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Measurements of Moderator Temperature Coefficients of Reactivity for Pressure-Tube-Type Reactors

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The moderator temperature coefficients of reactivity for a pressure-tube-type reactor consisting of highly heterogeneous cells with D_2O moderator, H_2O coolant, and 28-pin fuel cluster contained in a pressure-tube have been measured in order to clarify their dependence on the moderator temperature.

A new experimental method has been developed that is applicable to ordinary critical assemblies not equipped with any special temperature control system. In this method, temperature changes of the core, which is subjected to natural cooling that permits heat transfer from the D_2O moderator to the H_2O coolant, are measured continually, together with the resultant changes in reactivity. The data are analyzed with use of least-squares fitting to nonlinear functions.

It has been clarified that the moderator temperature coefficient of reactivity of this type of reactor is markedly dependent on the moderator temperature, decreasing with increase in the temperature. In a clean lattice of 1.2 wt% ^{235}U enriched UO_2 fuel that contains no ^{10}B in the moderator, the coefficient changes its sign from positive to negative at ~40°C. Addition of 3.9 ppm of ^{10}B into the D_2O moderator of the same lattice causes the value of the temperature coefficient to shift considerably toward the positive side.

Calculational results by the WIMS code reproduce quite well the experimental values of the temperature dependence of the moderator temperature coefficient of reactivity. However, their absolute values are rather small compared to the experimental ones.

INTRODUCTION

The advanced thermal reactor (ATR) now under development in Japan is a heavy-water-moderated, boiling-light-water-cooled, pressure-tube-type reactor.[1]

In this type of a reactor, there is an independent temperature coefficient of reactivity for the moderator separate from that of the coolant, and it is often positive, depending on lattice conditions such as fuel-coolant and fuel-moderator volume ratios. A burnable poison, ^{10}B, is also used in the moderator for suppression of excess reactivity in the initial core; then the coefficient is expected to shift largely to the positive side because of the dilution effect of the poison with decrease in the moderator density. When the coefficient depends on the moderator temperature so largely as to change its sign, its dependence on the temperature must be taken into account as a kind of lattice condition. Thus, it is important to understand the detailed behavior of the moderator temperature coefficient of reactivity.

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[1]S. SHIMA and S. SAWAI, "The FUGEN Project," *Proc. 13th Annual International Conf.*, Toronto, June 17-20, 1973, CONF-730612, CNA '73-204, Canadian Nuclear Association (1973).

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There exist several papers on this temperature coefficient for pressure-tube-type reactors,[2-5] but little work has been done to investigate the temperature dependence of the coefficient.

For the measurement of this temperature coefficient, it is necessary to provide a special temperature control system that can regulate temperatures of the moderator and the coolant independently. A power reactor uses this system, but is not suitable for the measurement of detailed temperature behavior because it is difficult to measure or predict actual temperatures of fuel and coolant, and, hence difficult to separate the moderator temperature effect on reactivity from other temperature effects.

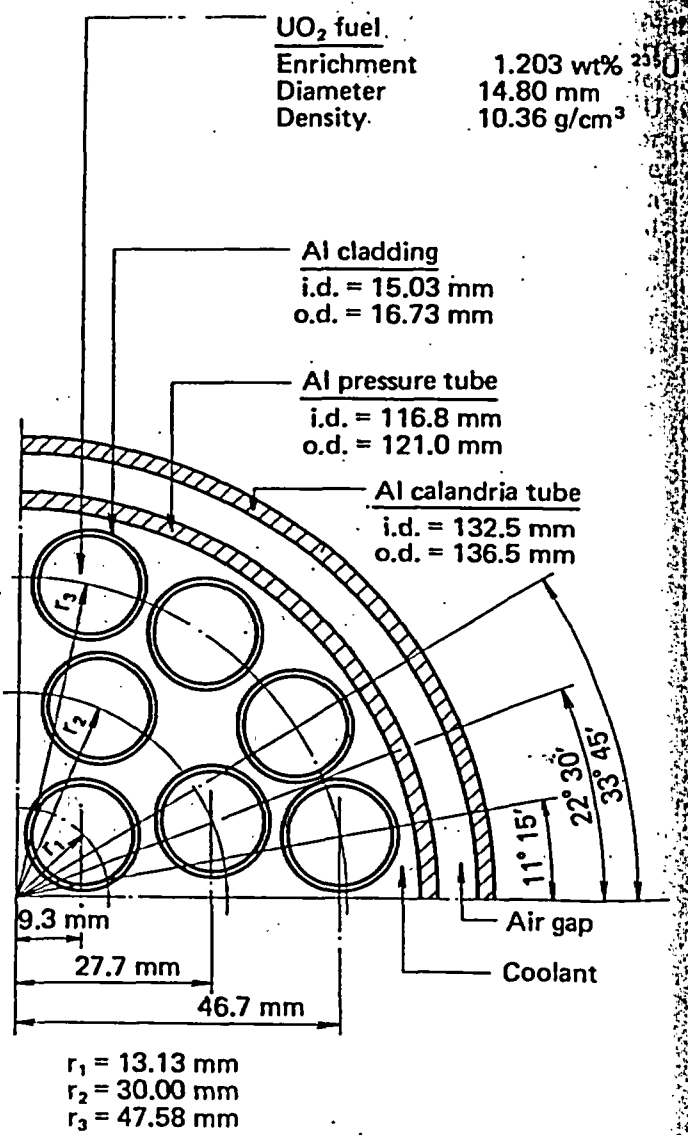
On the other hand, in critical assemblies the independent regulation of the moderator and coolant temperatures is difficult since they usually have no special temperature control system. It is especially difficult to hold the coolant temperature constant, because of heat transfer when setting the moderator at a desired temperature. This complicates the ensuing data analysis. For example, in the British Winfrith Steam Generating Heavy Water Reactor (SGHWR) mock-up the measurement of temperature coefficients was carried out at a coolant temperature of ~40°C (Ref. 2). However, the coolant temperature changed because of heat transfer during the experiment, which introduced a large and difficult correction necessary in the evaluation of the temperature dependence of the moderator coefficient. In order to clarify the behavior of the moderator temperature coefficient, it is necessary to separate the reactivity disturbance caused by the change in the coolant temperature.

The objective of the present experiment is to observe the dependence of the moderator temperature coefficient of reactivity on the moderator temperature and to establish an accurate and convenient method of experimentation and data analysis applicable to ordinary critical assemblies consisting of pressure-tube-type lattices.

In this method, an attempt is made to accumulate enough data for the above purpose by measuring changes in the temperature of both the moderator and the coolant simultaneously with positive use of the natural cooling of the critical assembly including its internal heat transfer. Once the dependence of the moderator temperature coefficients of reactivity on the moderator temperature is established over a wide range of temperatures, the fitting function of the experimental data may be simply derived. This should make it possible to establish an accurate and convenient data analysis method.

EXPERIMENTAL METHOD

The present experiments have been carried out using the deuterium critical assembly (DCA). The fuel cluster consists of 28 UO_2 fuel pins with aluminum cladding as shown in Fig. 1. The fuel pins in the cluster are arranged in the three concentric layers, counting from the center, there are 4 pins in the first



r_1 = 13.13 mm
r_2 = 30.00 mm
r_3 = 47.58 mm

Fig. 1. One-quarter cross section of a fuel cluster.

[2]A. J. BRIGGS, I. JOHNSTONE, D. A. NEWMARCH, and K. C. KENDALL, *J. Brit. Nucl. Energy Soc.*, 11, 215 (1972).

[3]J. R. ASKEW, F. J. FAYERS, and W. FOX, "Thermal Reactor Temperature Coefficient Studies in the U.K.," AEEW-R-886, United Kingdom Atomic Energy Authority, Winfrith (1973).

[4]A. C. WHITTIER, "Reactivity Measurements on NPD," AECL-2869, Atomic Energy of Canada, Limited (1967).

[5]A. A. PASSANEN and J. F. BLANSCHE, "Douglas Point HWR Startup Physics Measurements and Predictions," AECL-2712, Atomic Energy of Canada, Limited (1967).

layer, 8 pins in the second, and 16 pins in the third. The fuel clusters are arranged in a square lattice at a 25.0-cm pitch, and are contained in an aluminum tank (3.005-m i.d., 1.0-cm wall thickness). The coolant is separated from the moderator by an aluminum pressure tube, an air gap, and an aluminum calandria tube. Each pressure tube contains H_2O coolant and a fuel cluster. The moderator is heavy water of 99.4 mol% purity. In the case of the poisoned core, 3.9 ppm of ^{10}B was added to the moderator.

Measurements of the temperature coefficients were carried out over the range from room temperature to 60°C for the moderator by steps of ~5°C. The moderator temperature was raised with an electric heater in the heavy water storage tank. The coolant temperature (room temperature at the beginning) was not controlled artificially, but changed by heat transfer from the moderator. The resultant temperature range for the coolant was from room temperature to 40°C. After attaining the desired temperature, the moderator was poured into the reactor tank, and the reactor was made critical. The reactor was operated with an automatic moderator level controller at a power of 10 W over 2 to 5 h. Such continuous reactor operation was repeated at the different moderator temperatures above ~30°C. During this period of 2 to 5 hours, the core was left in the state of natural cooling, permitting its internal heat transfer. Changes in the moderator and coolant temperatures and the resultant changes in the critical moderator height were measured with an instrument system connected to a computer. The moderator dropped steadily in temperature by 1 to 5°C and the coolant rose by 2 to 10°C during measurement.

In the moderator temperature range below ~30°C, the changes in the moderator and coolant temperatures due to heat transfer are insignificant. In this temperature range, short-term reactor operation, instead of the continuous operation mentioned above, was repeated by changing the moderator temperature by a small step with an electric heater in the heavy water storage tank.

The moderator level in the reactor tank was measured with a level meter in a communicating tube. Reading accuracy of the meter in the present experiment is ±0.01 cm. However, random error in the measurement of the absolute moderator height is dependent on other factors, such as position sensitivity of the float of the meter, and was estimated as ±0.02 cm, including the above reading accuracy.

On the other hand, the following were considered as systematic errors in the measurement of the absolute moderator height.

Readings of the level meter did not indicate the true height of the moderator in the reactor tank because there was a difference in the temperatures of the heavy water in the reactor tank and in the communicating tube. The corrected height of the moderator, hc, was obtained by the following equation:

$$hc = \frac{ds}{dc} \times hs \ , \tag{1}$$

where ds and dc are the densities of heavy water in the communicating tube and in the reactor tank, respectively, and hs denotes a reading of the meter. This correction by the above equation shifted the moderator height by 1.4% or less in the present range of moderator temperature, yielding a measurement error of 0.2% in height. This value was further confirmed by an independent method described in the Appendix.

The critical moderator level changed, throughout the present experiment, from 1063 to 1075 mm in the clean core, and from 1618 to 1688 mm in the boron-bearing core; the H_2O coolant level, however, was not controlled and was set at 1070 and 1700 mm in the respective cores, due to the structural difficulty. The change in critical height due to this difference in levels between coolant and moderator was estimated to be at most 0.2% of the moderator height, which caused additional error in the critical height. The circumferential thermal expansion of the aluminum reactor tank and calandria tubes negligibly affected the height because the aluminum thermal expansion coefficient was small compared with that of heavy water.

These systematic errors, however, are considered to contribute little to the change in the moderator height. Consequently, the resultant uncertainty of the relative moderator height was estimated as ±0.03 cm, taking into account the above-mentioned random error in the measurement of the absolute height.

The temperatures were measured with Chromel-Alumel thermocouples located in the moderator and the coolant, and with a platinum resistance thermometer at the bottom of the level meter. The thermocouples were arranged in the reactor core as shown in Fig. 2. Mean temperatures for moderator and coolant regions, Tm and Tc, respectively, were obtained by averaging temperatures measured at the designated points in the core. The error in these mean temperatures was estimated at ±1.5°C by taking into account errors originating from the averaging process and from the calibration of the thermocouples. A calibration curve was obtained for each thermocouple by using a standard thermometer.

Reactivities were obtained by integrating the moderator level coefficient of reactivity over the change in critical height. This coefficient is described as follows by the one-group diffusion theory.

$$\frac{\partial \rho}{\partial h} = \frac{1}{\beta_{eff}} \cdot \frac{2\pi^2 M^2}{k_\infty} \cdot \frac{1}{(h+\delta)^3} \tag{2}$$

$$= \frac{A}{(h+\delta)^3} \ , \tag{3}$$

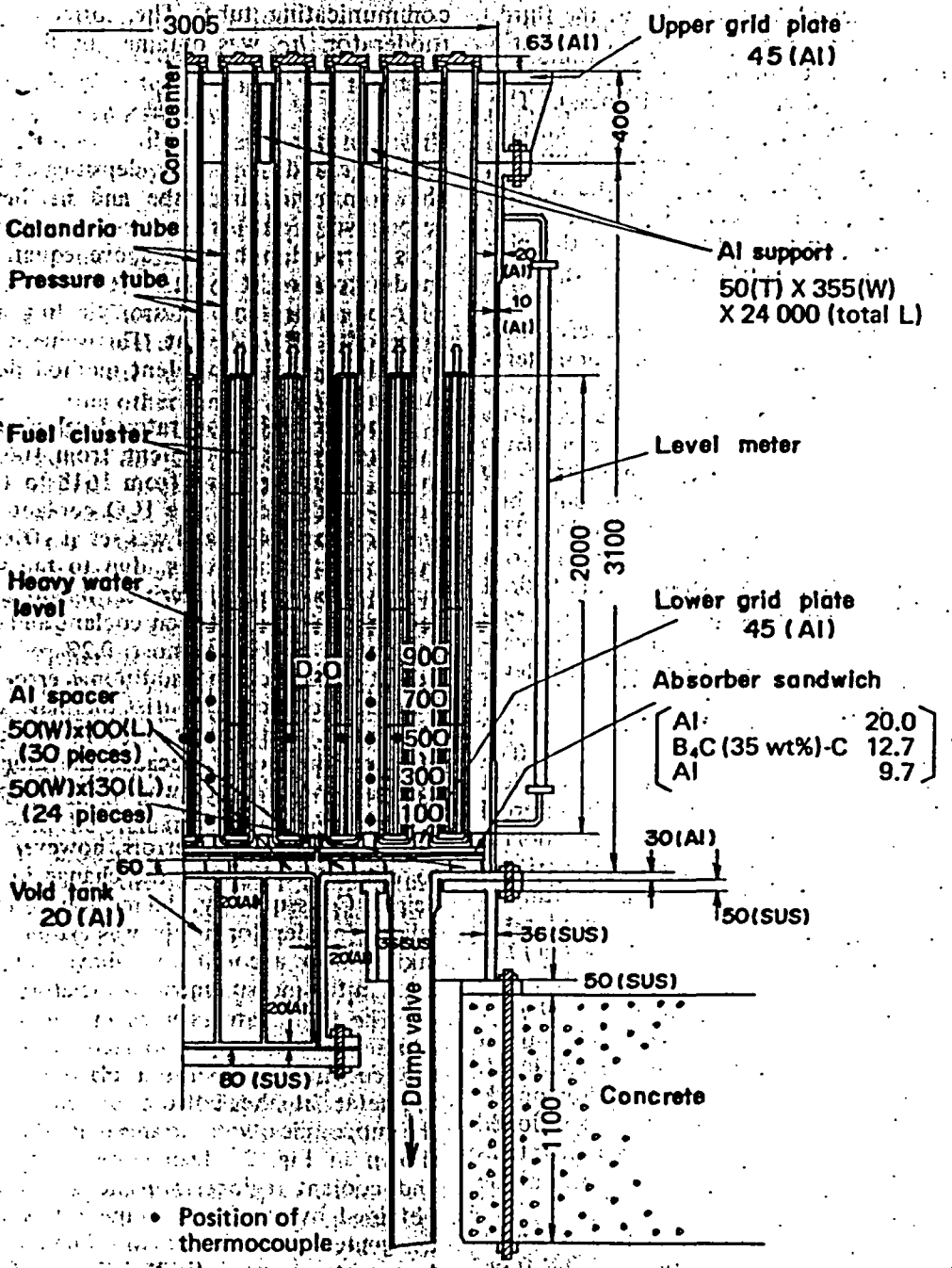


Fig. 2. Schematic diagram of the core of the deuterium critical assembly. All dimensions are in millimetres.

where

β_{eff} = effective delayed-neutron fraction

M^2 = migration area

k_∞ = infinite multiplication factor

δ = axial extrapolation distance

$A = 2\pi^2 M^2/\beta_{eff} k_\infty$.

The moderator-level coefficients of reactivity were measured by the positive reactor period method at various moderator temperatures in order to examine the temperature dependence of the quantity A. However, this variation in A was within the experimental uncertainty as seen in Fig. 3. Consequently, A was assumed constant. Therefore, the reactivity introduced into the core due to a change in temperature was obtained by integrating Eq. (3) over the

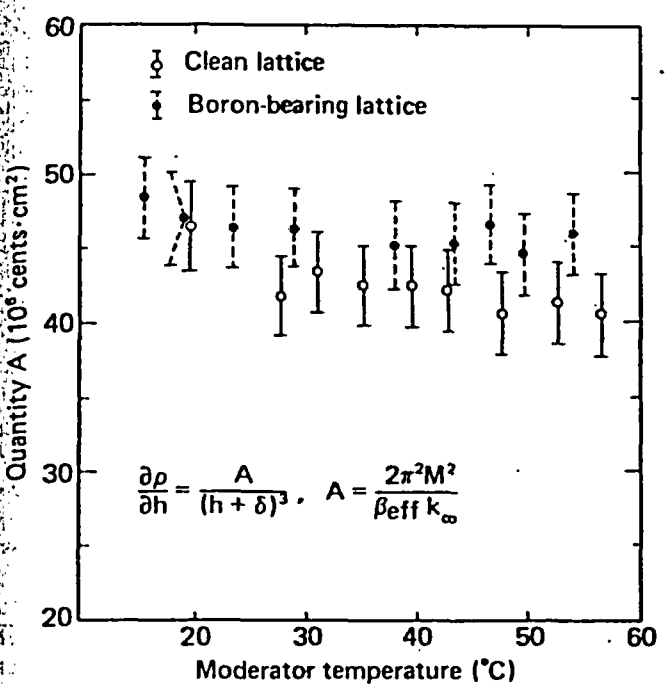


Fig. 3. Temperature dependence of reactivity coefficient of D_2O height.

change in the moderator height from h_1 to h_2.

$$\rho = \int_{h_1}^{h_2} \left(\frac{\partial \rho}{\partial h}\right) dh \ ,$$

$$= \frac{A}{2}\left[\frac{1}{(h_1+\delta)^2} - \frac{1}{(h_2+\delta)^2}\right] \ . \qquad (4)$$

The value of β_{eff} has been found as 0.0073 through similar procedure applied to the DCA core by Ueda et al.[6] Here, the delayed-neutron parameters were from Ref. 7; the gamma-ray self-shielding factor in the fuel cluster, Fr = 0.223, from Ref. 8; and the effects of gamma-ray production of delayed and photodelayed neutrons were calculated with use of Gwin's formula,[9] and the experimental fast fission ratio in Ref. 10.

To evaluate the effective core height, the axial flux distribution, measured by copper-wire activation, was least-squares fitted to a cosine function. The fitting was undertaken by successively dropping data near the core boundaries until fixed values of the effective core height were obtained. The effective axial extrapolation distance, δ, which also includes the reflector savings due to the upper and lower structures of the reactor, was determined from these fixed values to be 100 mm for the clean lattice and 105 mm for the boron-bearing lattice.

The critical moderator height and the temperatures of the moderator and coolant changed during the reactor operation. Typical behaviors of the measured parameters are shown in Fig. 4. At the beginning of the reactor operation the moderator temperature was higher by ~30°C than that of the coolant, which had been left at the room temperature. During the continuous operation, the moderator slowly decreased in temperature compared with the coolant, which rose rather rapidly because of its smaller heat capacity. Ranges of change in the moderator and the coolant temperatures and of the resultant change in the moderator critical height obtained for each continuous reactor operation are summarized in Table I. In this table data for the lower moderator temperature region, below ~30°C, are also shown. These were obtained in short-term reactor operation.

DATA ANALYSIS AND EXPERIMENTAL RESULTS

Confirmation of Temperature Dependence

In the case where the core has two regions at temperatures *Tm* and *Tc*, a change in reactivity induced by a small change in temperature can be expressed in the following relation:

$$\Delta\rho = \left(\frac{\partial \rho}{\partial Tm}\right) \cdot \Delta Tm + \left(\frac{\partial \rho}{\partial Tc}\right) \cdot \Delta Tc \ , \qquad (5)$$

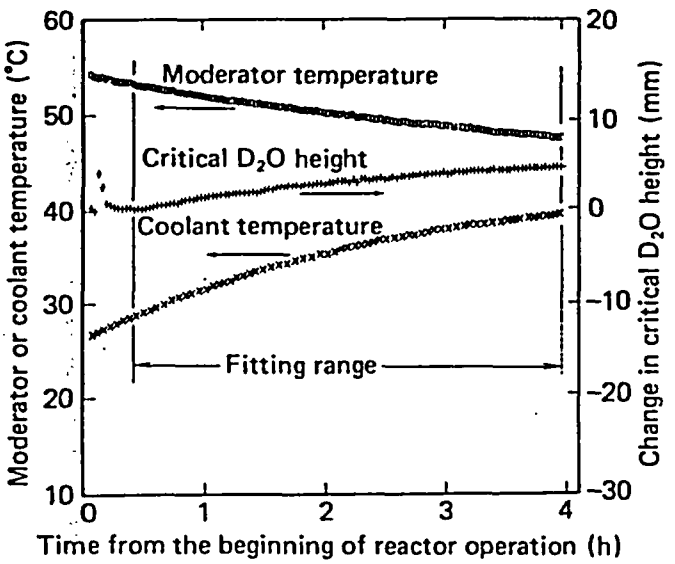


Fig. 4. Typical data of temperature and critical D_2O moderator height obtained during continuous reactor operation.

[6]M. UEDA, M. MATSUMOTO, and T. HAGA, *Nucl. Sci. Eng.*, 62, 559 (1977).

[7]G. R. KEEPIN, *Physics of Nuclear Kinetics*, Addison-Wesley Publishing Co., Inc., Reading, Massachusetts (1965).

[8]Y. KANEKO, *J. Nucl. Sci. Technol.*, 8, 34 (1971).

[9]"Reactor Physics Constants," ANL-5800, 2nd Edition, p. 443, Argonne National Laboratory (1963).

[10]Y. HACHIYA, N. FUKUMURA, A. NISHI, K. IIJIMA, and H. SAKATA, *J. Nucl. Sci. Technol.*, 13, 618 (1976).

TABLE I

Dependence of Critical Moderator Heights on Moderator and Coolant Temperatures

Clean Lattice			Boron-Bearing Lattice			
Moderator Temperature (°C)	Coolant Temperature (°C)	Critical Height[a] (mm)	Moderator Temperature (°C)	Coolant Temperature (°C)	Critical Height[a] (mm)	Remarks
14.3	17.9	1066.6	15.6	12.0	1687.8	Short-term reactor operation
14.8	14.3	1065.3	18.9	17.0	1687.6	
19.5	15.3	1064.3	19.1	18.1	1687.5	
24.3	17.9	1064.7	23.3	19.8	1677.5	
28.7 → 27.5	16.3 → 19.8	1063.2 → 1064.6	30.0 → 28.5	20.0 → 25.6	1657.7 → 1671.2	
32.5 → 30.9	21.4 → 25.4	1064.9 → 1066.7	---	---	---	
38.2 → 35.2	24.3 → 30.2	1066.2 → 1068.6	40.5 → 38.0	25.2 → 33.4	1637.7 → 1657.0	Continuous reactor operation
42.0 → 39.3	29.0 → 34.2	1068.0 → 1070.5	46.0 → 43.2	30.7 → 38.5	1634.1 → 1652.6	
45.0 → 42.6	30.0 → 35.4	1068.9 → 1071.7	49.9 → 46.7	33.6 → 41.5	1627.6 → 1649.0	
53.2 → 47.5	28.5 → 39.8	1068.7 → 1073.3	52.9 → 49.5	31.8 → 41.8	1617.8 → 1642.5	
57.8 → 52.8	33.0 → 42.3	1071.2 → 1075.0	57.2 → 53.9	35.7 → 44.6	1618.1 → 1638.9	

[a]Axial extrapolation distance, δ, is 100 mm for the clean lattice, and 105 mm for the boron-bearing lattice.

where

$\Delta\rho$ = change in core reactivity,

$\frac{\partial\rho}{\partial Tm}$ = moderator temperature coefficient of reactivity,

$\frac{\partial\rho}{\partial Tc}$ = coolant temperature coefficient of reactivity (strictly speaking, this coefficient also includes the fuel temperature coefficient),

and ΔTm and ΔTc are small changes in the moderator and coolant temperatures, respectively. These two temperature coefficients of reactivity can be obtained by use of least-squares fitting of ΔTm, ΔTc, and $\Delta\rho$ to Eq. (5), if these coefficients can be regarded as constant.

This data analysis method was applied to several data groups, such as that shown in Fig. 4, each of which consisted of many data sets of ΔTm, ΔTc, and $\Delta\rho$ obtained in a relatively narrow range of temperature during one continuous reactor operation. Each data group was obtained over a different range of moderator temperatures above ~30°C. As a result, temperature coefficients of reactivity were obtained as shown in Fig. 5 as circles with error bars. The results indicate that the moderator temperature coefficient of reactivity is largely dependent on its temperature, while the coolant temperature coefficient is constant within the experimental error.

When Eq. (5) is applied to the present experimental data, it should be noted that ΔTc is not proportional to ΔTm. If they were, definite values for both temperature coefficients, $(\partial\rho/\partial Tm)$ and

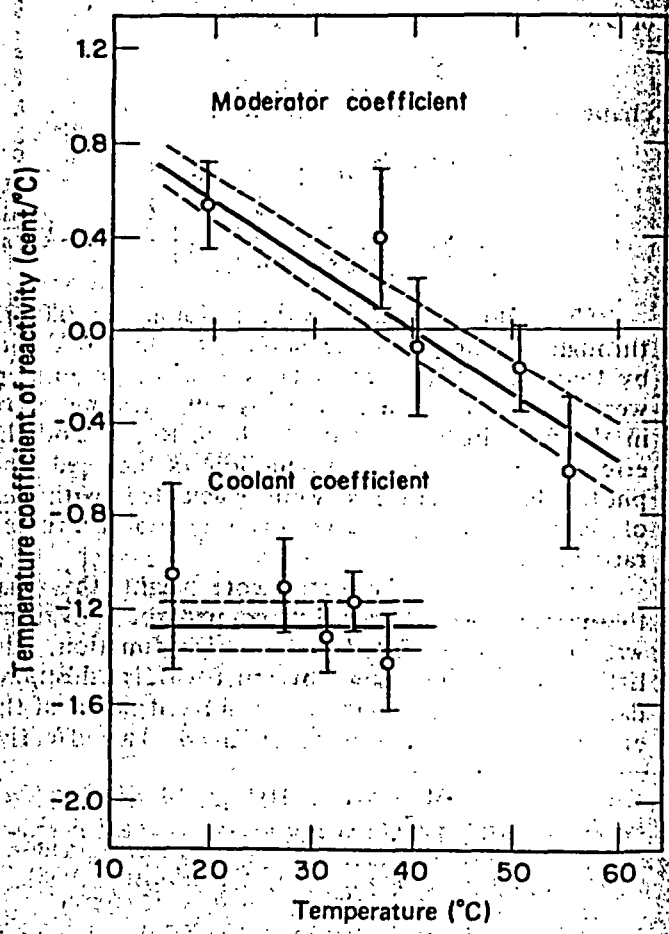


Fig. 5. Temperature coefficient of reactivity (clean lattice).

$(\partial\rho/\partial Tc)$ in Eq. (5) could not be determined mathematically. In the present experiments, the temperatures in the core were not controlled; only as the initial condition was the moderator temperature set higher than that of the coolant. During the reactor operation, each temperature naturally changed due to heat transfer from the moderator to the coolant. If there were no heat leakage out of the core, ΔTm might be proportional to ΔTc. Heat leakage, however, exists. When Tm was set much higher than room temperature, a decrease in moderator temperature was found to be accelerated, apparently due to heat loss to the atmosphere around the core. A typical example of temperature behavior is shown in Fig. 6, where ΔTm is observed not to be proportional to ΔTc. When Tm was nearly equal to room temperature, however, observed changes in Tm and Tc were almost proportional. This suggests that the method of least-squares fitting to Eq. (5) cannot be applied with good accuracy to the moderator temperature near room temperature. In the moderator-temperature range below ~30°C, short-term critical experiments were performed to obtain the four sets of values for ΔTm, ΔTc, and $\Delta\rho$ shown in Table I.

Simple Method of Data Analysis Including Temperature Dependence

Once the dependence of the moderator temperature coefficients of reactivity on the moderator temperature is confirmed over a wide temperature range, as shown in the previous section, a simple method is conceivable for the data analysis by the introduction of a (least-squares) fitting function that takes into account temperature dependence of the coefficient. Considering that the core reactivity can be expressed as a smooth curve in terms of Tm and Tc if there are no phase changes in the moderator and coolant, such as boiling or freezing, a general form of a function can be derived by using the Taylor expansion with two variables, the moderator and coolant temperature:

$$\rho = a\cdot Tm + b\cdot Tm^2 + c\cdot Tc + d\cdot Tc^2 + e\cdot Tm\cdot Tc + h \ , \tag{6}$$

where a, b, c, d, e, and h are constants, and terms higher than the third are ignored. The moderator and coolant temperature coefficients of reactivity are derived from Eq. (6) as

$$\partial\rho/\partial Tm = a + 2b\cdot Tm + e\cdot Tc \ , \tag{7}$$

$$\partial\rho/\partial Tc = c + 2d\cdot Tc + e\cdot Tm \ . \tag{8}$$

It was found, however, that actual values for the factors d and e became nearly zero when all the data on Tm, Tc, and ρ, measured over the present wide range of moderator temperature, were least-squares fitted to Eq. (6). It means that the cross effect between Tm and Tc is negligible, and also that the temperature dependence of the coolant temperature is negligible. Therefore, it is realistic to use the equation which follows instead of using Eq. (6), since the experimental error should also be taken into account:

$$\rho = a\cdot Tm + b\cdot Tm^2 + c\cdot Tc + h \ . \tag{9}$$

The following expressions give the temperature coefficients:

$$\partial\rho/\partial Tm = a + 2b\cdot Tm \ , \tag{10}$$

$$\partial\rho/\partial Tc = c \ . \tag{11}$$

Use of this simple method of data analysis, which takes into account temperature dependence, yielded the following values of the temperature coefficients of reactivity:

Moderator coefficient (cent/°C): $(1.12 \pm 0.08) - (0.028 \pm 0.002)\cdot Tm$,

Coolant coefficient (cent/°C): $-(1.27 \pm 0.08)$.

Experimental errors were estimated from the fitting errors including the effect of ignoring the two factors, d and e. The results, shown in Fig. 5 as solid lines, are in good agreement with the previous results obtained in each narrow range of temperature. In this final fitting to Eq. (9), of course, all the experimental data shown in Table I were used. The experimental accuracy, represented by dashed lines, is greatly improved with this simple data analysis method. As the result, the temperature dependence of the moderator temperature coefficient definitely became apparent.

Application to the Boron-Bearing Core

The above simple and accurate method of data analysis was applied to the data obtained from a

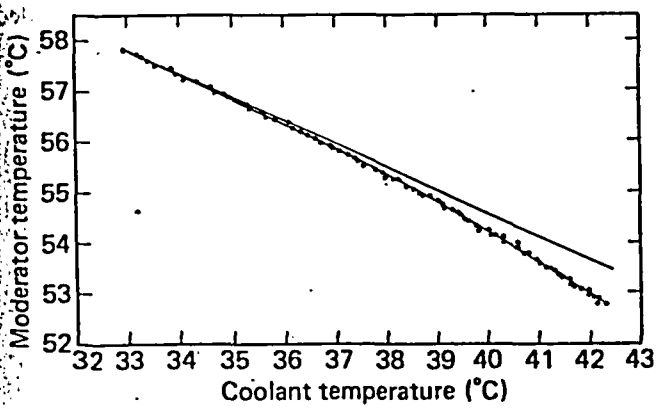


Fig. 6. Temperature change of moderator and coolant.

similar experiment for temperature coefficients of the boron-bearing core, which had 3.9 ppm of ^{10}B dissolved in the moderator; all the data sets on ρ, Tm, and Tc were least-squares fitted to Eq. (9). The following were then obtained as the temperature coefficients of reactivity:

Moderator
coefficient (cent/°C): $(3.38 \pm 0.13) - (0.029 \pm 0.005) \cdot Tm$,

Coolant
coefficient (cent/°C): $-(1.45 \pm 0.39)$.

The results are shown in Fig. 7. The temperature dependence of the moderator temperature coefficient also shows clearly in the boron-bearing core.

DISCUSSION

The moderator temperature coefficients of reactivity obtained in the present experiments decrease with moderator temperature for both clean and boron-bearing lattices. In the clean lattice the coefficient is positive in the lower temperature region and negative in the higher, changing at ~40°C.

In explanation of this behavior, the superposition of the following two main effects is considered when the density of D_2O moderator decreases with increase in temperature:

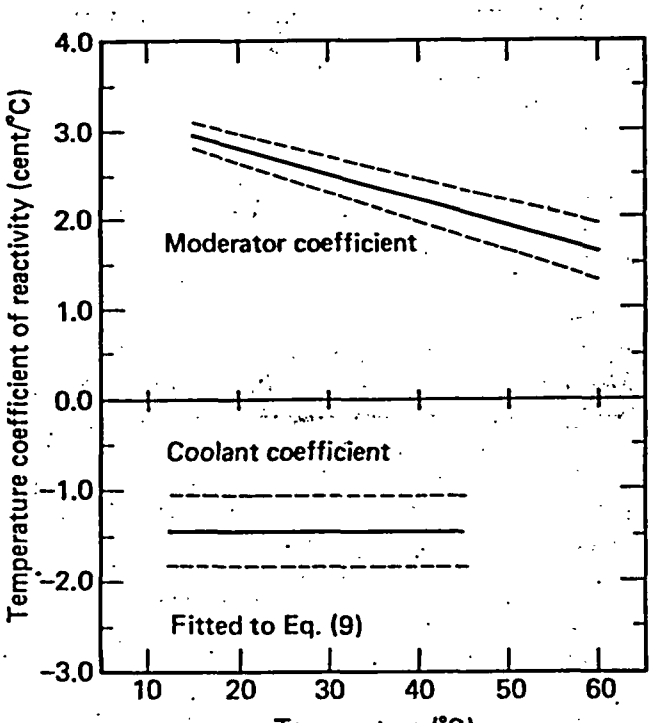


Fig. 7. Temperature coefficient of reactivity (boron-bearing lattice).

1. The thermal-neutron utilization factor f increases due to the decrease in the portion of neutron absorption in the core material other than fuel; the disadvantage factor decreases due to the increased diffusion coefficient in the moderator; and the macroscopic absorption cross section of the moderator decreases. As a result, positive reactivity is introduced. Since the 25.0-cm pitch lattice used in the present experiment is an overmoderated system,[10] this effect is considered to be fairly large.
2. Neutron leakage out of the system increases. As a result, negative reactivity is introduced. Since the migration area is inversely proportional to the square of the moderator density ($M^2 \propto 1/d^2$), this effect increases rapidly with the moderator temperature.

In the lower temperature region, the former positive effect is superior to the latter negative one; however, with an increase in the moderator temperature, the latter surpasses the former, resulting in the overall descending curves seen in Figs. 5 and 7. In the clean lattice, it is believed that the above two effects cancel out each other at ~40°C.

In the boron-bearing lattice, values of moderator temperature coefficients are large by ~2 cent/°C compared with the clean lattice, hence they are always positive in the present temperature range as seen in Fig. 7. It is understood that this difference is caused by positive reactivity due to an additional decrease in thermal-neutron absorption, by the ^{10}B dilution, with temperature and an additional decrease in neutron leakage due to an enlargement of the critical volume of this boron-bearing lattice by a factor of ~1.6.

Concerning the coolant temperature coefficients of reactivity, no dependence on the coolant temperature is observed beyond the experimental error and its sign is always negative as seen in Figs. 5 and 7. When the H_2O coolant density decreases with increase in temperature, thermal-neutron absorption in the coolant should decrease. This positive reactivity effect, however, is considered to be largely exceeded by the following effects, which produce negative reactivity:

1. There is a decrease in the number of fission neutrons per absorption in ^{235}U, η due to an increase in thermal-neutron temperature; the fuel temperature coefficient of reactivity is negative.[11]

[11] Y. HACHIYA, A. NISHI, H. SAKATA, and K. HIGUCHI, "Measurements of Fuel Temperature Coefficient of Reactivity with Two-Region Core System," SN 941 74-76, Power Reactor and Nuclear Fuel Development Corporation, Japan (1974) (in Japanese).

2. There is an increase in the ^{238}U resonance absorption of neutrons due to a decrease in slowing down by H_2O coolant; the number of neutrons having energy near ^{238}U resonance is increased, as is the mean-free-path in the fuel region.

When ^{10}B is dissolved in the D_2O moderator, the positive reactivity effect due to the decrease in thermal-neutron absorption in the H_2O coolant should decrease. This makes the value of the coolant temperature coefficient more negative. However, no marked difference is observed beyond the experimental error in the measured values of negative coolant temperature coefficients of reactivity between the clean and the boron-bearing lattices.

COMPARISON WITH WIMS-D CODE CALCULATION

The experimental results were compared with the calculational results by WIMS-D code developed by Askew et al.[12] for lattice calculation based on the transport theory to serve in the nuclear design of SGHWR. The transport equation is solved by the collision probability method using at most 69 neutron energy groups, which were condensed into 23 energy groups in the present calculation. For thermal-neutron scattering in heavy water and light water, the effective width and Nelkin models were adopted, respectively. The temperature-dependent density of heavy water was taken from Ref. 13. Changes in reactivity due to changes in moderator temperature were calculated by steps of 10°C over the range from room temperature to 60°C.

The calculated results are shown in Fig. 8 (the broken line represents the moderator temperature coefficients of reactivity) and in Table II.

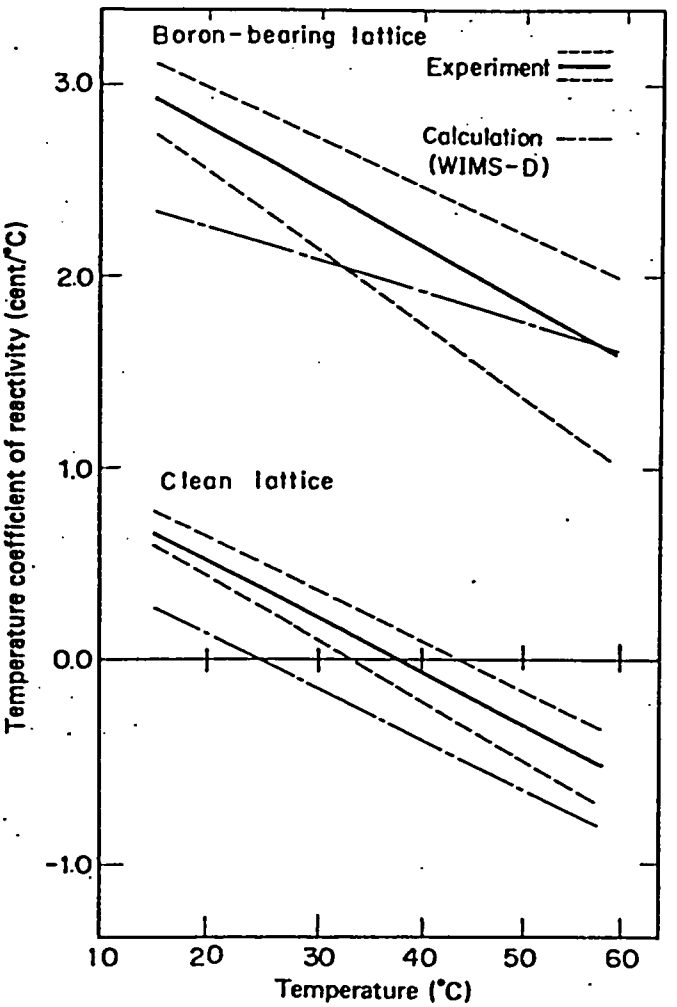


Fig. 8. Comparison of experimental and calculated moderator coefficients of reactivity.

TABLE II

Comparison of Experimental and Calculated Coolant Temperature Coefficient of Reactivity

Lattice	^{10}B Concentration, ppm in D_2O	Coolant Temperature Coefficient (cent/°C)	
		Experiment	WIMS
Clean	0	−1.27 ± 0.08	−1.85
Boron-bearing	3.9	−1.45 ± 0.39	−2.12

As seen from the figure, calculational results by WIMS-D code are in good agreement with the experimental results of the temperature dependence of the moderator temperature coefficients of reactivity; in the clean lattice, the calculated moderator coefficient has a positive sign in the lower temperature region and a negative one in the higher. However, the sign change occurs at a lower temperature than in the experimental results. In the boron-bearing lattice, the value of the temperature coefficient also shifts markedly to the positive side, but the code underestimates the temperature dependence of this moderator coefficient. In both lattices, the absolute values of the moderator temperature coefficient are small, on the whole, compared to the experimental ones. Relatively good agreement is obtained, however, in the boron-bearing lattice at the operation temperature (~60°C) of Fugen, the prototype reactor of the ATR.

[12]J. R. ASKEW, F. J. FAYERS, and P. B. KEMSHELL, *J. Brit. Nucl. Energy Soc.*, 5, 564 (1966).

[13]ROBERT C. WEAST, *Handbook of Chemistry and Physics*, 59th Edition, CRC Press, Inc., Cleveland, Ohio (1978).

Calculation also presents the coolant temperature coefficients of reactivity as almost constant and confirms the shift of the value to the negative side for the boron-bearing lattice. However, differences in the values between calculation and experiment are beyond the experimental error.

CONCLUSIONS

Temperature coefficients of reactivity have been measured in detail for the pressure-tube-type lattices consisting of D_2O moderator, H_2O coolant, and 28-pin UO_2 fuel clusters.

A new critical-experiment method that positively utilizes the temperature changes due to natural cooling and heat transfer in each part of the lattice has been developed. This method is applicable to the ordinary critical assemblies not equipped with any special temperature control system.

By this method, it has been determined that the moderator temperature coefficient of reactivity of this type of reactor has strong dependence on moderator temperature and that it decreases with increase in moderator temperature.

In the clean lattice of 1.2 wt% ^{235}U enriched UO_2 fuel, which contains no ^{10}B in the moderator, the coefficient has a positive sign in the lower temperature region and negative in the higher, the sign change occurring at ~40°C. This tendency is ascribable to the fact that the negative reactivity effect due to the increase in neutron leakage with temperature dominates the positive effect due to the increase in the thermal-neutron utilization factor.

Addition of 3.9 ppm of ^{10}B into the D_2O moderator of the same lattice makes the value of the temperature coefficient shift markedly to the positive side. It is considered that this shift is caused by the additional dilution effect of ^{10}B with an increase in the moderator temperature.

Calculational results by WIMS code well reproduce the experimental results concerning the temperature dependence of the moderator temperature coefficient of reactivity. However, their absolute values are rather small compared to the experimental ones.

APPENDIX

TEMPERATURE CORRECTION FOR LEVEL METER

The accuracy of the temperature correction for the level meter was confirmed by the following method. Heavy water, pre-heated to a desired temperature, was pumped into the core until it overflowed through a tube, which was positioned at a fixed height, *hc*, at the same temperature. When the surface of heavy water became still, the heavy water height indicated by the level meter, *hs*, was measured. Then the difference in heights in the core and in the level meter was obtained as follows:

$$\Delta h_{exp} = hc - hs \ .$$

On the other hand, the height difference was calculated by Eq. (1) using the measured temperatures of heavy water in the core and in the level meter, *Tc* and *Ts*, respectively.

$$\Delta h_{cal} = hs \cdot \left(\frac{d(Ts)}{d(Tc)} - 1 \right) \ ,$$

where $d(T)$ is the density of heavy water at temperature T°C. The above procedure was repeated at different temperatures of heavy water. Results are shown in Fig. 9. Agreement between experiment and calculation is fairly good. Experimental error includes thermal expansion of the supporting arms of overflow tube positioner. As a result, it is considered that the error in heavy water height corrected by Eq. (1) is within 2 mm at heights of ~1 m. This means that this temperature correction yields a measurement

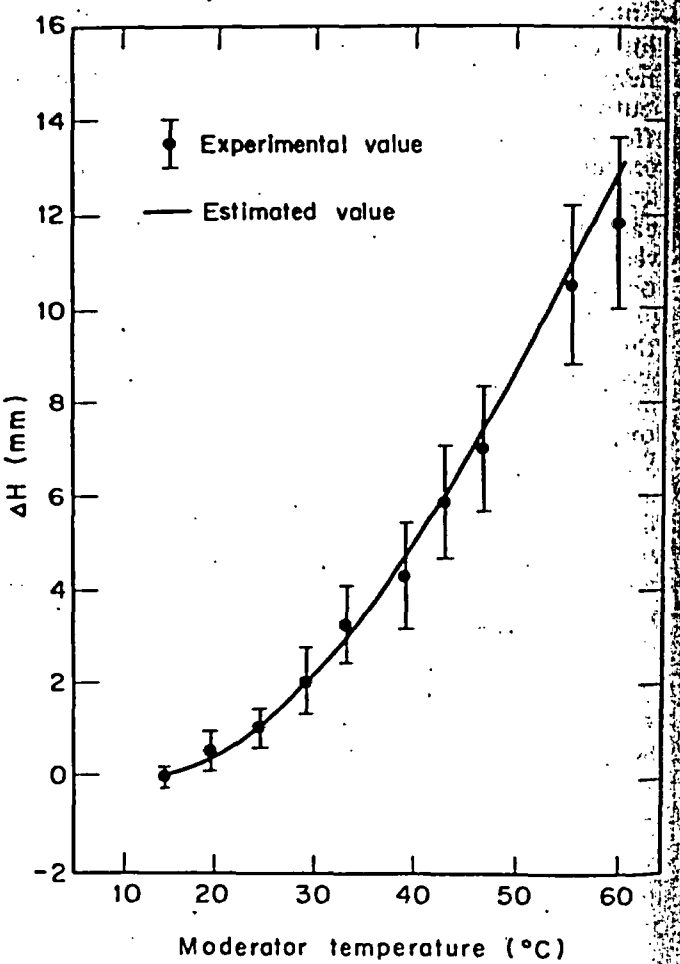


Fig. 9. Difference of D_2O height between core and level meter.

error of at most 0.2% in the height in the present range of moderator temperature.

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