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NEUTRONIC AND THERMAL HYDRAULICS ANALYSIS OF CONTROL ROD EFFECT ON THE OPERATION SAFETY OF TRIGA 2000 REACTOR

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ABSTRACT

NEUTRONIC AND THERMAL HYDRAULICS ANALYSIS OF CONTROL ROD EFFECT ON THE OPERATION SAFETY OF TRIGA 2000 REACTOR. Analysis of neutronic and thermal-hydraulics parameters of whole operation cycle is very important for the safety of reactor operation. During the reactor operation cycle, the position of the control rods will change due to reactivity changes. The purpose of this study is to determine the effect of control rods position on neutronic and thermal-hydraulics parameters in relation to the safety of reactor operation of the TRIGA 2000 reactor using silicide fuel of MTR plate type. Those parameters are power peaking factor, reactivity coefficients, and steady-state thermohydraulic parameters. Neutronic calculations are performed using a combination of WIMSD/5 and Batan-3DIFF codes and for thermal-hydraulics the calculations are done using WIMSD/5 and MTRDYN codes. The calculation results show that the reactivity coefficient values are negative for all control rod positions both at CZP and HFP conditions. The MTC value decreases when the control rod is inserted into the active core while the FTC value increases. The total ppf results and temperature in steady-state rise when the control rods are inserted of into the active core whereby the maximum value occurs at the position of the control rods of 20 cm from the bottom of the active core. The calculation results of ppf, reactivity coefficient, and thermal-hydraulics parameters lay below safety limits, indicating that the TRIGA 2000 reactor can safely use U_3Si_2-Al silicide fuel as a substitute fuel for cylindrical type fuel.

Keywords: neutronic, thermal-hydraulic parameter, control rod effect, TRIGA 2000, silicide fuel.

ABSTRAK

ANALISIS NEUTRONIK DAN TERMOHIDRAULIK PENGARUH POSISI BATANG KENDALI TERHADAP KESELAMATAN OPERASI REAKTOR TRIGA 2000. *Analisis parameter neutronikdan termohidraulik dari seluruh siklus operasi sangat penting untuk keselamatan operasi reaktor. Selama siklus operasi reaktor, posisi batang kendali akan berubah karena perubahan reaktivitas. Tujuan dari penelitian ini adalah untuk mengetahui pengaruh posisi batang kendali terhadap parameter neutronik dan termohidraulik terkait keselamatan operasi reaktor TRIGA 2000 menggunakan bahan bakar silisida jenis MTR. Parameter yang ditentukan adalah faktor puncak daya, koefisien reaktivitas, dan parameter termohidraulika pada keadaan tunak. Perhitungan neutronikl dilakukan menggunakan kombinasi program WIMSD/5 dan Batan-3DIFF dan untuk termohidraulik dilakukan menggunakan program WIMSD/5 dan MTRDYN. Hasil perhitungan menunjukkan bahwa nilai koefisien reaktivitas negatif untuk semua posisi batang kendali baik pada kondisi CZP dan HFP. Nilai MTC berkurang ketika batang kendali dimasukkan ke teras aktif sementara nilai FTC meningkat. Hasil ppf total dan parameter dalam kondisi tunak meningkat dengan memasukkan batang kendali ke dalam teras aktif dimana nilai maksimum terjadi pada posisi batang kendali 20 cm dari bagian bawah teras aktif. Hasil perhitungan ppf, koefisien reaktivitas dan parameter termohidraulik berada di bawah batas keselamatan, ini menunjukkan bahwa reaktor TRIGA 2000 dapat menggunakan bahan bakar silisida* U_3Si_2*-Al dengan aman sebagai bahan bakar pengganti bahan bakar jenis silinder.*

Kata kunci: *neutronik, parameter termohidraulik, efek batang kendali, TRIGA 2000, bahan bakar silisida.*

INTRODUCTION

The Bandung TRIGA 2000 reactor currently uses cylindrical TRIGA fuel type and by now it is planned to be replaced by U_3Si_2-Al MTR fuel type. These TRIGA fuel types are no longer produced by General Atomic so, it comes an alternative to replace them with MTR fuel types. The U_3Si_2-Al silicide fuel with a density of 2.96 g/cc is produced domestically by PT INUKI and used as RSG-GAS reactor fuel. For this reason, the calculation of the equilibrium core configuration has been carried out using the Batan-FUEL code[1]. The calculation results show that the reactor can be operated at a nominal power of 2 MW using 16 fuels and 4 control rods[2–4]. One of the important problems with nuclear reactor operation is safety. A safety system is designed for control reactivity and prevent accidents[5]. The control rod and reactivity coefficient are factors that can control the reactor power.

In this study, the effect of control rods positions on neutronic and thermal-hydraulic steady-state parameters will be calculated. The safety of reactor operation will be affected by core configuration, fuel fraction, type of fuel and fuel enrichment. During one cycle of reactor operation, the position of the control rod will change from the beginning of the cycle (BOC) to the end of cycle (EOC)[6]. The changes in the control rod positions will affect the reactor response to neutronic and thermal-hydraulic parameters. The control rods are generally used to control changes in reactivity, changes in power and to shut the reactor down[7]. The use of a control rod in a research reactor is different from a power reactor because the research reactor does not have a chemical shim rod to control reactivity[7]. The TRIGA reactor using MTR type fuel was designed to have 4 control rods for using as a compensation system. For this reason, the control rod position changes in one operating cycle may be significant enough to affect the safety of the reactor operation.

The parameters calculated in this study cover inherent safety parameters namely moderator temperature coefficient (MTC) and fuel temperature coefficient (FTC), as well as power peaking factor (ppf) and temperature at steady-state conditions. The inherent safety calculation is performed on the operating conditions cold zero power (CZP) and hot full power (HFP). Thermodynamic parameters due to the effect of the control rod position in the design of research reactors the MTR type is very important for safe operation and optimization of the fuel used[8,9].This data is needed for the preparation of the safety analysis report (SAR) for the conversion of fuel from the cylinder type to the MTR type.

The code used in these calculations is the WIMSD/5[10], Batan-3DIFF[11] and MTR-DYN code[12,13]. The WIMSD/5 is used for the generation of macroscopic cross-sections of fuel elements, control elements, structural materials, reflector elements, and water. The WIMSD/5 and Batan-3DIFF code used for calculation of inherent safety parameters and ppf. Calculation of steady-state thermal-hydraulic parameters of equilibrium core is done by using WIMSD/5 and MTR-DYN code.

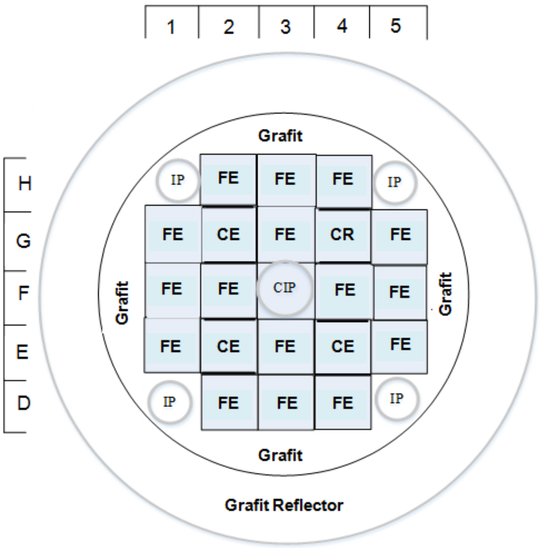
DESCRIPTION OF TRIGA 2000

The fuel element used in TRIGA 2000 is based on MTR technology and each standard fuel element consists of 21 fuel element plates. Each fuel element plate consists of an $AlMg_2$ clad, which wrap the U_3Si_2-Al meat dispersion plate. The control rod is designed as a fork-type inserted in a so-calledcontrol element. The number of fuel plates in the control element is 15 fuel plates and in both outer sides are for the absorber Ag-In-Cd blades which are cladded by stainless steel (material 1.4541, the same as SS 321). The parameters of the fuel element and the control element of silicide fuel with a density of 2.96 g/cc are shown in Table 1.

Equilibrium core configuration (TWC) of the TRIGA 2000 reactor is shown in Figure 1. The active core of TWC consists of 16 standard fuel elements, 4 control fuel elements, one irradiation position in the middle (CIP) and 4 irradiation positions (IP) inside the core. In addition to the arrangement of the reactor core 5 x 5, the reactor core is surrounded by a graphite reflector and in the graphite position, several irradiation facilities will be placed. The core parameters in the equilibrium core with the fuel loading pattern 4/1 are presented in Table 2.

Table 1. Parameters of the mechanical design of fuel and control element of TRIGA 2000[2].

Fuel Elements and Control Elements	
Types	MTR
Fuel Plates per Standard Fuel Element	21
Fuel Zone Thickness, mm	0.54
Fuel Zone Width, mm	62.75
Fuel Zone Length, mm	600.0
Type of Fuel	U_3Si_2-Al
Enrichment, %	19.75
Uranium Density in meat, g/cm^3	2.96
Cladding Thickness, mm (Rata-rata)	0.38
Cladding Thickness, mm (Minimum)	0.25
Cladding Material	AlMg2
Fuel Plate Thickness, mm	1.3
Fuel Plate Width, mm	70.75
Fuel Plate Width, mm	625.0
Type of Absorber	Fork type with two absorber blades
Fuel Plates per Fuel Control Element	15
Material Absorber	AgInCd
Thickness, mm	3.38
Cladding Material	Steels



Note: FE = Fuel Element, CE = Control Element,
IP = Irradiation Position, CIP = Central Irradiation Position

Figure 1. Equilibrium core TRIGA 2000 using U_3Si_2-Al fuel[2].

Table 2. Core parameters of the TRIGA2000 reactor using U_3Si_2-Al fuel[2].

Core parameters	Equilibrium core
Massa ^{235}U per standard fuel element (g)	250
Uranium density (g/cc)	2.960
Power (MWth) / cycle length (days)	2/120
Reactivity for one cycle (%Δ*k*/*k*)	2.183
Excess reactivity (%Δ*k*/*k*)	6.61
Total control rod values (%Δ*k*/*k*)	-20.60
Shutdown reactivity (stuck rod) (%Δ*k*/*k*)	-6.56
Power density (W/cc)	28.305
Average radial power peaking factor	1.225
Maximum discharged burn-up (%)	26.485
Reactivity of control rod G-2 fully up, others fully down (%Δ*k*/*k*)	-6.61
Reactivity control rod G-4 fully up, others fully down (%Δ*k*/*k*)	-6.56
Reactivity of control rod E-2 fully up, others fully down (%Δ*k*/*k*)	-6.61
Reactivity of control rod E-4 fully up, others fully down (%Δ*k*/*k*)	-6.60

METHODOLOGY

Core Calculation

The neutronic core calculation core is performed at the equilibrium core using Batan-3DIFF. This Batan-3DIFF codes, have been developed in the Batan for neutronic design and safety analysis. This code solves the three-dimensional multigroup neutron diffusion problems. Batan-3DIFF codes have been validated and have high accuracy in designing the equilibrium silicide core for the RSG-GAS reactor[14]. The Batan-3DIFF was used to calculate criticality and core reactivity as a function of control rod positions to power peaking factor. The calculation is performed for the control rod positions of 0 cm (fully down), 10 cm, 20 cm, 30 cm, 40 cm, 50 cm and 60 cm (fully up). The calculated data of axial and radial power peaking factor are needed for analysis of the thermal-hydraulic parameter calculations.

Calculation of Reactivity Feedback Coefficient

The reactivity coefficient is sometimes called the feedback reactivity coefficient which has a major influence on the safety of reactor operations[15]. Calculation of the feedback reactivity coefficient is done as a function of the position of the control rod. Cross-section calculations are performed using the WIMS-D5 program in 4 (four) neutron energy groups. Calculation of fuel temperature coefficient, the cross-section is generated with changes in meat temperature from 20 – 200 ^{o}C and moderator temperature are kept constant at 20 ^{o}C for cold zero power conditions and 40 °C for hot full power conditions. Calculation of moderator coefficient temperature, moderator temperature is changed from 20 – 100 °C and fuel temperature are kept constant at 20 ^{o}C for cold zero power conditions and 68 ^{o}C for hot full power conditions.

Core calculation is performed using the combination of WIMS-D5 and Batan-3DIFF codes. The moderator reactivity coefficient and the fuel reactivity coefficient are determined based on the keff value for each temperature as function of the control rod position.

The magnitude of the reactivity change per temperature change in a moderator, called the coefficient of temperature reactivity can be determined as follows:

$$\alpha_m = \frac{\Delta\rho_{Tm}}{\Delta T_m} \qquad (1)$$

where,

α_m : moderator coefficient temperature (pcm/^{o}C)
$\Delta\rho_m$: reactivity change (pcm)
ΔT_m : moderator temperature change (^{o}C)

The value of α_{TM} depends on the change in moderator temperature. Water moderated reactors have a negative α_{TM} value and will increase in value with an increase in water temperature. The fuel reactivity coefficient is defined as the change in reactivity per change temperature in fuel element which can be determined as follows:

$$\alpha_f = \frac{\Delta\rho_f}{\Delta T_f} \qquad (2)$$

where,

α_f : fuel coefficient temperature (pcm/^{o}C)
$\Delta\rho_f$: reactivity change (pcm)
ΔT_f : moderator temperature change (^{o}C)

The fuel temperature coefficient depends on the type and temperature of the fuel. Light water reactors generally have a negative fuel temperature coefficient where the reactivity will be reduced with an increase in fuel temperature.Change in reactivity was calculated as,

$$\Delta\rho = \frac{k_{\text{eff } 0-1}}{k_{eff\,0}} - \frac{k_{\text{efft } -1}}{k_{\text{efft}}} \qquad (3)$$

where,

k_{eff0}: effective multiplication factors at reference temperature 20 ^{o}C.
k_{efft}: effective multiplication factors at a specified temperature

Thermal Hydraulic Parameter Calculation

The calculation of thermal hydraulic parameter such as fuel temperature, cladding, and moderator as a function of the control rod is done using the MTR-DYN code. The MTR-DYN code depends on space and time, the diffusion theory of many groups is based on the steady-state analysis program and the transient MTR type research reactor. This program is designed for the transient model of research reactor criticality when additional reactivity and/or cooling system insertion occur. The MTR-DYN code basically consists of a 3-dimensional model of neutronic-thermohydraulic couplings which contains two main parts, the neutronic calculation module, and the thermohydraulic calculation module. The minimum flow rate of the primary cooling system is 70 kg/s and only 59.5 kg/s cools the reactor core. The core inlet temperature of 35 ^{o}Cand a pressure of 1.8 Mpa[16].

RESULTS AND DISCUSSION

The Effect of Control Rod Position on ppf Axial and Radial

Calculation results of radial and axial ppf as a function of the control rod are shown in Table 3.

Table 3. The maximum ppf value as a function of the control rod

Control rod position (cm)	k_{eff}	Maximum ppf radial	Maximum ppf axial	ppf total
60 (fully up)	1.0707938901	1.2132	1.2819	1.555201
50	1.0643241450	1.1982	1.3848	1.659267
40	1.0404020586	1.1791	1.5340	1.808739
30	1.0026041081	1.1661	1.7135	1.998112
20	0.9511311940	1.1684	1.8000	2.10312
10	0.9025688629	1.1705	1.4116	1.652278
0 (fully down)	0.8849318170	1.1742	1.2755	1.497692

Power peaking factor (ppf) is defined as maximum power divided by the average power in the reactor core or the ratio of maximum thermal neutron flux to mean neutron flux. High ppf value indicates that there is a high local power density in the reactor core. For the safety analysis of reactor operations, total ppf is used, which is a combination of axial and radial ppf values to guarantee that there is no damage to the fuel. Based on the data in Table 3, the maximum axial ppf values increase and as for the radial ppf decrease by increasing the control rod position to the core until the position is 20 cm from the bottom of the active core. The maximum total ppf value as a control rod position effect is still smaller than 3.00 which is used as a conservative value for reactor safety analysis.

Moderator Temperatur Coefficient

MTC is the function of the ratio of the moderator to fuel (N_m/N_f) is the ratio of moderator atom density of the reactor to fuel atom density. For the reactor design the N_m/N_f price in the reactor core is made optimum so that the moderating temperature coefficient is negative. The MTR type reactor is designed under an under moderator condition so that the N_m/N_f decreases resulting in a reduced k_{eff}. Changes in moderator temperature, without changes in density, resulting in increased resonance escape probability and reproduction factor (η).

Figure 2 shows the moderator temperature coefficient as a function of the control rod for the TRIGA 2000 core using U_3Si_2-Al silicide fuel. The MTC value in HFP conditions is more negative than CZP conditions because with the increase in temperature the moderator density decreases causing the neutrons to be at higher energy so that the probability of non-fission capture neutrons is increased. By reducing the Nm/Nf ratio due to the increase in moderator temperature, the thermalization factor increases in the core.

Changes in the moderator temperature coefficient due to changes in control rods have a major effect. The effect of the control rod on MTC is when the control rod is inserted to the core the moderator density decreases resulting in reduced reactivity. The control rod absorbs thermal and epithermal neutrons causing the probability of leakage of thermal neutrons to decrease and then to increase negative reactivity. When the moderator temperature rises and a partially of the control rod is inserted to the core, the neutron spectrum tends to harden. When the neutron spectrum hardening the value of the control rod increases because the control rod has a high absorption cross-section for thermal and epithermal neutrons. For this reason, when the control rod is inserted into the active core, the MTC becomes more negative and when the control rod is withdrawal, the MTC becomes more positive. In addition, when the control rod is inserted into the core the Nm/Nf decreases so that the core becomes under-moderated, resulting in a more negative MTC.

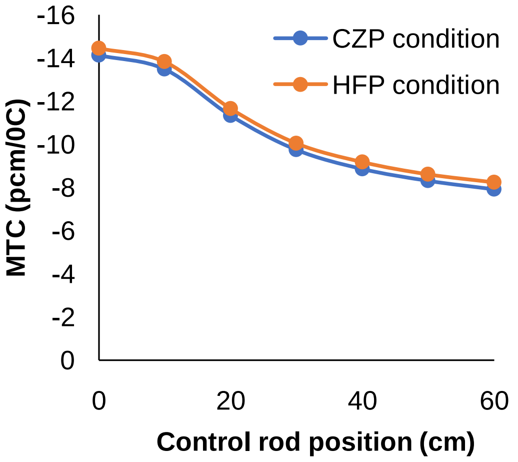


Figure 2. Effect control rod to moderator temperature coefficient

Fuel Temperatur Coefficient

The fuel temperature coefficient (FTC) and moderator temperature coefficient (MTC) are inherent safety features which are in the design of the reactor to produce negative reactivity due to increased power. In the low enrichment of thermal reactors, the contribution to the fuel temperature coefficient of reactivity comes from the Doppler broadening of the resonance capture cross-section of the fertile material. For this reason, the FTC is often called the Doppler reactivity coefficient, often abbreviated to Doppler. When the fuel temperature rises, the target energy has more energy so that fertile materials such as U-238 and Th-232 show large resonance peaks for neutron absorption and hence contribute to a large extent to the FTCThe results of the FTC calculation as a function of the control rod position are shown in Figure 3. The FTC value under the HFP operating conditions is more negative than the CZP condition. At high fuel temperatures, the resonance absorption peak for U-238 is broad, and most of the neutrons slowing down in the nucleus are captured in the resonant range.

The increase in temperature results in resonance absorption and the amount of thermal neutrons absorbed by U-235 is small so that the effect of the FTC is smaller at high fuel temperatures.The withdrawal of the control rod from the bottom of active core results in an increase in the FTC because the moderator is replaced with an absorbent material so that the thermal utilization factor decrease and the neutron spectrum tend to harden. Changes in reactivity due to control rods were smaller at about 2.8% compared to when control rods were withdrawn from the active core.

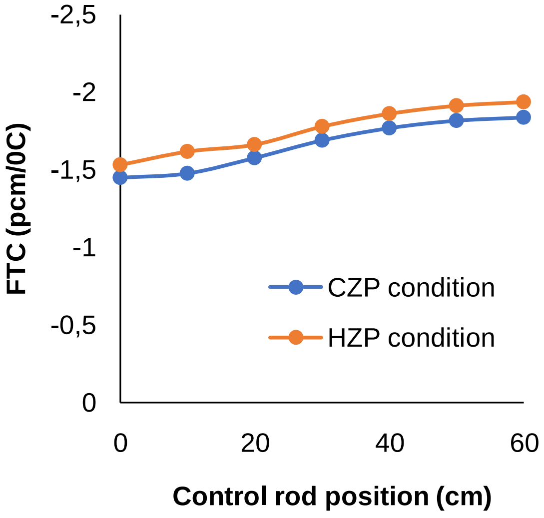


Figure 3. Effect control rod to fuel temperature coefficient

Effect of Control Rods Positions on ThermalHydraulic Parameters

Thermohydarulic analysis at steady-state conditions is very important for the safety of reactor operations. The results of the coolant, clad and fuel temperature calculations are shown in Table 4. Based on Table 4 the maximum temperature occurs when the control rod is 20 cm of the active core because in this condition the largest ppf occurs as shown in Table 3. The calculation results show that the maximum coolant temperature is 52.56 ^{o}C, cladding temperature is 90.85 ^{o}C and the fuel temperature is 91.08 ^{o}C. Coolant temperature is still below 100 ^{o}C and cladding temperature is still smaller than 120 ^{o}C, so there is no boiling on the reactor core.

Table 4. Coolant, clad and fuel temperature as a function of control rod position

Control rod position (cm)	Coolant temperature (^{o}C)	Clad temperature (^{o}C)	Fuel temperature (^{o}C)
60 (fully up)	51.70	81.27	81.45
50	51.71	83.49	83.68
40	51.91	86.92	87.13
30	52.03	90.41	90.63
20	52.20	90.85	91.08
10	52.41	82.83	83.01
0 (fully down)	52.56	83.37	83.56

CONCLUSION

The maximum axial ppf and total ppf values occur at the position of the control rod 20 cm from the bottom of the active core. MTC and FTC values at all control rod positions are negative, which show that the results are very good from the safety aspect of reactor operation. The average MTC change due to the changes in the position of the control rod increased by 12% due to the insertion of the control rod in the core. Meanwhile, changes in the FTC were not significant with changes in the control rod position. In thermal hydraulics conditions the coolant, cladding, and fuel temperatures are still below the permitted temperature so that the reactor operates safely.

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