Neutron Physics Investigations at FZK for High Conversion Light Water Reactors (HCLWR)

Summary of results of project investigations in the period 1980-1990 and outlook for the future

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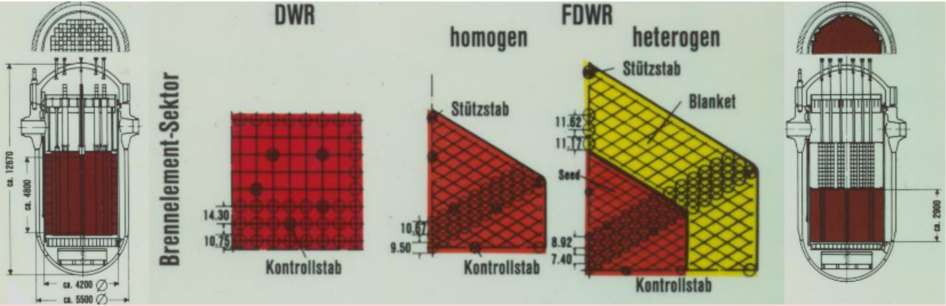


Outline

1. FZK HCLWR research in the eighties
2. FZK HCLWR neutron physics developments
3. HCLWR design investigations
4. KAPROS/KARBUS/KANEXT development
5. Use of thorium in HCLWR
6. Summary and Outlook

Characteristics of HCLWR related F&E activities in the eighties

- Motivation: enhancing uranium utilization in PWR by conversion ratio increase in view of delay of fast breeder reactor introduction
- Application of full MOX tight lattice cores
- International cooperation of several research center and industry
- Evolution from futuristic concept (moveable seed-blanket) to realistic conceptional designs (strong industry feedback)
- Strong neutronic and thermo-hydraulic experimental support
- Key neutronics problems were prediction of criticality and voiding effects in MOX fueled HCLWR cores (see KFK5072, Broeders, 1992)

▸ trilateral cooperation scheme

Selected results of past HCLWR neutron physics research at FZK

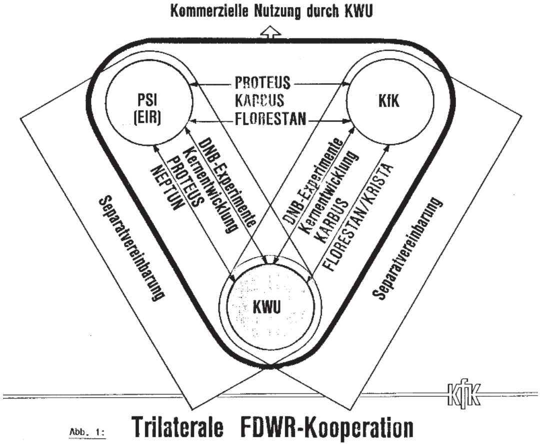


Fig: Trilateral cooperation HCLWR development in the eighties of last century

Selected results of past HCLWR neutron physics research at FZK

Selected publications out of 265 in KFK5072:

[1] H.D. Berger, A.W. Rowe, C. Broeders, M. Schatz, “Überprüfung der Berechnungsverfahren für enge Reaktorgitter von Fortschrittlichen Druckwasserreaktoren (FDWR) an experimentellen Anordnungen”, KfK 3389 / IfRR K 8212 (1982)

[2] H.D. Berger, “Neutronenphysikalische Untersuchungen zu einem fortgeschrittenen Druckwasserreaktor mit hoher Konversion”, Dissertation TU- Braunschweig (1984), GKSS 85/E/15.

[3] C.H.M. Broeders, M. Dalle Donne, “Conceptual Design of a $(Pu, U)O_2$ Core with a Tight Fuel Rod Lattice for an Advanced Pressurized Light Water Reactor”, Nuclear Technology Vol.71, p.82 (1985).

[4] M. Cigarini, “Thermohydraulische Untersuchungen zu den Vorgängen während der Flutphase nach einem Kühlmittelverlust bei einem fortgeschrittenen Druckwasserreaktor”, Dissertation Universität Karlsruhe, KfK 4302 (1987)

[5] C. Ferrero, “Untersuchungen zu LOCA- und ATWS-Störfällen beim homogenen und heterogenen fortgeschrittenen Druckwasserreaktor”, Dissertation Universität Karlsruhe, KfK 4352 (1988)

[6] B. Klüver, “Ganzcore-Abbrandrechnungen für einen fortgeschrittenen Druckwasserreaktor mit dem Programmsystem KARBUS”, Diplomarbeit TU Braunschweig, K8804, (1988)

[7] M. Klumpp, “Der nukleare Brennstoffkreislauf mit fortgeschrittener Reaktortechnologie - Eine Analyse seiner ökonomischer Grundlagen und Entwicklungsmöglichkeiten”, Dissertation Universität Karlsruhe, KfK 4641 (1989)

[8] C.H.M. Broeders, “Entwicklungsarbeiten für die neutronenphysikalische Auslegung von Fortschrittlichen Druckwasserreaktoren (FDWR) mit kompakten Dreiecksgittern in hexagonalen Brennelementen“, Dissertation Universität Karlsruhe, KfK 5072 (1992)

[9] D. Christophe, “Investigations on enhanced nuclear fuel utilization in light water reactors by mixing of uranium and thorium based heavy metals “, Diplomarbeit Universität Karlsruhe (2009)

[10] P. Oberle, “Application of a new resonance formalism to Presurized Water Reactors“, Dissertation Universität Stuttgart (2010)

Neutron physics contributions by FZK

- Development of unique deterministic multigroup method for handling reactor zones with thermal, epithermal and fast spectra in the framework of the modular code system KAPROS,
  in development at that time for the Fast Breeder Project.
- Significant contribution to creation of unique specific experimental database for HCLWR MOX fuel (SNEAK, PROTEUS)
- Conceptual design investigations for several HCLWR proposals, together with other FZK researchers and industry

Selected results of past HCLWR neutron physics research at FZK

Important outcome of the HCLWR project is:

- Creation and validation of multigroup cross section data procedures for all HCLWR states (normal to voided state).
- Creation and validation of burnup procedures, applicable for HCLWR
  ▸ IAEA/CRP-ADS 2010
- Extention of experimental database for HCLWR applications by dedicated experiments in the SNEAK and PROTEUS facilities
- Code validation was focused on the prediction of criticality level, conversion ratios and reactivity coefficients.
- Important contributions were a NEACRP HCLWR benchmark ▸ Result from KFK5072 and the series of PROTEUS HCLWR experiments ▸ PROTEUS-FDWR Dokumentation 1993.
- The KANEXT module PROEVA allows direct comparison of calculated results with experimental data from the PROTEUS project ▸ KANEXT PROEVA output samples.

Selected results of past HCLWR neutron physics research at FZK

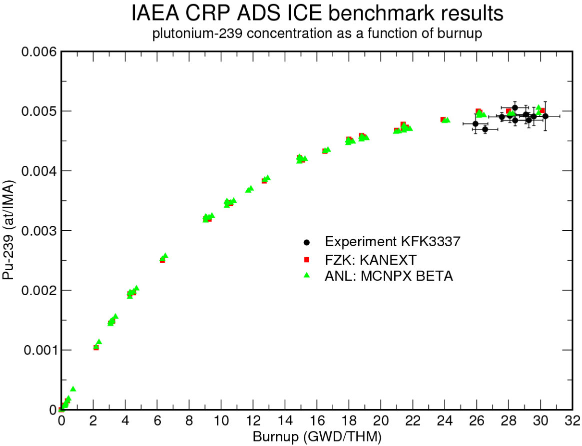


Fig: FZK and ANL results for Pu^{239} buildup in KWO ICE experiment (IAEA-CRP ADS 2010)

Selected results of past HCLWR neutron physics research at FZK

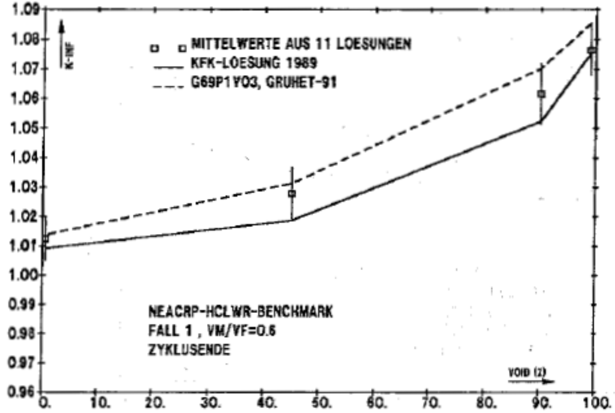


Fig: Comparison of FZK results for k_∞ in NEACRP HCLWR benchmark (KFK5072 1992)

Selected results of past HCLWR neutron physics research at FZK

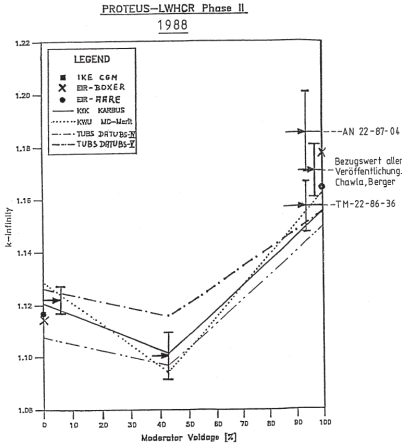


Fig: Comparison of calculational results for PROTEUS HCLWR experiments (PROTEUS-FDWR Dokumentation 1993)

Selected results of past HCLWR neutron physics research at FZK

EVALUATION FOR PROTEUS-CORE 7

NO EXPERIMENTAL DATA IF VALUE IS 1.

PARAM.	CALCUL.	EXPERIM.	C/E
K-INFIN	1.11740	1.12200	0.99590
F5/F9	0.90069	0.89300	1.00861
F8/F9	0.01345	0.01366	0.98489
F1/F9	1.67647	1.70300	0.98442
C8/F9	0.07772	0.07782	0.99872
C2/F9	1.15653	1.07438	1.07647

EVALUATION FOR PROTEUS-CORE 9

NO EXPERIMENTAL DATA IF VALUE IS 1.

PARAM.	CALCUL.	EXPERIM.	C/E
K-INFIN	1.10415	1.10200	1.00195
F5/F9	1.02882	1.00580	1.02288
F8/F9	0.01610	0.01643	0.98002
F1/F9	1.74998	1.78600	0.97983
C8/F9	0.09645	0.09632	1.00140
C2/F9	1.06211	0.99210	1.07057

EVALUATION FOR PROTEUS-CORE 8

NO EXPERIMENTAL DATA IF VALUE IS 1.

PARAM.	CALCUL.	EXPERIM.	C/E
K-INFIN	1.16938	1.17000	0.99947
F5/F9	1.06623	1.03890	1.02630
F8/F9	0.02455	0.02585	0.94979
F1/F9	1.41475	1.39320	1.01547
C8/F9	0.14483	0.14332	1.01057
C2/F9	0.26730	0.21260	1.25731

EVALUATION FOR PROTEUS-CORE 13

NO EXPERIMENTAL DATA IF VALUE IS 1.

PARAM.	CALCUL.	EXPERIM.	C/E
K-INFIN	1.14621	1.14500	1.00106
F5/F9	0.72868	0.72000	1.01205
F8/F9	0.00895	0.00940	0.95165
F1/F9	1.49315	1.49600	0.99809
C8/F9	0.05305	0.05040	1.05259
C2/F9	1.00704	0.94090	1.07029

EVALUATION FOR PROTEUS-CORE 15

NO EXPERIMENTAL DATA IF VALUE IS 1.

PARAM.	CALCUL.	EXPERIM.	C/E
K-INFIN	1.08789	1.00000	1.08789
F5/F9	0.86257	0.84020	1.02662
F8/F9	0.01175	0.01223	0.96041
F1/F9	1.64817	1.00000	1.64817
C8/F9	0.07421	0.07214	1.02864
C2/F9	1.17584	1.00000	1.17584

EVALUATION FOR PROTEUS-CORE 14

NO EXPERIMENTAL DATA IF VALUE IS 1.

PARAM.	CALCUL.	EXPERIM.	C/E
K-INFIN	1.15376	1.00000	1.15376
F5/F9	1.06881	1.00000	1.06881
F8/F9	0.02432	1.00000	0.02432
F1/F9	1.41791	1.00000	1.41791
C8/F9	0.14534	1.00000	0.14534
C2/F9	0.26895	1.00000	0.26895

Table: Sample of output of KANEXT module PROEVA

Selected results of past HCLWR neutron physics research at FZK

Developments for the calculation of effective resonance cross sections:

- Treatment of heterogenities in homogenized fuel elements on the basis of selfshielding factor interpolations
- Treatment of heterogenities in the basic fuel cells of the fuel elements on the basis of selfshielding factor interpolations
- Original derivation of new formulation for Bell-Levine factor for resonance escape probabilities Bell/Levine.
- Using fine-flux spectra for direct calculation of effective cross sections in the special modules ULFISP (part of PhD in KFK5072) and RESABK (IKE Stuttgart solution) ULFISP/RESABK fluxes
- Quite large effects were observed for single resonances of the very important isotope U^{238} with compensating tendencies U-238 capture.
- Recently a PhD thesis at INR by Oberle [10] was devoted to improved scattering treatment in the energy region with resolved resonances, resulting in an improved module ULFISP ULFISP.

Selected HCLWR results at FZK
New Bell factor determination

Based on equivalencies between homogeneous and heterogeneous reactor zones Wigner proposed the rational approximation for escape probabilities from absorbing bodies. Bell and Levine found that introduction of a factor **a** is valid within this theory and may improve the equivalencies (in Wigner formulation a=1)

$$P_e = \frac{1}{1 + \frac{\Sigma_t^F \bar{\ell}_F}{a}} \quad (1)$$

Σ_t^F total macroscopic cross section in fuel
$\bar{\ell}_F$ chord length in absorbing body

Available codes at that time applied constant **a** values between 1.16 and 1.53

In 1964 Otter introduced an improvement with an energy group dependant **a** value. An original contribution of [8] is the derivation of a group dependant value **a** from formula (1), assuming that a good approximation for P_e is available

$$a = \frac{P_e}{(1 - P_e)} \cdot \Sigma_t^F \bar{\ell}_F \qquad (2)$$

The comparison of these two proposals shows good agreement Broeders-Otter

Selected results of past HCLWR neutron physics research at FZK

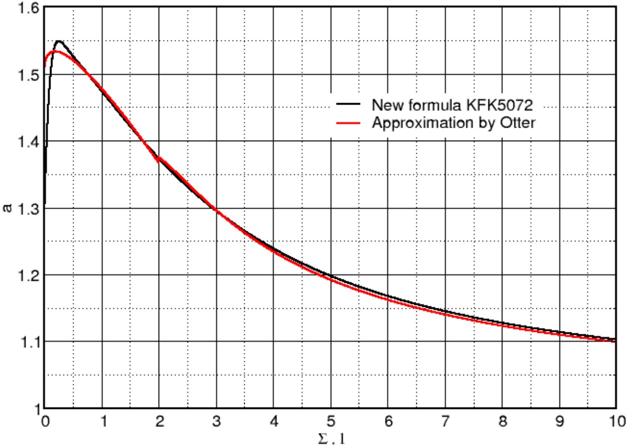


Fig: Comparison of Bell-Levine factor of new methodal with literature data

Selected results of past HCLWR neutron physics research at FZK

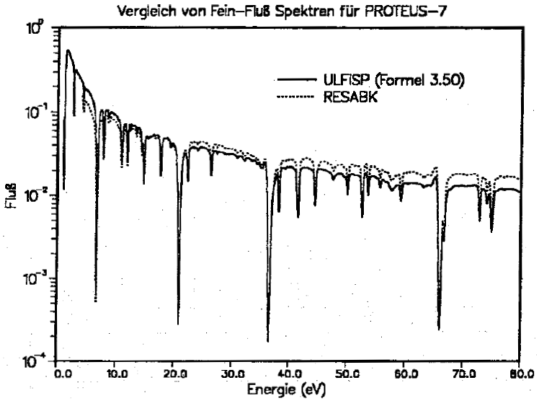


Fig: Fine flux spectra for the PROTEUS-7 experiment calculated with modules ULFISP and RESABK

Selected results of past HCLWR neutron physics research at FZK

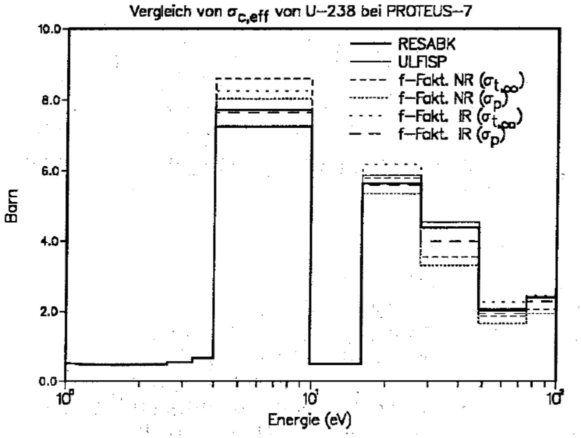


Fig: Effective capture cross sections for different calculation methods

Selected results of past HCLWR neutron physics research at FZK

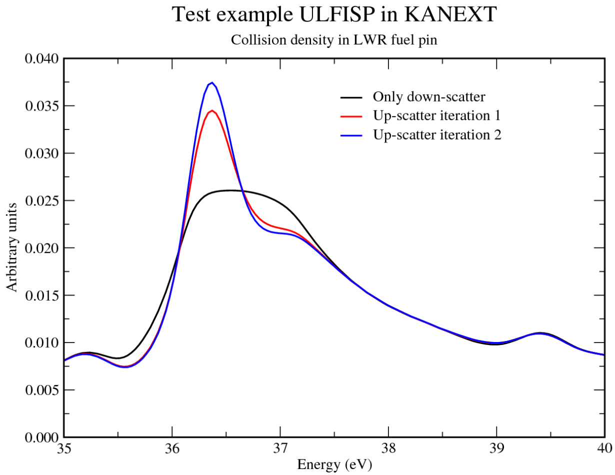


Fig: Collision density for U-238 36eV resonance with improved ULFISP

Selected results of past HCLWR neutron physics research at FZK

After systematic exploratory investigations, detailed conceptual design studies were performed for two basic core concepts:

- Heterogeneous core with relatively small high enriched ”seed” and low enriched ”blanket” fuel elements ▸ Original SBL Model
  Note: This solution replaces the big ”seed-blanket” module of the entry slide by a bundle of small fuel assemblies with equivalent neutronic properties and is an original contribution of the work in [8].
- Homogeneous core with larger fuel elements and medium enrichment

- Both cores contain three radial zones with inceasing enrichment in the outward direction for power flattening ▸ HCLWR core concepts.
- The voiding behaviour of investigated HCLWR proposals demonstrates that caution is necessary with undermoderated LWR with MOX fuel ▸ HCLWR voiding.

Selected results of past HCLWR neutron physics research at FZK

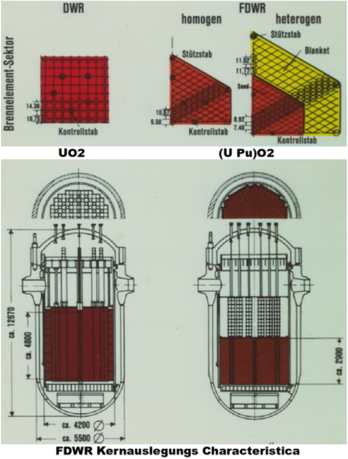
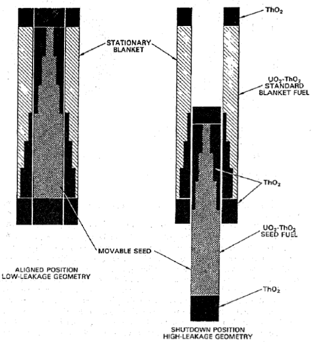
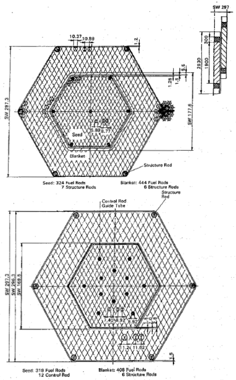


Fig: HCLWR core design characteristics (from Project Management slide)

Selected results of past HCLWR neutron physics research at FZK

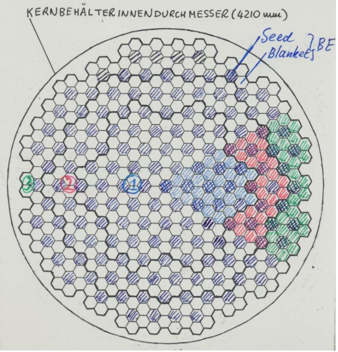


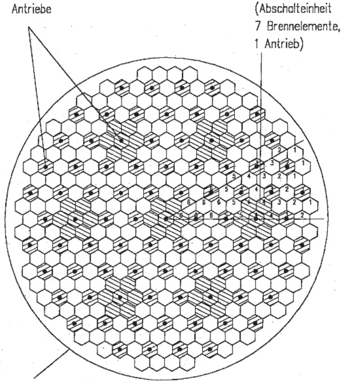


Case: Moveable Seed-Blanket principle (Radkowsky)

Case: Moveable and fixed Seed-Blanket designs

Selected results of past HCLWR neutron physics research at FZK





Case: Heterogeneous design

Case: Homogeneous design

Table: Cross sections of investigated HCLWR cores (KFK5072)

Selected results of past HCLWR neutron physics research at FZK

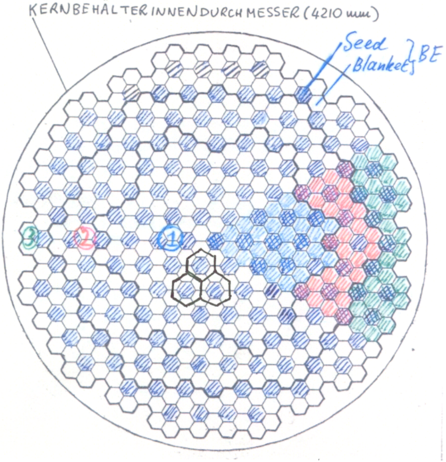


Fig: Original proposal for seed/blanket core with small hexagons (KFK5072)

Selected results of past HCLWR neutron physics research at FZK

	PWR *	HCLWR			
		Homogeneous		Heterogeneous	
		Tight	Wider	Tight	Wider
Power (MW_{th})	3765	3720	3730	3460	3705
Power rating (W/cm)	208	160	180	176/147 ‡	195/159
Core diameterr (cm)	360.5	389.0	386.0	384.0	385.0
Core height (cm)	390.0	205.1	220.6	195.7	218.3
Number fuel assemblies	193	349	301	151 §	151/348
Pins per fuel assembly	236	313	313	313/408	259/169
Total number of pins	45550	109237	94210	108870	97920
Pin diameter (mm)	10.75	9.5	9.5	7.4/11.2	7.4/11.1
p/d	1.33 †	1.12	1.20	1.21/1.04	1.30/1.10
V_M/V_S	1.25	0.39	0.59	0.70/0.23	0.85/0.33
Mean enrichment (%)	2.49	7.53	7.40	14.2/4.8	14.8/4.5
Fissile inventory (TSM)	2.57	8.83	8.02	8.39	8.41
Fuel inventory (TSM)	103.5	120	111	122	121

* *KWU data*
† *quadratic lattice*
‡ *xx/yy for Seed/Blanket*
§ *SBL-Modules*

Table: Comparison of results for PWR/HCLWR designs 1987, part 1.

Selected results of past HCLWR neutron physics research at FZK

	PWR *	HCLWR			
		Homogeneous		Heterogeneous	
		Tight	Wider	Tight	Wider
k_{eff} (BOC)	-	1.0296	1.0325	1.0262	1.0253
Cycle time (FPD)	360	365	300	380	320
Burnup $(\frac{MWT}{TSM})^{\star}$	33000	34000	31000	48400	41000
k_{eff} (EOC)	-	1.0012	0.9941	1.0015	0.9966
Δk_{Void} (EOC) (10^{-2})	-	+1.61	-1.05	-0.40	-1.34
Conversion ratio (EOC)	**0.55**	**0.96**	**0.90**	**1.00**	**0.96**
$\Delta k / VLT (10^{-4} / VLT)$	-3.0	-0.95	-1.28	-0.82	-0.95
$\frac{dk}{d\rho}$ **(EOC)** $(10^{-2} / \frac{g}{cm^3})$	**+10.0**	**$\approx$ 0**	**+7.0**	**$\approx$ 0**	**+3.0**
$\frac{dk}{dT_{fuel}}$ (EOC) $(10^{-5} / K)$	-2.1	-3.2	-3.0	-3.1	-3.0

* *KWU data*
⋆ *Seed zones 6, otherwise 3 burnup cycles*
BOC *Begin of cycle*
EOC *End of cycle*

Table: Comparison of results for PWR/HCLWR designs 1987, part 2. KFK5072, Table 6.9

Selected results of past HCLWR neutron physics research at FZK

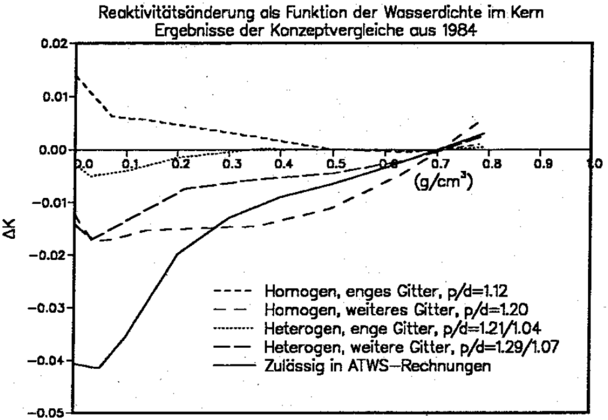


Fig: Comparision of coolant density reactivity effects for HCLWR proposals (KFK5072 1992)

Selected results of past HCLWR neutron physics research at FZK

The HCLWR core simulator ARCOSI

Based on the work of Klüver in [6] the module ARCOSI (**A**dvanced **R**eactor **CO**re **SI**mulator) was developed with the following objectives:

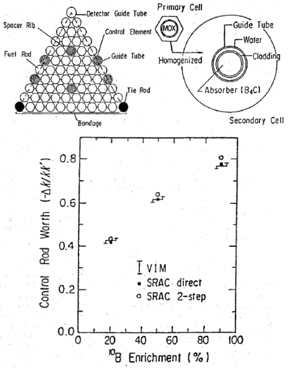
- Automatized handling multiple cycles with reload and shuffling capabilities to study HCLWR equilibrium cores
- Option to determine critical boron concentration for reactor states of interest
- Options for the determination of safety coefficients like coolant density and Doppler coefficients for reactor states of interest
- Sufficient evaluation aids for judgement of results
- Acceptable computer requirements at that time

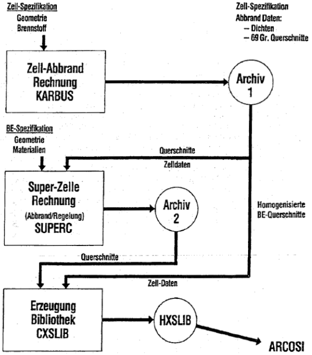
Selected results of past HCLWR neutron physics research at FZK

Features of the HCLWR core simulator ARCOSI:

- Embedded in the modular code system KAPROS
- Precalculated macroscopic cross sections for several states of the HCLWR fuel elements like temperatures, coolant density, boron concentration and burnup
- Control rod simulation with super-cell model
- Powerful interpolation schemes within cross section database
- Fast 3D flux calculations with adapted version of KWU code HEXNOD
- Flexible options for reload and shuffling of fuel assemblies
- Starting from reasonable estimates for a first trial core, repeated simulation of the same core management scheme shows good convergence to an equilibrium state

Selected results of past HCLWR neutron physics research at FZK





Validation: SRAC/VIM HCLWR supercell

Creation: HXSLIB library in KAPROS

Table: Validation and creation of cross section data for HCLWR

Selected results of past HCLWR neutron physics research at FZK

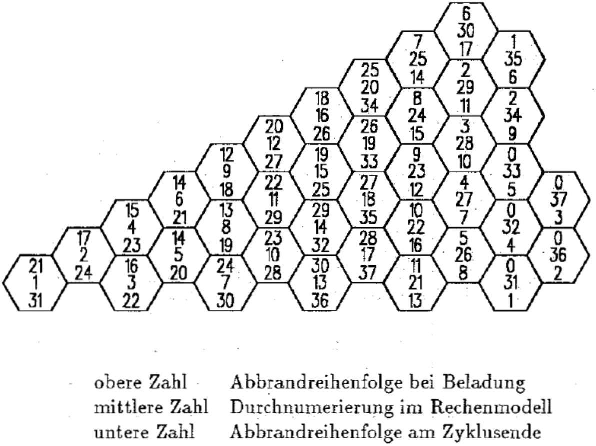


Fig: Simulation model for equilibrium study

Selected results of past HCLWR neutron physics research at FZK

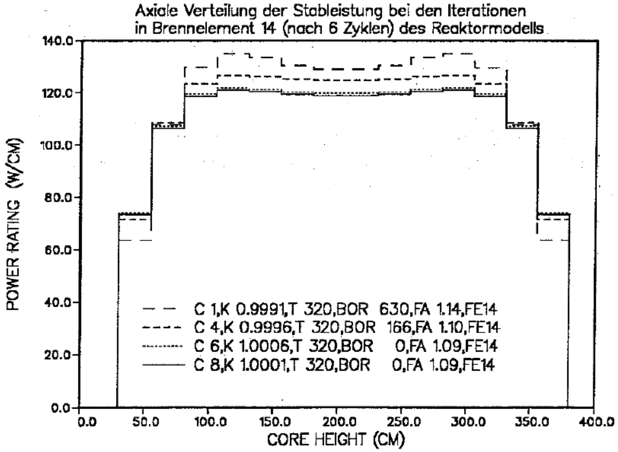


Fig: Iteration results for equilibrium search for axial power

Selected results of past HCLWR neutron physics research at FZK

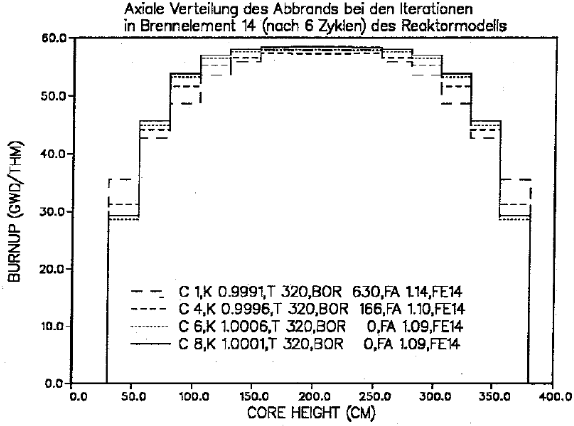


Fig: Iteration results for equilibrium search for axial burnup

Selected results of past HCLWR neutron physics research at FZK

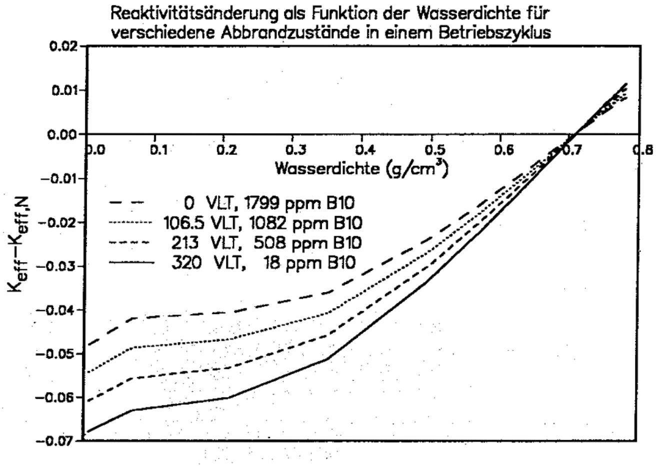


Fig: Void reactivity effects in critical HCLWR as a function of burnup

Developments of the code system KAPROS/KARBUS/KANEXT

A more detailed overview of the KAPROS/KANEXT development may be found at: http://inrwww.fzk.de/kanext.html

- Starting in the late sixties the modular code system KAPROS for nuclear reactor simulations was developed in FZK/INR
- The initial application area was Fast Breeder development
- For the HCLWR with its epithermal neutron spectra, the fast spectrum methods were expanded by typical features of thermalized systems.
- Together with additional reactor burnup capabilities the KAPROS module KARBUS was developed and validated.
- The original IBM Mainframe KAPROS version was successfully adapted for UNIX workstations and LINUX OS computer.
- The KAPROS/KARBUS/KANEXT system was applied in many R&D projects in the past 40 years (SNR300, HCLWR, ADS, HPLWR, GEN-IV proposals, fuel cyle analysis, ..).

  Examples: ▸ HPLWR validation, ▸ XTADS fuel management

Selected results of past HCLWR neutron physics research at FZK

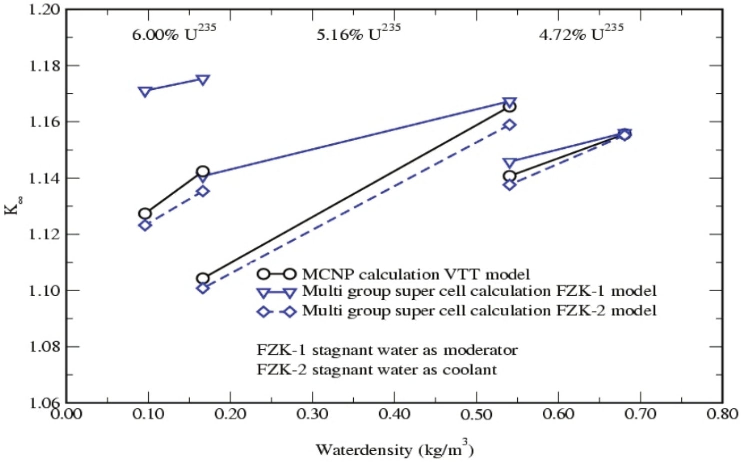


Fig: KAPROS validation with MCNP for HPLWR project (ICAPP-2003)

Selected results of past ADS neutron physics research at FZK

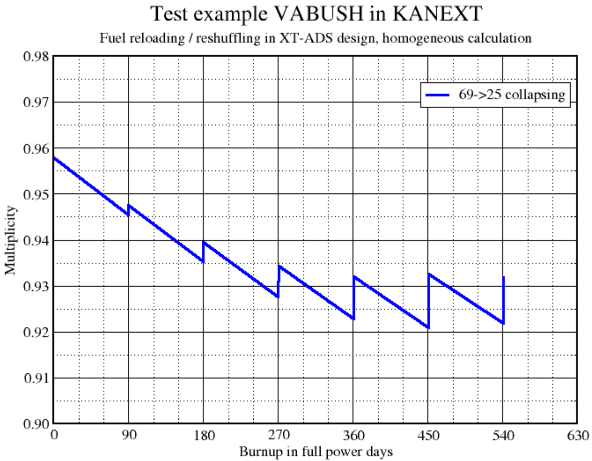


Fig: KANEXT test example for fuel management in sub-critical XT-ADS design

Considerations for introducing thorium in modern PWR

During a recent seminar at KIT on perspectives for HCLWR, several groups presented investigations on use of U^{233} in HCLWR, implicitely assuming availability of this isotope with very good fissile characteristics. Several arguments suggest this type of future fuel utilization in LWR:

- U^{233} is a fissile isotope with very good characteristics for use in nuclear reactors
- U^{233} is created by neutron absorption in the heavy metal thorium. This material is available on earth in considerable quantities in several politically independant states.
- Recycling of U^{233} from irradiated thorium fuel is proven technology on laboratory scale (THOREX process comparable with PUREX for plutonium recycling from irradiated uranium fuel)
- The accompanying isotope U^{232} in this cycle is an advantage in view of proliferation risks, but leads to the need of more expensive remote handling during manifacturing

Considerations for introducing thorium in modern PWR

- The **main drawback** of using thorium fuel in nuclear reactors is the **missing fissile isotope**, as available in uranium with the isotope U^{235}.
- The required fissile isotopes may be taken from available uranium or from spent fuel in uranium based reactor systems (plutonium, usually with a mixture of fissile and fertile isotopes). The uranium might be enriched to any reasonable U^{235} level.
- A specific complication may appear due to the relatively long halflife of about 28 days of the parent isotope Pa^{233} of the final fissile isotope U^{233}. In contrary to the Xenon effects after shut-down of thermal reactors with strong negative reactivity effects on the timescale of half days, the decay of the strong neutron absorber Pa^{233} in thorium fueled reactors may cause strong positive reactivity effects on a timescale of weeks.

Considerations for introducing thorium in modern PWR

- The promising features of introducing thorium in a closed fuel cycle for LWR, were recently analyzed in a diploma thesis at FZK/INR by Christophe [9].
- Some of the findings of this diploma work are presented in the following slides

Scenarios for introducing thorium in PWR

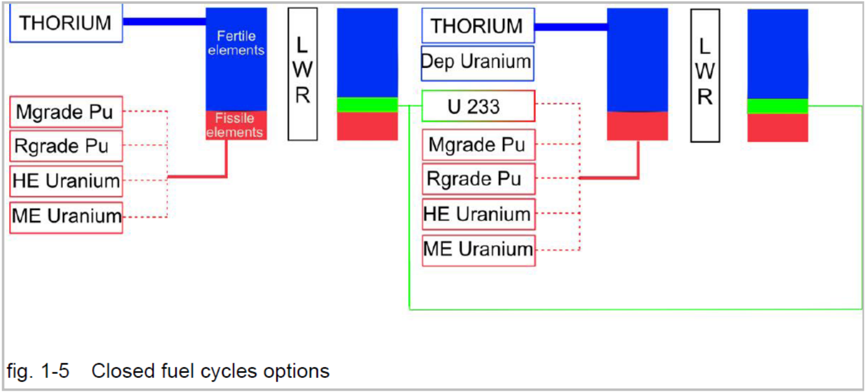


Fig: Scenarios for introducing thorium in modern PWR, Diploma thesis Damien Christophe, FZK-INR 2009

Introducing thorium in PWR

Thorium Concentration BOC w%	Fissile material (U-235) Concentration BOC w%	U-235 enrichment of the Uranium vector w%
10	4,8	5,3
20	5,0	6,3
30	5,3	7,5
40	5,5	9,2
50	5,6	11,2
70	5,7	19

Tab. 3-1 Composition of the different fuels considered in the study

Fig: Investigated fuel specifications for thorium/uranium mixtures in PWR

Introducing thorium in PWR

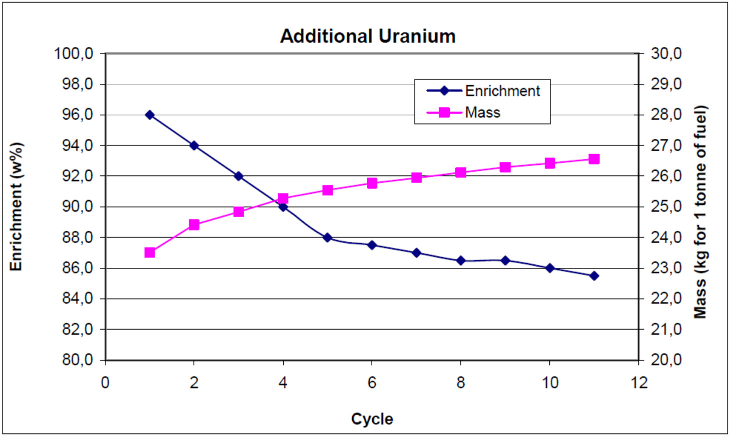


fig. 3-4 Enrichment of the additional uranium in w% for a fuel containing 73% Th

Fig: Specification of uranium supply during thorium introduction in PWR

Introducing thorium in PWR

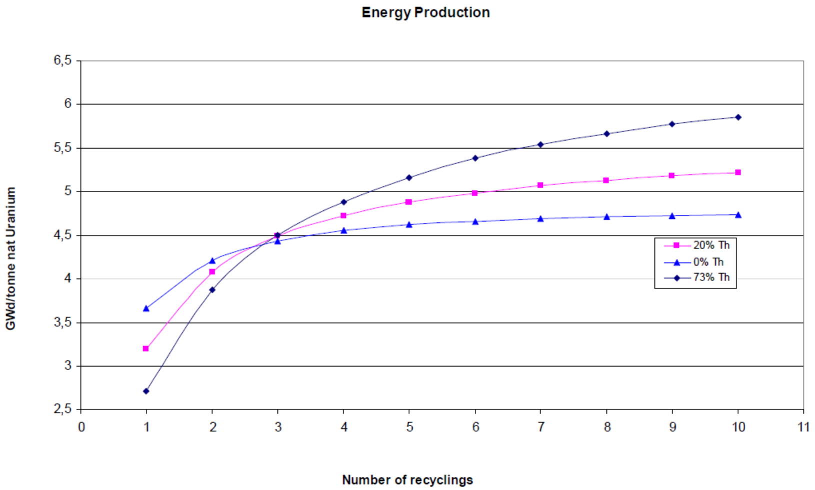


Fig: Extracted energy from uranium during thorium introduction in PWR

Introducing thorium in PWR

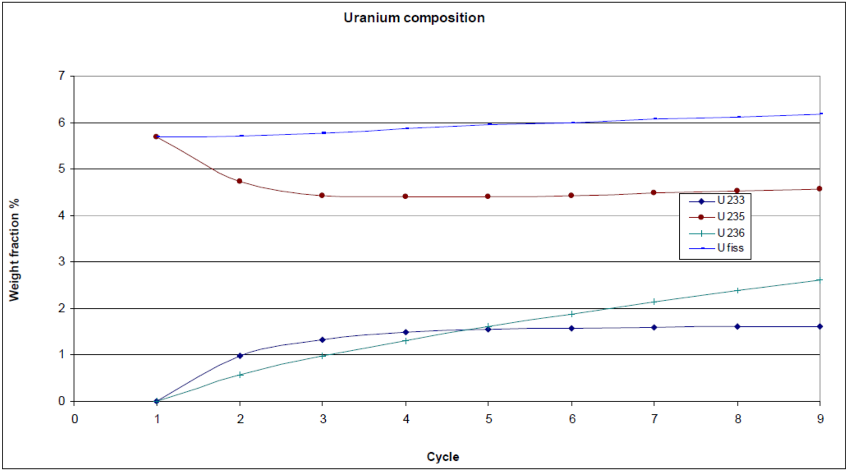


Fig: Uranium composition changes with increasing recyclings for 73% thorium case

Introducing thorium in PWR

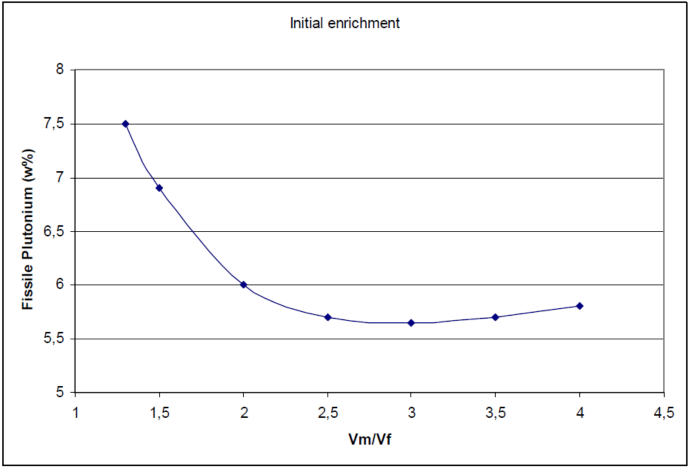


Fig: Reactor grade plutonium content as a function of moderation ratio to reach 45 GWD/THM burnup

Selected results of past HCLWR neutron physics research at FZK

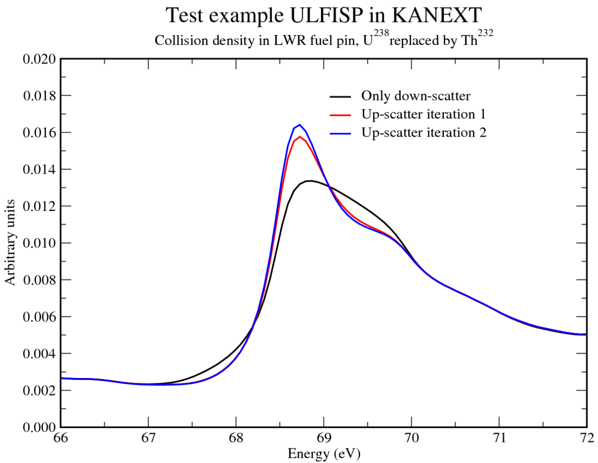


Fig: Collision density for Th-232 68eV resonance with improved ULFISP

Summary and Outlook I

- The successful international HCLWR cooperation in the eighties between research centers, universities and industry was an important R&D issue in this period
- Systematic investigation of all relevant aspects lead to detailed conceptional design proposals. Due to changing of the world-wide boundary conditions, realisation was (at least) postponed.
- Broad experimental programs in several disciplines supported the HCLWR project
- A number of PhD thesis in several scientific areas have been prepared in the framework of the HCLWR project

Summary and Outlook II

- At FZK the fast reactor options of the modular code system KAPROS were extended with typical features of thermalized systems.
- Together with the reactor burnup developments the resulting module KARBUS is a powerful tool for investigation of a wide range of nuclear systems (from very thermalized to fast spectrum ADS)
- The current version KANEXT for LINUX OS is well suited for investigations of innovative reactors.
- Part of the validation work nowadays can be performed by comparison with Monte Carlo simulations.
- In view of possible new related HCLWR projects, the main finding of the previous project must be kept in mind:

problematic voiding characteristics of strongly undermoderated LWR with MOX fuel.

The current version KANEXT for LINUX OS is tested with Open Source FORTRAN- and C- compiler.

Administrative procedures are ongoing to make available KANEXT to interested scientific groups and other partner.

Summary thorium introduction in PWR I

- Recently the introduction of thorium in PWR was subject of a diploma thesis in FZK-INR
- Several scenarios were considered, including use of enriched uranium classes and plutonium
- Most interesting issues were:
  - a) total extracted energy from uranium,
  - b) needed enriched uranium supply for a closed fuel cycle,
  - c) safety related reactivity coefficients,
- Preliminary conclusions:
  - a) Introduction of thorium in a long term scenario for utilization of nuclear fission reactors, initially based on uranium fuel, offers several benefits if a closed fuel cycle is applied.
  - b) The amount of energy extracted from uranium may be significantly increased and thorium may be used for fission energy extraction by conversion to U^{233}.
  - c) Best results will be obtained with high enriched U^{235} for the uranium feed in succeeding reactor cycles during thorium introduction.

Summary thorium introduction in PWR II

- The uranium composition shows nearly constant fractions at higher cycle number, with exception of U^{236} which keeps slightly increasing
- Some of the investigated options show improvements when the fuel lattice becomes wider. This could be beneficial for coolability problems during malfunctions of the reactor

The end

?