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INVESTIGATION OF IMPORTANCE-WEIGHTED INFINITE MULTIPLICATION CONSTANTS IN CLEAN AND POISONED LWHCR LATTICES

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ABSTRACT

The experimental procedures for obtaining importance-weighted k_∞ values in clean and B_4C-poisoned LWHCR test lattices with different simulated moderator voidage states are described. The results of these measurements, presented as calculation/experiment values, are interpreted in two different ways, viz. in terms of the reactivity effect of B_4C as control absorber and the effect of poison on the moderator void coefficient. The current experiments represent a significant broadening of the integral data base being generated in the PROTEUS-LWHCR Phase II program. Viewed in conjunction with the reaction rate ratio measurements performed in the clean lattices, they have revealed important deficiencies in the standard methods/data commonly applied in LWHCR design.

INTRODUCTION

Possibly the most important, single constraint on the technical feasibility of alternative light water high converter reactor (LWHCR) designs[1] is the sign and magnitude of the moderator void coefficient. Uncertainties in the prediction of this parameter using standard LWR physics codes and data libraries have been much too large to permit an adequately reliable optimization of core-lattice geometry. An important component of the ongoing international R & D efforts for the LWHCR has, as a consequence, been the performance of representative critical experiments with particular emphasis on the investigation of moderator voidage effects.

The bulk of the experimental results pertaining to LWHCR void coefficients which have been reported to date has been in terms of fundamental-mode characteristics measured for clean reference lattices under different moderator voidage conditions. Thus, in both the PROTEUS-LWHCR Phase I and Phase II programs[2,3], k_∞ and various reaction rate ratios were measured in test lattices with water (0% void), Dowtherm (an organic liquid simulating 42.5% H_2O-voidage) and air (100% void). These measurements led to the deduction of the clean-lattice k_∞ void coefficient, α_v – net as well as in terms of its individual components α_{vi} (due to changes in the reaction rate ratios R_i).

The validation of LWHCR physics design tools on the basis of integral results for the clean-lattice k_∞ void coefficient is widely accepted as being a fundamental requirement. In an operating power reactor, however, further effects – such as leakage, temperature and the presence of control absorbers and/or fission products – influence the reactivity response on moderator voidage significantly. While the applicability of a zero-power critical facility for the

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investigation of such effects is naturally limited in certain respects, a special series of measurements has recently been carried out to provide an experimental basis for one of these, viz. the effect on α_v of the presence of control absorbers in the core. The study has been conducted as part of the PROTEUS-LWHCR Phase II program at Würenlingen and has involved the consideration of test zones (again moderated with H_2O, Dowtherm and air) in which every 37^{th} PuO_2/UO_2 fuel pin was substituted by a natural-B_4C rod of identical geometry.

The current paper reports on the experimental procedures for obtaining importance-weighted k_∞ values in both the clean and poisoned Phase II test lattices and discusses the results in terms of calculation/experiment comparisons (C/E values).

REALIZATION OF THE LATTICES IN PROTEUS

The fuel pins used in the experiments contained mixed-oxide fuel clad in stainless steel. The fuel was made from LWR plutonium, its enrichment being about 7.5% Pu_{fiss}. The outer diameter of the fuel pins was 9.57 mm and the pitch of the hexagonal lattices currently investigated was 10.7 mm, resulting in a moderator-to-fuel volume ratio of 0.5. Both types of lattices (clean and poisoned) were investigated with either water or Dowtherm (an organic liquid with 42.5% less hydrogen content than water) as moderator and completely dry, i.e. with void contents of 0%, 42.5% and 100%, respectively.

The central test zone in each case had a diameter of 0.50 m and a height of 1.40 m (0.84 m mixed-oxide and 0.28 m top and bottom axial blankets of depleted UO_2). In the clean experiments the test zone consisted of about 1900 fuel pins, while in the poisoned case 55 of these were replaced by natural B_4C-rods.

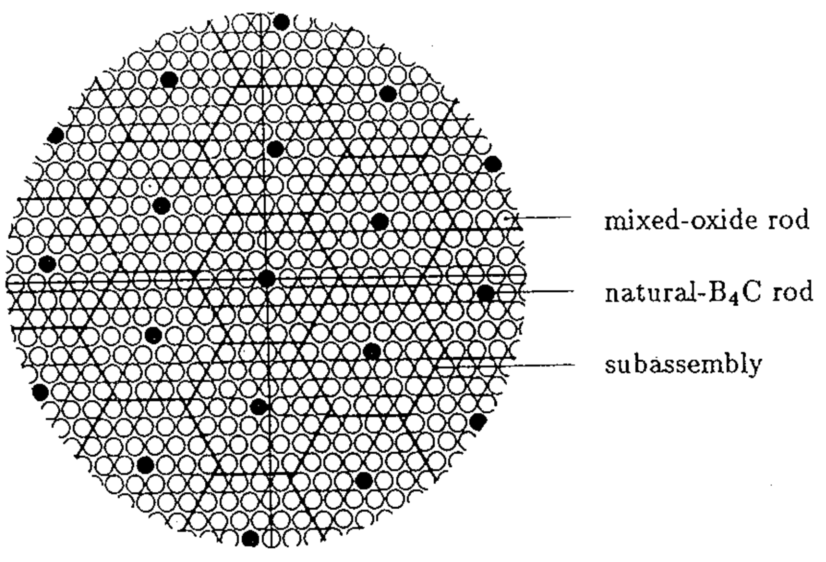

Fig. 1 Pattern of natural-B_4C absorber rods in the poisoned test zones of the PROTEUS-LWHCR phase II cores

Figure 1 indicates how a "quasi-homogeneous" poisoning was achieved with the test zone effectively divided into small hexagonal subassemblies, each containing an absorber rod in the center. The choice of a 37-rod subassembly along with natural B_4C as the absorber was dictated by several considerations, e.g. that the k_∞ values for the moderated lattices were expected to be close to 1.0 (as in an operating power reactor) and that B_4C is a control material of primary interest for LWHCR applications[3].

EXPERIMENTAL PROCEDURES

Alternative k_∞ Measurement Techniques

The experiments in clean lattices have been aimed at the determination of the reaction rate balance from activation measurements, supplemented by the measurement of radial and axial bucklings for the evaluation of k_∞. From k_∞ and the measured reaction rates integral results pertaining to the non-measurable reaction rates can be deduced.

For a verification of the k_∞ measurements via bucklings, which for dry lattices is particularly difficult to apply due to the larger perturbations of the test zone by the surrounding buffer and driver regions, an independent method for the determination of the related quantity, k^+, the ratio of importance-weighted neutron production to removal, was developed. It combines the results from four different measurements, the most important being that of the reactivity worth of a central unit cell (PCTR-method[4]).

After a thorough comparison of the two methods in the clean lattices the cell-worth method was also applied in the poisoned configurations, where the experimental program was limited to the determination of the k_∞ values for the 37-rod "supercells". This – in conjunction with the k_∞ results for the clean lattices – enabled an evaluation of the reactivity effect of the control absorber under normal operating conditions, as well as of the influence on the void coefficient for full and partial voidage.

For the moderated poisoned lattices (H_2O and Dowtherm) both measurement techniques were applied. The material buckling was obtained by measuring radial and axial reaction rate traverses across the test zone. For the monitoring of the radial component of B^2 only a limited number of lattice positions (identical in their relative coordinates with respect to the B_4C-rods) were used, in order to avoid dealing with the micro-structures caused by the absorber rods.

In contrast to the buckling method, the cell-worth method was shown to give reliable results in both moderated and dry test zones. For the poisoned lattices the dimensions of the 37-rod "unit cell" rendered the measurement of the cell-worth more difficult. With the k_∞ values being closer to unity, however, the final accuracies achieved were comparable with those of clean lattice experiments.

Theoretical Basis for the Determination of k^+

The PCTR-technique was formerly applied in graphite-moderated and fast reactor lattices. It is based on the argument that a central lattice cell with neutron production equal to neutron absorption can be removed from the lattice without changing the reactivity of the assembly, i.e. for $k_\infty=1$. If there is a finite reactivity change ρ_c connected with such a removal, it can be used as a measure of the deviation of k_∞ from unity.

Several methods exist for the normalization of such reactivity measurements. We have adopted the normalization used by Redman and Bretscher[5] in their experiments for the determination of the ^{235}U capture-to-fission ratio in fast reactors. The reactivity worth ρ_s of neutrons from the spontaneous fission of ^{252}Cf is measured at several power levels. In addition the fission rate R_f at each power level is determined by foil activation[6]. With the known value of the source strength S of the calibrated ^{252}Cf source the ratio of measurable quantities becomes

$$\frac{\rho_c}{\rho_s} \cdot \frac{S}{R_f} = \overline{\nu} \frac{\overline{\phi^{+}}^{X}}{\overline{\phi^{+}}^{S}} \cdot \left(1 - \frac{1}{k^{+}}\right) \qquad (1)$$

$\overline{\nu}$ (the average number of neutrons emitted per fission), $\overline{\phi^{+}}^{X} / \overline{\phi^{+}}^{S}$ (the ratio of importance of fission neutrons generated in the fuel to the importance of ^{252}Cf source neutrons) and the relation between k^{+} and k_{∞} (which differ in the weighting functions used in their definition) need to be deduced from calculations, the latter two ratios being close to unity.

Principal Measurements

In order to make possible the removal of complete lattice cells over a given height at the core center the fuel pins used in this region were divided into two axial sections. By raising the upper section a space without fuel was created at the core center. In a dry lattice this corresponded directly to removing one or more lattice cells. In the moderated lattices hexagonal thin-walled boxes made of glass fibre and epoxy resin were made to occupy the space created. The dimensions of the void regions in clean lattices were varied between 30 and 68 mm in effective diameter and between 100 and 200 mm in height. In poisoned lattices a complete supercell, consisting of 36 fuel pins and one B_4C-pin, was lifted by 100 or 200 mm.

Only relative measurements of reactivity are needed with the currently developed method. These were carried out by determining the insertion depth of a wedge-shaped servo-rod required for compensating a given reactivity change. For obtaining adequate accuracy in the measurements all changes were made without shut-down of the reactor.

Fission rates were determined by activation measurements using fissile foils. Absolute results were obtained by comparing the γ-activity of foils irradiated between fuel pellets on the one hand, and in calibrated fission chambers located in the test region on the other. The small contribution of fissions in ^{240}Pu and ^{242}Pu was not measured but derived from calculations. In the poisoned lattices only the fission rate of ^{239}Pu was measured and the total fission rate was deduced from calculated fission rate ratios.

The source strength of the ^{252}Cf source was verified by comparing it with other calibrated sources available in Switzerland and in West Germany.

In the dry lattice the normalization via ^{252}Cf neutron worth and fission rate was compared with an independent procedure involving the measurement of reactivity worths and absolute capture and fission rates of small reference samples. These experiments provided a useful confirmation of the ^{252}Cf-method in dry lattices. In moderated lattices the reference-sample normalization procedure was not easily applicable because of difficulties arising in its interpretation. The uncertainties in calculated corrections to account for non-measured reaction rates in the sample, e.g. the contribution of scattering to the sample worth, were much larger than errors in the Redman and Bretscher normalization method.

Measurement of Corrections

The removal of a number of unit cells achieved by lifting the upper section of a central fuel pin-bundle not only created a void near the center of the test region, but also changed the shape of the upper core boundary. The reactivity effects of these changes were measured by simulating them using specially fabricated short-length fuel pins.

In clean moderated lattices these corrections were of the order of several percent of the cell-worth. They increased to as much as 20% for the dry clean lattice and even further for the poisoned lattices with their very low absolute cell-worths.

The boxes used for void simulation in moderated lattices caused two perturbations which required additional corrections, viz. (a) their volume was not identical with the volume of the unit cells to be replaced and (b) their walls were of finite thickness. Accordingly, a special box was constructed with variable volume. By changing the inside pressure of this box well-defined moderator volumina could be replaced by void and the associated reactivity changes could be observed. Further, pieces of wall material were inserted in the narrow gaps between fuel pins and the variation of reactivity measured. These corrections were of the order of 10% of the cell-worth in clean lattices. In the poisoned lattices they were of the same magnitude as the cell-worths.

Deviations from linearity of the reactivity measuring devices and of the power monitors were measured and corrections applied. They amounted to $< 5\%$ in $1\text{-}1/k^+$.

COMPARISON OF CALCULATIONAL AND EXPERIMENTAL RESULTS

As predicted by the calculations the k_∞ values of the moderated poisoned lattices were found to be close to unity, while the infinite multiplication factors of the corresponding clean lattices were about 0.1 higher. The present results in the poisoned lattices are based on the k^+ method only and may change slightly after the final evaluation of the buckling experiments. In the clean lattices agreement between the two measurement techniques for k_∞ (cell-worth, bucklings) was within experimental errors in each of the lattices.

For illustration of the k^+ measurement technique via ^{252}Cf normalization, Table I gives the experimental values and accuracies of the various individual quantities measured in the clean and poisoned water-moderated lattices.

TABLE I

Principal Quantities Measured in the k^+ Experiments in the Water-Moderated Lattices

	Core 7 clean		Core 12 poisoned	
Measured Data:				
ρ_c (r/cm^3)	1.34	± 0.07	0.034	± 0.020
ρ_s (r·f)	$1.48 \cdot 10^9$	± 3%	$5.73 \cdot 10^8$	± 3%
source strength (1/s)	$6.87 \cdot 10^6$	± 3%	$5.20 \cdot 10^6$	± 3%
fission rate (1/(f·cm^3·s))	$23.8 \cdot 10^{-3}$	± 2%	$9.15 \cdot 10^{-3}$	± 5%

Note:
All uncertainties are 1σ. r and f are measures of reactivity and neutron flux in units based on the PROTEUS instrumentation. The absolute values cancel in the determination of k^+.

The clean lattice experiments have been analysed using a variety of codes and cross-section libraries[7,8]. The following discussion of calculation-to-experiment (C/E) values will concentrate on those two codes which currently have also been employed in the analysis of the poisoned experiments, viz. the U.K. lattice code WIMS/D[9] with its so-called 1981 library and the German cell code KAPER4[10] with the KEDAK-4 based data set G69CT005. The latter is an improved version of the data set G69COLD[11] used in former analyses.

While the recommended procedures for analyzing pin-cell geometries have been used for calculating the clean lattice experiments by both codes (DS_n in WIMS and collision probability in KAPER4), special options had to be employed for calculating the poisoned lattices. A multicell option based on collision probabilities was applied for calculating the 37-rod supercells with WIMS, while the KAPER4 route employed a cylindrical model with a correction to account for the inappropriate mean-chord-lengths of the fuel-pin-containing annuli. Table II gives the comparison of calculated and experimental k_∞ values for both the clean and poisoned test lattices for the three different H_2O-voidage states investigated.

TABLE II

Calculation/Experiment Values for k_∞ in the Clean and Poisoned PROTEUS-LWHCR Lattices of the Phase II Program

H_2O-Voidage	0%		42.5%		100%	
Code	WIMS	KAPER4	WIMS	KAPER4	WIMS	KAPER4
Clean	1.012	0.998	1.034	1.006	1.037	0.997
Poisoned	1.016	0.998	1.029	1.003	1.024	1.002

The accuracies achieved in the k_∞ measurements were typically $\pm$ 0.5% (1σ). In spite of the fact that the individual predictions are discrepant by upto as much as 4%, the C/E values for the clean and poisoned lattices appear relatively consistent with both calculational methods.

Two types of information may be deduced from Table II, viz. related to (a) the reactivity effect of the control absorber $(\Delta k_\infty)_{B_4C}$ and (b) the effect of the poison on the moderator void coefficient α_v. It is seen that while in the moderated lattices $(\Delta k_\infty)_{B_4C}$ is well-predicted by both codes, the reactivity effect of the control absorber is significantly overestimated by the WIMS code in the dry lattice.

Table III compares k_∞ void coefficients in the clean and poisoned lattices. Here one sees that

(i) within the experimental accuracies achieved the moderator void coeffient (between 0 and 100% void) is the same in the clean and poisoned lattices

(ii) the reactivity changes associated with 100% moderator voidage are reasonably well predicted for both types of lattices with KAPER4, whereas in the WIMS calculations α_v is significantly overestimated for the clean lattice.

More detailed information about the quality of the nuclear data used in these analyses can be obtained from the C/E values for reaction rate ratios measured in the clean lattices[12].

TABLE III

The k_∞ Void Coefficient α_v between 0% and 100% Voidage for the Clean and Poisoned LWHCR Lattices

	α_v [10^{-4}/%] Experiment	WIMS	KAPER4
clean	+4.2 ± 0.8	+6.7	+4.1
poisoned	+4.7 ± 0.8	+5.5	+5.1

Table IV gives the results for fission rates of ^{238}U, ^{235}U and ^{241}Pu relative to fission of ^{239}Pu (F8/F9, F5/F9 and F1/F9) as well as for capture rates of ^{238}U and ^{242}Pu (C8/F9 and C2/F9), the experimental uncertainties being typically between ± 2% and ± 3%. It is seen that even in the case of well predicted k_∞ values there can be a significant compensation of errors in individual neutron balance components.

TABLE IV

Calculation/Experiment Values for Reaction Rate Ratios in the Clean PROTEUS-LWHCR Lattices of the Phase II Program

H_2O-Voidage	0%		42.5%		100%	
Code	WIMS	KAPER4	WIMS	KAPER4	WIMS	KAPER4
C8/F9	0.982	1.009	0.970	1.017	1.007	1.059
F8/F9	1.030	1.046	1.019	1.059	1.026	1.073
F5/F9	0.995	1.014	0.998	1.026	1.013	1.008
F1/F9	1.054	1.017	1.065	1.004	1.152	0.969
C2/F9	1.729	0.951	1.650	0.969	0.962	1.145

To take a particular example, one may consider the C/E values for C2/F9. In the WIMS'81 cross-section library the self-shielding of the 2.7 eV capture resonance of ^{242}Pu is neglected. This explains the unusually high C/E values in the moderated lattices. Taking the self shielding of this resonance into account would increase k_∞ of the water-moderated clean lattice by 0.9% and of the Dowtherm-moderated lattice by 0.6%, but not change k_∞ of the dry lattice. Thus, this effect alone would reduce the WIMS void coefficient prediction (0 – 100% void) by about $1 \cdot 10^{-4}$/%. This illustrates how individual improvements in methods/data can cause significant changes in calculated results for k_∞ or the void coefficient.

The results of Table IV reveal a compensation of errors in the KAPER4 calculations as well. The fission rate of ^{238}U is overestimated in all lattices. Its effect on k_∞ is more than compensated in the dry lattice by the overestimation of the capture rate of ^{238}U. These effects are an indication of deficiencies in the fast data for ^{238}U in the KEDAK4 file, which determine the reaction rate ratios in the dry lattice to a large extent. Similar discrepancies were found earlier in the analysis of neutron spectrum measurements in uranium assemblies with a 208-group cross-section set based on KEDAK3. They led to modifications of the capture cross-section of ^{238}U in the adjusted data set used for the calculation of fast breeder reactors[13]. Recent evaluations of ^{238}U capture cross-sections in the unresolved resonance region for the generation of the JEF-2 file have also yielded reductions of several percent[14].

CONCLUSIONS

Analyses of k_∞ and reaction rate measurements in various clean LWHCR test lattices in PROTEUS have, in the past, helped to identify several shortcomings in the standard calculational methods/data commonly applied to LWHCR design. The current paper reports on the extension of the PROTEUS Phase II program to include measurements in poisoned – and thus, more realistic – lattices with k_∞ close to unity. The cell-worth method for determining importance-weighted k_∞ values has been applied succesfully in both clean and B_4C-poisoned LWHCR lattices, thereby enabling conclusions to be drawn regarding the reactivity effect of the control absorber for different moderator-voidage states.

On the basis of calculation/experiment (C/E) comparisons with the WIMS-D/1981 and KAPER4/KEDAK-4 codes, the reactivity effect of B_4C appears to be well predicted for moderated LWHCR lattices. Within the experimental error of about $\pm$ $0.8 \cdot 10^{-4}$/%, the k_∞ void coefficient α_v (0 – 100% void) was found to be the same in the clean and poisoned lattices. While the α_v predictions with KAPER4 appear satisfactory, WIMS-D/1981 overestimates the coefficient, particularly in the clean case.

Consideration of the C/E values for various reaction rate ratios measured in the clean lattices shows that, even in the case of a satisfactory prediction of k_∞, significant compensating errors can occur in a given calculational route. Clearly, for a detailed qualification of LWHCR design tools, an experimental program such as that in PROTEUS must be sufficiently broad-based (see also Ref. 15). It is only then that appropriate theoretical methods/data developments[8,16] can take place.

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