Available online at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Investigating Heavy Water Zero Power Reactors with a New Core Configuration Based on Experiment and Calculation Results

Zahra Nasrazadani*, Raana Salimi, Afrooz Askari, Jamshid Khorsandi, Mohammad Mirvakili, and Mohammad Mashayekh

Reactor Research School, Nuclear Science and Technology Research Institute, Atomic Energy Organization of Iran, P.O. Box 81465/1589, Esfahan, Iran

ARTICLE INFO

Article history:
Received 20 December 2015
Received in revised form
4 May 2016
Accepted 1 July 2016
Available online xxx

Keywords:
CITATION
Criticality Assembly
Heavy Water
Lattice Pitch
MCNP
Safety
WIMS
Zero Power

ABSTRACT

The heavy water zero power reactor (HWZPR), which is a critical assembly with a maximum power of 100 W, can be used in different lattice pitches. The last change of core configuration was from a lattice pitch of 18–20 cm. Based on regulations, prior to the first operation of the reactor, a new core was simulated with MCNP (Monte Carlo N-Particle)-4C and WIMS (Winfrith Improved Multigroup Scheme)–CITATON codes. To investigate the criticality of this core, the effective multiplication factor (K_{eff}) versus heavy water level, and the critical water level were calculated. Then, for safety considerations, the reactivity worth of D_2O, the reactivity worth of safety and control rods, and temperature reactivity coefficients for the fuel and the moderator, were calculated. The results show that the relevant criteria in the safety analysis report were satisfied in the new core. Therefore, with the permission of the reactor safety committee, the first criticality operation was conducted, and important physical parameters were measured experimentally. The results were compared with the corresponding values in the original core.

1. Introduction

In heavy water zero power reactors (HWZPRs), natural metallic uranium is used as a fuel, heavy water as a moderator, and graphite as a radial reflector. The reactor is provided with safety rods, control rods, and an emergency dump system. The reactor is located in the reactor research school of Esfahan, Iran. There are two pairs of top and bottom grid plates, which can form four lattice pitches. The first pair of grid plates form square lattice pitches equal to 20 cm and 14.14 cm, and the second one forms lattice pitches equal to 18 cm and 12.73 cm. The reactor has been operating in 18 cm lattice pitch with a maximum of 124 fuel rods until now. For this core configuration, different physical parameters have been measured. In order to study the physical parameters in other lattice pitches, the lattice pitch of the core was changed

---

* *Corresponding author.*
E-mail address: zahranasr50@yahoo.com (Z. Nasrazadani).

http://dx.doi.org/10.1016/j.net.2016.07.004

Please cite this article in press as: Z. Nasrazadani et al., Investigating Heavy Water Zero Power Reactors with a New Core Configuration Based on Experiment and Calculation Results, Nuclear Engineering and Technology (2016), http://dx.doi.org/10.1016/j.net.2016.07.004

to 20 cm. In this case, the maximum number of fuel rods in the core is equal to 112. As the lattice pitch was changed, first of all, the possibility of criticality of the new core should be verified. According to the safety analysis report, near critical state, the reactivity insertion rate in the core should not be more than 2×10^{-4} (Δk/k)/s, the reactivity worth of each safety rod should be more than 1% Δk/k, and the reactivity worth of each control rod should be less than 0.2% Δk/k [1]. Therefore, prior to the first startup, the effective multiplication factor, the critical water level, the reactivity worth of heavy water, the reactivity worth of safety rods and control rods, and temperature reactivity coefficients are calculated using the MCNP (Monte Carlo N-Particle)-4C, WIMS (Winfrith Improved Multigroup Scheme), and CITATION codes. If all results meet the safety criteria, the operation of the new core is permitted.

2. Reactor description

The HWZPR core is cylindrical and has two control rods, two safety rods, and 112 fuel rods, with a 20-cm square lattice pitch. In each fuel rod, there are 20 fuel slugs with height and diameter equal to 100 mm and 35 mm, respectively. The fuel tubes and clad of fuel slugs are made of aluminum alloy. The core of the reactor is surrounded by annular graphite reflector, which is 75 cm thick. The heavy water is kept under low pressure nitrogen gas to avoid heavy water degradation. The height and diameter of the active core are 205 and 238 cm, respectively [1].

3. Calculation methods

MCNP-4C was used to simulate a three-dimensional configuration of the HWZPR new core. The continuous energy cross section data from LANL/T-2 and ENDF-VI libraries, S(α,β) thermal scattering model, and $T = 300°K$ were used in the calculations [2]. The core was defined as a lattice, with a 20-cm lattice pitch. Regarding the deterministic method, cell and core calculations were done by WIMS and CITATION codes, respectively. WIMS code is a general lattice program that uses the transport theory to calculate flux as a function of energy and position in the cell. WIMS first calculates spectra for a few spatial regions in the full number of energy groups of its library (69 groups) and uses them to condense the cross sections into a few groups. A few group calculations are then carried out using a much more detailed spatial representation. In WIMS code, a variety of geometries can be treated. HWZPR including fuel cell, D_2O cell, and graphite cell were simulated by WIMSD4 code [3,4]. For example, the lattice cell of fuel in HWZPR is shown in Fig. 1A. This cell is divided into annulus region including fuel material, can, and coolant. The cross section data in WIMS is from ENDF/B-V. The generated cross sections by WIMS code for different cells were used as inputs in the CITATION code [5]. The core of the reactor was simulated by the CITATION code in three-dimensional slab geometry (XYZ). The reactor was divided into several zones of different materials, and each zone was divided into mesh intervals (Fig. 1A). The lattice pitch was 20 cm, and each mesh interval was 6.67 cm (Fig. 1B). CITATION calculation was done in two groups of energy, fast and thermal. The cross sections for these two groups were obtained from the WIMS code by using a ZADOC card. 1E-5 was used as iteration convergence criteria for calculation of multiplication factor in the CITATION code.

3.1. *Calculation of critical water level and reactivity worth of heavy water*

Prior to the first criticality experiment, the neutronic calculation had to be done to obtain the critical water level, water level reactivity coefficient, and reactivity worth of the control and safety rods under the new lattice of the fuel loading. Therefore, the new core configuration was simulated using

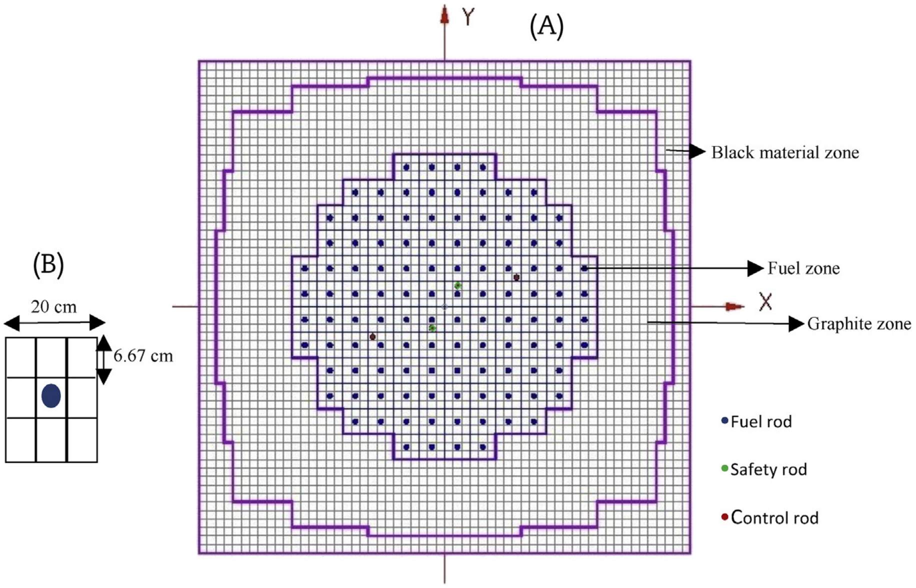
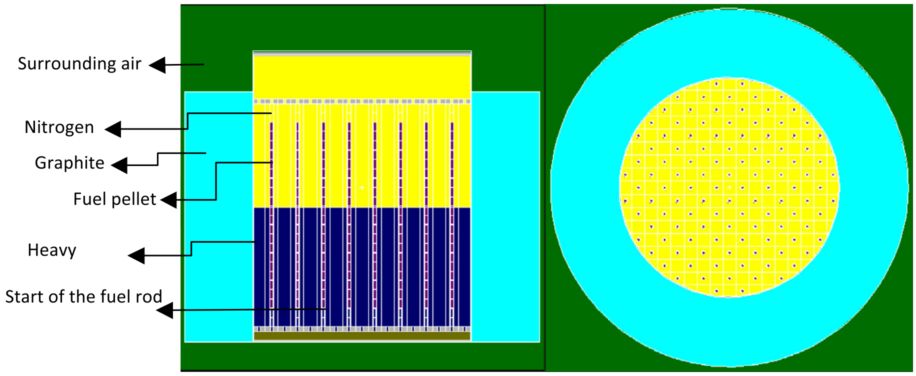


Fig. 1 – Schematic modeling used for simulation. (A) Simulation with CITATION code. (B) Simulation with HWZPR lattice cell.

Please cite this article in press as: Z. Nasrazadani et al., Investigating Heavy Water Zero Power Reactors with a New Core Configuration Based on Experiment and Calculation Results, Nuclear Engineering and Technology (2016), http://dx.doi.org/10.1016/j.net.2016.07.004



(A) (B)

Fig. 2 – View of HWZPR new core. (A) Vertical view. (B) Horizontal view.

MCNP-4C and CITATION codes. The vertical and horizontal views of HWZPR, extracted from the output of MCNP-4C, are shown in Figs. 2A and 2B, respectively. The accuracy of the data library and calculation method was verified, by comparing the calculated and experimental results for HWZPR with lattice pitch equal to 18 cm [2]. The description of natural metallic uranium and aluminum cladding, Al guide tubes, and Al tank are shown in Table 1. The concentration of heavy water was considered equal to 99.82%.

The new core of HWZPR was simulated, using the MCNP-4C code, in three dimensions. The effective multiplication factor was calculated by a KCODE card with 700 cycles and 5,000 histories per cycle in five different heavy water levels. The number of cycles and histories were chosen so that the standard errors of the calculated K_{eff} satisfied one-sigma statistical uncertainty with 68% confidence interval. By increasing the heavy water level in the input file, the value of K_{eff} was calculated in subcritical, critical, and supercritical states. In each case, the run was repeated three times, and the average of the results is saved as the K_{eff}. In the first run, a KSRC card was used and, in addition to K_{eff}, the source file was created. Then, the KSRC card was removed from the input file, and the source file was used in the execution of the code.

Finally, the critical water level and reactivity worth of heavy water were calculated using the MCNP-4C, WIMS, and CITATION codes. In all calculations, the temperature was equal to 27°C. The change in the effective multiplication factor versus heavy water height is shown in Fig. 3, and the calculated results are compared in Table 2.

It should be noted that the calculated results in HWZPR were compared by experimental results in the lattice pitch of 18 cm, and the validity of the calculation model had previously been verified [6].

Table 1 – Material description of natural metallic uranium and aluminum cladding.

Impurity of natural metallic uranium (ppm)	$\rho = 18.95 \times 10^3$ (kg/m^3)
U-235 abundance (wt.%) 0.712	
C = 500	Fe = 100
B = 0.3	Ni = 50
Mn = 40	Si = 110
Impurity of Al cladding LF_2 (ppm)	$\rho = 2.68 \times 10^3$ (kg/m^3)
Fe = 2,400	Si = 1,600
Zn = 300	Mn = 100
Ti = 100	Cu = 120
Mg = 100	Li = 6
Cd = 1	B = 1

3.2. *Calculation of safety and control rods reactivity worth*

In order to calculate the reactivity worth of the safety and control rods, the geometrical specification and material composition were defined in the MCNP-4C and CITATION input files. The height of water was considered equal to the critical water level, and the effective multiplication factor was calculated when two safety rods or two control rods were inserted in the core. Using the equation:

$$\rho = \frac{K_2 - K_1}{K_2 K_1}, \qquad (1)$$

the reactivity worth of the safety and control rods was calculated. In this equation, K_2 is the effective multiplication factor when two safety rods or two control rods are inserted, and K_1 is the effective multiplication factor of the clean core (without any experimental guide tubes) at the critical water level. The results are given in Table 3.

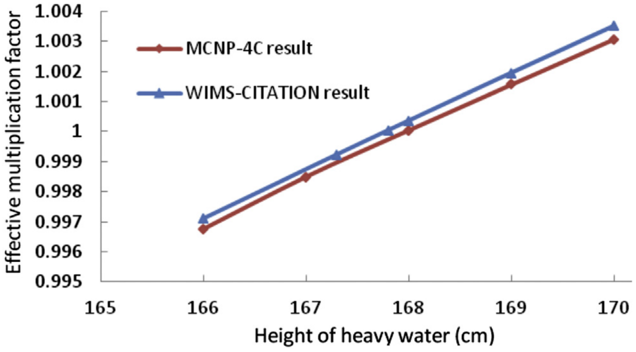


Fig. 3 – Change of effective multiplication factor versus heavy water height.

Please cite this article in press as: Z. Nasrazadani et al., Investigating Heavy Water Zero Power Reactors with a New Core Configuration Based on Experiment and Calculation Results, Nuclear Engineering and Technology (2016), http://dx.doi.org/10.1016/j.net.2016.07.004

Table 2 – Calculation results of critical level and reactivity worth of heavy water (lattice pitch = 20 cm).

Code	MCNP-4C	WIMS and CITATION	Difference (%)
Critical water level, mm	1,680 ± 0.2%	1,678	0.12
D_2O reactivity worth, (Δk/k)/mm[a]	$1.38 \times 10^{-4} \pm 4.5\%$	1.41×10^{-4}	2.1

MCNP, Monte Carlo N-Particle; WIMS, Winfrith Improved Multigroup Scheme.

[a] (Δk/k)/mm was calculated near critical between heavy water heights of 166 cm and 170 cm.

Table 3 – Calculation results of reactivity worth of safety and control rods (lattice pitch = 20 cm).

Reactivity worth, Δk/k	MCNP-4C	WIMS & CITATION	Difference (%)
2 safety rods	0.03259 ± 3.8%	0.03057	6.2
2 control rods	0.00376 ± 5.4%	0.00396	5.3

MCNP, Monte Carlo N-Particle; WIMS, Winfrith Improved Multigroup Scheme.

3.3. *Calculation of temperature reactivity coefficient*

Because of the low power of HWZPRs, in the normal operation of the reactor, the increase in fuel and moderator temperature is negligible. However, in order to study the behavior of the reactor in accident conditions, the fuel and moderator temperature reactivity coefficients were calculated by WIMS code. In order to study the fuel temperature coefficient, a fuel cell was simulated. Then, K_{eff} and reactivity in different temperatures (27°C, 100°C, 250°C, 400°C, 550°C, 625°C, 800°C, and 1,000°C) were calculated. Ambient temperature, i.e., 27°C, was the reference temperature for the reactivity coefficient calculation. In order to obtain more precise results, a buckling card was used. The procedure was the same for the calculation of the moderator temperature reactivity coefficients, the only difference being that temperature was changed from 27°C up to 100°C (27°C, 40°C, 50°C, 60°C, 70°C, 80°C, 90°C, and 100°C), and the density of the moderator was changed. The results are given in Table 4, and the temperature reactivity coefficients were compared for two different lattice pitches.

A comparison of the results shows that in the new lattice pitch, the fuel and moderator temperature reactivity coefficients decrease; therefore, the new core is safer than the original core.

4. Criticality experiments

The calculation results ensure a safe approach, in order to reach critical and supercritical states. Therefore, the core configuration of HWZPR was modified as shown in Fig. 1. Installation of the new grid plates and 112 fuel rods in the new core configuration were followed by the adjustment of the position of safety rods, control rods, and neutron detectors. Then, the first criticality experiment was performed according to the procedure. In the first startup, the critical water level was estimated to be in a subcritical state. Then by increasing the water level, the reactor was made supercritical with different doubling periods, and the reactivity worth of water and critical water level were measured in the supercritical state.

4.1. *Measurement of critical water level in subcritical condition*

In the first criticality experiment, based on the procedure, the water level was increased step by step. In each step, the neutron count and water level were recorded. By drawing the curve of the reciprocal of count ($1/n$) versus water level (h), a straight line was fitted to two points. Extrapolating the fitted line to $1/n = 0$ ($\rho = 0$), the critical water level (h_{cr}) was measured [7]. These steps continued until $K_{eff} = 0.996$. The extrapolated water level in this stage was recorded as the measured critical water level in the subcritical condition (1,716.85 mm).

4.2. *Measurement of reactivity worth of heavy water and critical water level in supercritical state*

In this experiment, the reactor was made supercritical based on the procedure [8]. By increasing the water level, the reactor was made supercritical, by four different doubling periods, i.e., 45 seconds, 69 seconds, 79 seconds, and 97 seconds. The doubling periods were measured accurately by a power measuring system on the console and a stopwatch. The equivalent reactivity of each doubling period was obtained using a ρ–T table. By drawing the change of reactivity versus the water level, $\partial\rho/\partial h$ and h_{cr} were obtained (Fig. 4). The measured results for critical water level and reactivity worth of water were obtained as: $h_{cr} = 1{,}717.3$ mm and $\partial\rho/\partial h = 0.136$ mk/mm.

4.3. *Measurement of critical water level in critical state*

By decreasing the core water level slowly until the power or the neutron detector current stayed constant for about 10 minutes, the water level gauge indicated the accurate value of critical level in critical state. This value was equal to $h_{cr} = 1{,}717.0$ mm.

5. Conclusion

Prior to the first criticality experiment, the theoretical calculation had to be carried out to obtain the critical water level,

Table 4 – Calculation results of fuel and moderator temperature reactivity.

Fuel temperature reactivity coefficients, (Δk/k)/°C		Moderator temperature reactivity coefficients, (Δk/k)/°C	
Lattice pitch = 18 cm	Lattice pitch = 20 cm	Lattice pitch = 18 cm	Lattice pitch = 20 cm
-1.0×10^{-5}	-1.06×10^{-5}	-6.19601×10^{-5}	-8.69×10^{-5}

Please cite this article in press as: Z. Nasrazadani et al., Investigating Heavy Water Zero Power Reactors with a New Core Configuration Based on Experiment and Calculation Results, Nuclear Engineering and Technology (2016), http://dx.doi.org/10.1016/j.net.2016.07.004

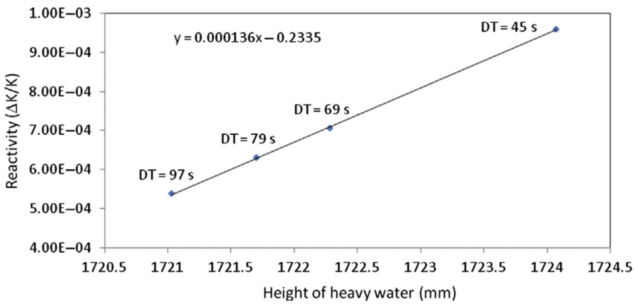


Fig. 4 – Measurement of heavy water reactivity worth and critical water level in supercritical state.

Table 5 – Comparison of calculated and experimental critical water level and reactivity worth of heavy water (lattice pitch is equal to 20 cm).

Physical parameters	Calculated	Measured	Difference (%)
Critical water level, mm	1,680 ± 0.2%	1,717 ± 0.1%	2.2
D_2O reactivity worth, (Δk/k)/mm	$1.38 \times 10^{-4} \pm 4.5\%$	$1.36 \times 10^{-4} \pm 2.6\%$	1.5

Table 6 – Comparison of physical parameters in new core and original core.

Lattice pitch	18 cm	20 cm
Measured critical water level, cm	158.3	171.7
Measured reactivity worth of heavy water, (Δk/k)/mm	1.47×10^{-4}	1.36×10^{-4}
Calculated reactivity worth of 2 safety rods, Δk/k	0.02802	0.03057
Calculated reactivity worth of 2 control rods, Δk/k	3.35×10^{-3}	3.76×10^{-3}

water level reactivity coefficient, the reactivity worth of the control and safety rods, and the relation of the power doubling period with the reactivity under the lattice of the fuel loading. Therefore, the new core configuration was simulated by MCNP-4C and WIMS–CITATION codes. In order to verify the accuracy of the data library and calculation method, the results of the calculation were compared with the experimental results for a lattice pitch equal to 18 cm [2].

The calculation results show that the new core satisfied the necessary requirements, and the criticality of the new core is possible. Therefore, the first criticality experiment was carried out. In this operation, the calculated critical water level and reactivity worth of water were used as reference data. Then, the physical reactor parameters were measured (Table 5). According to the difference of the theoretical and experimental results in the fourth column of Table 5, the consistency of the results is good.

The physical parameters in different lattice pitches of 18 cm and 20 cm are compared in Table 6. As we expected, in the overmoderated region, when the ratio of moderator to fuel or lattice pitch was increased, the effective multiplication factor decreased. Therefore, the critical water level increased, and the reactivity worth of heavy water decreased in the new core. The reactivity worth of control and safety rods in the new core satisfied the safety criteria.

The new core configuration can be effectively used for verification of calculation tools by further experimental work on the safety and control rod's reactivity worth, thermal and fast neutron flux, neutron spectrum, and dynamic parameters measurement.

Conflict of interest

All authors have no conflicts of interest to declare.

Acknowledgments

The authors express their gratitude to the HWZPR installation and operation groups.

REFERENCES

[1] China Institute of Atomic Energy, Preliminary Safety Analysis Report on Heavy Water Zero Power Reactor, Internal Report, 1992.

[2] J.F. Briesmeister, MCNP A General Monte Carlo N-Particle Transport Code System (version C), Los Alamos National Laboratory, Los Alamos (NM), 2000.

[3] M.J. Halsall, A Summary of WIMSD4 Input Options, 1967.

[4] M.J. Roth, The preparation of input data for WIMSD4, General Reactor Physics Division, Atomic Energy Establishment, 1967.

[5] National Energy Software Center Note, CITATION, NESC No. 387, July 1980

[6] A. Moosakhani, M.N. Nasrabadi, B. Teimuri, Monte Carlo calculation of the core of the heavy water zero power reactor (HWZPR), using MCNP4C, Nucl. Eng. Des. 241 (2011) 1459–1462.

[7] J. Khorsandi, Z. Nasr, R. Salimi, M. Adavoodi, H. Khalafi, Heavy water zero power reactor (HWZPR) mixed core, first criticality, calculation and experiment, Prog. Nucl. Energy 85C (2015) 613–616.

[8] China Institute of Atomic Energy, HWZPR Safe Operation Manual, Internal Report, 1992.

Please cite this article in press as: Z. Nasrazadani et al., Investigating Heavy Water Zero Power Reactors with a New Core Configuration Based on Experiment and Calculation Results, Nuclear Engineering and Technology (2016), http://dx.doi.org/10.1016/j.net.2016.07.004