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Original Article

# Three dimensional analysis of temperature effect on control rod worth in TRR

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ABSTRACT

In this paper, three-dimensional neutronic calculations were performed in order to calculate the dependency of CRW on the temperature of fuel and moderator and the moderator void. Calculations were performed using the known MTR_PC computer codes in the core configuration 61 of TRR. The dependency of CRW on the fuel temperature in the range of 20–340 °C and the moderator temperature of each control rods were studied. Based on the positions of the control rods, the calculations were performed in three different cases, named case A, B and C. By the results, the worth of each control rods increases by increasing of the coolant temperature in all methods, however, the total CRW is somewhat independent of the fuel temperature. In addition, the results showed that the variation of CRW versus density depends on the positions of the control rods and the most change in CRW in the coolant temperature, 20–100 °C (279 pcm), belongs to SR4. Finally the effect of void on CRW was studied for different void fraction in coolant. The most worth change is about $2 for 40% void fraction related to SR1 and SR3 in case B. For 40% void fraction, the total CRW increases about $7.5, $6 and $7 in cases, A, B and C, respectively.



## 1. Introduction

Movement of the control rods which are the movable part of neutron-absorbing materials, affects on the multiplication factor of the reactor core. Thus, they are used for keeping a reactor critical and operating at a specified power level [1]. The reactivity worth of control rods (the efficiency of absorbing excess reactivity) is an important parameter in the design and analysis of a nuclear reactor core [2]. The reactivity of the core is adjusted by control rods which are made of neutron absorbing materials. The control rods can be used for coarse and fine control or fast shutdown. They are also employed to compensate of short term reactivity effects due to fission product poisons, etc. [3].

Understanding of the relation between the reactivity changes and position of control rods is an essential knowledge required by a reactor operator. The movement of control rods may result in different reactivity variation due to changing core conditions. The operator must understand how designing of the control rods and changing core conditions affect the control rod worth (CRW) and know the reason.

CRW is affected by the control rods positions in the core, their operational time, surrounding materials and fuel burn up as well as the concentrations of fission products such as xenon and samarium. Dependency of the rods worth on the fuel burn-up and the Xe concentration level has been studied in a conceptual symmetric reactor core, based on the MTR fuel assemblies [4]. The study showed that at the presence of Xe in the core, the CRW is significantly reduced, while the variation of CRW due to the increasing of the burn-up depends on the rods positions in the core grid.

The effect of fuel burn-up on the CRW has been investigated by comparing the results of a fresh and irradiated core of Ghana's MNSR for both HEU and LEU cores. The results showed that CRW decreases with the burn-up for the LEU while the rod worth increases with burn-up for the HEU core [5].

Various conditions in TRR core affect the reactivity worth of the control rods. The main purpose of this work is investigation of the dependency of the CRW on the fuel and moderator temperature and the void fraction of the moderator in the reference core No: 61 of TRR. For the deterministic approach, the neutronic code system

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**Nomenclature**

| | |
|---|---|
| TRR | Tehran research reactork multiplication factor |
| $k_{eff}$ | effective multiplication factor |
| CR | control rod |
| CRW | control rod worth |
| LEU | low enriched uranium |
| HEU | highly enriched uranium |
| SFE | standard fuel element |
| CFE | control fuel element |
| $\rho_{excess}$ | excess reactivity |

composed of WIMS and CITVAP (modules of the MTR_PC code system) hase been used, while the stochastic one has been made using the Monte Carlo code MCNP. In addition, to justify the accuracy of the existing deterministic based code, similar calculation based on well-known Monte-Carlo code (MCNP) was provided as a code-to-code justification in the studying of the void effects.

## 2. Material and methods

### 2.1. Description of TRR and control rods

The TRR is pool type research reactor with slab geometry and heterogeneous and solid fuel which moderated and cooled by light water. It uses graphite reflectors and is loaded with MTR-type fuel elements, while its maximum operational power is 5 MW. Other details about TRR features can be found in safety analysis report. The diagram of TRR pool and the core configuration No: 61 of TRR have been shown in Figs. 1 and 2, respectively. It has 28 SFE +5 CFE, including 19 and 14 LEU (19.75% $U_{235}$/U) fuel plates, respectively. Specifications of TRR fuel assemblies are given in Table 1. In addition, the burn-up of the fuel elements (in the percent of the initial value of $U_{235}$) at the begin of the cycle is given in Fig. 2. Each one of the CFE assemblies hosts a control rod.

TRR reactor is controlled by insertion of four shim safety rods which made of neutron absorbing materials and one stainless steel regulating rod (RR) within the core lattice. The old control rods shape of TRR was oval type. After performing the core conversion from the use of HEU to the use of LEU, the shape of control rods changed from oval type to fork type. Comparing between oval and

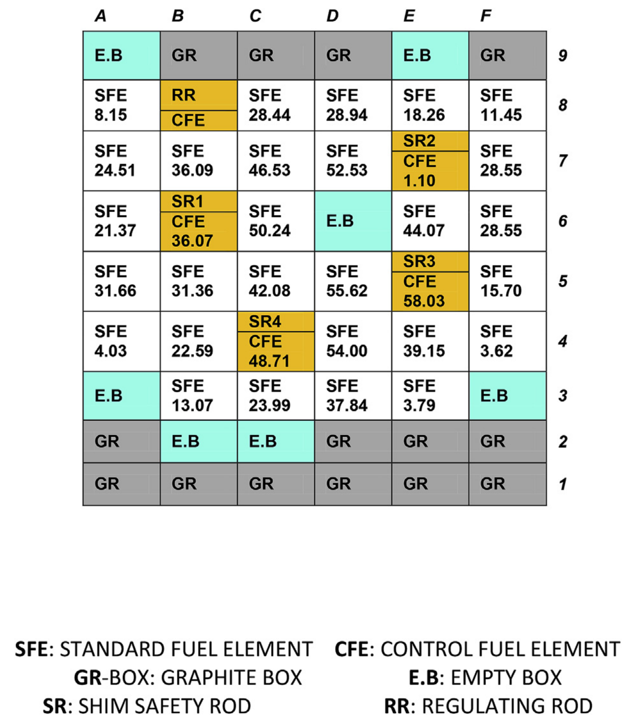



**Fig. 2.** TRR 61 core configurations.

fork type absorbers, it follows that considering the same absorber material and fuel enrichment, fork-type control rods are more effective than oval by a ratio ranging from 1.25 to 1.36 [6]. The effectiveness of a control rod is defined as the ratio of the CRW in the specific position of the core with two geometry. (1.25–1.36 = (Fork type CRW)/(oval type CRW). Fork type assembly is used for both of safety and regulating rod. This assembly is composed of two reactivity control plates (Fig. 3). Absorbing plates are made of silver (Ag), indium (In) and cadmium (Cd) alloy (80, 15, and 5 wt %, respectively). Fig. 4 shows more geometric details of the CFE and absorber rod (1/4 symmetry).

In any core configuration, the reactivity worth of the shim safety rods is sufficient for keeping the core in a deep sub-criticality in normal operating conditions as well as abnormal occurrences such as stuck rod.

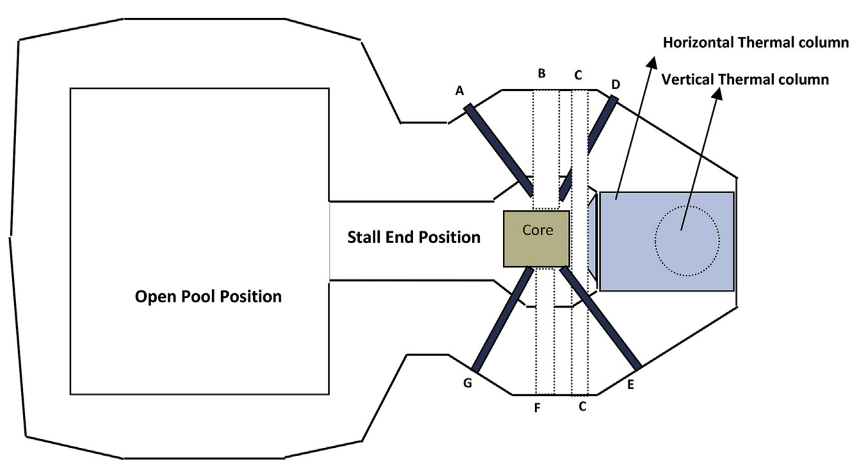



**Fig. 1.** Schematic view of TRR pool and facility.

**Table 1**
Specifications of TRR fuel assemblies.

| Parameter | Fuel Assembly Type | |
|---|---|---|
| | SFE | CFE |
| Meat material | $U_3O_8$-Al | $U_3O_8$-Al |
| Enrichment | 20% | 20% |
| Number of fuel plates | 19 | 14 |
| No of outer dummy plates | 0 | 0 |
| Meat thickness | 0.07 cm | 0.07 cm |
| Cladding thickness | 0.04 cm | 0.04 cm |
| Water channel thickness | 0.27 cm | 0.27 cm |
| Meat width | 6 cm | 6 cm |
| Meat length | 61.5 cm | 61.5 cm |
| Side wall thickness | 0.45 cm | 0.45 cm |
| Total plate width (wall to wall dist.) | 6.7 cm | 6.7 cm |
| FE dimensions | 8.01 × 7.71 × 89.7 cm | 8.01 × 7.7 × 61.5 cm |
| Uranium per fuel plate | | 15.26 g |
| Weight Of U-235 per Fuel Assembly | | 213.7 g |
| Density of Total Uranium in meat | | 3.0 gr/cc |
| Total Density Of Meat | | 4.8 gr/cc |
| Density of U-235 in Meat | | 0.591 gr/cm$^3$ |

**Fig. 3.** View of fork type of the control rod assembly.

## 2.2. Description of the codes

The MTR-PC package has been used in this work for main cell and core calculations based on macroscopic cross sections. It was developed by the INVAP S.E. to perform real neutronic, thermal-

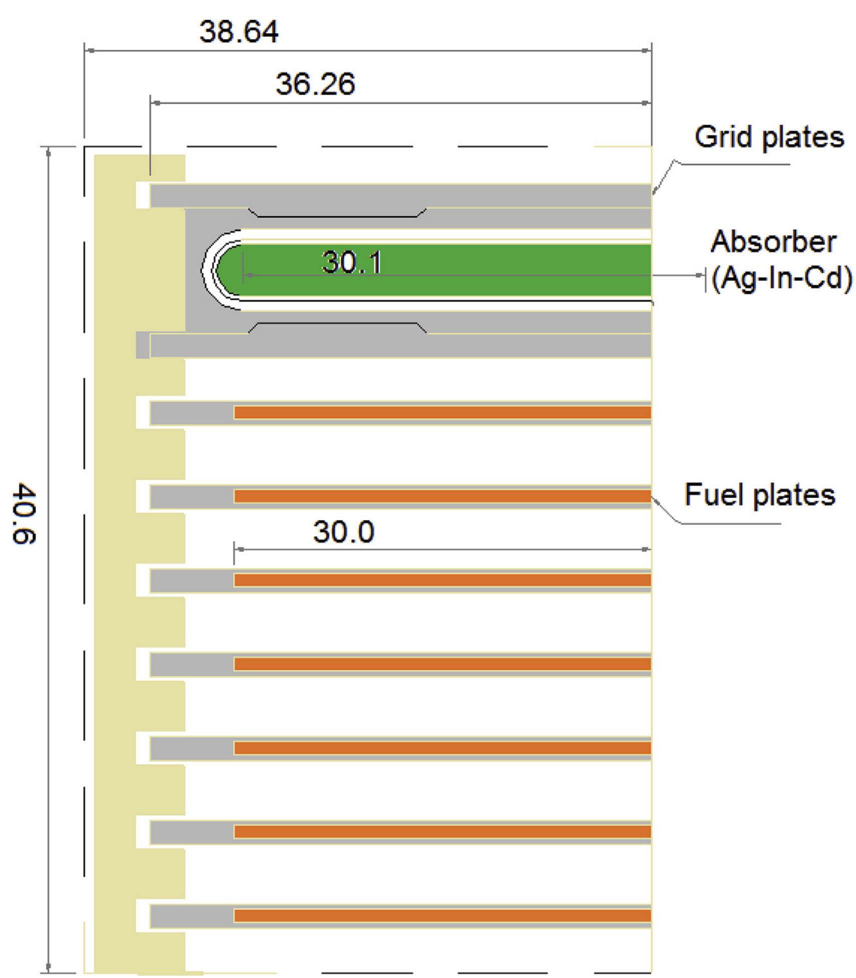



**Fig. 4.** LEU control fuel element (1/4 symmetry) (Dimensions in mm).

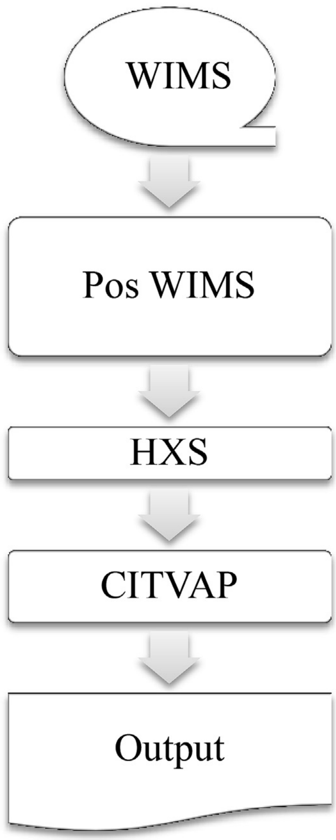



**Fig. 5.** Diagram of the MTR_PC calculations.

hydraulic, and shielding calculations of MTR-type reactors in personal computers [7]. Macroscopic cross sections for the cells are calculated using the WIMSD5B code [8]. It is an updated version of the WIMSD4 code [9]. WIMSD with ENDF/B-IV library was employed for macroscopic cross-section generation which provides nuclear cross-sections in the form of 69-group energy structure. The POS_WIMS code, which is a post processor program of WIMS [10], is used to condense and homogenize the required cross-sections in 3 groups structure, for suggested core regions and the energy-group structure from WIMS output. The HXS program (Handle Cross-Section) makes the connection between cell and core calculations [11]. The methodology and the interfaces between neutronic parts of MTR_PC has been shown in Fig. 5. The CITVAP code is applied for the global core calculations with the macroscopic cell cross-sections [12]. More details of neutronic simulation and group structures for any regions can be found in previous works [13,14].

For the accuracy of reliability results, CRW of the reference core in studying of the void effects is performed with MCNP code and the results are compared with CITVAP code. The MCNP5 code [15] and ENDF-VII library [16] are applied for calculating the neutronic parameters of the new core.

### 2.3. Calculation of the rods worth

The rod worth is calculated using the excess reactivity of the core configuration which is one of the CITVAP outputs. Excess reactivity in each run is calculated according to the global multiplication factor. The CRW and $\rho_{excess}$ are calculated using following formulas:

$$\rho = \frac{k_{eff} - 1}{k_{eff}} \tag{1}$$

$$CRW = \rho_{fw} - \rho_{fi} \tag{2}$$

Where $\rho_{fw}$ and $\rho_{fi}$ are the excess reactivity of the core with the control rod fully withdrawn from the core and fully inserted in it, respectively. In this work, three different procedures named case A, B and C are used for the determination of the CRW. The three cases are defined as follows:

Case A: full withdrawal of the examined rod while keeping the others fully inserted.

Case B: full insertion of the examined rod while keeping the others fully withdrawn.

Case C: The worth of bank control rods measured by fully insertion and withdrawal.

In all cases, the core power level is kept at 5 MW in the Xe poisoning equilibrium condition.

## 3. Results and discussion

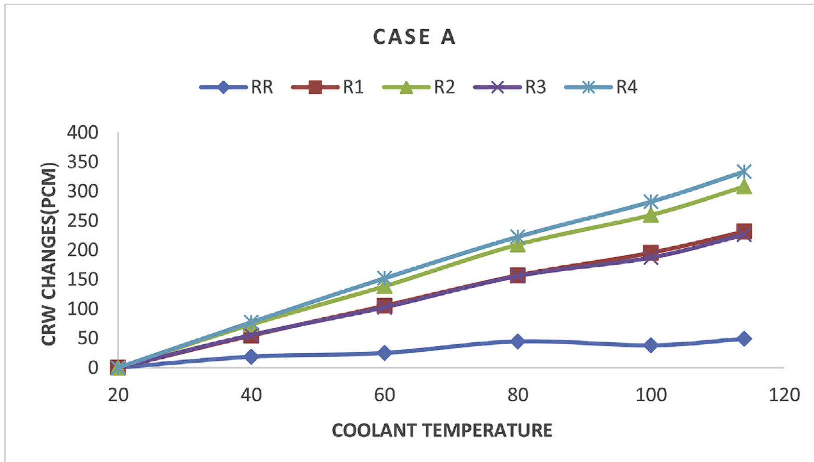
### 3.1. Temperature effect

At first, the effect of the temperature of the fuel and moderator on CRW is investigated. Table 2 shows the total CRW of TRR in two different fuel temperatures. It is seen that, by increasing of the fuel temperature from 20 °C to 340 °C, the total CRW increases slowly. Fig. 6 shows the changes in CRW in four SR and one RR of TRR due to the changes of the moderator temperature. The dependency of CRW on moderator temperature studied in two cases, A and B, individually and the sum of CRW in both cases is compared with case C. The results show that in both cases, A and B, the worth of each of control rods increases by increasing of the coolant temperature.

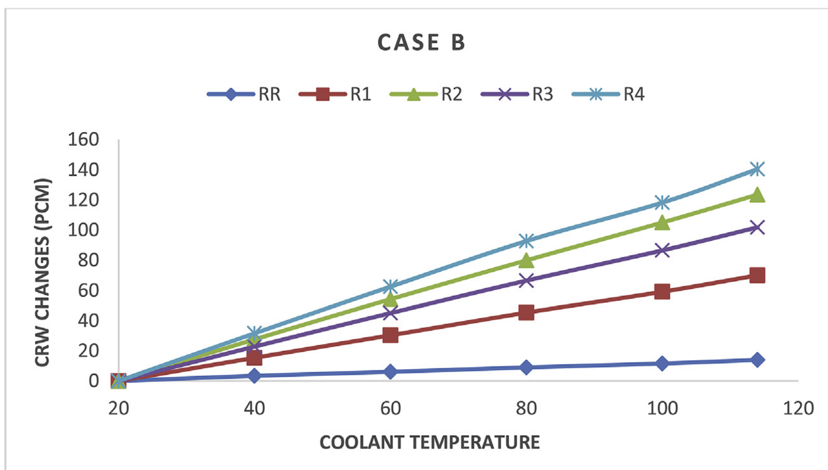
The main reason of the changes in CRW versus temperature is the changes in the temperatures of the various materials in the core (fuel and moderator) which leads to the changes in the energy distribution of the thermal neutrons. Since the kinetic energy of the atoms of any material depends on its temperature, the changes in the temperature of the moderator, coolant or fuel will affect the neutron spectrum, and the average thermal neutron energy. The average neutron energy is proportional to the absolute temperature of the moderator, so it is approximately doubled by going from 293 K to 573 K [17]. A plot of the neutron energy spectrum at two temperatures (293 K and 573 k) has been shown in Fig. 7. This data obtained from the WIMS calculations in the coolant of TRR. By increasing of the coolant temperature from 293 K to 573 K, the peak of thermal flux moves to the higher energy. This movement

**Table 2**
Total CRW of TRR in two different fuel temperatures.

| Fuel Temp | keff | | Excess Reactivity (pcm) | | Total Control Rods Worth (pcm) | Total Control Rods Worth changes (pcm) |
|---|---|---|---|---|---|---|
| | Control rods out | control rods in | Control rods out | control rods in | | |
| 20 $C^0$ | 1.021 | 0.989 | 2051 | −1162 | −13653 | 0 |
| 340 $C^0$ | 1.016 | 0.989 | 1600 | −1290 | −13690 | −37 |




a)

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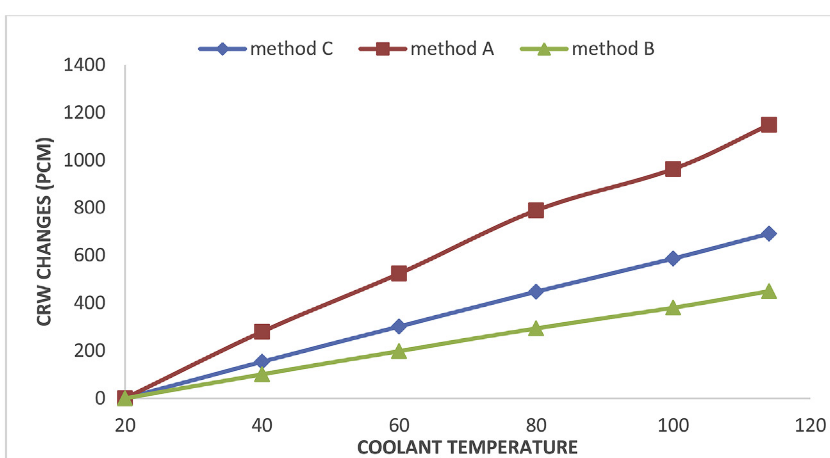



c)

**Fig. 6.** Changes in the CRW due to the changes of coolant temperature; (a) in case A and (b) in case B. (c) Total CRW in three methods.

towards higher neutron energies is often referred to the *neutron hardening*. Since the fission and absorption cross-sections depend on the neutron energy, the changes in the thermal neutron spectrum due to the temperature alter the balance between the fission and absorption rates in the core. As the moderator volume in TRR core is more than the fuel volume, the dependency of CRW to

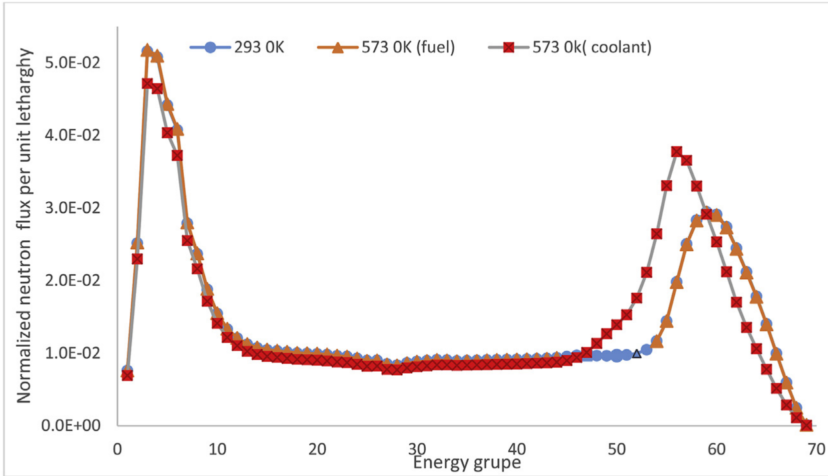



**Fig. 7.** Neutron energy spectrum at the two temperatures (Normalized Flux per unit lethargy vs. Energy).

the moderator temperature is more significant than the fuel temperature.

Increasing of the moderator temperature not only changes neutron energy, but also reduces the neutron absorption of the water in the thermal and epithermal regions. These both effects increase the worth of the control rods. In the case of the fuel material, as temperature increased, Doppler broadening effect cause broadening of the resonance absorption and make more absorption of neutrons in the energy higher than the thermal energy. This effect reduce the epithermal neutron flux in the fuel but cannot change the neutron spectrum and flux in the moderator that control rods exist. Fig. 7 shows normalizes neutron flux per unit lethargy vs. neutron energy groups in the moderator. The blue curve belong to the neutron flux that the temperature of the all material are about 293 K. It is clear that the neutron energy can be divided into three (fast, epithermal and thermal) groups. In the next step the temperature of the fuel material changed to 573 °C (triangle mark). As shown the neutron flux in the moderator cannot change. The results show that Doppler Effect in the fuel could not change the spectrum of the neutron energy in the moderator and has a little effect on increasing of the CRW that is negligible. Changing the coolant temperature to 573 °C, changes not only magnitude of neutron flux but also energy of neutrons.

By the results, the changes in the worth of the control rods in case A is greater than case B. It is due to the fact that in case A, all the control rods except the examined one are fully inserted which leads to the increasing of the thermal and epithermal neutron flux in the position of the control rods respect to case B. The more neutron flux leads to the more absorption in control rods, and so increasing of the control rods worth.

Figures (6-a) and (6-b) show the most and the least CRW changes in SR4 and RR, respectively, in the moderator temperature range. The results is reasonable since RR has been made of stainless steel and SR4 is neutron absorber.

### 3.2. Density effects

In addition to increasing of the energy of thermal neutrons, increasing of the reactor core temperature reduces the density of materials in the core. Here, the decreasing of the density of moderator has been investigated while the effect of fuel density on CRW has been ignored. Ignoring the effect of fuel density is reasonable since the volumetric expansion coefficient of solid is much lower than liquids and also, the moderator volumetric ratio is high in liquid form. Fig. 8 shows the variation of CRW versus temperature corresponding to the coolant density in both cases A and B. By the results, the worth of each control rods increases by decreasing of the moderator density.

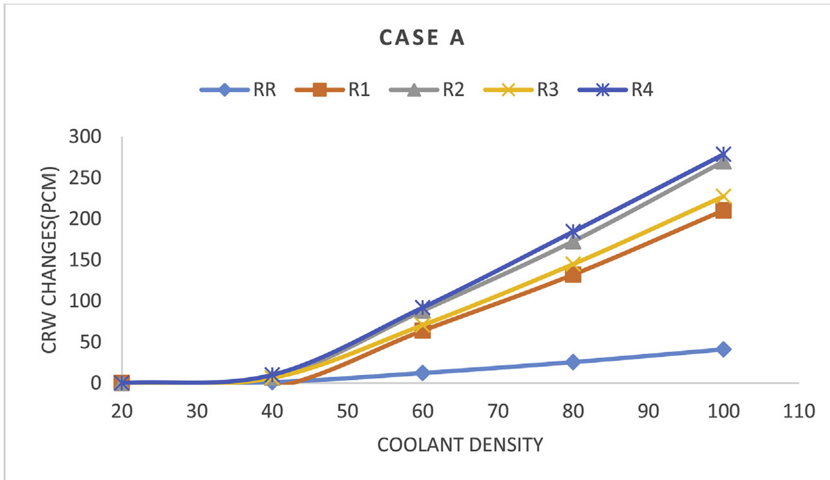
By increasing of the temperature, the density of moderator/coolant decreases which leads to more traveling of the neutrons before interacting with water molecules. Since neutrons travel a greater distance, the probability of absorption by control rods will be increased. By increasing of the moderator/coolant temperature, the CRW increases due to the control rod's increased sphere of influence. The results show that the decrease of the moderator density versus temperature is not linear which leads to the larger changes in the CRW at higher temperature.

Fig. 8 shows the CRW in cases A and B. The results show that the variations of CRW in term of the decreasing of the density in case A is more than that of case B. It is due to the changes of the neutron flux in both cases. In case A, the neutron flux in the position of each of the rods is more than case B. In addition, the results show that the most change in CRW in the range of 20–100 °C (279 pcm) belongs to SR4.

To compare the changes in total CRW versus the density and temperature, the total worth of the control rods has been plotted in terms of the temperature and density in Fig. 9 for cases A and B. By the results, in spite of the density effect, the change of total CRW linearly depends on the temperature. As a result of this fact, although the temperature effect is more than the density effect in low temperature, however, the density effect dominates at higher temperature. The results show that the domination process is faster in case A.

Fig. 10 shows the total temperature effect (both of temperature and density effects) on the worth of each of the control rods in both cases, A and B. the results show that in spite of case A, in case B, the worth of the control rods number SR4 and SR3 are similar to SR2 and SR1, respectively. In case A, the worth of each rod is measured independent of the other rods, so, the increasing of the reactivity of each rod according to its location is independent of other rods. In case B, the worth control rods is similar to each other and the shadow effect is minimum. Studying the total temperature shows that using case A is more reliable than case B in investigation of the CRW changes.

Fig. 10-c shows the total CRW in term of temperature and density in two cases, A and B. The results show that the total CRW in case A are more than twice as much as case B. The core-average delayed neutron fraction in the TRR is about 768 pcm that equals

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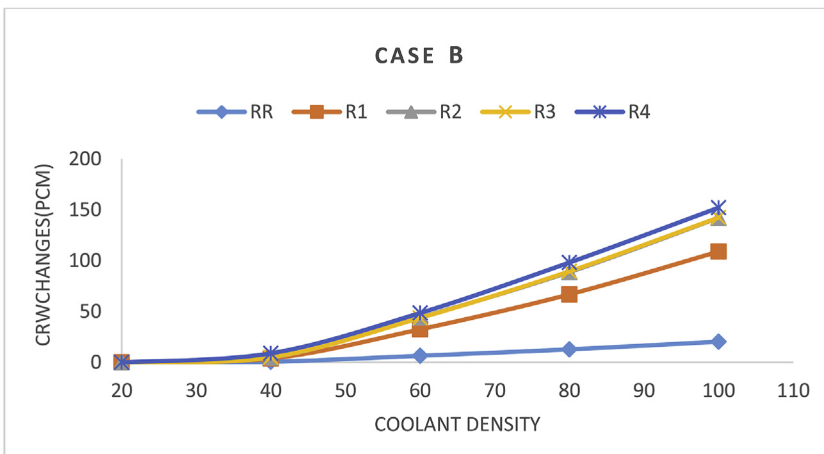


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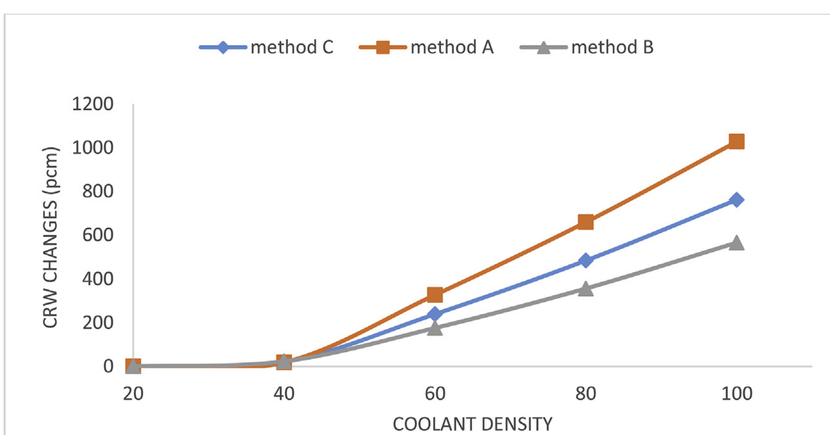
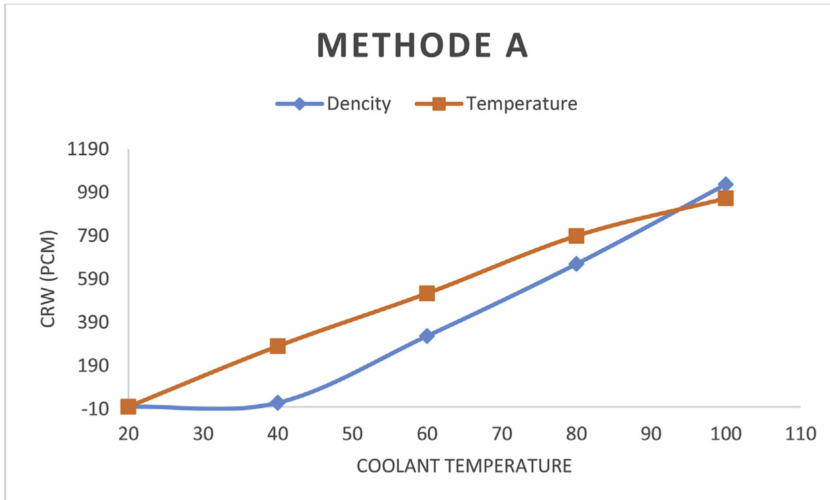


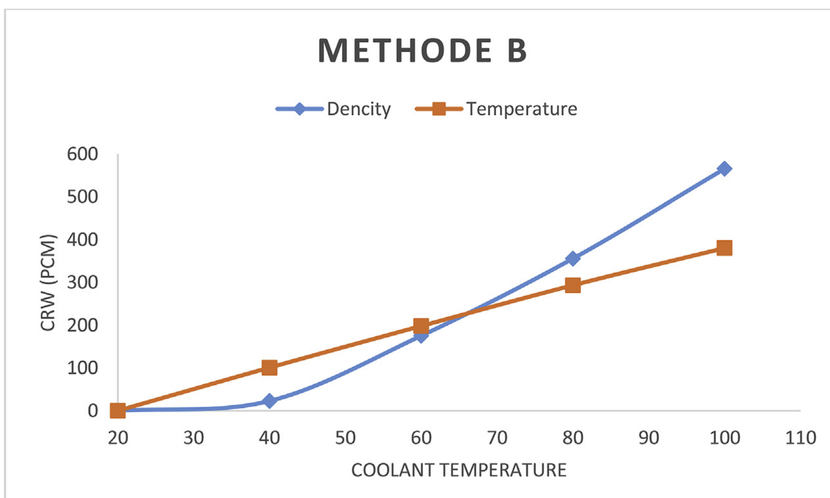

c)

**Fig. 8.** Changes in the CRW due to the changes in coolant density. (a) In methods A and (b) in method B. (c) Total CRW in three methods.

to one duller ($1) [12]. By the results, 80 °C increasing in the moderator temperature leads to 1952 pcm ($2.50) and 914 pcm ($1.2) increasing of CRW in cases A and B, respectively. Table 3 shows the CRW coefficients of TRR in term of temperature in two cases A and B. The results show that the maximum CRW coefficient (7 pcm/$^{o}$C) is related to SR4 in case A. In addition, the total CRW coefficient in cases A and B are 25 pcm/$^{o}$C and 12 pcm/$^{o}$C, respectively. These results show that measuring the reactivity in the




a)




b)

**Fig. 9.** Effect of the density and temperature on total CRW changes. (a) In case A and (b) in case B.

reactor core, which is calculated by measuring the displacement of the control rods, is affected by the reactor coolant temperature.

### 3.3. Void effects

Here, the effect of void on CRW is studied. If the coolant temperature in the nuclear reactors dominates the saturated temperature, the coolant is beginning to boil in the reactor core and makes bubbles. Increasing the number of bubbles due to the temperature changes, leads to reduction of the coolant density. According to the high steam or void production in the boiling process, the amount of production is measured as the percentage of void produced in the coolant. In both CITVAP and MCNP codes, the void effect is considered as homogeneous reduction in coolant.

Fig. 11 shows the CRW changes in term of the percentage of the void in the coolant for each TRR control rods. Also, the absolute worth values have been presented in Table 4.

As Fig. 11 and Table 4 show, the CRW is higher at the presence of the void. By the result, the worth of each control rods in term of the void fraction increases significantly, in two cases A and B. The results obtained by the Monte Carlo case are higher than those obtained by the deterministic case. The difference of the results in case B is lower than case A (9.5% and 14%, respectively). Also, the results show that in both approaches, the higher CRW is found in case A.

The most changes of the worth in MCNP and CITVAP codes are about \$3.2 and \$2 for 40% void fraction related to SR3 and SR2 in case A, respectively. The total CRW in term of the void fraction in the coolant in two cases A, B has been compared in Fig. (11-c) which shows minimum 4600 pcm and maximum 7900 pcm changes in the CITVAP (Case B) and MCNP (Case A). Void production in coolant leads to significant reduction of coolant density and slowness power. Therefore, the neutrons energy increases which leads to increasing of the CRW.

## 4. Conclusion

The dependency of CRW to the temperature and void fraction

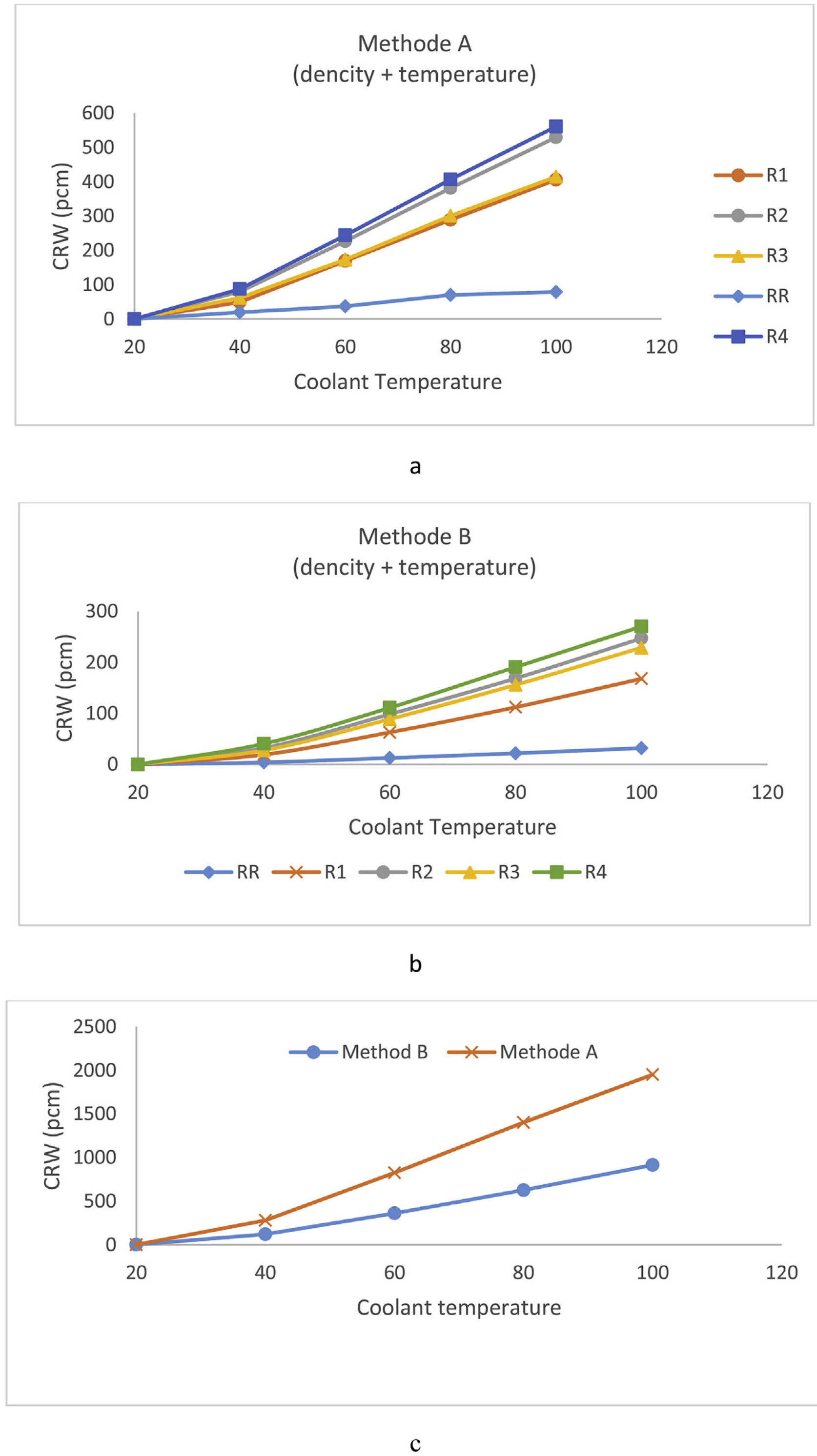
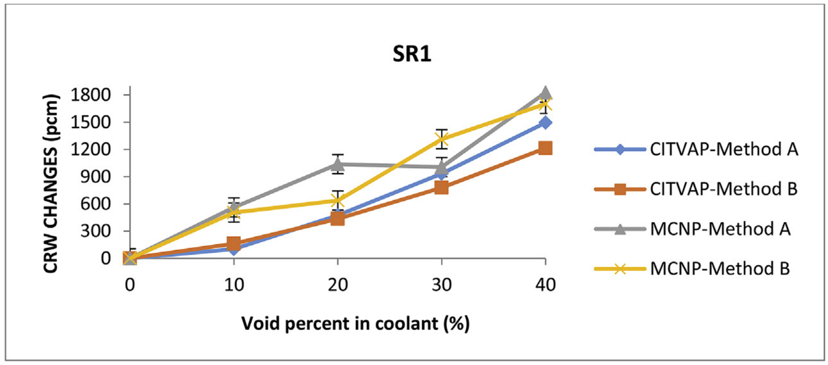



**Fig. 10.** Total temperature effect (effects of temperature and density) on CRW changes. (a) In case A and (b) in case B. (c) Total CRW in three cases.

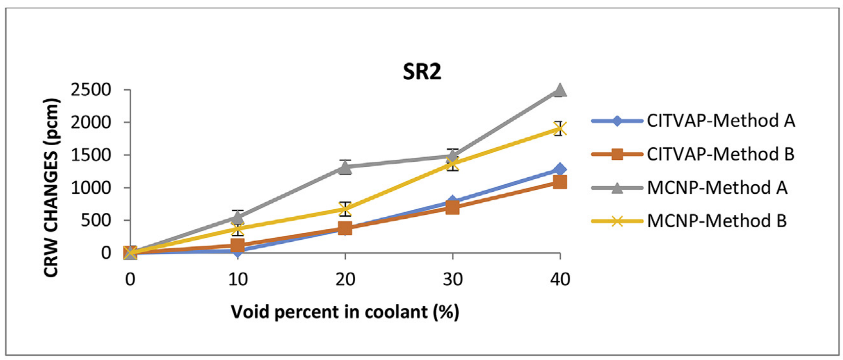
**Table 3**
CRW coefficients of Tehran reactor in term of temperature in two cases, A and B.

| SR's | A pcm/°C | B pcm/°C |
|---|---|---|
| RR | 0.4 | 1.0 |
| SR1 | 2.1 | 5.1 |
| SR2 | 3.1 | 6.6 |
| SR3 | 2.9 | 5.2 |
| SR4 | 3.4 | 7.0 |
| Total | 11.8 | 24.9 |

was examined quantitatively at the Tehran research reactor. Based on the results, increasing of the temperature and void fraction in Tehran reactor core leads to the increasing of CRW. The investigation was performed through three cases named A, B, and C, based on the positions of the control rods. Calculations in three cases lead to different results of the CRW due to the different flux distribution in the reactor core, whereas the variation of CRW with respect to the fuel and moderator is found similar.




a

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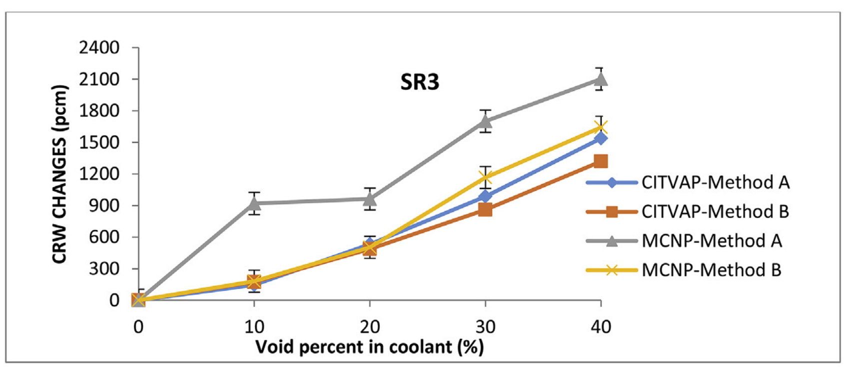


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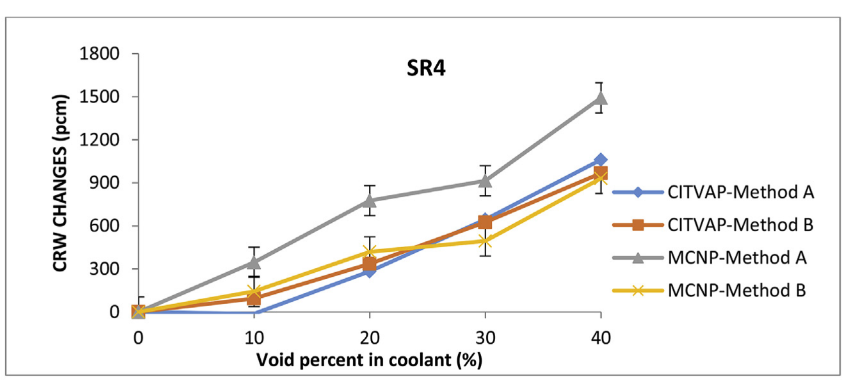


d

**Fig. 11.** CRW changes for the various void fraction by CITVAP and MCNP simulations in two cases, A and B.

**Table 4**
Absolute control rods worth for the various void fraction for equilibrium reference core of TRR.

| SR | Void (%) | CRW (method A) (pcm) | | CRW (method B) (pcm) | |
|---|---|---|---|---|---|
| | | CITVAP | MCNP | CITVAP | MCNP |
| R1 | 0 | 3836 | 5714 ± 106 | 1949 | 2804 ± 106 |
| | 10 | 3939 | 6275 ± 106 | 2111 | 3309 ± 106 |
| | 20 | 4311 | 6752 ± 106 | 2385 | 3442 ± 106 |
| | 30 | 4770 | 6719 ± 106 | 2728 | 4116 ± 106 |
| | 40 | 5332 | 7541 ± 106 | 3164 | 4507 ± 106 |
| R2 | 0 | 5088 | 3989 ± 106 | 2832 | 1782 ± 106 |
| | 10 | 5121 | 4537 ± 106 | 2948 | 2154 ± 106 |
| | 20 | 5458 | 5305 ± 106 | 3210 | 2456 ± 106 |
| | 30 | 5871 | 5473 ± 106 | 3527 | 3149 ± 106 |
| | 40 | 6366 | 6487 ± 106 | 3915 | 3686 ± 106 |
| R3 | 0 | 4018 | 4428 ± 106 | 2540 | 2992 ± 106 |
| | 10 | 4165 | 5346 ± 106 | 2715 | 3173 ± 106 |
| | 20 | 4550 | 5389 ± 106 | 3027 | 3495 ± 106 |
| | 30 | 5005 | 6128 ± 106 | 3401 | 4159 ± 106 |
| | 40 | 5557 | 6529 | 3861 | 4635 ± 106 |
| R4 | 0 | 5573 | 6471 ± 106 | 3160 | 4010 ± 106 |
| | 10 | 5561 | 6818 ± 106 | 3255 | 4153 ± 106 |
| | 20 | 5856 | 7247 ± 106 | 3496 | 4428 ± 106 |
| | 30 | 6218 | 7385 ± 106 | 3785 | 4504 ± 106 |
| | 40 | 6634 | 7963 ± 106 | 4127 | 4940 ± 106 |

By the results, the effect of the increasing of the fuel temperature in range 20–340 °C on the worth of each control rods and total worth of the rods is negligible. The results showed that at low coolant temperature, the temperature dependency of CRW is more than density dependency and the temperature dependency of CRW in case B is more than case A. Investigation of the CRW dependency on void fraction in coolant showed a significant increase of CRW in terms of the percentage of void production in the core. Investigation of the CRW dependency on the fuel burnup level and presence of Xe in the TRR reference core is suggested for future studies.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.net.2018.07.020.

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