Principles and Realization of the Modular Program System KAPROS-E and Applications for Innovative Reactor Systems

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Outline of presentation

- **Introduction, stages of development of KAPROS**
- **Main features of original KAPROS version:**
  - **Basic principles**
  - **Criticality, flux- and power-distribution calculations**
  - **Cross section generation and collapsing, improvements of methods (up-scattering) and libraries**
  - **Burn-up calculations, code developments and validation, fuel cycle investigations**
- **KAPROS-E: coupling of KAPROS with stand-alone codes. Examples of recent applications: FR (ADS, critical), HPLWR fuel assembly, PWR fuel asssembly**
- **Summary and outlook**

Introduction

- Special feeling to make, after 35 years as user and developer, a seminar presentation of the FZK modular code development KAPROS
- KAPROS was developed and maintained over a long period by many colleagues, covering a broad range of computer hard- and software environments, aiming at supporting actual at that time R&D requirements
- Implementation of KAPROS on LINUX operating system around 2000 improved strongly portability (enabling e.g. home versions for testing)
- LINUX version in IRS lead to increased KAPROS applications. Some reasons:
  - KAPROS is a very well suited system for use in actual R&D activities in IRS in this period
  - KAPROS could be included as essential parts of education activities (diploma thesis etc)
  - The development of the KARBUS-E procedure with systematic use of UNIX shell scripts enabled quite easily new application areas for coupled multi-physics problems

History of KAPROS/KARBUS development

Early seventies:	NUSYS-KAPROS	Bachmann, Buckel, Hoebel,
Late seventies:	KAPROS-KAPROS77	Braun, Kleinheins, Moritz
Late seventies:	Begin KARBUS development	Broeders, Stein, Wiegner, ...

Early eighties problems with computer environment, progress of KAPROS questionable

Early eighties:	Restricted KSSK subsystem	Hoebel with MATAS
Early eighties:	KSSKBU with nearly full functionality	Broeders, Stein,
Midth eighties:	KSSKBU KAPROS3 full functionality, fast storage < 9 MB	Braun, Buckel, Kiefhaber, Woll
Late eighties:	KAPROS3-KSSKXA fast storage extension > 16 MB	Broeders
Late eighties:	Begin KSSKXA-KSSKUX for UNIX	Broeders
Midth nineties:	KSSKUX operation on IBM RS6000 workstations	Broeders, Woll
January 2000:	Full KSSKUX operation on LINUX PC	Broeders
2006	64 bit PC, INTEL FORTRAN compiler	Broeders, M. Becker

Current status:

Operation without problems of LINUX Versions 2.20 / 3.00 on several LINUX OS systems

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Characteristics of KAPROS (I)

- Fully modular code system for the calculation of nuclear reactor systems
- Development since about 35 years with more than 100 man-years efforts by many contributors
- Since KAPROS77 kernel, FORTRAN77 with only few exceptions (now C-routines)
- Calculation modules mostly FORTRAN77
- Common data bases on different levels:
  - Fast memory storage as much as available
  - Temporary disk storage as much as required
  - Disk/tape storage of data archive

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Characteristics of KAPROS (II)

- **Standard KAPROS interfaces available for cross sections, spectra, fluxes, etc**
- **Use of international standard interfaces convenient for new developments**
- **Powerful archiving and restart features**
- **On-line WEB-browser based documentation available (mostly German language)**
- **Exhaustive applications for FBR and TLLWR investigations, subsystem KARBUS for depletion calculations, several procedures for specific calculation tasks**
- **Portable version for UNIX workstations, including LINUX PC**

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Reactor calculations with KAPROS/KARBUS (I)

Several options for reactivity and flux calculations:

- **KAPROS modules strongly coupled with KAPROS:**
  - **WEKCPM (1-d collision density method from WIMS)**
  - **ONETRA (1-d S_n transport method)**
  - **DIXY2, including evaluations (2-d diffusion)**
  - **D3D / AUDI3 (3-d diffusion)**
  - **HEXNODK (3-d nodal transport/diffusion)**

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Reactor calculations with KAPROS/KARBUS (II)

- **Stand-alone codes loosely coupled with KAPROS**
  - **DANTSYS (3-d S_n transport)**
  - **DOORS (3-d S_n transport), implemented by M. Becker 2007**
  - **SCALE-5.1 (LWR analysis; XS generation, burnup, ..), implemented by P. Oberle**
  - **CITATION (3-d diffusion)**
  - **VARIANTK / DIF3D (3-d Hex-Z nodal transport)**
  - **HEXNODYN (HEXNOD successor developed at SCK/CEN)**
  - **MCNP and MCNPX Monte Carlo Codes**

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KAPROS / KARBUS cross section processing (I)

Unique FZK-own development GRUBA library / GRUCAL processing code

- Multi-group library GRUBA with very flexible data storage options
- Data structures are combination of features of fast and thermal reactor codes (up-scattering, separate treatment of elastic, inelastic, (n-2n), .. processes, improved fission spectrum, etc)
- Directives for cross section calculations are not hard-coded in GRUCAL program, but defined on “Steuerfile” with calculation rules; unique solution for cross section calculations.
- Easy to use features for the application of special data testing (secondary input)
- Refined resonance treatment based on self-shielding tabulations (improved Bell-factor formalism), fine flux cross section calculations optional (ULFISP, RESABK, …)
- Well validated for various applications (LWR, TLLWR, FBR, ADS, HPLWR, …)

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KAPROS / KARBUS cross section processing (II)

Options for fine flux calculations for cross section generation

- Available KAPROS modules, currently not yet operable in LINUX version:
  - RESABK; uniform lethargy grid for point cross section data (IKE Stuttgart development)
  - ULFISP; variable energy grid for point cross section data (FZK development)
- OZMA; standalone uniform lethargy grid for point cross section data
- CENTRM; SCALE5.1 module with own data base with variable energy grid for cross sections
- Work in progress to re-implement ULFISP and RESABK in current KAPROS version, including common data base for ULFISP, RESABK, OZMA and CENTRM
- Improvement of fine flux calculation methods will be assessed (resonance up-scattering?)

Characteristics of 69 group master library

- **FZK own library structure on direct access files, including retrieval and management software, is standard library structure for microscopic cross section storage in KAPROS**
- **Contains all data needed for multi-group diffusion and transport calculations, including data for delayed neutrons, for ≈160 isotopes.**
- **Contains additional EAF2001 69 group cross sections for depletion and activation calculations for ≈700 isotopes**
- **Well validated for a broad range of applications with different fuel, moderator and coolant in thermal, epithermal and fast neutron spectra**
- **Validation efforts still in progress (TRIGA fuel, Lead coolant, sub-critical systems, burnup, …)**

Currently available multi group master libraries

- **26 group ABBN energy group structure (FZK FBR research):**
  - **KFKINR: first official FZK 26 group library (“Steuerfile”: F26)**
  - **KFKINR2: final extended FZK 26 group library (“Steuerfile”: F26TN)**
- **69 WIMS energy group structure:**
  - **G69CT005: final 69 group test library with one up-scatter temperature (T = 300K) (“Steuerfile”: F69V2STR)**
  - **G69P1V03: 69 group library KFK5072 with one scattering matrix (“Steuerfile”: F69V2STR)**
  - **G69P5E65B: latest ENDF/B-6.5 based 69 group library (“Steuerfile”: F69UD06)**
  - **G69P5J30B: latest JEFF3.0 based 69 group library (“Steuerfile”: F69UD06)**
- **78 extended WIMS energy group structure up to 150 MeV:**
  - **G78P5001: first 78 group test library upper energy 150 MeV (“Steuerfile”: F78V01)**
- **334 groups library with extended WIMS fine group structure:**
  - **G334EAF2: fine group structure for spectral investigations (KFK5072): “Steuerfile”: F69UD04)**

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Generation of coarse multi-group cross sections (I)

- Coarse group constant sets (≈10 groups) applied for dynamic reactor simulations
- Coarse group constant generation is sensitive to the weighting spectrum
  ⇒ dependant on reactor system and on the state of the system
- Commonly used methods for coarse multi-group generation:
  - Application of few group microscopic libraries in standardized format (SIMMER)
  - Collapsing of many-to-few group macroscopic cross sections
- New master library collapsing procedure COLLIB in KAPROS;
  existing multi-group procedures applicable for collapsed libraries

Generation of coarse multi-group cross sections (II)

New procedure COLLIB in KAPROS applying two-step procedure:

- **Step 1: Well validated complete microscopic master library (with 69 groups)**
- **Step 2: Collapsing to system dependant coarse group cross section library with same microscopic library structure as master library:**
  - **Use of representative weighting spectrum for collapsing**
  - **Materials and data-types selectable for planned application**
  - **Group boundaries selectable (problem dependant)**
  - **Collapsing procedure straight-forward, but care is required for self-shielding tables and threshold reactions**

Validation of the coarse group generation

Whole core criticality deviation for FZK ThO_2/UO_2 ADS design: $(K_{ref}-K_{collib}) / K_{ref}$ = 0.47%

Influence of mass, density and temperature perturbations in channel 1 on system reactivity

Type of perturbation	Relative error: $(\Delta K_{ref}-\Delta K_{collib})/\Delta K_{ref}$	Absolute error: $(\Delta K_{ref}-\Delta K_{collib})/K_{ref}$
10% of original fuel mass in channel 1	1%	0.00007
50% of coolant density in channel 1	25%	0.00005
1000^0 K increase in channel 1 (from 1400K)	12%	0.00006
1000^0 K decrease in channel 1 (from 1400K)	12%	0.00019

Assessment of nuclear library data for Lead in MUSE project (I)

Exp.	Critical Core radius cm)	Core Critical mass (gram)	Internal void radius (cm)	Thickness Lead reflector (cm)	External Assembly Radius (cm)	K_{eff}
B1	6.668	18773	-	-	-	1.000±0.0025
B2	6.000	13739	1.00	3.04	9.04	1.000±0.0040
B3	5.350	9722	1.00	28.45	33.80	1.000±0.0040

Fuel composition:Pu^{239} 95.30%, Pu^{240} 1.75%, Ni 1.28%, Ga 1.67%

Specification of the Russian critical assembly data for lead benchmark

Assessment of nuclear library data for Lead in MUSE project (II)

Exp.	Case	G69P1UX3	G69P1UD3	MCNP4C	G69P5E65B
B1	M1	0.9892	0.9935	0.9960	1.0072
	M2	0.9898	0.9880		1.0012
B2	M1 M4	0.9094	0.9921	1.0121	1.0014
	M1 M5	1.0001	1.0017		0.8946
	M2 M4	0.9094	0.9877		0.9969
	M2 M5	1.0000	0.9973		0.8892
B3	M1 M4	0.8179	1.0007	1.0284	1.0155
	M1 M5	1.0195	1.0185		0.8015
	M2 M4	0.8179	0.9975		1.0122
	M2 M5	1.0195	1.0153		0.7969

M1: Ni isotopes, M2: Ni element, M4: Pb isotopes, M5: Pb element in calculation

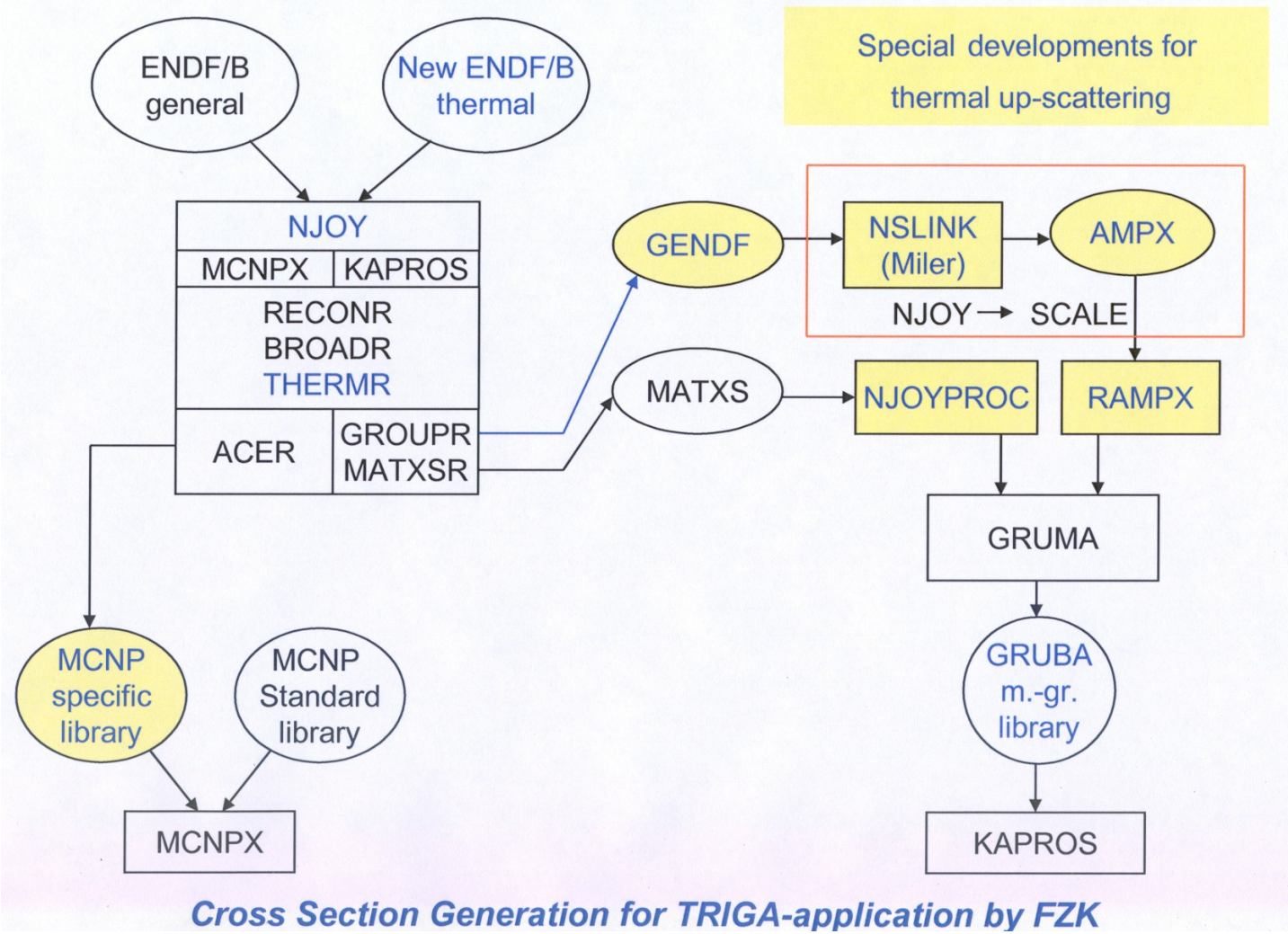
Table 3: KAPROS / KARBUS validation results for Russian Criticality Benchmarks (critical experiment with lead)

Consequence: automatic support for use of isotopes instead of elements in KARBUS (module SPLSTR)

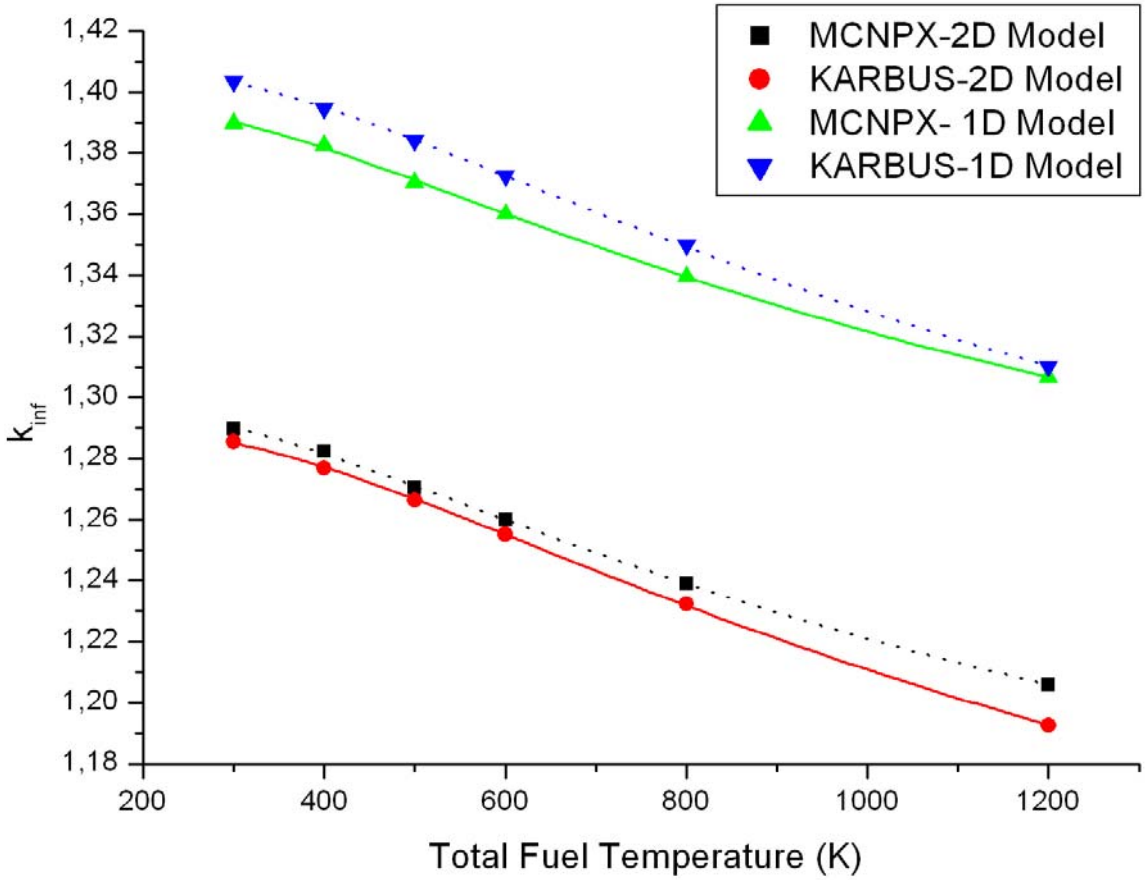
Improvement of up-scattering data for TRADE and YALINA (I)

- Status 2002: 69 group library with up-scattering data from external resources (WIMS, IKE Stuttgart)
- TRADE project needed additional data for up-scattering from hydrogen bounded in Zirconium Hydride; later the same in YALINA project in ECATS for Polyethylene and Graphite
- No standard routes to transfer NJOY up-scatter results to multi-group libraries
- NSLINK software package supports transfer from NJOY up-scatter results to the AMPX format of widely used SCALE system for LWR licensing
- New program RAMPX converts AMPX libraries to input data sets for GRUBA library management
- New library data generated for most available lattice bindings

Improvement of up-scattering data for TRADE and YALINA (II)



Comparison of MCNPX / KARBUS reactivity results for TRIGA fuel (TRADE)



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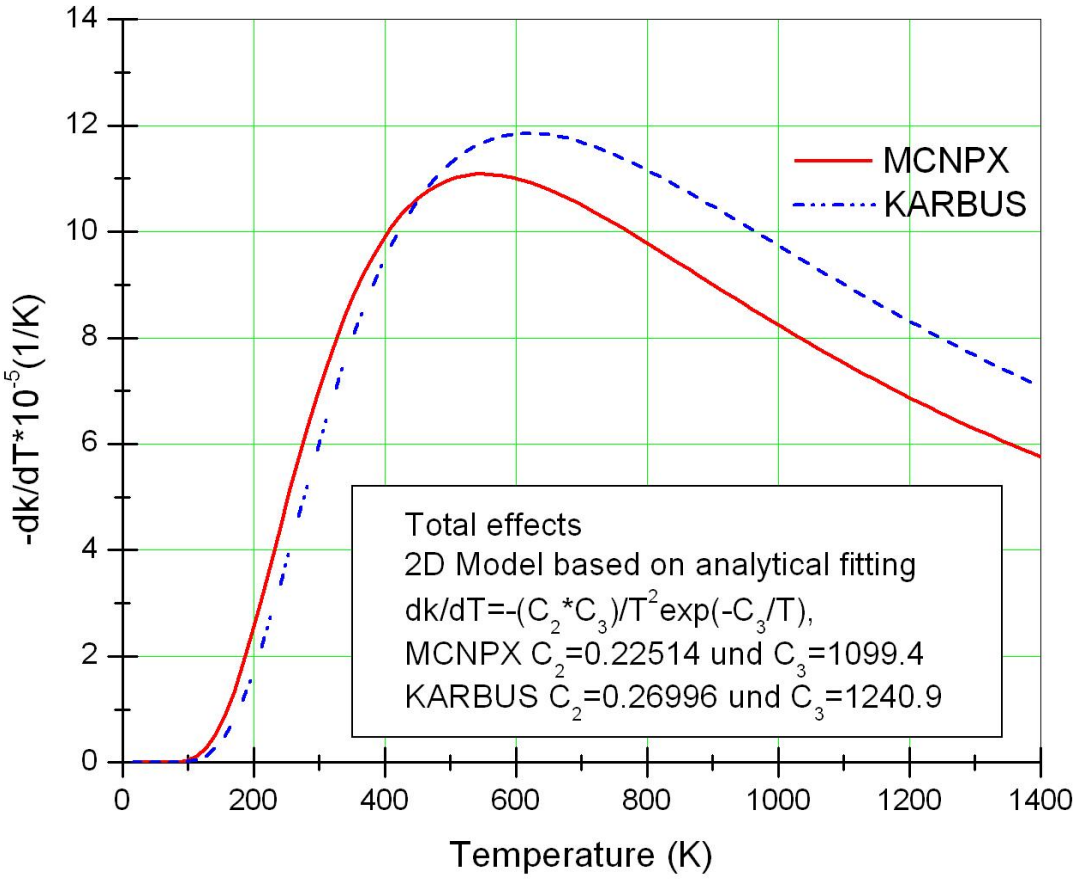
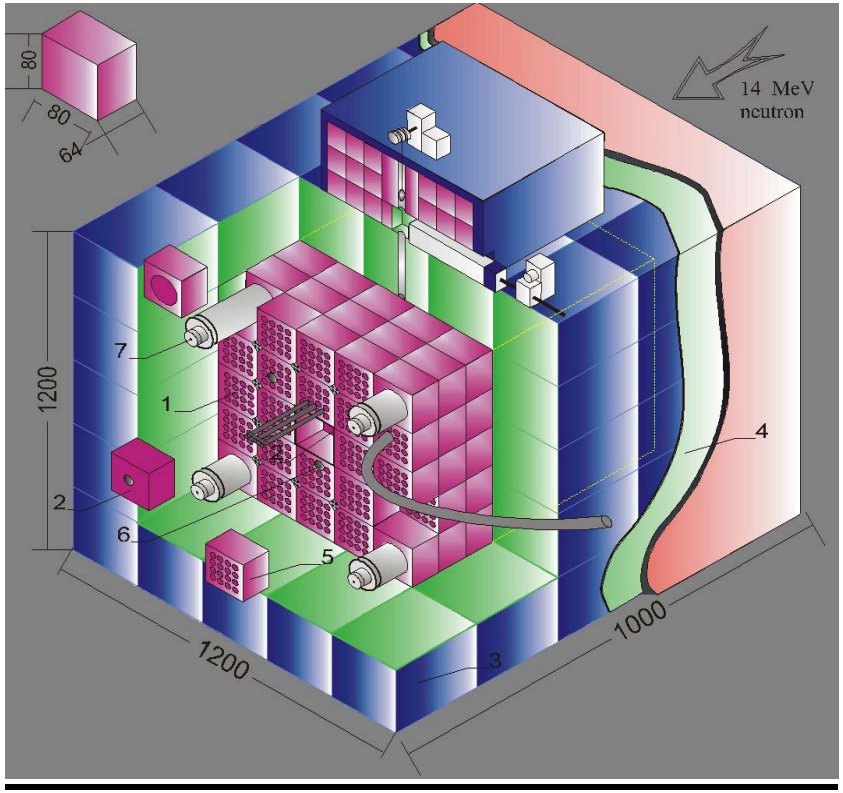


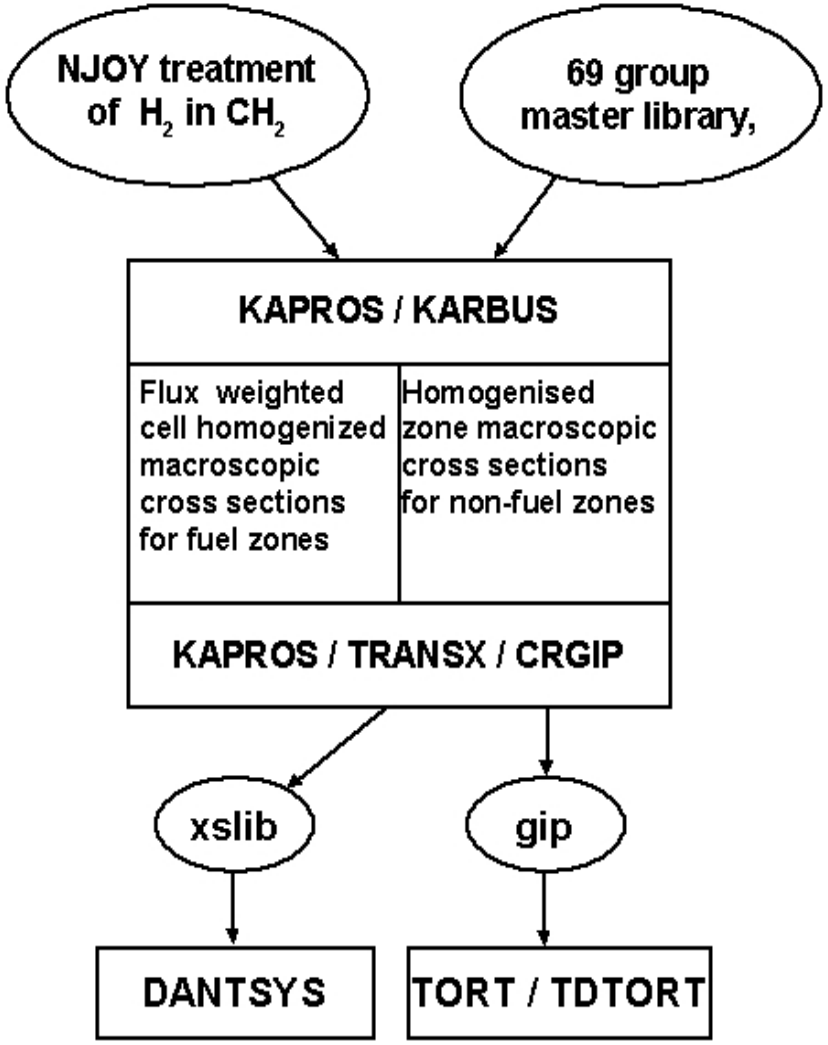
Schematic view to the complete YALINA reactor (EUROTRANS / ECATS)

1. **Core**
2. **Lead target**
3. **Graphite reflector**
4. **Cadmium screen**
5. **Polyethylene block**
6. **Experimental channel**
7. **Detectors for neutron flux monitoring**



Multi group cross section generation for YALINA

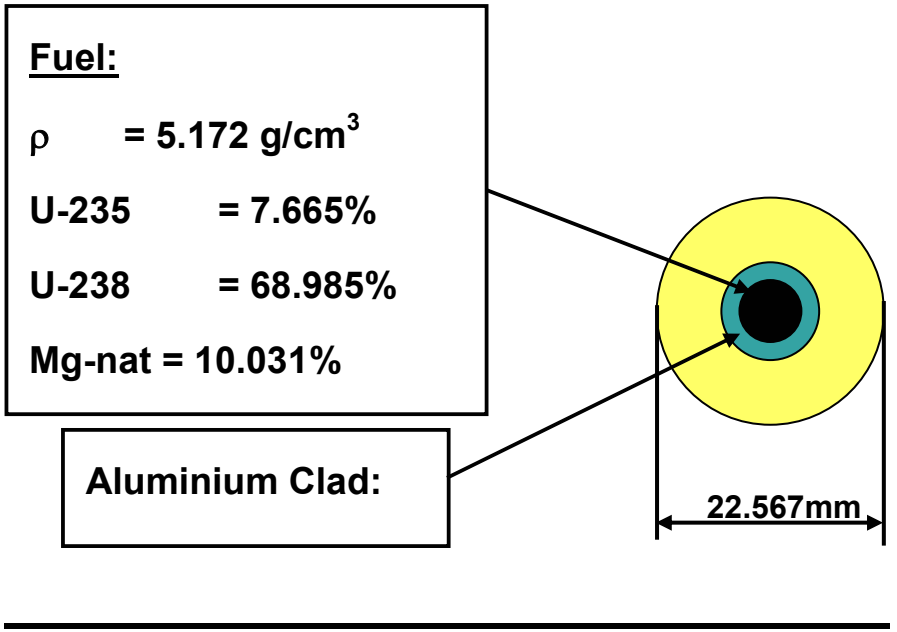
- Standard 69 group libraries
  - G69P5E65B, G69P5E7
  - G69P5J30A, G69P5J31
- NJOY for handling of hydrogen in Polyethylene
  - Data from „poly thermal from ENDF/B-VI Tape 118“ available from LANL
  - First tests with “secundäry input” option in KARBUS / GRUCAL to replace hydrogen in H_2O
  - Final solution with additional name on extended library
- Modules TRANSX and CRGIP to create interface files with cross sections



Preliminary results for YALINA (EUROTRANS / ECATS)

- Wigner-Seitz cell
  - without air gap
  - enlarged clad thickness and reduced density of aluminium
  - cylindrical boundary
  - white boundary
- Results in K_{eff}
  - KARBUS 1.37881 without air gap
  - DANTSYS 1.37868 without air gap
    - Convergence criterion 0.0001
  - MCNP 1.36795 without air gap
  - MCNP 1.36814 with air gap

- Standard deviation 0.00013



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Burnup and depletion calculations in KAPROS (I)

The KArlruher Reactor BUrn-up System KARBUS is a KAPROS sub-system developed for burn-up and depletion calculations of nuclear reactors since early eighties. Important KARBUS modules and procedures are

- **The main KAPROS burn-up module BURNUP is based on the formalisms of the KORIGEN code, developed at FZK from ORIGEN**
- **The early developed procedure BURN0D enables burn-up investigations with the help of fundamental mode calculations**
- **The procedure KARBUS enables complicated burn-up calculations for reactor unit cells or for reactor systems**

The KARBUS cell burnup calculations were re-validated for the UNIX version by comparison with results from the ICE burnup experiment in KWO PWR, as done initially for the KAPROS MVS version (diploma thesis work)

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Burnup and depletion calculations in KAPROS (II)

Characteristics of the module BURNUP for burnup/depletion calculations:

- Developed from early FZK version of ORIGEN, utilizing solver solution for isotope transitions, but omitting specific evaluation parts (irradiation table generation, etc)
- ORIGEN library with decay information was reorganized and extended to total number of about 3500 isotopes on BURNUP libraries.
- All essential extensions in later versions of KORIGEN were implemented in BURNUP, e.g. extension of fission product yields for additional fuel isotopes
- In the module BURNUP all required system dependant one-group cross sections may be taken from best estimate preceding detailed reactor calculations. If no problem dependant data is available (delivered in standard KAPROS structure SIGMN), more global data is taken from standard BURNUP files

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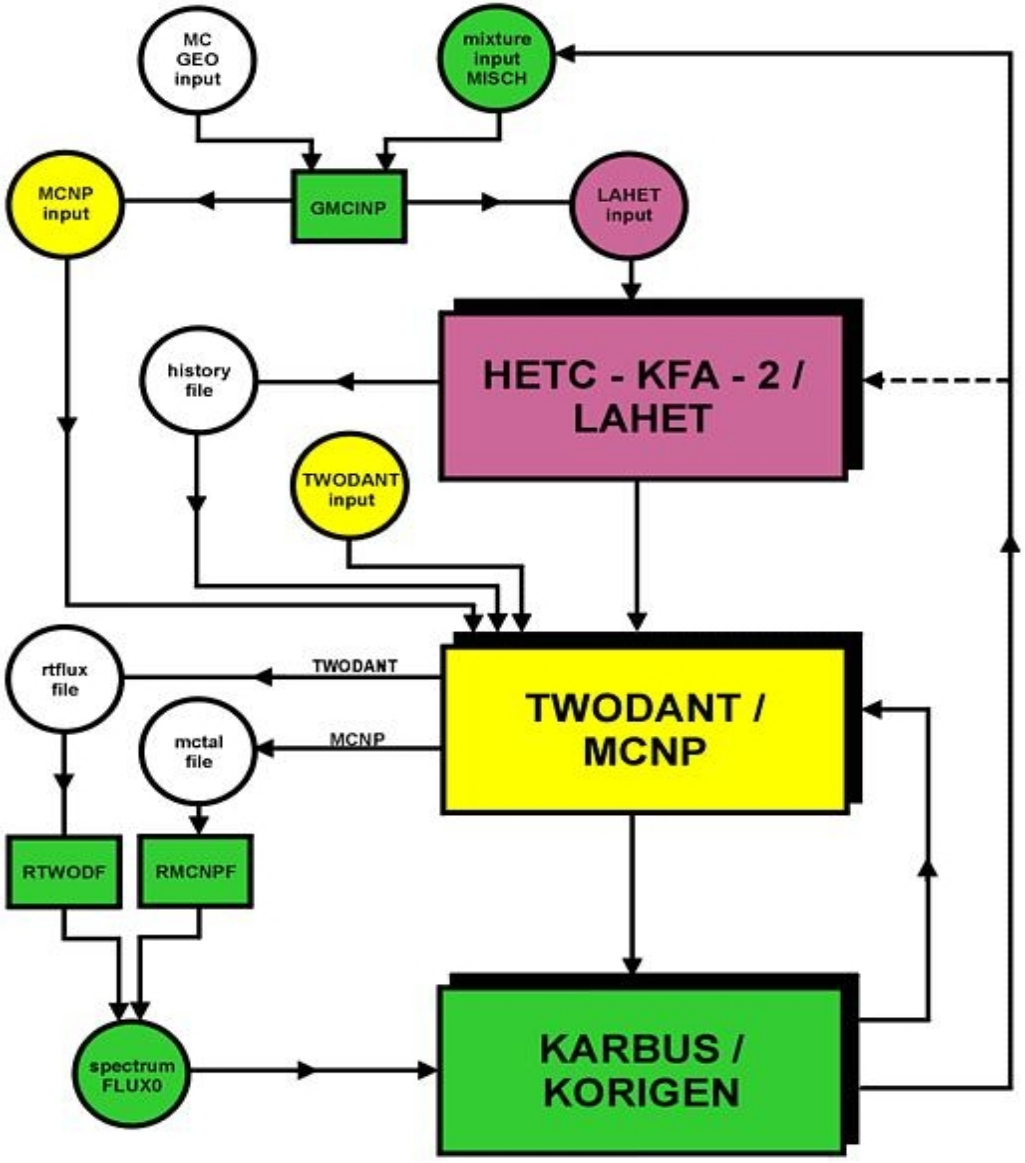
Burnup and depletion calculations in KAPROS (III)

- The procedure **BUTWOD** couples the stand-alone codes LAHET, MCNP and TWODANT with KAPROS burnup options. E.g. applied for burn-up and depletion calculations of **ADS designs (XADS, XT-ADS, EFIT)**
- The procedure **SPALEV** enables long term analysis of the reaction products by proton and neutron irradiation in **ADS targets**. The spallation product source term is retrieved automatically from MCNPX output. Applied in **Marie Curie project ACITADS (EC)**.
- An automatic link is established by the KAPROS interface module **KORINT** with the current KORIGEN code to enable calculation of activity and inventory data. E.g. recently applied for **EC project EUROTRANS DM1 EFIT** design
- KARBUS is further used for various applications, e.g. recently for
  - Fuel cycle investigations in view of enhanced proliferation resistance of MOX fuel by Pu238 adjustment (*Broeders - Kessler, NSE May 2007*) and for
  - Plutonium inventories in the German nuclear park (*Merk, Broeders, 2006*)

KAPROS Procedure BUTWOD for burn-up and depletion calculations of ADS designs.

The procedure was developed during participation to IAEA benchmark for Thorium fueled lead-cooled ADS, based on proposal of Prof. Rubbia for sub-critical energy amplifier.

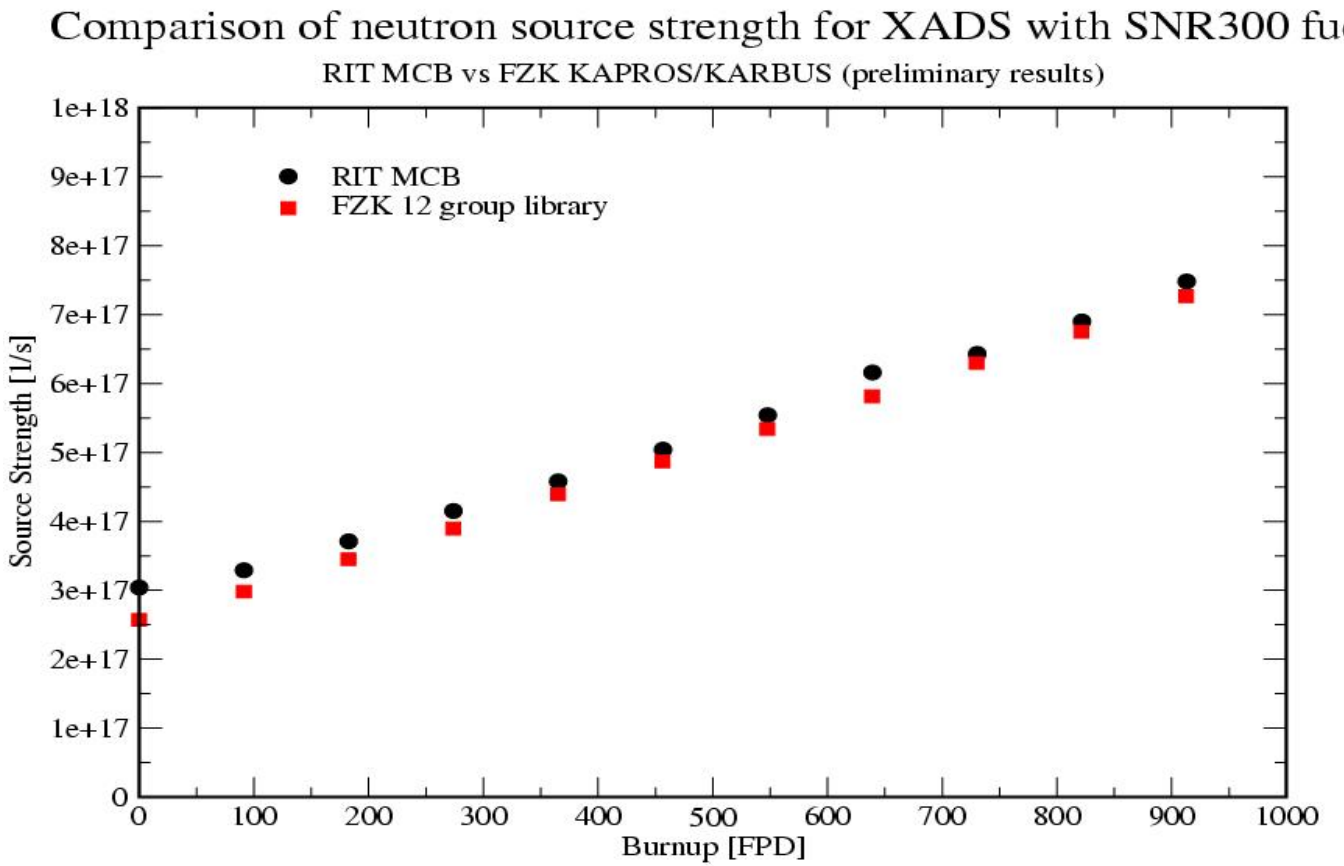
The lower part of BUTWOD is used in the projects of the 6. ECFP for design calculations and burn-up behavior of innovative reactor systems and dedicated experiments: TRIGA, YALINA, XT-ADS, EFIT, GUINEVERE, ELSY, EISOFAR, …



Burn-up investigations for an XADS benchmark core with SNR300 fuel (I)

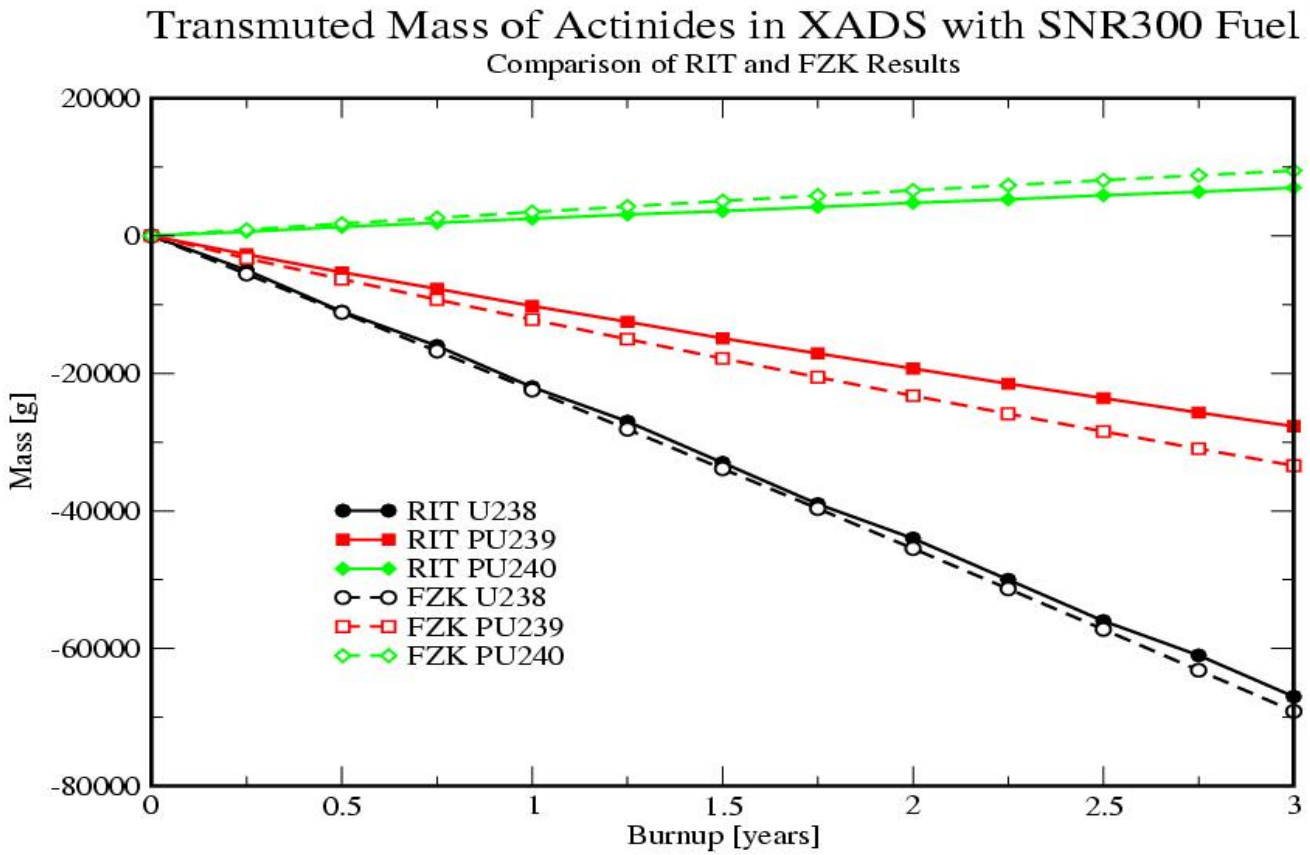
- Applied calculation methods
  - Monte Carlo code MCB1C by KTH Stockholm
  - Procedure BUTWOD of deterministic multi-group code system KAPROS
- Calculation model
  - Appropriate (R-Z) geometry in both calculation methods
  - Three radial and eight axial burn-up zones same in both methods
- Mostly same JEF2.2 data base for cross section data
- Detailed source from MCNPX calculation in Monte Carlo method, simplified constant source treatment in deterministic code
- Satisfactory agreement in preliminary results; reactivity loss 6..7 pcm/fpd

Burn-up investigations for an XADS benchmark core with SNR300 fuel (II)



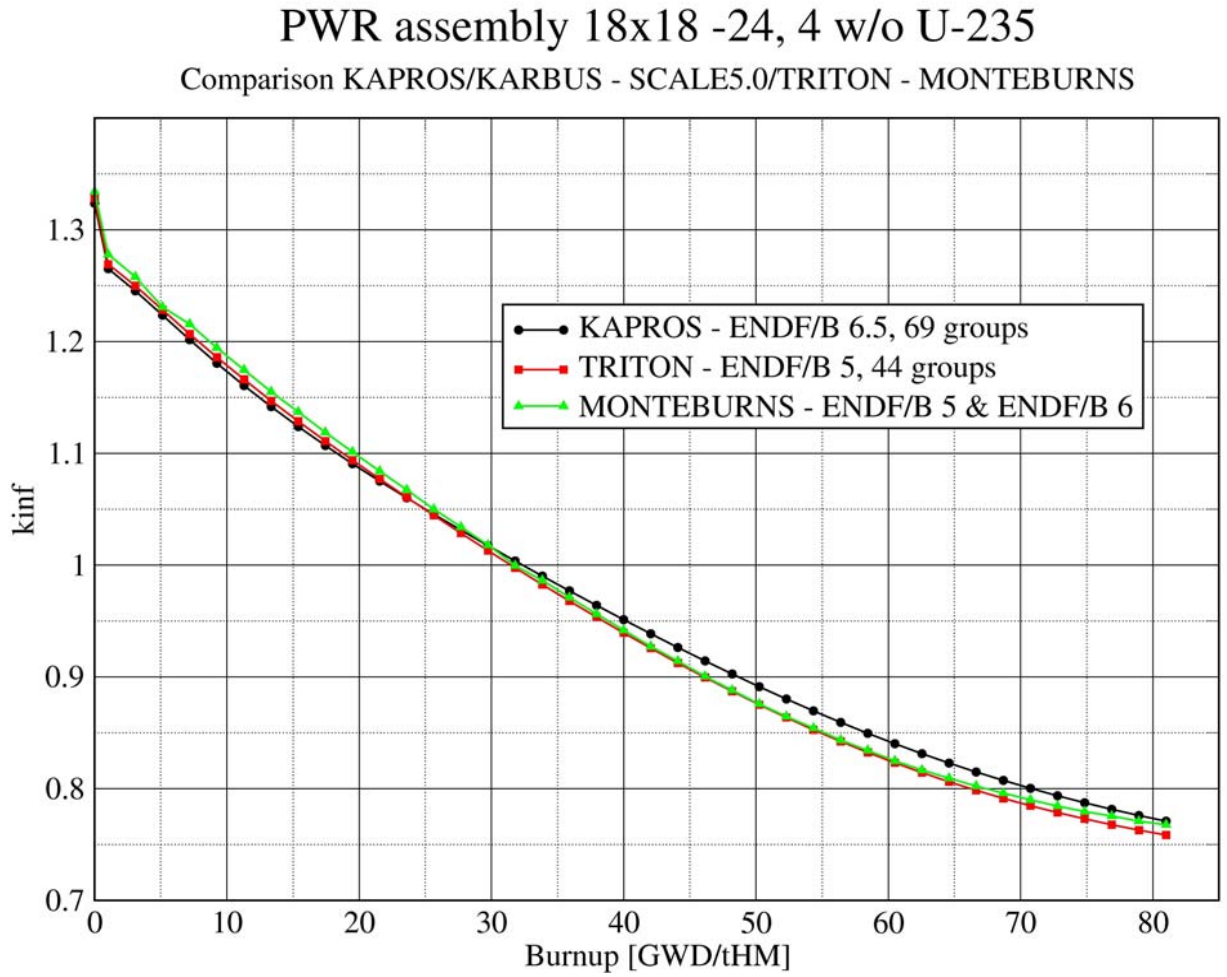
Comparison of KTH Monte Carlo and FZK deterministic results for burn-up dependant source strength for XADS with SNR300 fuel

Burn-up investigations for an XADS benchmark core with SNR300 fuel (III)

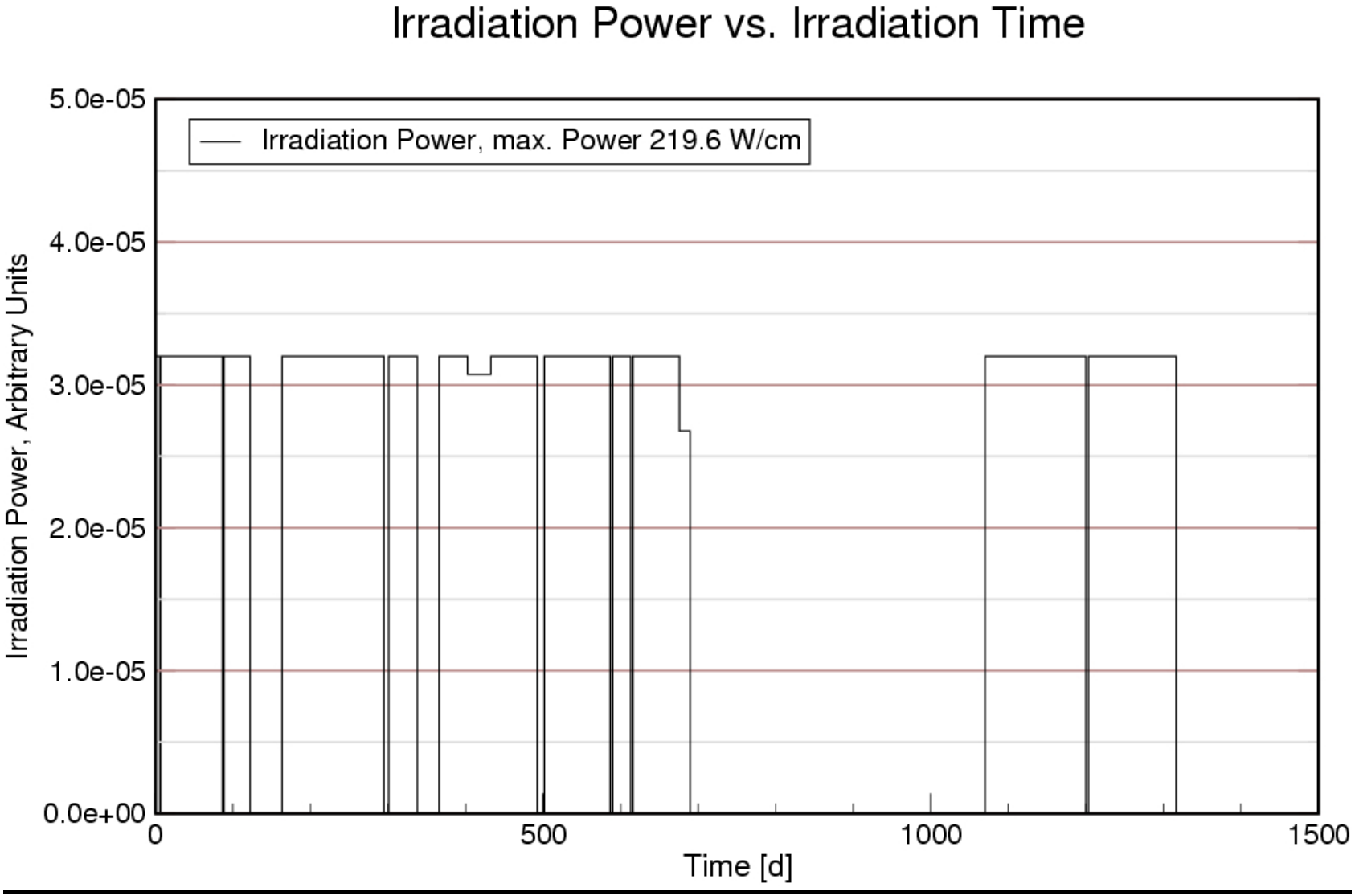


Comparison of KTH Monte Carlo and FZK deterministic results for burn up dependant mass change

Results for GRS PWR Fuel Assembly Burn-up Benchmark
(details about benchmark later on KAPROS-E / COBRA-TF slide)



Result of re-validation work for KARBUS using ICE KWO experiment (I)



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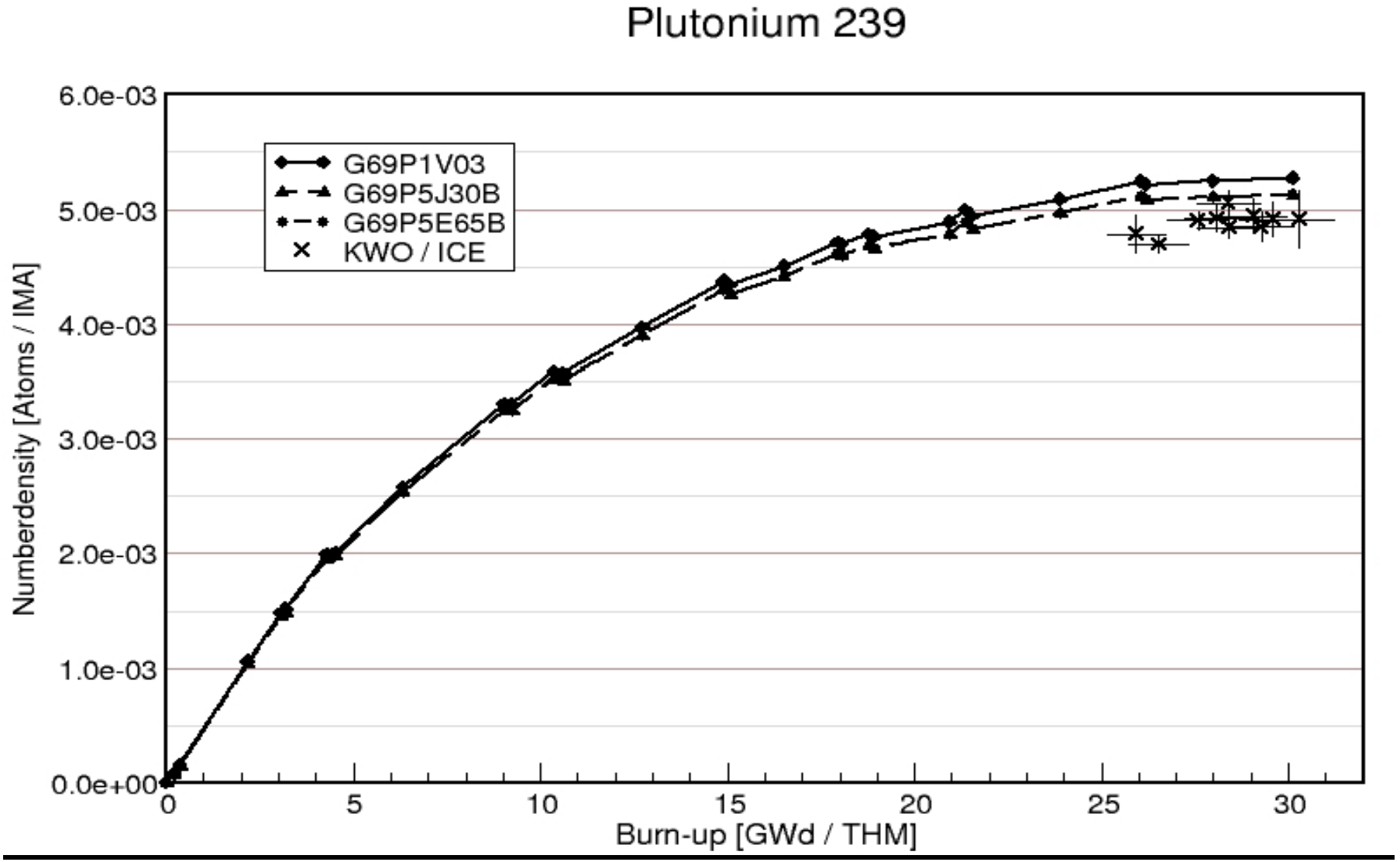


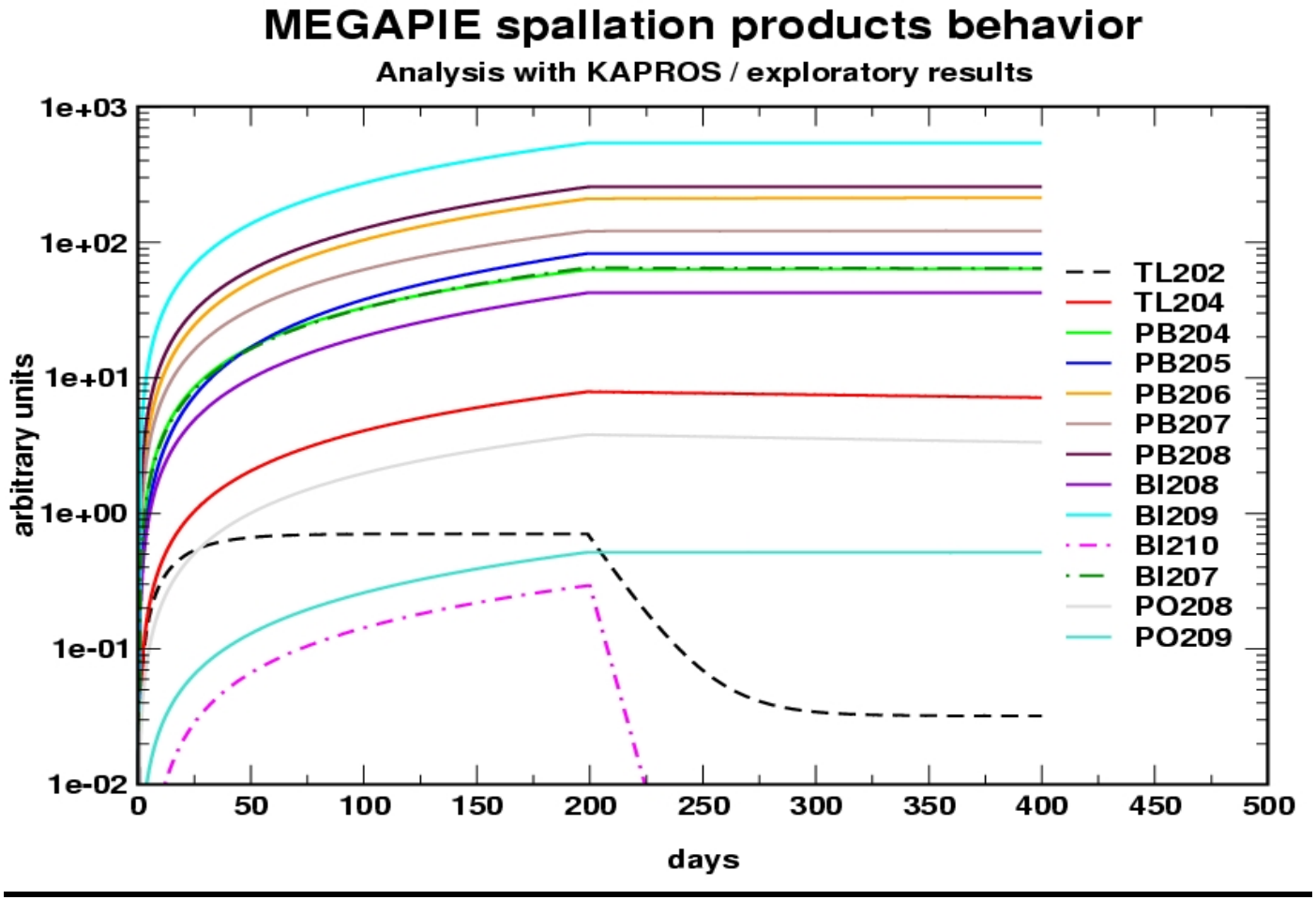
SPALEV: KAPROS procedure for spallation product evaluation in ADS targets (I)

(applied in EC Marie Curie Project ACITADS)

- Three files are prepared with MCNPX runs with corresponding input:
  - Spallation product (SP) yields are stored on HISTP file
  - Neutron fluxes in 69 WIMS group structure in file MCTAL
  - Auxiliary code HTAPE3X of MCNPX creates from HISTP specific SP file OPT8A
- OPT8A file is processed by KAPROS module HETMIX to create standard input block for material specifications: MISCH block
- MCTAL file is processed by KAPROS module MCFLX0 to create standard flux block for weighting spectra : FLUX0 block
- Using specific input, burn-up calculations are performed with standard module BURN0D
- Evaluations of results are performed in module BUDEVA
- With small time steps a quasi continuous feed of SP may be simulated

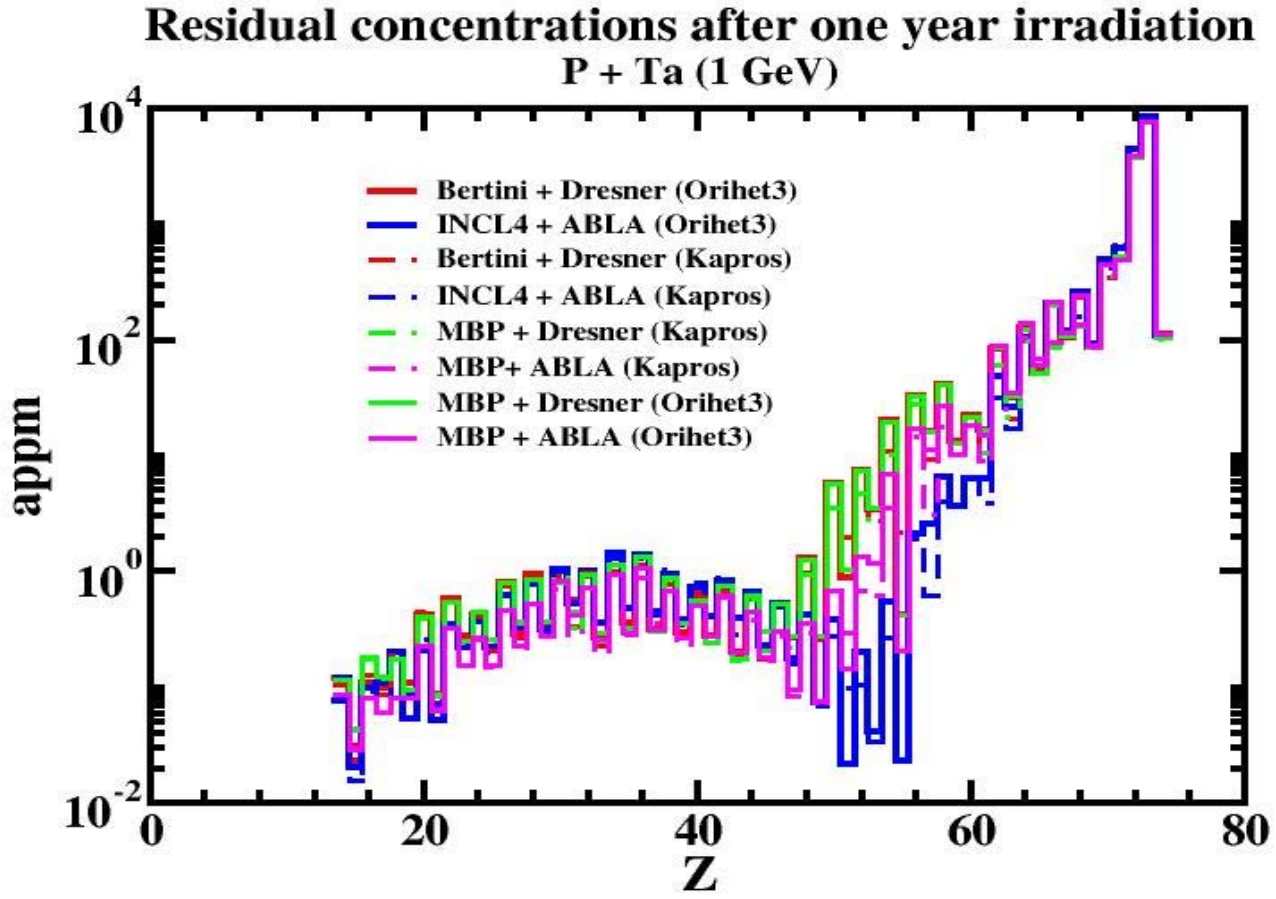
SPALEV: Procedure for spallation product evaluation in ADS targets (II)

Inventory of selected isotopes during and after 200 days irradiation



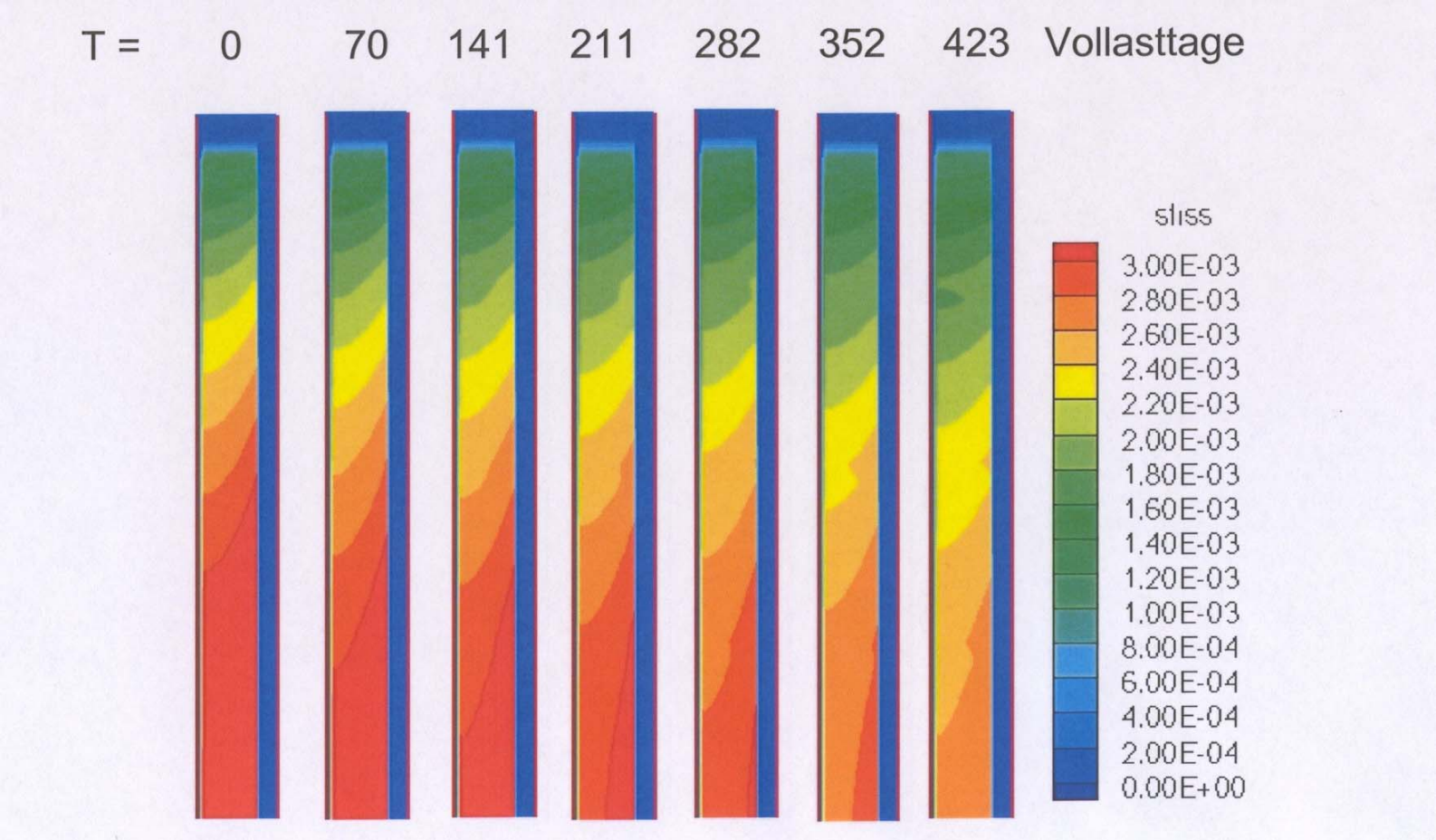
SPALEV: Procedure for spallation product evaluation in ADS targets (III)

Analysis of Ta target with (Marie Curie project ACITADS, Kerntechnik 2006), Quasi continuous feed of SPALEV is compared to special continuous feed code ORIHET3

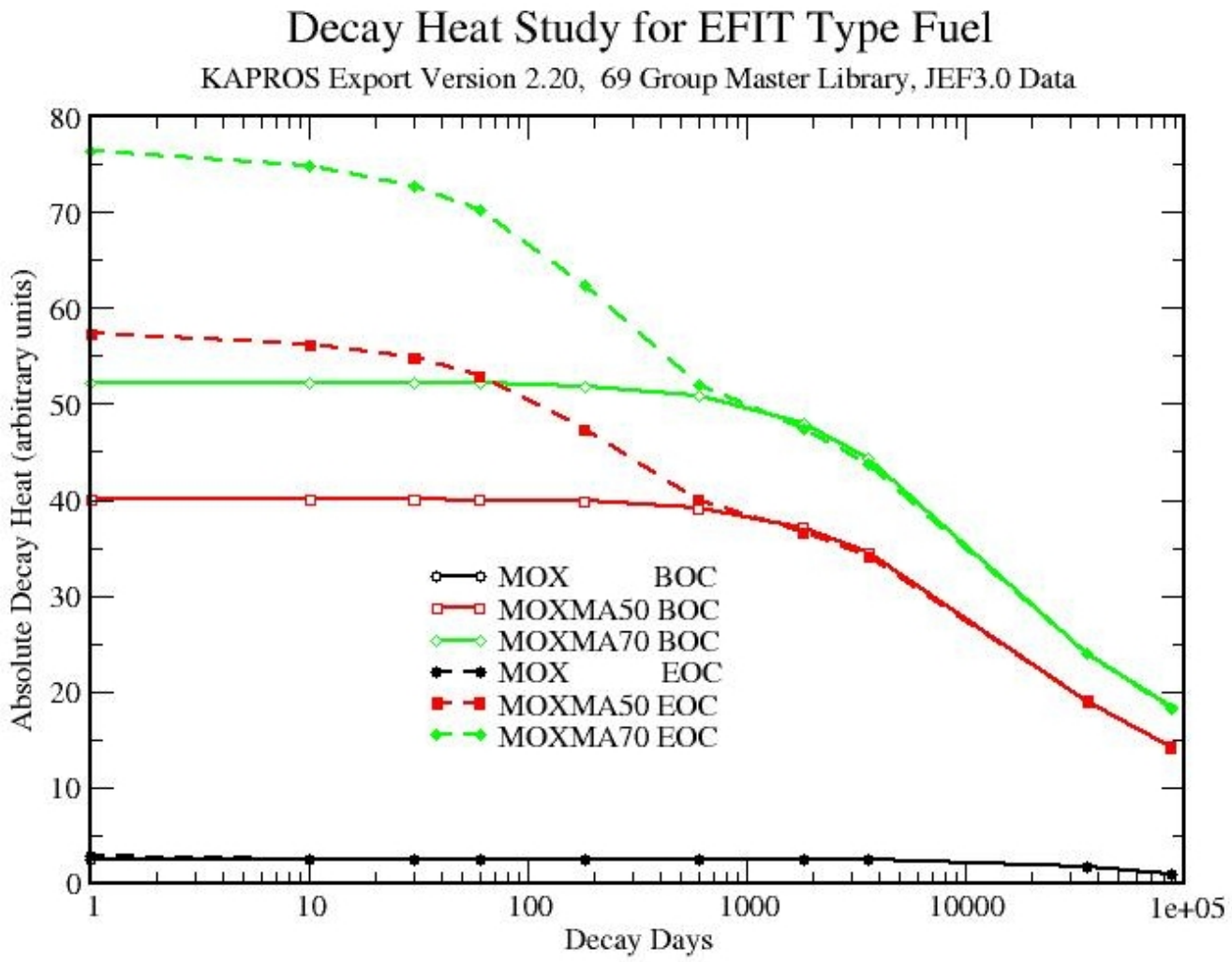


First burnup results with KAPROS/KARBUS for TRADE fuel element

Power distribution in RC1 TRIGA fuel element as a function of irradiation time in full power days (improved characterization of core loading in view of reactor physics experiments)



Absolute decay heat comparison for different EFIT Fuels (arbitrary units) results from KAPROS BURNUP-KORINT-KORIGEN code sequence



Selected results of fuel cycle investigations (I)

Fuel cycle options for the production and utilization of denatured Plutonium (*Kessler, Broeders, 2007*)

Table III: Dedicated fuel compositions for fuel cycle calculations (NSE May 2007)

Fuel type	pitch /diameter P/D	moderator /fuel ratio MFR	Fuel composition	Th wt %	U wt %		Plutonium wt %		MA wt %
					Total	Fissile	Total	Fissile	
A	1.4427	2.2039	Re-enriched recycled U	0	100	5.52	0	0	0
B	1.3389	1.7133	Re-enriched recycled U + Pu1	0	93.9	5.00	6.1	64.5	0
C	1.3389	1.7132	Re-enriched recycled U + Pu2	0	94.9	5.00	5.1	54.3	0
D	1.4068	2.0302	Re-enriched recycled U + Pu1–MA	0	92.5	5.00	6.5	64.5	1.0
E	1.5926	2.9780	Enriched U + Th +Pu1-MA	52.6	35.1	6.00	10.7	64.5	1.6

Selected results of fuel cycle investigations (II)

Fuel cycle options for the production and utilization of denatured Plutonium (*Kessler, Broeders, 2007*)

Table VII; Summary of reactivity coefficients for LWR lattices with dedicated fuels

Reactivity coefficients		Fuel Type				
		A	B	C	D	E
Moderator Density Coefficient (MDC)	BOC	0.1257	0.1542	0.1692	0.1616	0.1744
	EOC	0.1336	0.1706	0.1840	0.1721	0.1677
Moderator Temperature Coefficient (MTC)	BOC	-4.048.10-4	-5.449.10-4	-4.965.10-4	-5.204.10-4	-5.617.10-4
	EOC	-4.302.10-4	-5.923.10-4	-5.494.10-4	-5.541.10-4	-5.400.10-4
Doppler Constant (A_D)	BOC	-2.113.10-2	-2.212.10-2	-2.203.10-2	-1.911.10-2	-1.330.10-2
	EOC	-1.172.10-2	-2.012.10-2	-2.001.10-2	-1.796.10-2	-1.269.10-2
BOC boron in ppm		4600	6100	4800	4000	2100
Boron efficiency (pcm/ppm)	BOC	-5.73	-1.80	-1.64	-1.85	-2.60
	EOC	-5.20	-1.81	-1.64	-1.92	-2.67

MDC: Moderator Density Coefficient calculated from 10% reduction at nominal density

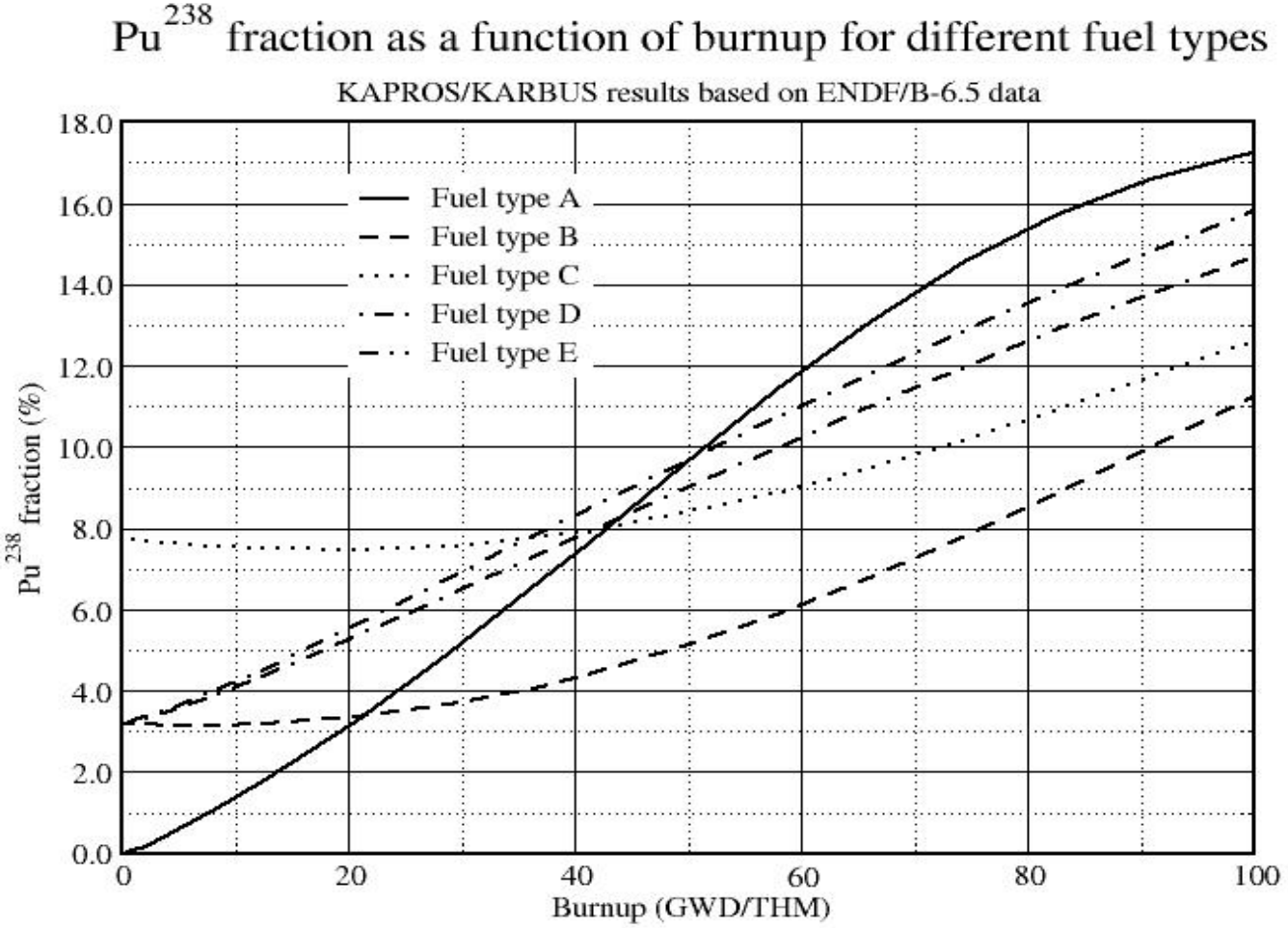
MTC: Moderator Temperature Coefficient, being –3.22.10-3 x MDC at nominal coolant conditions

A_D: Doppler constant for calculation of Doppler Coefficient from fit of $dk/dT = A_D / T$ for T=300, 900 and 2100K

Boron at BOC: The boron concentration to obtain $k_\infty \approx 1.03$ at BOC

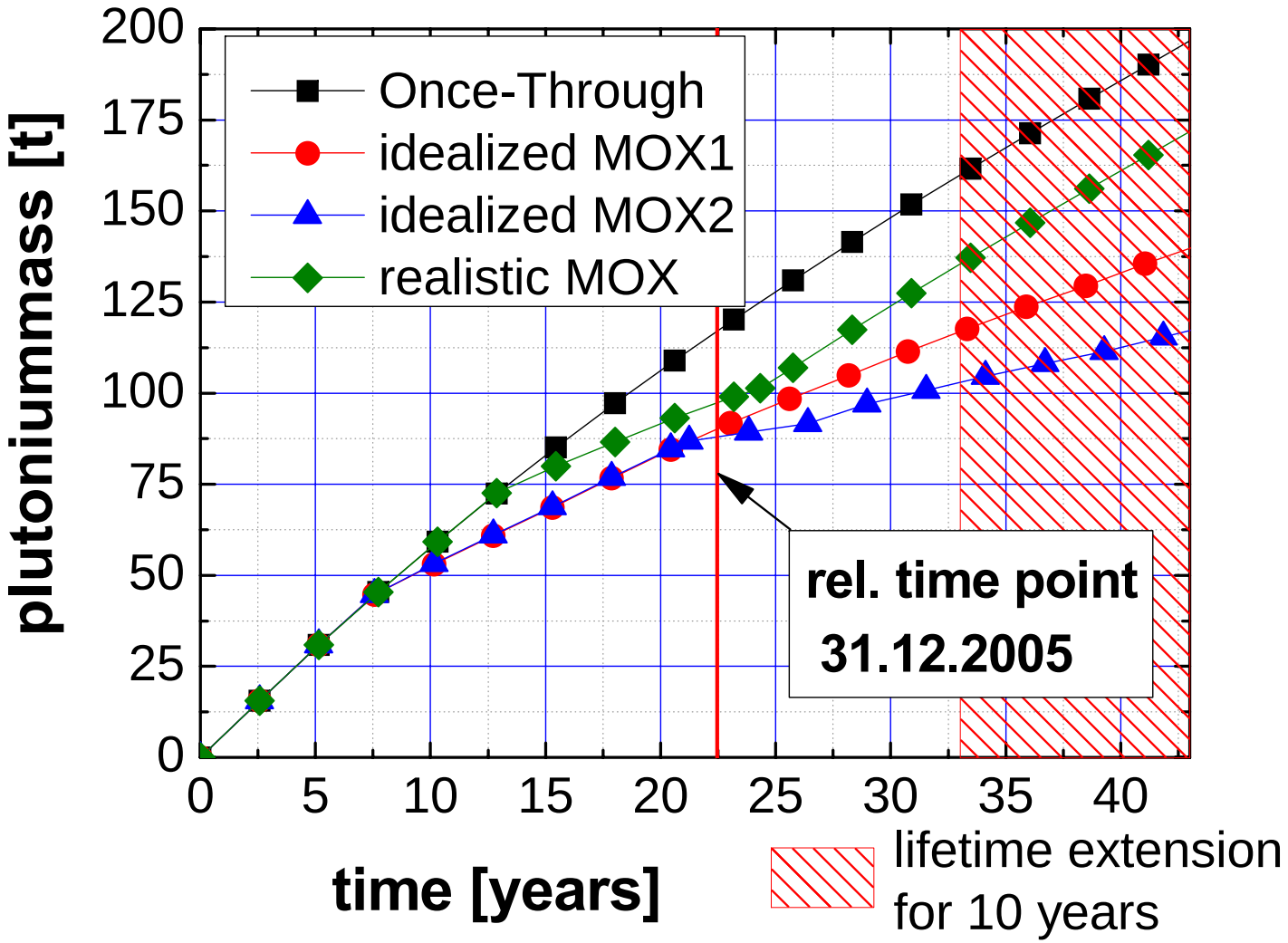
Selected results of fuel cycle investigations (III)

Fuel cycle options for the production and utilization of denatured Plutonium (*Kessler, Broeders, 2007*)



Selected results of fuel cycle investigations (IV)

Scenario studies for Plutonium mass accumulation in German reactor park (*Merk, Broeders, 2006*)



Selected results of fuel cycle investigations (V)

Scenario studies for Plutonium mass accumulation in German reactor park (*Merk, Broeders, 2006*)

	Once-Through (OT)	Once recycle MOX (MOX1)	Twice recycle MOX (MOX2)	Close to reality MOX (MOXr)
Fixed operating time (FOT)				
Plutonium mass [t]	**~160**	**~117**	**~103**	**~135**
comparison to OT	**100%**	**-27%**	**-35%**	**-15%**
Operating time increase				
Plutonium mass [t]	**~37**	**~23**	**~15**	**~37**
comparison to FOT	**+23%**	**+20%**	**+14%**	**+27%**
Total after 43 Years				
Plutonium mass [t]	**~197**	**~140**	**~118**	**~172**
comparison to MOXr and FOT	**145%**	**103%**	**87%**	**127%**

Summary of produced Plutonium masses for different scenarios

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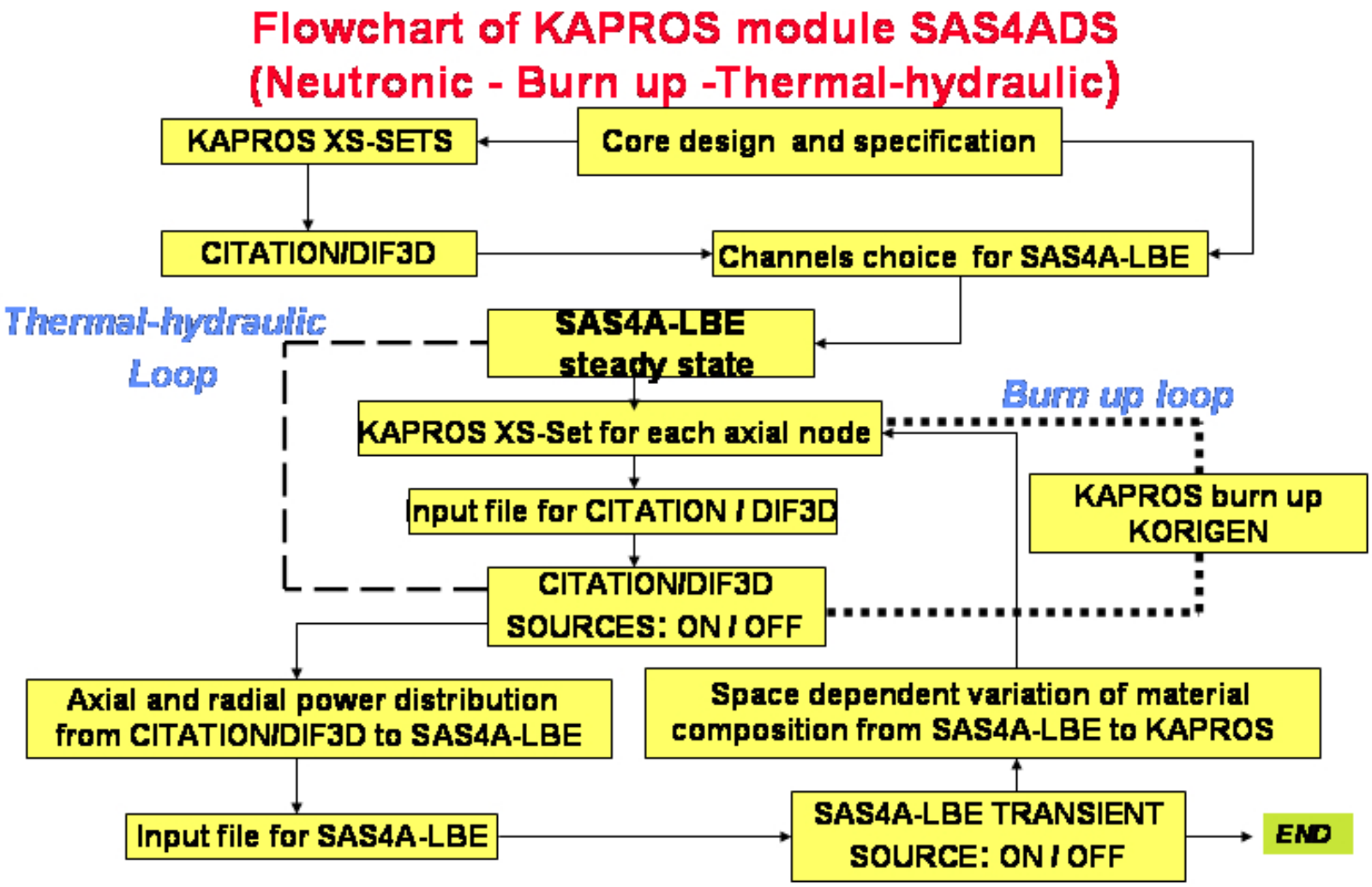
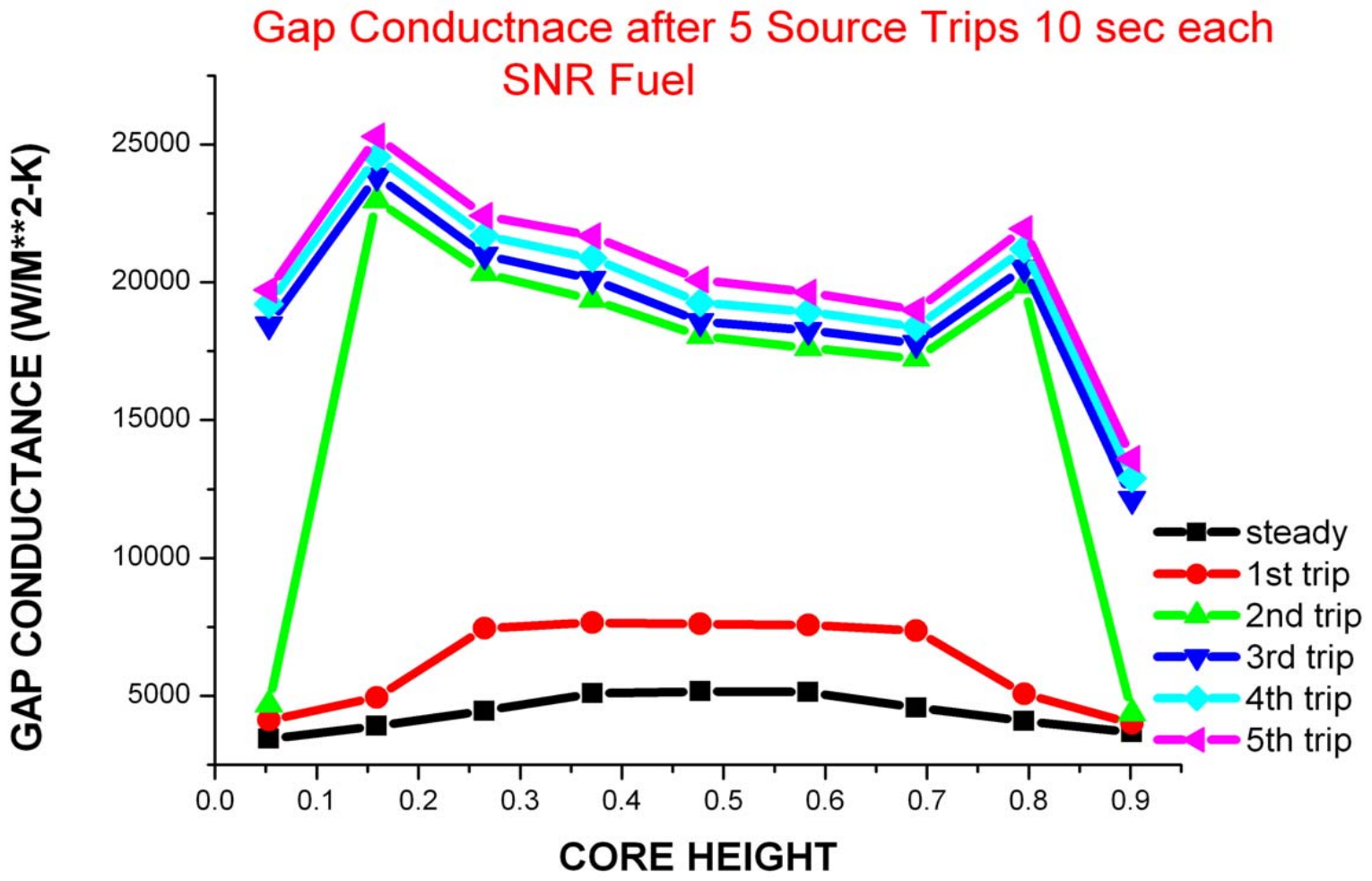
KAPROS-E; coupling of multi-physics codes with KAPROS

- Shell scripting facilitates automatic consistent coupling of neutron physics and thermo hydraulics / dynamics tasks in UNIX version of KAPROS.
- However, effective file archiving of multi-step results from KAPROS-E calculations is more complicated than KAPROS data block archiving
- Most important coupled multi physics calculation procedures in KAPROS-E
  - SAS4ADS; coupling of KAPROS neutron physics, including burnup, with SAS4A steady state and transient fast reactor code, including treatment of fuel pin mechanics behaviour
  - R5PROC; coupling of KAPROS neutron physics with steady state thermo hydraulics of RELAP5 system code
  - COBRAP; coupling of KAPROS neutron physics with steady state thermo hydraulics of COBRA-TF sub-channel code
- Current KAPROS procedure KARBUSE enables burn up calculations with consistent thermo hydraulic and neutron physics description of the reactor (COBRAP linked with BURNUP).

Flow chart of SAS4ADS code for improved 3-D ADS transient analysis



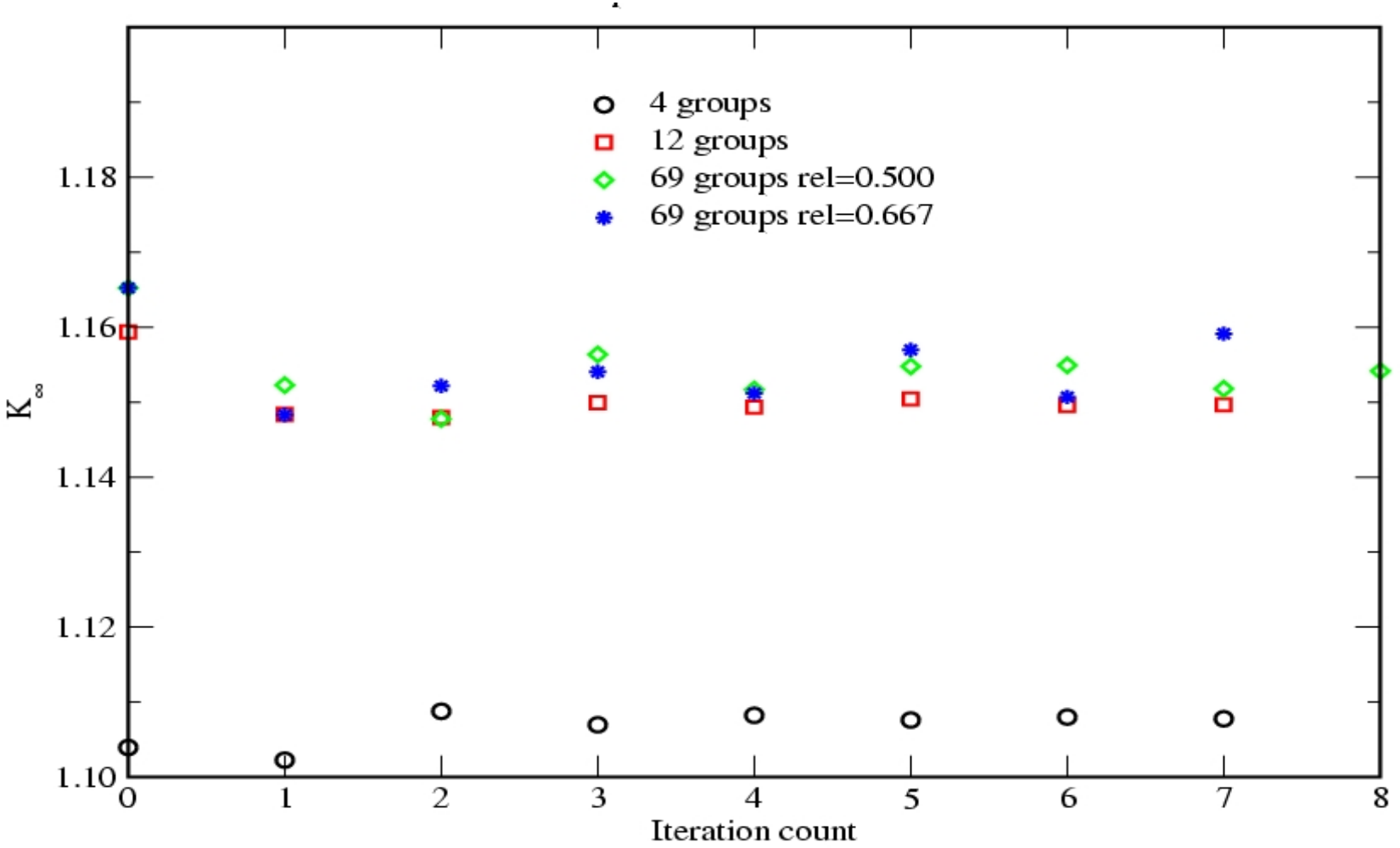
Results of SAS4ADS for Source Trip effects in ADS with SNR300 fuel



Procedure R5PROC: Coupling of codes for HPLWR investigations

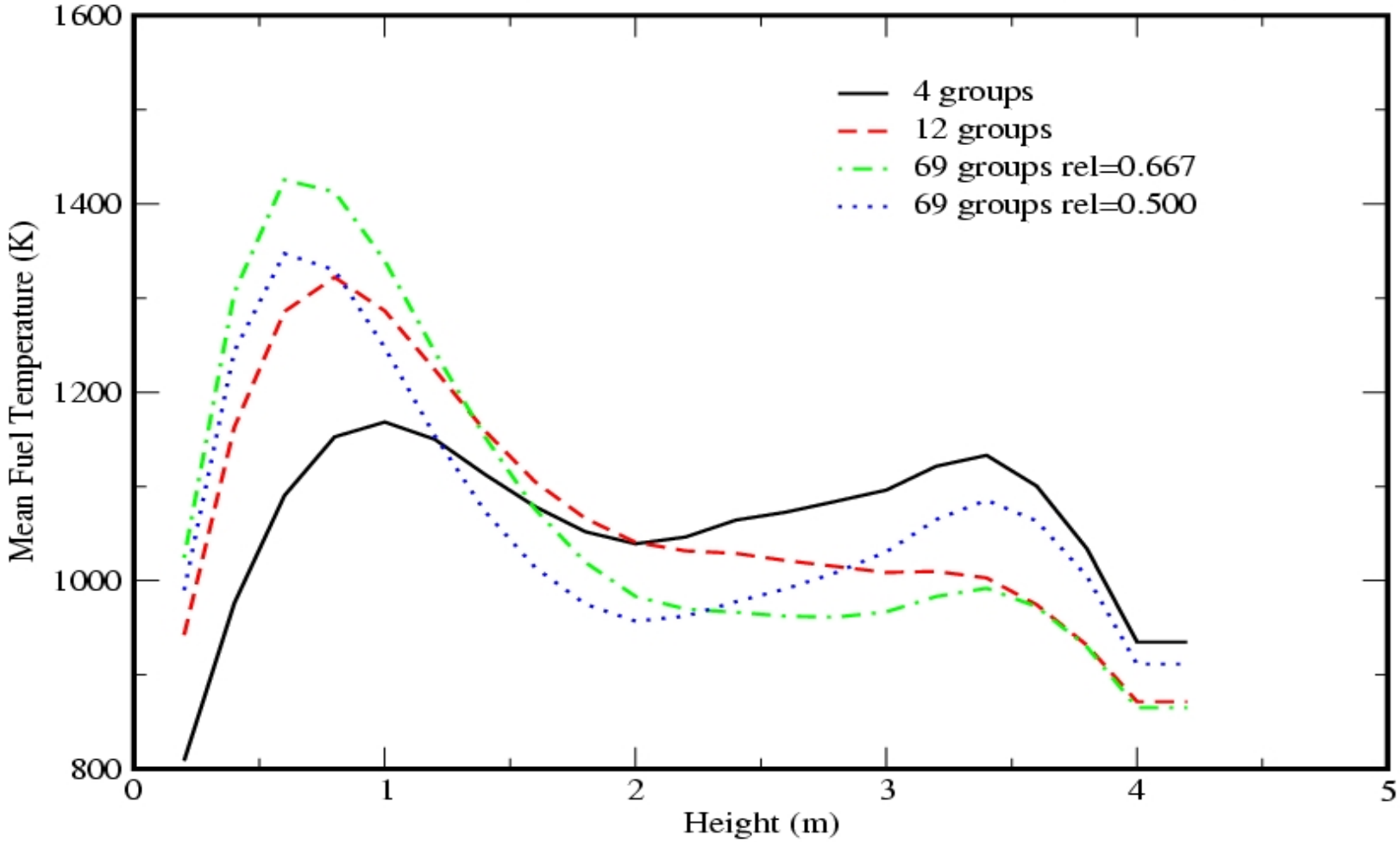
- Neutron physics code: KAPROS/KARBUS modular system developed at FZK with large efforts since mid-seventies:
  - Cross section generation with procedures developed and validated for Tight Lattice Light Water Reactor investigations
  - Super-cell (R-Z) calculations with loosely to KAPROS coupled TWODANT transport code
- Thermal-hydraulic code: RELAP5 version improved at FZK for HPLWR investigations
  - Integral plant simulation
  - One channel core representation

Results of coupled RELAP5 / KARBUS calculations with R5PROC (I)



Reactivity changes during iteration steps

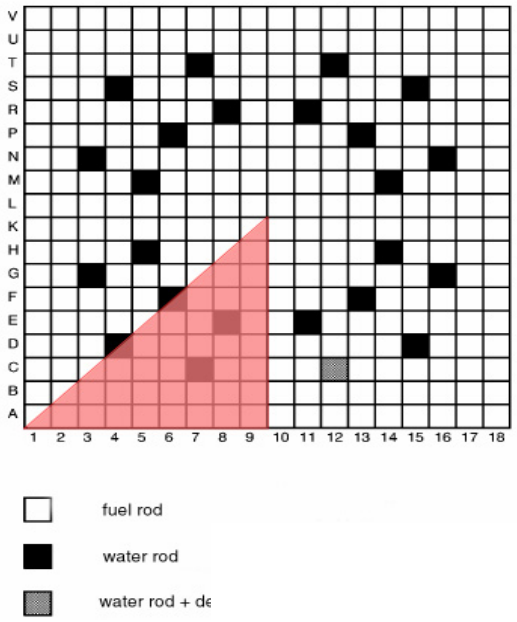
Results of coupled RELAP5 / KARBUS calculations with R5PROC (II)



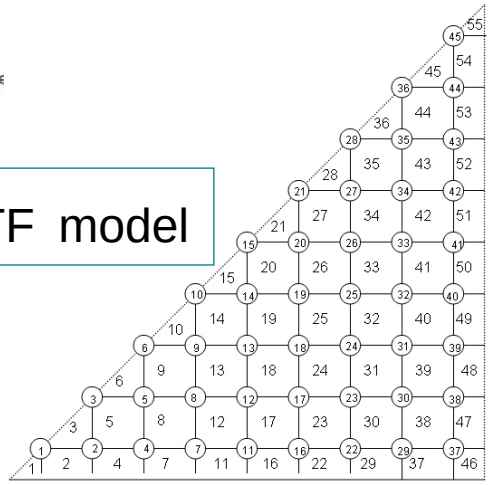
Axial distributions of the mean fuel temperature after 8 iterations

KAPROS-E / COBRA-TF:
Model and selected results for PWR Fuel Assembly- Benchmark

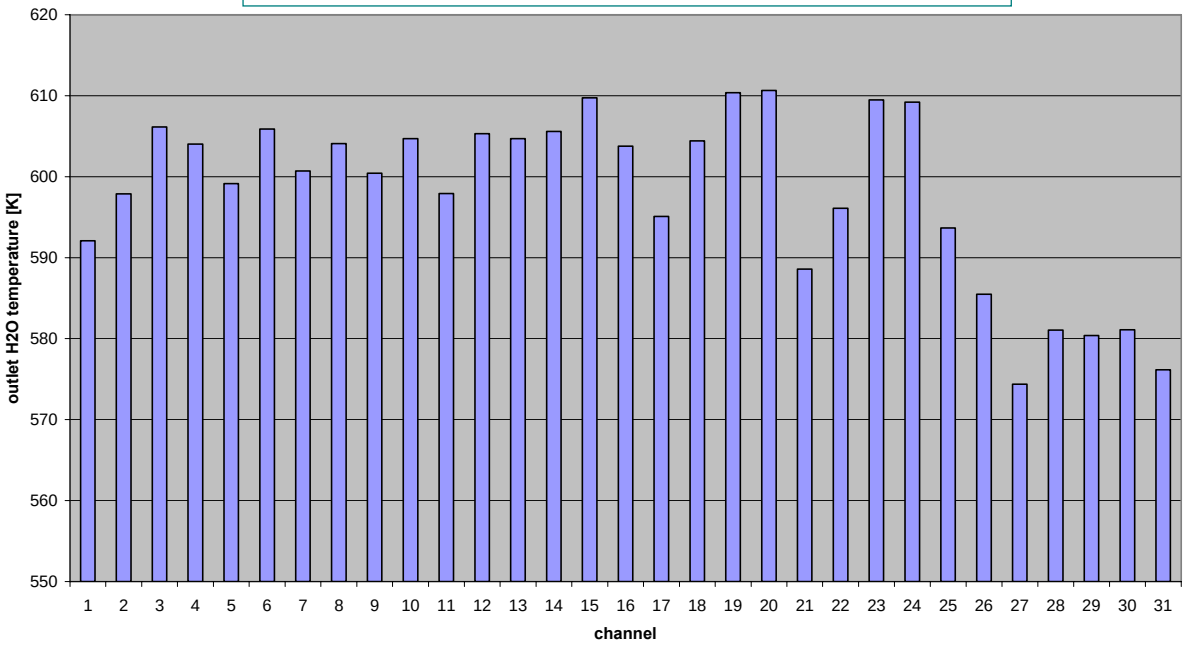
DWR-BE



COBRA-TF model

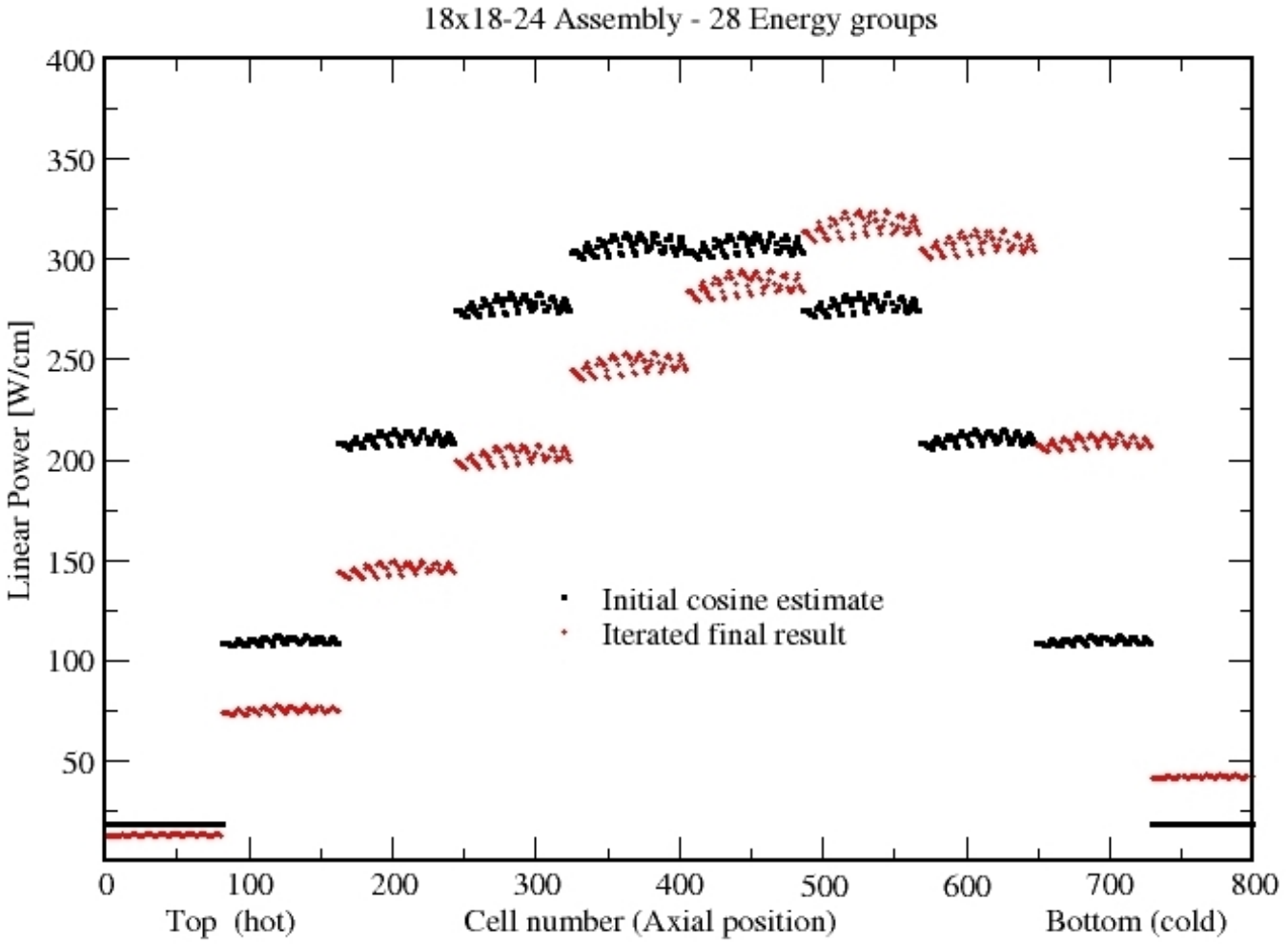


COBRA-TF: coolant temperature per sub-channel at FA-outlet



COBRAP: KAPROS-E - COBRA-TF consistent coupling

Cosine estimate and iterated axial power profiles in PWR FA- Benchmark



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Summary and outlook (I)

- The basic concept of the modular system KAPROS is well suited to develop complicated variable sequences of calculation tasks. It survived several development stages of computer hardware and software systems
- In the early stage of KAPROS development, modules were strongly integrated and were mainly restricted to neutron physics calculations
- The scripting capabilities of UNIX facilitates loosely coupling of current KAPROS version with international available stand-alone codes and applying standard interface files
- The current system is running on LINUX workstations without problems. Several powerful stand-alone codes, including thermo-hydraulic and transient codes, are loosely coupled to the extended version KAPROS-E
- Increasing number of users and applications may be observed since KAPROS LINUX version is operable. Some reasons:
  - KAPROS is well suited for current R&D projects
  - Integration of students work in KAPROS applications

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Summary and outlook (II)

- **Not yet implemented modules for fine flux based group cross section calculations are currently in the adaptation phase for the KAPROS LINUX version. The data base format of the international code system SCALE for point wise energy dependant cross section storage will be applied.**
- **Principles of, and experiences with KAPROS, are a good basis for participation in projects for development of future coupled code systems. The proposed NURESIM2 project for 7. ECFP could be a good platform for such developments (but experiences with current NURESIM FP6 are quite disappointing up till now).**
- **Documentation of current UNIX version of KAPROS and its main modules has been started with FZK report preparation**

With many thanks to
all colleagues who contributed
to the developments, enabling
this presentation of
a really old powerful tool
for the simulation of
nuclear reactor systems
(NURESIM-0??)