

Reactivity Worth Measurement of Calcium Hydride Sample in UTR-KINKI Reactor

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Abstract. Small modular reactors (SMR) using calcium hydride (CaH₂) as a moderator have attracted attention due to their passive safety and economic efficiency. In order to design the nuclear design of the SMR, the integral validation of the cross section considering the thermal neutron scattering law ($S(\alpha, \beta)$) of CaH₂ is necessary. However, there are no integral experiments using CaH₂ in the reactor. As the first integral experiment in nuclear reactors, we performed reactivity worth measurements of CaH₂ samples in a university training and research reactor (UTR-KINKI) of Kindai University. The measured sample reactivity worth was compared with the results calculated by the continuous energy Monte Carlo code MVP3 and JEFF-3.1, and integral validation of the CaH₂ cross section stored in JEFF-3.1 was performed. To obtain the sample reactivity worth components, we carried out perturbation calculations.

1 Introduction

Small modular reactors (SMRs) have been developed as new types of reactors with passive safety features and high economic efficiency in the world.

One of the SMRs was developed using calcium hydride (CaH₂) as a solid moderator [1]. This solid moderator is installed to give a passive safety characteristic for the SMR. When the moderator temperature exceeds 800 degrees Celsius in abnormal high-power operation, the hydrogen in the moderator will deviate. Consequently, the reactor will lose its neutron-moderating capability and achieve passively subcritical state.

The CaH₂ cross section with the thermal neutron scattering law ($S(\alpha, \beta)$) has large contribution to the criticality of the SMR. Accuracy of neutron cross section is important for a nuclear design. The accuracy of nuclear data used in the nuclear design must be calculated by performing integral and differential validations. However, the CaH₂ moderator has never been used in a nuclear reactor. In addition, critical experiments of CaH₂ using nuclear reactors have never been reported. In critical experiments, nuclides other than those of interest have also sensitivity to criticality. On the other hand, only the nuclide or material of interest can be sensitive to sample reactivity worth. Thus, CaH₂ sample reactivity worth as integral experiment were measured by using the university training and research reactor (UTR-KINKI) of Kindai University. A sample reactivity is the effect of a sample on the criticality of a reactor expressed as a reactivity value. In this study, in order to examine the relationship between a sample weight and the reactivity worth, the sample reactivity worth was measured using the samples of various weights. Furthermore, the measured sample

reactivity worth was compared with calculated reactivity worth. The calculated values were obtained by the continuous energy Monte Carlo code MVP3 [2] and the nuclear data library JEFF-3.1 [3]. The CaH₂ cross section with the $S(\alpha, \beta)$ was only stored in JEFF libraries.

2 Experiment

2.1 Experiment Systems

The UTR-KINKI is a highly enriched light water moderated graphite reflection two-cores reactor. **Figure 1** shows the core configuration of UTR-KINKI. The neutron spectrum of the central irradiation hole has standard $1/v$ and Maxwell distributions. **Figure 2** shows neutron spectrum in the irradiation hole calculated by MVP3 and JENDL-4.0[4]. The spectrum has an impact on the neutron scattering reaction with $S(\alpha, \beta)$.

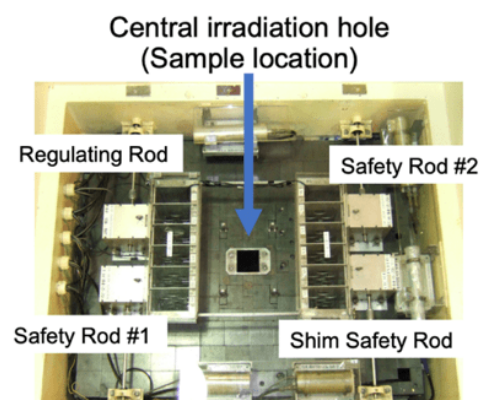


Figure 1. Core configuration

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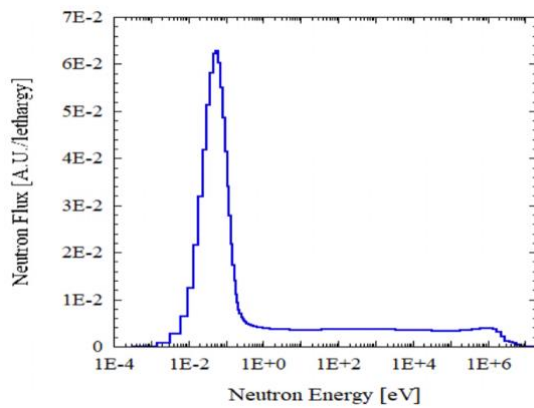


Figure 2. Neutron spectrum in the central irradiation hole

Figure 3 shows the sample geometry. The CaH₂ sample in an aluminium case was set into a graphite holder. Here, a sample diameter was 3.0 cm, sample heights were 2.54 cm, 5.08 cm and 10.16 cm. **Table 1** shows sample heights and sample weights. The sample purity was 95 wt%. The graphite holder was loaded in the central irradiation hole.

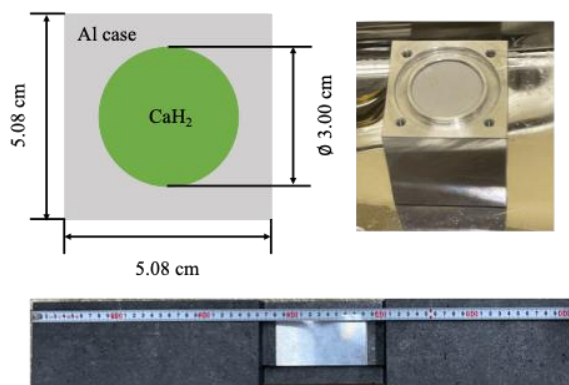


Figure 3. Sample geometry (upper left), CaH₂ sample in Al case (upper right), graphite holder (lower)

Table 1. Sample height and weight

Sample height h [cm]	Sample weight w [g]
2.54	21.20
5.08	41.00
10.16	78.72

2.2 Measurement of sample reactivity worth

The sample reactivity worth was defined as the difference of excess reactivity with the aluminium case installed with the CaH₂ sample and the aluminium case without the CaH₂ sample. **Table 2** shows the experimental conditions. The Shim Safety Rod was withdrawn from the lower limit (L.L.) to the upper limit (U.L.), and the neutron time sequence data were measured by the fission counter of the in-core equipment. From the data, the reactor period T was estimated by the least-squares method, and the excess reactivities were obtained by the positive-period method. Kinetic parameters were calculated by MVP3,

JEFF-3.1 and JENDL-4.0. **Table 3** shows the parameters.

Table 2. Experimental conditions

Core Temp. [°C]	20.5
Safety Rod#1	U.L.
Safety Rod#2	U.L.
Regulating Rod	L.L.

Table 3. Kinetic parameters

Weight [g]	Effective Delay Neutron Fraction	Neutron Generation time [s]
21.20	7.2535E-3 ± 5.6E-6	1.8257E-4 ± 3E-8
41.00	7.2516E-3 ± 5.6E-6	1.8227E-4 ± 3E-8
78.72	7.2623E-6 ± 5.6E-6	1.8170E-4 ± 3E-8

3 Numerical analysis

3.1 Monte-Carlo Calculation

In numerical calculations, the sample reactivity worth was defined as the difference of k_{eff} with and without CaH₂ in the aluminium case. The sample reactivity worth was calculated numerically by the MVP3 with the JEFF-3.1 and JENDL-4.0. The neutron histories were 1.5×10^9 . In addition, in order to examine the impacts of $S(\alpha, \beta)$ to the calculated reactivity worth, numerical calculations using a free gas model of CaH₂ cross section were also carried out.

3.2 Perturbation Calculation

To evaluate the energy component of the sample reactivity worth, perturbation analysis was carried out with the 78.72 g sample. Effective microscopic cross sections for CaH₂ were generated using FRENDY/MG [5,6] and JEFF-3.1. The sample temperature was set to 296 K as stored in JEFF-3.1. Other effective macroscopic cross sections were calculated using SRAC2006 [7] and JENDL-4.0. Here, the CaH₂ cross sections with $S(\alpha, \beta)$ or with the free gas model were generated. Using the cross sections, a forward and an adjoint fluxes were calculated by the diffusion calculation. The sample reactivity worth was obtained from the exact perturbation analysis in equation (1).

$$\rho = \frac{\int_V dV \psi \Delta M \phi}{\int_V dV \psi F \phi} \quad (1)$$

Here, ϕ and ψ are the forward and the adjoint flux, ΔM is the Boltzmann operator with various partial cross section data, and F is the production operator. The sample geometry was a rectangle of 2.659 cm × 2.569 cm × 10.16 cm to match the experimental sample volume.

4 Discussions

Table 4 shows the measured reactor periods, the excess reactivities, and sample reactivity worth with the samples of 21.20 g, 41.00g and 78.72 g, respectively. The measured reactivity worth has the relative errors of 2.6 % to 6.7 %. **Figure 4** shows the relationship between the sample weight and the sample reactivity worth. As the results, according to the least-squares fitting results using equation (2), the relationship between sample weight and reactivity was linear within the experimental range of this study. The sample reactivity worth per unit weight (α) was -0.00020 ± 0.00001 $\% \Delta k/k/g$ in the present experiment.

$$\rho = \alpha w \quad (2)$$

Table 4. Results of reactor period, excess reactivity, and sample reactivity worth

Sample weight w [g]	Sample	Reactor Period T [s]		Excess reactivity [% $\Delta k/k$]	
21.20	without	47.54	± 0.19	0.12367	± 0.0019
	with	50.08	± 0.20	0.11951	± 0.0021
41.00	without	51.78	± 0.26	0.11676	± 0.0021
	with	57.68	± 0.56	0.10815	± 0.0019
78.72	without	58.79	± 0.69	0.10651	± 0.0026
	with	73.87	± 0.34	0.09065	± 0.0032

Sample weight w [g]	Sample reactivity worth ρ [% $\Delta k/k$]	
21.20	-0.00417	± 0.00028
41.00	-0.00861	± 0.00028
78.72	-0.01587	± 0.00041

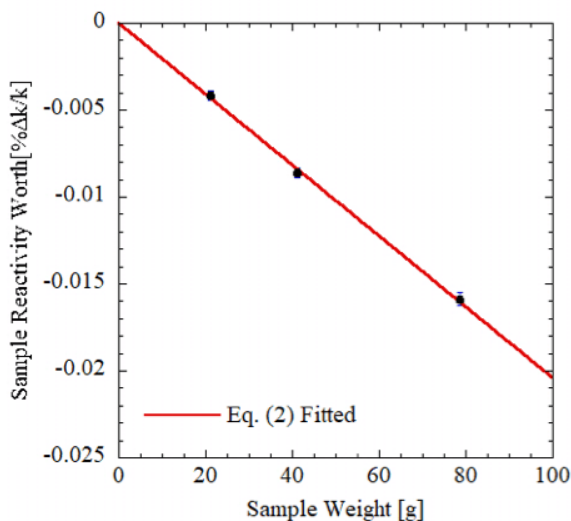


Figure 4. Sample weight and sample reactivity worth

Table 5 shows the results of the calculated sample reactivity worth by the MVP3. The calculated results agreed with the experimental results within the error range. **Table 6** shows difference of the calculate reactivity worth between $S(\alpha,\beta)$ model and the free gas model. In the 41.00 g and 78.72 g samples, the $S(\alpha,\beta)$ of CaH_2 contributes positively to about 42% of the sample reactivity worth. **Figure 5** shows the neutron spectrum in the CaH_2 sample of 78.72 g considering the $S(\alpha,\beta)$ or free gas model. Using the $S(\alpha,\beta)$ model, the neutron

spectrum shifts to the harder side than the free gas model. This is due to the contribution of up-scattering by the $S(\alpha,\beta)$ model.

Table 5. Numerical Results of Sample Reactivity Worth

Sample Weight [g]	Reactivity Worth ρ [% $\Delta k/k$]		C/E	
21.20	-0.0050	± 0.0026	1.19	± 0.72
41.00	-0.0069	± 0.0026	0.806	± 0.347
78.72	-0.0139	± 0.0026	0.874	± 0.189

Table 6. Difference of the calculate reactivity worth between $S(\alpha,\beta)$ model and the free gas model

Sample Weight [g]	Difference of calculated reactivity worth [% $\Delta k/k$]	
21.20	-0.0069	± 0.0026
41.00	0.0030	± 0.0026
78.72	0.0059	± 0.0026

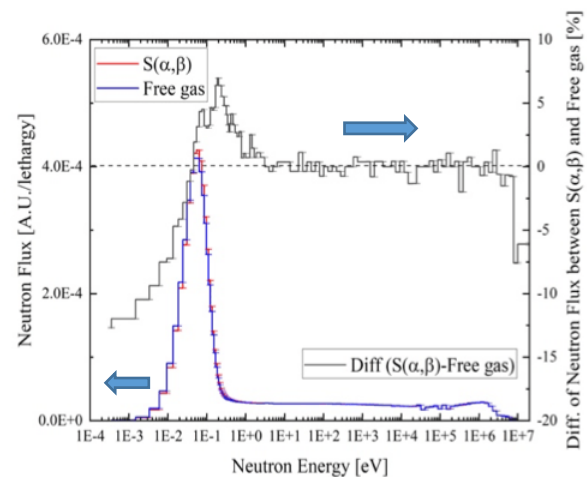
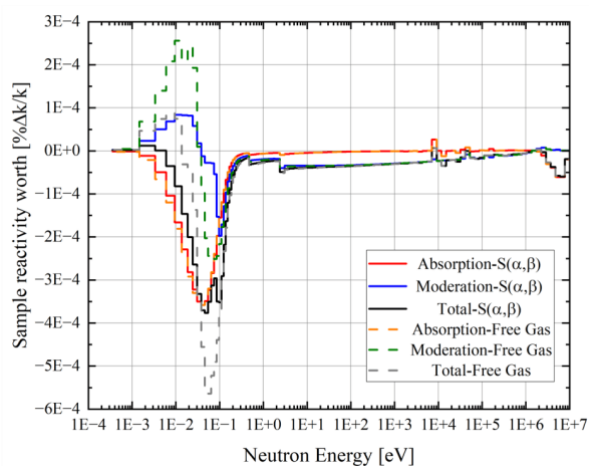


Figure 5. Neutron spectrum of the CaH_2 sample at 78.72 g

Table 7 and **Figure 6** shows the results of the perturbation calculation in the sample of 78.72 g. In **Table 7**, the difference of moderation component between the $S(\alpha,\beta)$ model and the free gas model is only 0.0004 $\% \Delta k/k$. The $S(\alpha,\beta)$ of CaH_2 contributes about 6% of the sample reactivity worth. In **Figure 6**, the moderation component of the $S(\alpha,\beta)$ model contributes to positive reactivity below about 0.064 eV and negative reactivity above about 0.064 eV. On the other hand, in the moderation component of the free gas model, the positive and negative reactivities are reversed at about 0.031 eV. Consequently, due to neutron spectrum hardening by upper-scattering of the $S(\alpha,\beta)$, the energy position of the positive and negative inversion of the moderated component is shifted. Furthermore, focusing on the energy region from 0.5eV to 0.01eV, the total reactivity worth of the $S(\alpha,\beta)$ model was about -0.0043 $\% \Delta k/k$ and that of the free gas model about -0.0053 $\% \Delta k/k$. Thus, even though the difference of the total reactivity worth is small, the energy contributions have large differences.

Table 7. Component of sample reactivity worth

Reaction	Component of Reactivity Worth [% $\Delta k/k$]	
	$S(\alpha,\beta)$	Free Gas
Absorption	-0.0043	-0.0043
Moderation	-0.0022	-0.0026
Total	-0.0065	-0.0069

**Figure 6.** Energy distribution of sample reactivity worth components

5 Summary

In this study, the sample reactivity worth of CaH_2 samples were measured by UTR-KINKI for integral validation of the CaH_2 cross section.

The measured reactivity worth was -0.00417 % $\Delta k/k$ (21.20 g), -0.00861 % $\Delta k/k$ (41.00 g), and -0.01587 % $\Delta k/k$ (78.72 g), respectively. As a results, the relationship between the sample weight and the reactivity worth was linear in the present experimental range.

The experimental results were compared with the calculated results. As a result, the experimental results were agreement with the calculated results within the error range. The $S(\alpha,\beta)$ of CaH_2 contributes to the positive reactivity by hardening the neutron spectrum in the sample. The results of perturbation calculations showed that the difference in the total reactivity worth was small: however, the modulation component of the reactivity worth differs significantly between the $S(\alpha,\beta)$ model and the free gas model in the energy region below 0.5 eV.

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