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Control Rod Worth Uncertainty Propagation from Nuclear Data for NUR Research Reactor

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ABSTRACT

Control rod worth is one of the most critical parameters in operating and controlling any nuclear reactor. Accurate calculation is more and more required; any uncertainties should be identified and estimated. In this work, we focalize on the control rod worth uncertainties due to the nuclear data uncertainties. The sensitivity and uncertainty (S/U) analysis of the control rod worth has been performed for the NUR research reactor using the first-order perturbation theory as implemented in the SCALE package. The IV.N configuration -with fresh fuel elements and five control rods- has been simulated in a 3D model using the KENO V.a of the SCALE package. Only one control rod worth has been considered in the analysis to simplify the problem. Uncertainty propagation of nuclear data has been evaluated by calculating sensitivity coefficients of eigenvalue-difference worth coefficients after computing sensitivity coefficients for the k-eigenvalues at every two states of the NUR reactor configuration and combining them to obtain sensitivity coefficients for the difference. Each state has been defined by an incrementing of control rod insertion. The k-eigenvalue sensitivities have been calculated using the TSUNAMI-3D sequences in SCALE. The reactivity sensitivity coefficients have been combined with covariance data to determine the uncertainty in the reactivity response using the TSAR code of the SCALE package. The main contributors (nuclide and reaction) in the control rod worth uncertainties have been identified for each step of control rod insertion. The contribution amount of each element and reaction has been evaluated.

1. INTRODUCTION

A Series of works were performed worldwide to know the impact of the quality of nuclear data on the main integral parameters for nuclear reactor such as the effective multiplication factor (k_{eff}), the reactivity coefficients, and control rod worth.

The sensitivity and uncertainty analyses with respect to nuclear data have been performed with different method and tools; citing the XSUSA (Cross Section Uncertainty and Sensitivity Analysis) [1] tools, which is applied in many works [2, 3] to investigate the impact of nuclear data uncertainty on the main physical parameter and applied in Ref. [4] to analyze the influence of the nuclear data covariance on a rod ejection transient. Another innovative method was presented by Chen Hao and al [5] that combines the CITATION code [6] and TSUNAMI-IP [7] to evaluate the uncertainty in control rod worth.

In this work, we base on generalized perturbation theory [8] such as implemented in SCALE 6 (Standardized Computer Analyses for Licensing Evaluation) [7] to calculate control rod worth uncertainties due to uncertainties in nuclear data.

TSAR (Tool for Sensitivity Analysis of Reactivity Responses) [7] is a SCALE functional module that computes nuclear data sensitivity coefficients for eigenvalue-difference responses such as reactor reactivity and worth coefficients. The k-eigenvalue sensitivities are obtained by calculating the direct and adjoint fluxes such as implemented in TSUNAMI-3D [7, 9] sequences in

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SCALE 6.1 calculated. The reactivity sensitivity coefficients are combined with nuclear data covariance data to determine the uncertainty in the reactivity response. In this work, the IV.N configuration of the NUR research reactor was selected. It contains a fresh fuel core with five control rods. However, just one control rod worth has been analyzed. It was simulated in a 3D model by using the Monte Carlo code: KENO V.a [7] of SCALE code system. Sensitivity and uncertainty analyses were applied in each step of insertion of the control rod using TSUNAMI-3D. Sensitivity coefficients calculated in this step were used to calculate sensitivity coefficients for eigenvalue-difference responses. The main contributors to control rod worth uncertainties have been identified for every two states of control rod insertion.

2. METHODOLOGY AND MODELING

2.1 Code and method

The first-order perturbation theory for sensitivity and uncertainty (S/U) analysis of a response corresponding to the difference in critical eigenvalues for two distinct states of the system has been used. The lambda-eigenvalue form of the neutron transport equation for a multiplying medium is given by:

$$(\mathrm{L}-\lambda\,\mathrm{P})\Phi = 0 \qquad (1)$$

Where L and P are the loss and production operators, respectively. $\lambda=1/k$, λ is the fundamental lambda-eigenvalue and k is multiplication factor.

We consider two states: First, configuration in initial position of control rod with the eigenvalue of $\lambda1$ and the reactivity as: $\rho_1 = 1-\lambda_1$.

The second, new configuration in new position of control rod with the eigenvalue of $\lambda2$ and the reactivity as: $\rho_2 = 1-\lambda_2$.

The reactivity associated with the designated change in conditions is defined as [10, 11]:

$$\rho_{1\to 2} = \rho_2 - \rho_1 = \lambda_1 - \lambda_2 \qquad (2)$$

TSAR code of SCALE package edits the eigenvalues for the two reactor states and the value of the reactivity obtained from (2).

The relative change in the reactivity response due to an arbitrary relative variation (or uncertainty) in parameter α (nuclear data) is defined as:

$$\frac{\Delta\rho_{1\to 2}}{\rho_{1\to 2}} \sim S_{\rho,\alpha}\frac{\Delta\alpha}{\alpha} \qquad (3)$$

Where: $S_{\rho,\alpha} = \frac{\lambda_1 S_{k1,\alpha} - \lambda_2 S_{k2,\alpha}}{\rho_{1\to 2}}$ **(4)**

$S_{k1,\alpha}, S_{k2,\alpha}$: k1-sensitivities, k2-sensitivities for state1, 2 respectively.

TSUNAMI-3D control sequences in SCALE calculate k-sensitivities for each state and TSAR of SCALE combines them to obtain sensitivity coefficients for the difference.

TSAR also combines the reactivity sensitivity coefficients with nuclear data covariance information to determine the uncertainty in the reactivity response (standard deviation):

$$\sigma_\rho^2 = S_\rho^T C_{\alpha\alpha} S_\rho \qquad (5)$$

where $C_{\alpha\alpha}$ is the relative covariance matrix describing nuclear data uncertainties and correlations.

For two states as illustrated in Figure 1, TSAR provides the total uncertainty or partial uncertainties in reactivity coefficients due to individual nuclide-reaction uncertainty.

Relative variance in an eigenvalue-difference response is equivalent to:

$$\sigma_\rho^2 = \frac{{\lambda_1}^2}{(\lambda_1-\lambda_2)^2}\,\sigma_{k1}^2 + \frac{{\lambda_2}^2}{(\lambda_1-\lambda_2)^2}\sigma_{k2}^2 - 2\,c_{1\to 2}\frac{2\lambda_1\lambda_2}{(\lambda_1-\lambda_2)^2}\,\sigma_{k1}\,\sigma_{k2} \qquad (6)$$

σ_{k1} and σ_{k2} are relative standard deviations of the multiplication factors for the two states. The correlation coefficient between the two reactor states is designated as: $c_{1\to 2}\epsilon$ [-1,1].

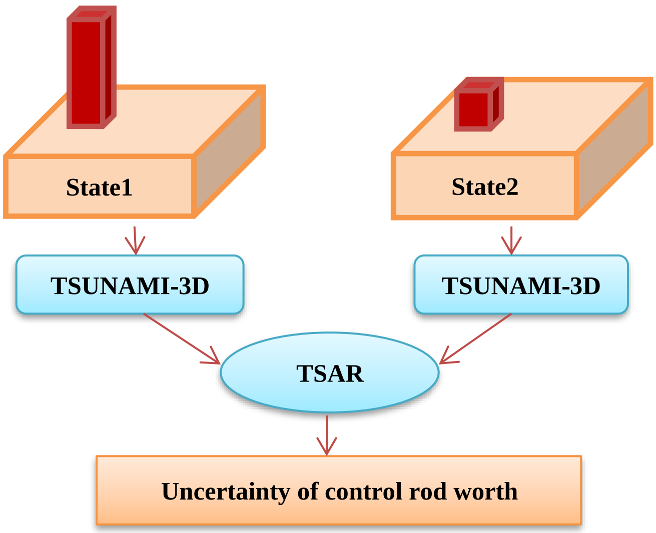

Fig. (1): Code flowchart calculation

2.2 Modeling control rod

NUR nuclear reactor is an MTR reactor enriched approximately to 19.7%. The reactor uses light water as a coolant and moderator. The reactivity control system of the reactor is made of five Ag-In-Cd absorbing rods: (C1, C2, C3, and C4) and one fine regulating rod (F). The IV-N configuration of the NUR reactor core (Figure 2) with fresh fuel has been modeled by KENO V.a (Monte Carlo criticality transport code) [2] of SCALE 6.1 package in 238 energy groups using ENDF/B-VII.0 cross-section data, Figure 2. Only one control rod (C1) has been inserted and analyzed in this work.

The reactivity worth obtained with KENO V.a were compared with the measurement for the same core configuration in previous work. This was used as an indicator to assess the accuracy of the control rod model. The standard fuel element contains 19 fuel plates. Each plate contains U_3O_8-Al as fuel and aluminum as cladding however the control fuel rod contains just 14 fuel plates with control elements consisting of flat forked blades composed of the Ag-In-Cd alloy.

The total effective length of one control rod is 61.5 cm and geometric specifications are illustrated in Figure 3 and the KENO model of the control rod is presented in Figure 4.

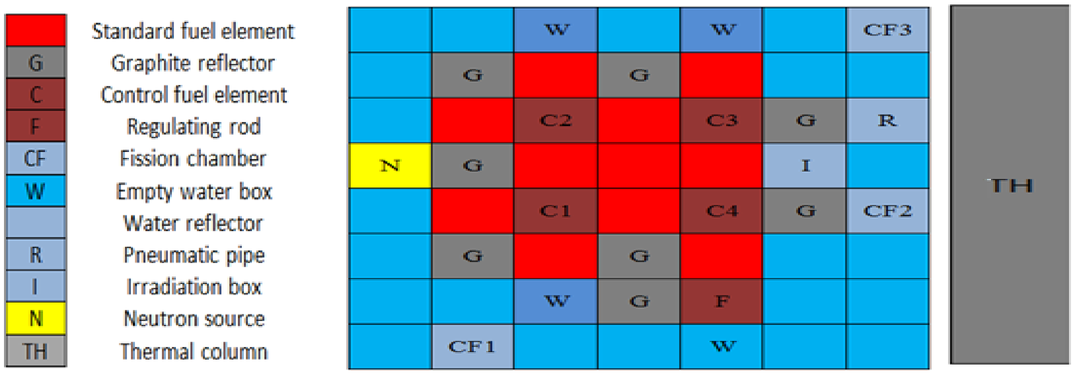

Fig. (2): Core configuration IV-N of the NUR

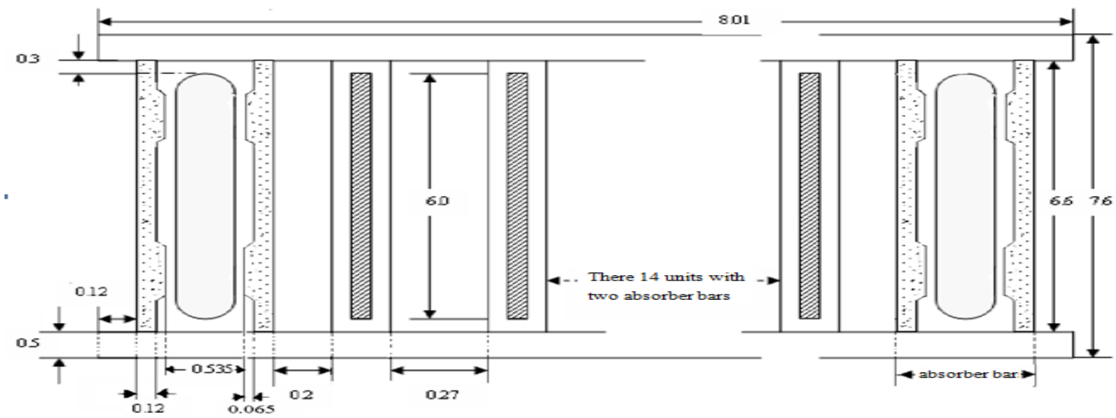

Fig. (3): Section of control rod (scale in cm)

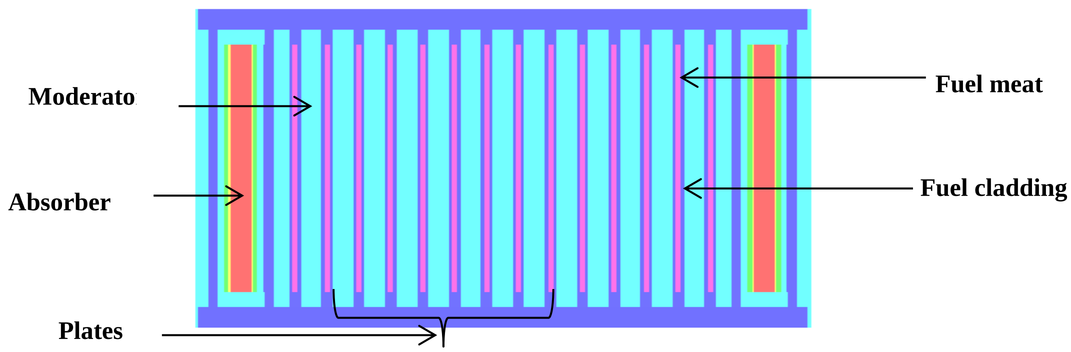

Fig. (4): Keno model of standard fuel element

Table I lists the main material composition used in the model; the uranium is 62 % by weight in a plate of fuel meat (U_3O_8, Al). The fuel cladding is made of 27Al including some impurities and light water without impurities is used as a coolant and moderator. The reflector is made of c-graphite and the absorber is made of Ag-In-Cd neutron absorbing material. The temperature for all materials is considered to be 293k.

Table (I): Main component material composition

Component	material
Fuel meat	U_3O_8-Al
Fuel uranium	62% of U_3O_8-Al
Fuel cladding	27Al with 0.67% silicon, 0.99% magnesium, 0.27% iron and 0.27% cooper
Coolant and moderator	H2O
Reflector	C-graphite
Uranium	19.81 wt% 235U 80.065 wt% 238U 0.125 wt% 234U
Control rod absorber	79.9 wt% Ag 14.26 wt% In 5.84 wt% Cd

We divide the hole modeling control rod into 12 sections as mentioned in Figure 5. Each section inserted we consider it, one state of the core configuration. The referential state is when the control rod is withdrawn.

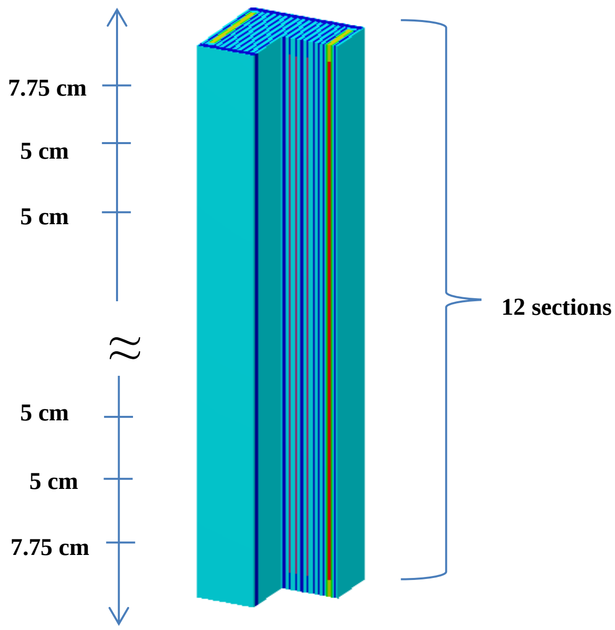

Fig. (5): Control rod sections modeling by SCALE6.1

Each insertion indicates a new configuration and for each configuration, an uncertainty and sensitivity analysis has been performed by TSUNAMI-3D. The sensitivities of a computed k_{eff} value to cross-section data were coupled with cross-section-covariance data to produce uncertainty in k_{eff} due to uncertainties in the evaluated nuclear data in 44 group covariance library, compatible with the 238-group library used in the calculation.

3. RESULTS AND DISCUSSIONS

3.1 Calculation of reactivity

Calculations of control rod reactivity have been performed for each state (portion inserted of control rod) by executing the KENO V.a sequence in TSUNAMI-3D. Reactivity differences (in pcm) between the two states are reported in Figure 6. Even though the control rod has been inserted by equi-distance section, reactivity differences between states corresponding to the middle of the control rod are larger comparing those in the extremities. Change in reactivity is quick in the center of the core. This is explaining by that in the center of the core (vertically) there more neutron population, and the absorber efficiency is more obvious.

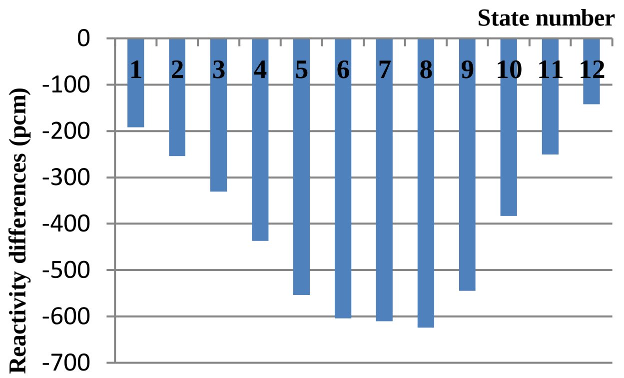

Fig. (6): Reactivity differences between control rod insertion states

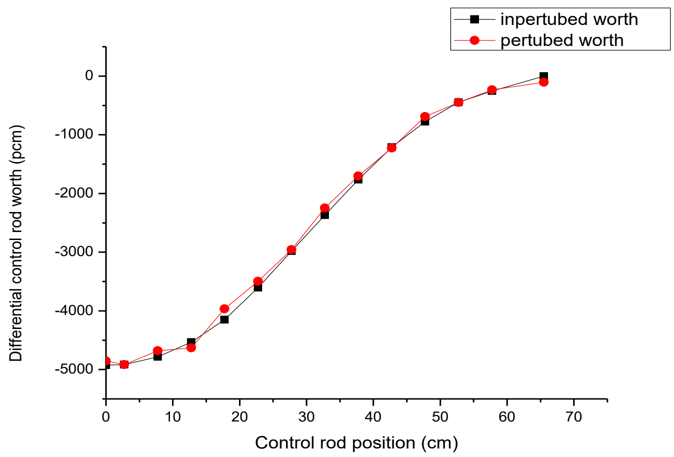

Fig. (7): Control rod worth calculation

Calculations of a control rod worth have been performed for the IV-N configuration by determining the reactivity of one control rod (C1) inserted separately and subtracting the reactivity worth. Calculated values for the worth of control rods for perturbed and in the perturbed state are reported in Figure 7. The most adequate calculation parameters in TSUNAMI 3D were chosen, to obtain the best sensitivity coefficients. Perturbed differential control rod worth curve is very close to the unperturbed curve, this is an indicator of a good result of perturbation theory and recommended in TSUNAMI 3D code (the k_{eff} values for both the forward and adjoint calculations should be equivalent [9]).

3.2 Sensitivities and uncertainties analysis

Nuclear data sensitivities and uncertainties for the effective multiplication factor have been obtained using TSUNAMI-3D analysis for each new insertion control rod configuration model.

Calculations were performed using the number of 10,000 generations for the forward calculation, and the 30,000 generations for the adjoint calculation. The TSUNAMI-3D results include sensitivity coefficients and the uncertainty in k_{eff} due to cross-section-covariance data saved in the SDF file for each state.

The reactivity sensitivity coefficients have been calculated for every two states. Each state was defined by an incrementing of control rod insertion. Those coefficients are calculated by

TSAR code using sensitivity coefficients obtained from the SDF file (*Structure Data File*) of TSUNAMI-3D analysis previously calculated for each state. The reactivity sensitivity coefficients are combined with covariance data to determine the uncertainty in the reactivity response.

The standard deviation in reactivity due to cross-section covariance data for every two states of control rod insertion has been calculated.

Results reported in Table II show that the maximum standard deviation due to the uncertainty of nuclear data is about 5.55 pcm, while the minimum is 1.61 pcm.

Table (II): Control rod worth uncertainty using TSAR

N°	Control rod position (cm)	Reactivity difference $\rho_{1\to2}$(pcm)	standard deviation σ(pcm)	Uncertainty (%) $\frac{\sigma * 100}{\rho_{1\to2}}$
1	0 -7.75	-191.75	3.20	-1.67
2	7.75 -12.75	-254.37	1.61	-0.63
3	12.75 -17.75	-330.45	1.80	-0.54
4	17.75 -22.75	-436.76	2.96	-0.68
5	22.75 -27.75	-553.49	3.16	-0.57
6	27.75-32.75	-603.91	4.41	-0.73
7	32.75-37.75	-610.54	3.28	-0.54
8	37.75-42.75	- 624.31	5.55	-0.89
9	42.75-47.75	-544.87	2.79	-0.51
10	47.75-52.75	-382.94	3.46	-0.90
11	52.75-57.75	-250.89	1.62	-0.65
12	57.75-65.5	-142.31	1.73	-1.22

Results in Table II and Figure 8 also show the uncertainty (per cent) of control rod worth due to the uncertainty of nuclear data. In absolute value, the maximum uncertainty of the control rod worth is about 1.67%, while the minimum is 0.51%. Uncertainty in the first section is more important, this section is between the state without absorber and the state with the first insertion, so two different states in materials.

The main contributors (nuclide and reaction) in control rod worth uncertainties have been identified for each step of control rod insertion. The contribution amount of each element and reaction has been evaluated. Table III and Figure 8 represent the main contributor, their contributions (in pcm), and their amount in (%) regarding the totality of contributors in each state.

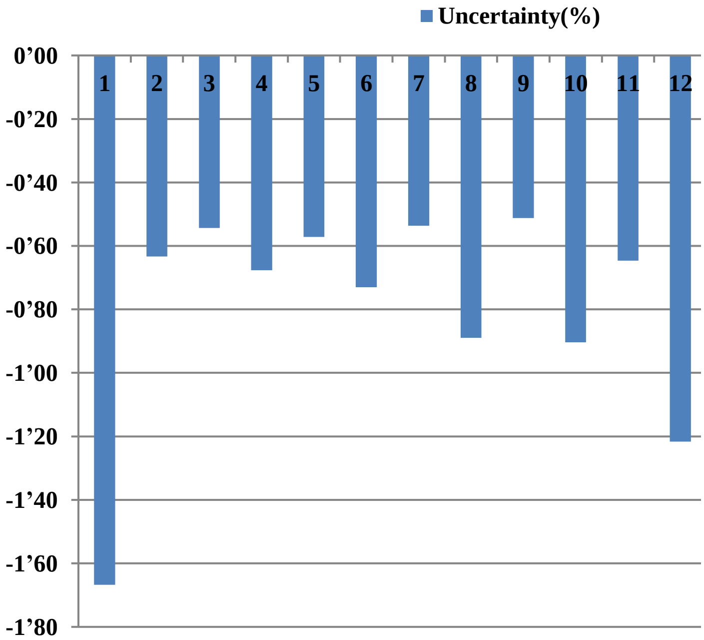

Fig. (8): Reactivity difference uncertainties (per cent) for each state

The main contributors to uncertainty are ^{235}U-chi, ^{235}U-nubar, and ^{235}U-fission one of them (^{235}U-chi for example) can cause alone more than 71% of the total cross-section uncertainty.

Table (III): Main contributors and their contribution

State number	main contributor	Contributions to Uncertainty in pcm (main contributor)	Contributions to Uncertainty in % of the main contributor
1	^{235}U-chi	2.10	66
2	^{235}U-chi	0.81	50
3	^{235}U-nubar	0.95	53
4	^{235}U-chi	1.89	64
5	^{235}U-nubar	1.60	51
6	^{235}U-chi	2.85	65
7	^{235}U-nubar	1.76	54
8	^{235}U-chi	3.92	71
9	^{235}U-fission	1.62	58
10	^{235}U-chi	2.18	63
11	^{235}U-nubar	0.71	44
12	^{235}U-chi	1.01	58

^{235}U is the nuclide that is the main source of neutron population, any uncertainty in this element and practically with a fission reaction, nubar (average number of neutrons emitted per fission) and chi (prompt fission emission spectrum), cause uncertainty in the progression of neutron population and thus reactivity worth.

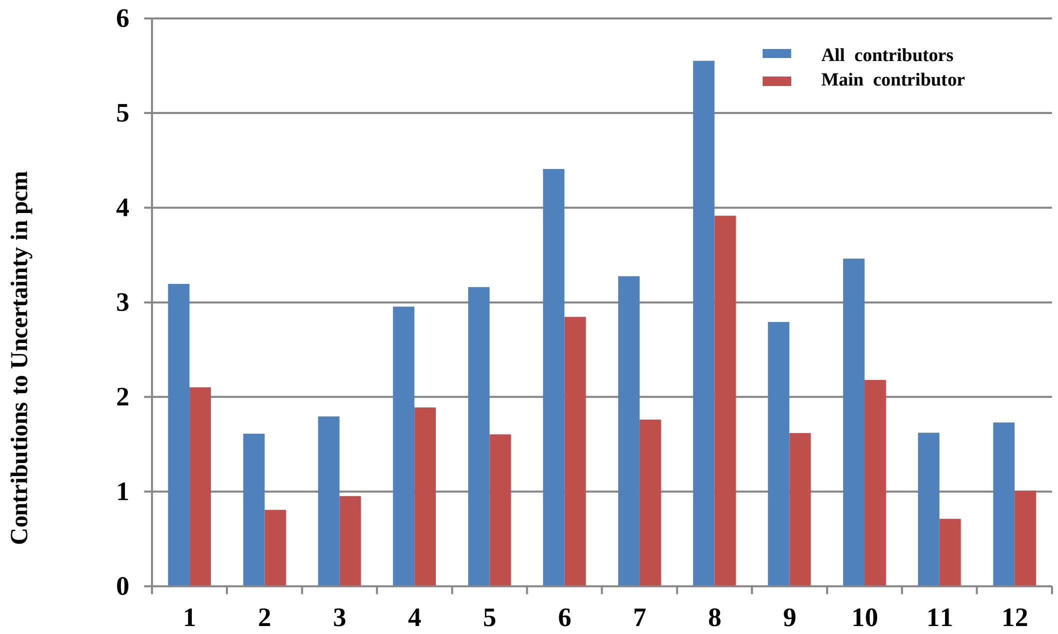

Fig. (9) : Uncertainty for all and main contributors

4. CONCLUSION

Sensitivity and uncertainty analysis of control rod worth has been performed for VI.N configuration with fresh fuel of NUR research reactor using perturbation method such as implemented in TSUNAMI-3D and TSAR of SCALE system. Uncertainty propagated from nuclear data to control rod worth is a complicated issue; regarding interference between many factors and this work gives us a global assessment of these uncertainties. Results show that the maximum uncertainty of control rod worth due to uncertainty of nuclear data is about 1.67%, while the minimum is 0.51%. The main contributors to uncertainty are ^{235}U-chi, ^{235}U-nubar, and ^{235}U-fission one of them (e.g. ^{235}U-chi) can cause alone more than 71% of the total cross-section uncertainty. The eigenvalue calculations of the two states are correlated because they both use the same nuclear data libraries. In this case, the relatively small control rod worth uncertainties obtained is justified by the fact that there is a positive correlation that reduces the uncertainty in the reactivity because common uncertainties tend to cancel from the eigenvalue difference.

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