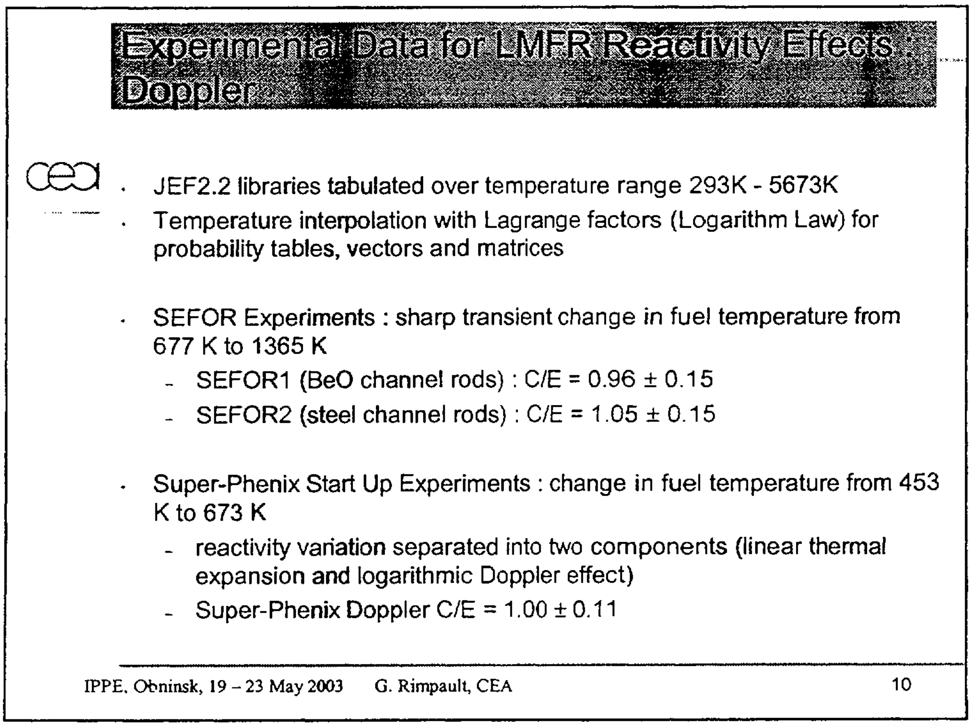


ERALIB1

- Clean core measurements performed in the MASURCA, ZEBRA and SNEAK facilities have been selected to assess the performance of the ERALIB1 library

	Average (C-E)/ E	Standard Deviation
Critical Mass	+83 pcm	100 pcm
Buckling	-260 pcm	150 pcm
K-infinity	+123 pcm	240 pcm
Spectral Indices f(Pu239)/ f(U235)	+0.3 %	0.5 %
f(U238)/ f(U235)	-1.0 %	0.8 %
c(U238)/ F(U235)	+1.0 %	0.5 %
f(Pu240)/ f(U235)	-1.3 %	1.5 %
f(Pu241)/ f(U235)	+0.5 %	1.2 %
f(Pu242)/ f(U235)	-1.6 %	1.3 %
c(B10)/ F(U235)	-1.3 %	0.8 %

- The results are very satisfactory and are associated with significantly reduced uncertainties



Experimental Data for LMFR Reactivity Effects : Doppler

- JEF2.2 libraries tabulated over temperature range 293K - 5673K
- Temperature interpolation with Lagrange factors (Logarithm Law) for probability tables, vectors and matrices

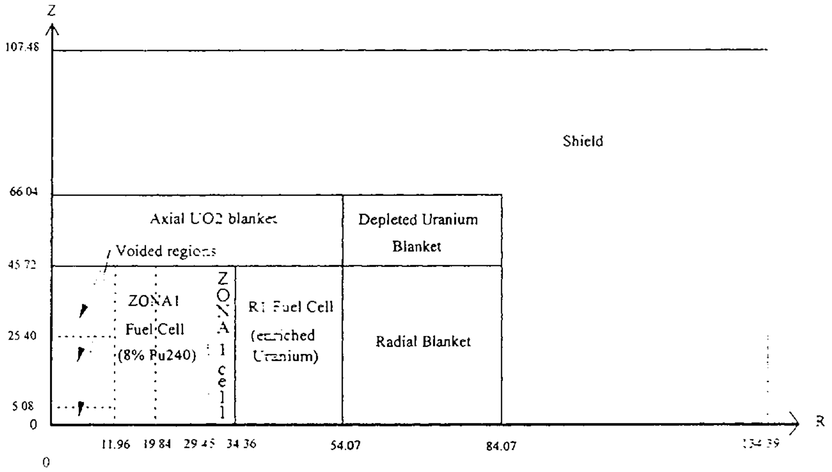
- SEFOR Experiments : sharp transient change in fuel temperature from 677 K to 1365 K
  - SEFOR1 (BeO channel rods) : C/E = 0.96 ± 0.15
  - SEFOR2 (steel channel rods) : C/E = 1.05 ± 0.15

- Super-Phenix Start Up Experiments : change in fuel temperature from 453 K to 673 K
  - reactivity variation separated into two components (linear thermal expansion and logarithmic Doppler effect)
  - Super-Phenix Doppler C/E = 1.00 ± 0.11

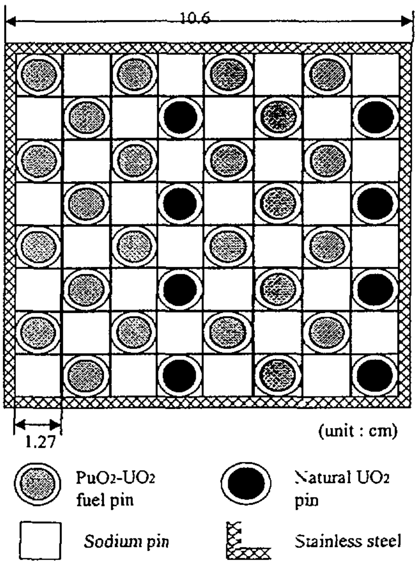
Experimental Data for LMFR Reactivity Effects : Sodium Void

- MASURCA configurations containing voided zones with different heights and radii
  - ZONA1 cores (PRE-RACINE programme)
    - 8% and 18% Pu240 content in fuel
  - ZONA2 cores (CIRANO programme)
    - 8%, 18% and 30% Pu240 content in fuel
- Increase of sodium void reactivity worth when degrading the plutonium quality is well reproduced by calculation
- Decrease of sodium void reactivity worth when increasing the plutonium enrichment is well reproduced by calculation

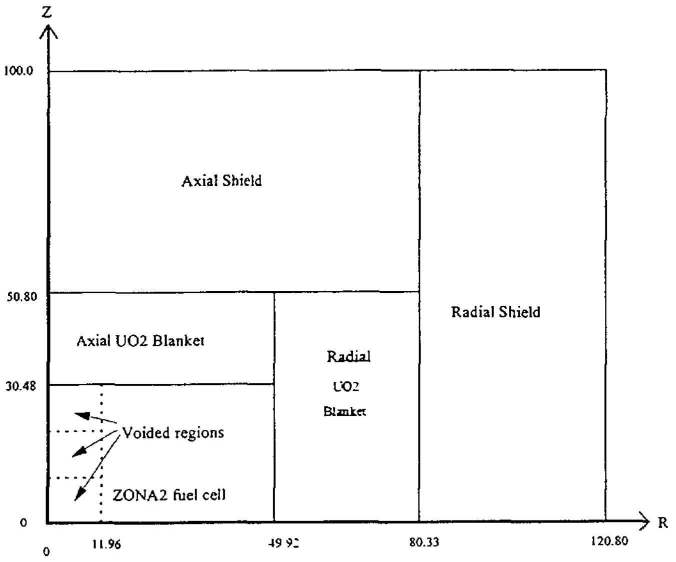
RZ Geometry for the ZONA1/R1 PRE-RACINE Clean Core (Units : cm)



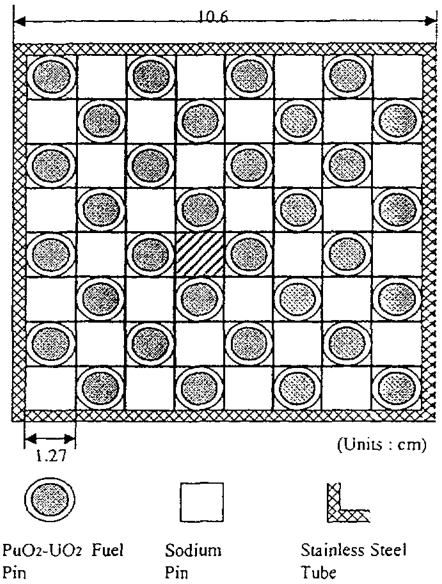
ZONA1(8%Pu-240) and ZONA1(18%Pu-240)Cell Model of the PRE-RACINE core



RZ Geometry for the CIRANO ZONA2A Core (Units : cm)



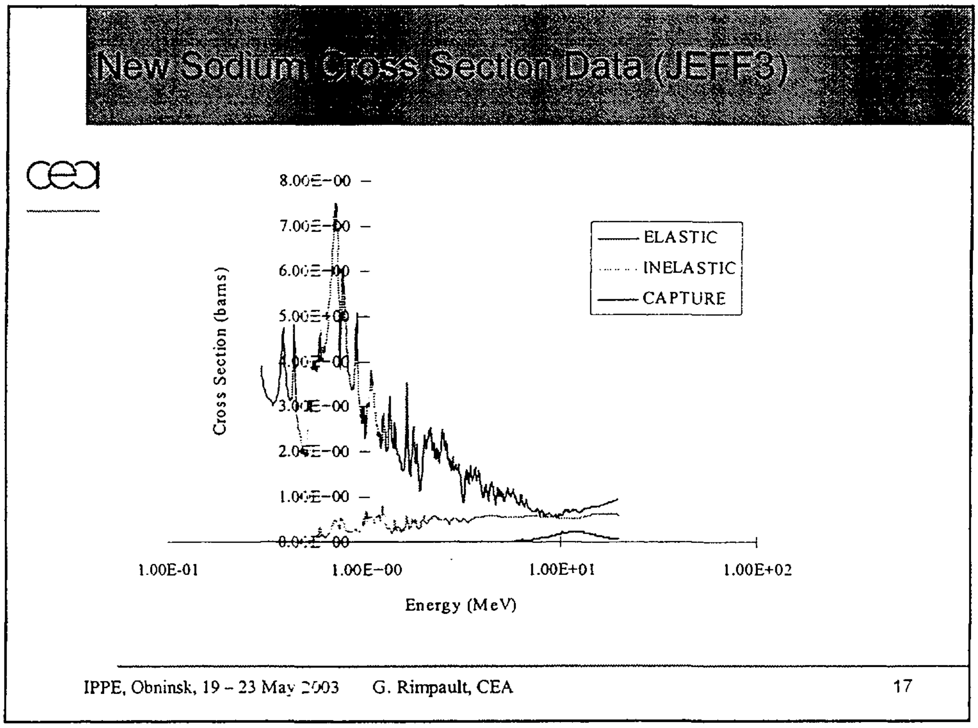
ZONA2PIT Two-Dimensional Cell Model of the CIRANO ZONA2A core



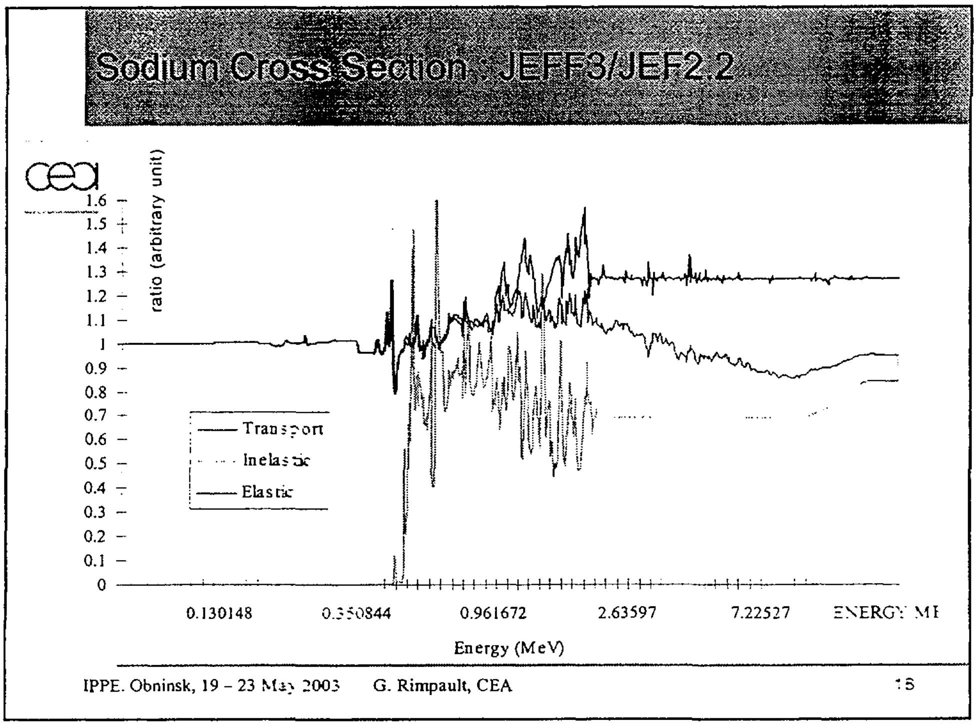
Sodium Void Reactivity Effects

Analysis is performed using

- transport S4 theory with P1 scattering and anisotropy of streaming with consistent algorithms for self-shielding, condensation and smearing
  - leakage and the non-leakage terms are in the following order :
    Transport S4 P0 > Transport S4 P1 > Diffusion
- new sodium cross section data determined from recent Geel and Oak-Ridge differential measurements



New Sodium Cross Section Data (JEFF3)



Sodium Cross Section : JEFF3/JEF2.2

Sodium Void Reactivity Effects
Evaluation of Calculation Accuracy

Perturbation calculation is performed in 2 dimensional RZ geometry with the S4 P1 transport theory approximation

- non-leakage and leakage terms are separated

- In transport theory :

Leakage term =

$$\sum_g \delta\Sigma_{t,g} \left\langle \frac{1}{(4\pi)^2} \int_{4\pi} d\vec{\Omega}\Phi_g(\vec{\Omega}) \int_{4\pi} d\vec{\Omega}\Phi^+_g(\vec{\Omega}) - \frac{1}{4\pi} \int_{4\pi} d\vec{\Omega}\Phi_g(\vec{\Omega})\Phi^+_g(\vec{\Omega}) \right\rangle + \sum_g \sum_{g'} \sum_{\ell > 1} \delta\Sigma_{s,g\to g',\ell}\phi_{g,\ell}$$

where $\Phi_g(\vec{\Omega})$ is the angular flux and $\phi_{g,\ell} = \int_{4\pi} d\vec{\Omega}\Phi_g(\vec{\Omega})P_\ell(\vec{\Omega})$

Non-leakage term = Total reactivity worth - leakage term

Sodium Void Reactivity Effects
Evaluation of Calculation Accuracy

- Function to be minimised is :

$$F \equiv \sum_i \frac{1}{(ER_i)^2}\left(\rho_{ex_i} - \alpha \cdot NL_{cal_i} - \beta \cdot L_{cal_i}\right)^2$$

  - where : ER_i is the experimental error of the ith measurement
  - ρ_{exi} is the measured reactivity worth
  - NL_{cal} and L_{cal} are the calculated non-leakage and leakage terms
  - α and β are the bias factors for the non-leakage and leakage term respectively
- The terms are linked by the following linear relationship :

$$\frac{\rho_{ex}}{NL_{cal}} = \alpha + \frac{L_{cal}}{NL_{cal}} \cdot \beta$$

Sodium Void Reactivity Effects
Summary of Experimental Analysis

Sodium void reactivity measurements in the ZONA1 and ZONA2 MASURCA configurations have been analysed using the newly available sodium cross section data

Component	Nuclear Data	ZONA2 (E/C)	ZONA1 (E/C)
Non-Leakage	JEF2.2	0.966	0.911
α	ERALIB1	0.978	0.914
	ERALIB1 + JEFF3 Na	1.025	0.959
Leakage	JEF2.2	1.058	1.061
β	ERALIB1	1.076	1.087
	ERALIB1 + JEFF3 Na	1.017	1.018
Leakage	JEF2.2	1.007	1.002
γ	ERALIB1	1.005	1.016
	ERALIB1 + JEFF3 Na	0.994	0.986

Sodium Void Reactivity Effects
Summary of Experimental Analysis

Component	Nuclear Data	ZONA2	ZONA1
Khi^2	JEF2.2	4.60	4.30
before	ERALIB1	6.40	2.92
adjustment	ERALIB1 + JEFF3 Na	0.68	1.14
Khi^2	JEF2.2	0.30	0.32
after	ERALIB1	1.63	0.38
adjustment	ERALIB1 + JEFF3 Na	0.36	0.44

Sodium Void Reactivity Effects
Summary of Experimental Analysis

- Sodium void effect for Super-Phenix 'Coeur Propre' (pcm)

Nuclear Data	Non-Leakage	Axial Leakage	Radial Leakage	Total
JEF2.2	2414	-657	-283	1475
ERALIB1	2251	-597	-258	1396
ERALIB1 + JEFF3 Na	2271	-668	-290	1313

- Sodium void effect for CAPRA Reference 4/'94m (pcm)

Nuclear Data	Non-Leakage	Axial Leakage	Radial Leakage	Total
JEF2.2	1758	-514	-252	992
ERALIB1	1671	-479	-237	955
ERALIB1 + JEFF3 Na	1680	-534	-266	880

CONCLUSION

Prediction of reactivity coefficients
is very much associated to a combination

of advanced computational tools
and recent and precise evaluations on one hand

and integral experiments sufficiently well designed to allow precise validation on the other hand

ERANOS and available experiments allow
such approach with the following achievements

STATUS OF VALIDATION FOR LMFR NEUTRONIC CHARACTERISTICS

Measurement	(E-C)/C	Particular Points
Critical Mass	< 100 pcm	Direct Run (No Corrections)
Control Rod Worth	< 5%	SPX CMP and PX (REACTIVIX)
Power Map distribution	Residual Discrepancy of 5%	SPX CMP
γ Heating	Residual Discrepancy of 10%	Measurements in critical facilities RACINE and CIRANO programmes in MASURCA
Burn-up Swing	- 5%	Possible compensation effects between MA and FP
β_{eff}	dispersion de 6.5%	Measurements in critical facilities BERENICE programme in MASURCA
Doppler Constant	0%	SPX CMP (Debye correction necessary)
Sodium Void	Correction factor of 1.1 for the leakage component due to an incorrect total xs 10%	Correction confirmed by a new Na evaluation Measurements performed in MASURCA

Methods to Determine the Calculational Uncertainties Associated with LMFR Reactivity Effects

- Analysis of mock-up experiments at the beginning of life
- Sensitivity calculations of LMFR reactivity effects to nuclear data at the beginning of life
- Evaluation of uncertainties on reactor values at the beginning of life
- Sensitivity calculations of LMFR reactivity effects to nuclear data at the end of life (coupling of Bateman and Boltzmann equations)
- Analysis of experiments specific to fuel irradiation
  - irradiation of well characterised pins (PROFIL measurements in PHENIX)
  - minor actinide and fission product oscillation measurements
- Determination of uncertainties on reactor values at the end of life