The Measurement and Calculation of the Kinetic Parameter $\beta_{\text{eff}}/\Lambda$ of a Small High-Temperature Like, Critical System

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This paper demonstrates that it is well possible to determine the kinetic parameter $\beta_{\text{eff}}/\Lambda$ in a neutronically very slow system by means of noise measurements in the critical state. The advantages of this technique are that it can be conducted in a critical reactor directly, and that no special measurement equipment is needed. The comparison to calculated values for four configurations, which differ in the amount of moderation in the core region, shows a satisfactory agreement.

KEYWORDS: HTR reactor, LEU-HTR, measurements, noise, spectral-density, transfer functions, calculations, experimental data, reactor kinetics, comparative evaluations

I. Introduction

From July 1992 to July 1996, a programme of integral experiments at the PROTEUS facility of the Paul Scherrer Institute (Switzerland) was carried out, comprising investigations of the safety-related reactor physics properties of low-enriched uranium fuelled, HTR (high-temperature reactor) type pebble-bed systems. In particular, the effects of accidental water ingress on the system criticality and on the reactivity effect of control rods situated in the radial reflector were of importance(1). These reactivity effects were measured with kinetic techniques, i.e. PNS (pulsed neutron source) and inverse kinetics, which themselves depend on the ratio of the effective fraction of delayed neutrons $\beta_{\text{eff}}$ to the generation time $\Lambda$. Since the margin to prompt criticality and the prompt neutron reproduction time are also important factors in reactor transient analysis, the measurement of the ratio $\beta_{\text{eff}}/\Lambda$ and the validation of the applied procedure to calculate $\beta_{\text{eff}}$ and $\Lambda$, are not only important for the analysis of the kinetic experiments in HTR-PROTEUS, but are also useful in a broader context.

This paper first describes the experimental facility, then it gives a review of the applied technique to measure $\beta_{\text{eff}}/\Lambda$. This section is followed by a detailed description of the calculational procedure. After a summary of the results, the paper ends with a discussion and conclusions.

II. Description of the PROTEUS Facility

A schematic side view of the HTR-PROTEUS facility is shown in Fig. 1. The system can be described as a graphite cylinder of 3.26 m diameter and 3.3 m height with a cylindrical cavity with a radius of 62.5 cm and ~170 cm in height located 78 cm above the base of the system. The core region consists of moderator (pure graphite) and fuel (16.7% enriched) HTR-type pebbles of 6 cm diameter, arranged in either deterministic or random arrangements. The deterministic loadings were chosen to improve the benchmarking quality of the measurements and for experimental convenience. Above the pebble-bed is a cavity surmounted by an upper graphite reflector of thickness 78 cm. As the maximum power is limited to 1 kW, no active cooling systems are required.

Shutdown of the reactor is achieved by means of borated-steel rods situated in the radial reflector at a radius of 68 cm. In total there are eight, identical rods divided into two groups of four rods each. One of these groups is selected as the safety rod group and the other as the shutdown rod group. Also situated in the radial reflector but at a radius of 90 cm, are four withdrawable stainless-steel rods (the fine control rods) which are used for reactor control. Criticality can be maintained by means of an automatic control rod (autorod) positioned at a similar radius as the fine control rods. More detailed information about the facility can be found elsewhere(2).

The four cores discussed in this work (cores 5, 7, 9, and 10) were all columnar-hexagonal (orthorhombic) pebble lattices with a filling factor of 0.6046. The simulation of accidental water ingress conditions was achieved using polyethylene (CH2) rods inserted into the vertical inter-pebble channels, see Fig. 2. Note that in the columnar-hexagonal packing geometry with 6 cm diameter pebbles, the inter-pebble channels have a diameter of 9 mm in the vertical direction and 19.7 mm in the horizontal direction.

Cores 5 and 7 had a moderator-to-fuel pebble ratio of 1 to 2, whereas in cores 9 and 10 this ratio was 1:1. The actual value of the ratio may be slightly different because of the presence of a partially fuelled top layer. Such a layer was sometimes required to achieve a critical balance within the range of the fine control rods. Cores 7
Fig. 1  A schematic side view of the HTR-PROTEUS facility (dimensions in mm)

Fig. 2  A view from above of HTR-PROTEUS with the upper reflector removed. Also indicated are the columnar-hexagonal loading patterns of cores 5 and 7 with a moderator-to-fuel pebble ratio of 1:2. Core 7 is the same as core 5 but with water-ingress simulation.
and 10 were variants of cores 5 and 9, respectively, with polyethylene rods inserted to simulate water-ingress conditions. In core 7, these rods had a diameter of 8.3 mm, whereas in core 10, the rod diameter was only 6.5 mm. Hence, the rods occupied 8.8% and 4.0% of the interpebble volume in cores 7 and 10, respectively. Table 1 summarises some characteristic figures of the four cores. More detailed information about the core configurations can be found elsewhere (3).

To order the cores to the amount of moderation, the so-called effective carbon density $N_{C,\text{eff}}$ was introduced (4). It is defined as the sum of the real carbon density and the hydrogen density multiplied by a weight factor:

$$N_{\text{C,eff}} = N_C + \frac{Q}{\xi_s C} N_H$$

where $\xi$ is the average lethargy gain of a neutron in a collision with a nucleus and $\sigma_s$ is the scattering cross section. Hence, the weight factor is the moderating power of hydrogen relative to that of carbon. The resulting effective carbon densities relative to the $^{235}$U densities can be found in the last row of Table 1 and show for example, that core 7 is better moderated than core 10.

III. Measurement of $\beta_{\text{eff}}/\Lambda$

The value of $\beta_{\text{eff}}/\Lambda$ can be obtained by making a fit of the theoretical APSD and CPSD (auto- and cross-power-spectral-density, respectively) to the measured spectra of the neutron detector signals. The advantage of this technique is, that it can be conducted in a critical system and thus avoids the need of an extrapolation to the critical state of subcritical PNS or noise measurements, a procedure which has been shown to yield accurate results only if proper account is taken of the kinetic behaviour of the system around critical (5). It is a well-known technique that was already applied by Cohn (6) in 1959, and for example more recently by Ragan et al. (7). However, the difference is that due to the long generation time of HTR-PROTEUS (1.5–2 ms), the prompt decay constant is of the same order of magnitude as the decay of the fastest delayed neutrons, and hence, no plateau in the APSD and CPSD can be recognised anymore. Consequently, the frequency range of interest is very low and for this reason, also the effect of the finite measurement time was considered.
counts, i.e. the counts due to neutrons belonging to the same neutron chain. The second term between braces is the finite measurement time correction which is seen to become significant at low frequencies (for a typical HTR-PROTEUS configuration at frequencies <0.1 Hz).

If two detectors are used, one can also compute the CPSDs\(^{(11)}\). Since the detection processes in both detectors are uncorrelated, the white noise component disappears, leaving for the expectation value of the CPSD:

\[
W_{12}^m(\omega) = \frac{4\upsilon_1 \cdot \upsilon_2}{F} D_v \sum_p A_p s_p G(s_p) \left( \omega^2 + s_p^2 \right) \\
\cdot \left\{ 1 + \frac{\omega^2 - s_p^2}{\omega^2 + s_p^2} \cdot \frac{1 - e^{-s_p T_0}}{s_p T_0} \right\}.
\]

(6)

Although the CPSD normally is a complex quantity, note that in a point reactor it is a real quantity. This implies that in a point model there is no phase difference between the detector signals, irrespective of the detector positions.

The measured spectra were fitted to Eqs. (5) and (6), with \(2\beta_2 Q/C, \epsilon/(Q \beta_2)\) and \(4\upsilon_1 \cdot \upsilon_2 / (F \beta_2)\) as linear parameters and the reduced generation time \(\Lambda^*\) as the only non-linear parameter. For given \(b_i\) and \(\lambda_i\), \(\Lambda^*\) is the only parameter at critical which determines the values of the roots \(-s_p\) of the inhour equation (the denominator of Eq. (3)), which for a critical system can be reduced to

\[
\Lambda^* = \sum_{i=1}^6 \frac{b_i}{\nu^2 + \lambda_i}, \quad p = 0 \cdots 5.
\]

(7)

Obviously, the last root \(s_6\) in a critical system is zero and thus independent of \(\Lambda^*\). The roots in turn determine the values of the residues \(A_p\) and the values of \(G(s_p)\), which are both inversely proportional to \(\beta_{\text{eff}}\). Thus, by including \(\beta_{\text{eff}}\) to the linear fit parameters, its value is not required. The actual fitting is carried out by the non-linear least-squares routine VARPRO\(^{(12)}\), which is an implementation of a modified Levenberg-Marquardt algorithm. The advantage of VARPRO is that no initial values for the linear fit parameters have to be supplied.

2. Experiment

The experiments were conducted in a critical reactor (with the autorod position frozen) at a power level of about 1 W. The neutron flux was measured with two uncompensated ionisation chambers, one placed in the side reflector, the other on top of the pebble bed in the radial centre. With a zero-suppression filter (cut-off frequency at 0.01 Hz), the DC-component was removed from the detector signals. After the remaining fluctuating components were amplified, they were sampled with a PC-based signal analysis system which calculated on-line the APSDs, the CPSD, and the coherence between the signals via FFT (fast Fourier transform) processing. A sampling frequency of 16 Hz was used, which along with a 256 points record, yields a record length \(T_0\) of 16 s. As the analysis system also calculates the correlation functions via inverse FFT of the power-spectral-densities, 256 zeros are added to the record before the FFT in order to achieve an unbiased estimate for the correlation functions\(^{(19)}\). A side effect of this procedure which is relevant for the experiments, is that the frequency resolution of the spectra is doubled.

Per measurement, about 300 records were measured, corresponding to a total measurement time of about 80 minutes. The measurements were then stopped, because the flux was always seen to drift away slowly from the level at the beginning of the experiment. This can be expected since the reactor is critical and the autorod position frozen and hence, there is no force driving the neutron flux back to the original flux level. After a measurement was stopped, the flux level was brought back to its original value, the autorod was frozen again, and a new measurement was started. Eventually, the results of several measurements were averaged. These averaged spectra and the phase difference between the detector signals were corrected for the frequency response of the instrumentation channels:

\[
\text{APSD} : W_{\text{corr}}(\omega) = \frac{W_{\text{meas}}(\omega)}{|H(j\omega)|^2}
\]

(8)

\[
|\text{CPSD}| : |W_{\text{corr}}(\omega)| = \frac{|W_{\text{meas}}(\omega)|}{|H_1(j\omega)| \cdot |H_2(j\omega)|}
\]

(9)

Phase : \(\phi_{\text{corr}}(\omega) = \phi_{\text{meas}}(\omega) + \phi_{H_1}(\omega) - \phi_{H_2}(\omega),
\]

(10)

where \(H_i(j\omega)\) is the magnitude and \(\phi_{H_1}(\omega)\) and \(\phi_{H_2}(\omega)\) are the phase change of the frequency response of instrumentation channel 1 and 2, respectively. The frequency responses of the instrumentation channels were measured as follows. The detector—-which produces the input signal for the instrumentation channel—was replaced by a battery (to yield a proper DC level) and a noise source (producing white noise in the frequency range of interest) in parallel. According to systems theory, the frequency response of the instrumentation channel can be obtained directly by measuring the CPSD of its input and output, and dividing it by the APSD of the input signal. The coherence between input and output was about 0.96, and practically independent of frequency.

IV. Calculation of \(\beta_{\text{eff}}/\Lambda\)

The calculational route starts with the generation of broad group cross sections. Special attention was paid to the double heterogeneity in the core region. This double heterogeneity arises because of the fuel grains inside the fuel region of a fuel pebble and secondly, because of the pebble lattice containing fuel and moderator pebbles. A simple homogenisation of the fuel region in a fuel pebble would in particular underestimate the resonance absorptions by \(^{238}\text{U}\). Therefore, a seven-step procedure was developed which takes account of the double heterogeneity in the core region properly, and also generates separate cross sections for the reflector region. A detailed description of this procedure can be found elsewhere\(^{(4)}\).

The produced 13 group cross-section library in CCCC
format is used by the BOLD VENTURE diffusion theory code to compute the neutron flux and the adjoint function. In R-Z geometry, a spatial mesh of about 3 cm was found to be adequate. In these calculations, the cavity above the pebble-bed was treated as recommended by Gerwin and Scherer\(^{(14)}\). However, as BOLD VENTURE does not offer the possibility of a directional dependent diffusion coefficient, the diffusion coefficient in the cavity was limited to the Gerwin and Scherer value in the axial direction in order to model the neutron streaming between core and upper axial reflector properly. This is considered to be more important than the correct modelling of the radial dependence of the neutron flux in the cavity.

Recall that the void fraction of the core configurations analysed in this work amounts to about 40%. As a result, the homogenisation of the core region indeed conserves the reaction rates, but not the neutron diffusion properties. In consequence, the homogenised core model underestimates the neutron leakage from the core. This was demonstrated by two Monte-Carlo calculations, one in which all pebbles were modelled explicitly and a second one in which the core region was fully homogenised\(^{(15)}\). In diffusion theory, this increased leakage can be accounted for by increasing the diffusion coefficient of the homogenised core\(^{(16)}\). As mentioned in Chap. II, the horizontal and vertical inter-pebble channels are of different sizes, which requires separate DCMs (diffusion coefficient modifiers) for these directions\(^{(17)}\). Again, BOLD VENTURE does not offer this possibility, and therefore we had to resort to a single DCM for all directions and all energy groups. The value of this DCM was chosen as to yield the same reduction in \(k_{\text{eff}}\) as determined with the Monte-Carlo calculations.

To obtain a critical system, the partially inserted control rods were represented by a grey curtain in which the \(^{10}\)B nuclide density of the radial reflector was increased. The resulting reduction in \(k_{\text{eff}}\) corresponds to the specified worth in the critical balances\(^{(3)}\). The \(^{10}\)B nuclide density in the radial reflector was then increased to represent the presence of the nuclear instrumentation, startup source, etc. At this point, the calculations should yield \(k_{\text{eff}} = 1\) but in practice they don’t because of inaccuracies in the data applied and the approximations in the calculational model. There are several ways to make the system critical of which two were chosen. The first way is to adjust the core height (without changing the densities) which is based on the idea that the effectiveness of neutron production in the core is not correct due to inaccuracies in the data applied. The second way is to change the radius of the core region (and simultaneously adjust the atom densities to maintain the correct total masses) which is based on the idea that the neutron streaming between core and radial reflector is not correct due to inaccuracies in the modelling of the core-reflector boundary. The changes in the core radius or core height necessary to make the system critical are modest, as can be seen in Table 2. The system is considered critical if the calculated value of \(k_{\text{eff}}\) is within 10 pcm of 1.

The neutron flux distribution and the adjoint function in the critical configurations as calculated by BOLD VENTURE, are used by the first-order perturbation theory code PERT-V to compute the parameters \(\beta_{\text{eff}}\) and \(\Lambda\). The effective delayed neutron fraction is given by

\[
\beta_{\text{eff}} = \sum_{k=1}^{6} \beta_{k}^{NIBC} \]

\[
= \sum_{k=1}^{6} \sum_{i=1}^{\text{NIBC}} \int dV \left\{ \sum_{j} \left( X_{d,l,j}^{k} \phi_{l}^{*} \right) \nu_{d,l} \sum_{i} \left( \Sigma_{i}^{f,j} \phi_{l} \right) \right\} ,
\]

\[
 \left\{ \sum_{j} \left( X_{j}^{*} \phi_{l}^{*} \right) \sum_{i} \left( \nu \Sigma_{i}^{f,j} \phi_{l} \right) \right\} ,
\]

(11)

where NIBC is the number of fissionable isotopes (in HTR-PROTEUS \(^{235}\)U and \(^{238}\)U are taken into account), \(X_{d,l,j}^{k}\) is the delayed fission source (spectrum fraction) for precursor decay group \(k\) for isotope \(l\) in energy group \(j\), \(\nu_{d,l}\) is the absolute delayed neutron yield (per fission) for isotope \(l\), \(\Sigma_{i}^{f,j}\) is the macroscopic fission cross section for isotope \(l\) in energy group \(j\), \(\Sigma_{i}^{j}\) is the total fission source in group \(j\), \(\nu \Sigma_{i}^{f,j}\) is the macroscopic fission neutron production cross section for group \(i\), and the other symbols have their usual meaning. The generation time is given by

\[
A = \int dV \left\{ \sum_{i,j} \left( \phi_{i} \phi_{j}^{*} \right) \frac{v_{i}}{v_{j}} \right\} ,
\]

\[
\int dV \left\{ \sum_{j} \left( X_{j}^{*} \phi_{l}^{*} \right) \sum_{i} \left( \nu \Sigma_{i}^{f,j} \phi_{l} \right) \right\} .
\]

(12)

Although the cross section data is based on the JEF-2.2 data library, the delayed neutron data used in PERT-V stems from JEF-1. The reason is that the delayed neutron data in JEF-2.2 has been shown to be inconsistent\(^{(13)}\).

V. Results

The results of the calculations are summarised in Table 3. The generation time is seen to vary between about 1.5 and 2 ms. The two chosen ways to make the system critical yield practically the same values for the kinetic parameter, with a maximum difference of only 0.3%. In Table 4, the results of the measurements can be found. An example of the corrected APSDs and

<table>
<thead>
<tr>
<th>Table 2 Adjustments in core radius or core height to obtain criticality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core 5</td>
</tr>
<tr>
<td>Change in radius (cm)</td>
</tr>
<tr>
<td>Change in height (cm)</td>
</tr>
</tbody>
</table>
The Kinetic Parameter of a Pebble-Bed HTR

CPSD, together with the results of the least-squares fitting, can be seen in Fig. 3, which also shows the phase difference and the coherence between the detector signals. Since the generation time is long, the prompt decay is quite close to the decay of the fastest delayed neutrons and as a result, no intermediate plateau can be recognised anymore. The figure also illustrates the elimination of the detection noise by the CPSD. The zero phase difference between the detector signals indicates that the point reactor model can be used indeed to describe the kinetic behaviour of HTR-PROTEUS in a frequency range up to at least 2 Hz.

VI. Discussion and Conclusions

The value of the kinetic parameter is very small, even smaller than the values reported for the Japanese VHTR\textsuperscript{(18)}. This is due to the small core dimension and the packing geometry which lead to a large fraction of core neutrons escaping to the reflector region. Here, the neutrons reside for a relatively long time before returning to the core. Hence, the generation time is sensitive to the absorption properties of the reflector. This means for example, that the insertion of an absorber rod in the reflector will not only change the reactivity, but also the kinetic parameter. The leakage from the core and thus the kinetic parameter is also influenced by the moderation in the core: as mainly fast neutrons escape from the core, an increase in moderation decreases the leakage. Thus, the neutron population in the reflector decreases relatively to the population in the core, as a result of which the generation time decreases. Since the change in the generation time is much more important than the change in $\beta_{\text{eff}}$, the value of the kinetic parameter increases, as is confirmed by Table 5. The fact that the value of $\beta_{\text{eff}}/A$ in core 9 is lower than in core 5 can be explained by the increased core height.

To compare the calculational and experimental results, the average of the two values in the last row of Table 3 were taken together with the results from the CPSD-fit. The CPSD result was chosen as it is the most accurate estimate (the CPSD comprises the information from two detectors). Table 5 shows that the value of $\beta_{\text{eff}}/A$ could be determined with an accuracy better than 4.4%. Looking at the last row of Table 5, it can be concluded that the agreement between the calculations and experiments is satisfactory. There is no clear relationship between the observed discrepancy and the moderation, core height, or adjustments necessary to obtain a critical system (see Table 2). This indicates that it is unlikely that the discrepancies in cores 7 and 9 are the result of systematic errors in the calculations, e.g. the use of a single, isotropic diffusion coefficient modifier. Since the discrepancies arise for the minimum and maximum of the measured values, this could indicate that the sampling conditions in cores 7 and 9 were not optimal. Unfortunately, in the applied signal analysis system the maximum number of points per record is limited to 256. Therefore, a sampling frequency of 16 Hz was selected in all experiments as it leads to a good compromise between the lower (1/32 Hz, equal to the frequency resolution) and the upper boundary (about 5 Hz) of the resulting fitting interval.

With these experiments, we have demonstrated that it is possible to determine the kinetic parameter $\beta_{\text{eff}}/A$ in a neutronically very slow system by means of noise measurements in a critical state. The difficulty with the measurements is the often encountered drift of the neutron flux. The advantages of this technique are that it can be conducted in a critical reactor directly and that

### Table 3

The calculated kinetic parameter $\beta_{\text{eff}}/A$ in a system made critical by adjusting the core radius

<table>
<thead>
<tr>
<th></th>
<th>Core 5</th>
<th>Core 7</th>
<th>Core 9</th>
<th>Core 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{\text{eff}}$</td>
<td>$7.1986 \times 10^{-3}$</td>
<td>$7.2848 \times 10^{-3}$</td>
<td>$7.1806 \times 10^{-3}$</td>
<td>$7.2201 \times 10^{-3}$</td>
</tr>
<tr>
<td>$(7.2003 \times 10^{-3})$</td>
<td>$(7.2849 \times 10^{-3})$</td>
<td>$(7.1815 \times 10^{-3})$</td>
<td>$(7.2196 \times 10^{-3})$</td>
<td></td>
</tr>
<tr>
<td>$A$ (ms)</td>
<td>1.9639</td>
<td>1.5220</td>
<td>2.1349</td>
<td>1.8721</td>
</tr>
<tr>
<td></td>
<td>(1.9580)</td>
<td>(1.5194)</td>
<td>(2.1311)</td>
<td>(1.8732)</td>
</tr>
<tr>
<td>$\beta_{\text{eff}}/A$ (s\textsuperscript{-1})</td>
<td>3.665</td>
<td>4.786</td>
<td>3.363</td>
<td>3.857</td>
</tr>
<tr>
<td></td>
<td>(3.677)</td>
<td>(4.795)</td>
<td>(3.370)</td>
<td>(3.854)</td>
</tr>
</tbody>
</table>

### Table 4

The kinetic parameter $\beta_{\text{eff}}/A$ as obtained by fitting theoretical to measured spectra

The unit of the indicated uncertainties is one standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>Core 5</th>
<th>Core 7</th>
<th>Core 9</th>
<th>Core 10</th>
</tr>
</thead>
<tbody>
<tr>
<td># records</td>
<td>368</td>
<td>500</td>
<td>1,631</td>
<td>800</td>
</tr>
<tr>
<td>APSD det.1</td>
<td>3.66 ± 0.19</td>
<td>5.29 ± 0.20</td>
<td>3.10 ± 0.29</td>
<td>4.05 ± 0.10</td>
</tr>
<tr>
<td>APSD det.2</td>
<td>3.89 ± 0.17</td>
<td>5.24 ± 0.19</td>
<td>3.11 ± 0.12</td>
<td>3.87 ± 0.12</td>
</tr>
<tr>
<td>CPSD</td>
<td>3.69 ± 0.16</td>
<td>5.26 ± 0.11</td>
<td>3.01 ± 0.11</td>
<td>3.90 ± 0.10</td>
</tr>
</tbody>
</table>
Fig. 3 The upper plots show the measured (solid lines) and fitted (dashed lines) auto- and cross-power-spectral-densities in core 10. The lower plots show the corresponding coherence and phase difference between the signals.

Table 5 Measured and calculated values of the kinetic parameter $\beta _{\text{eff}}/A$ in the four chosen core configurations.

<table>
<thead>
<tr>
<th></th>
<th>Core 5</th>
<th>Core 7</th>
<th>Core 9</th>
<th>Core 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{c,\text{eff}}:N_{235}$</td>
<td>5,667:1</td>
<td>14,206:1</td>
<td>7,539:1</td>
<td>12,841:1</td>
</tr>
<tr>
<td>$H$ (cm)</td>
<td>138</td>
<td>108</td>
<td>168</td>
<td>144</td>
</tr>
<tr>
<td>$\beta _{\text{eff}}/A$ (s$^{-1}$) $C^\dagger$</td>
<td>3.67</td>
<td>4.79</td>
<td>3.36</td>
<td>3.86</td>
</tr>
<tr>
<td>$\beta _{\text{eff}}/A$ (s$^{-1}$) $E^{\dagger}$</td>
<td>3.69$\pm$0.16</td>
<td>5.26$\pm$0.11</td>
<td>3.01$\pm$0.11</td>
<td>3.90$\pm$0.10</td>
</tr>
<tr>
<td>$(C - E)/E$ (%)</td>
<td>$-0.5\pm4.3$</td>
<td>$-8.9\pm1.9$</td>
<td>$11.6\pm4.1$</td>
<td>$-1.0\pm2.5$</td>
</tr>
</tbody>
</table>

$^\dagger$C: Calculation; $^\dagger$E: Experiment
no special measurement equipment is needed. Therefore, the technique may also be useful for the measurement of $\beta_{\text{eff}}/A$ in other neutronically slow systems, like the Japanese HTTR.

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The authors would like to thank the operational staff of HTR-PROTEUS, namely P. Bourguin, M. Fehlmann and T. Steiner for the safe and efficient operation of the facility during the course of the experiments. Furthermore, we would like to thank the reactor physicists of HTR-PROTEUS, namely Dr. T. Williams and Dr. R. Seiler, for their co-operation, support, and interest.

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