lNuclear Data Sensitivity and Uncertainty Analysis for the Canadian Supercritical Water- cooled Reactor (SCWR) 64 – element Fresh Fuel Lattice Cell

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Abstract

One of the fundamental requirement for any nuclear reactor model isan accurate and complete nuclear data. The Canadian supercritical water-cooled reactor (SCWR) is an advanced GEN-IV reactor concept for whichoperating conditions and materials differ significantly from conventional reactors in addition to its design complexity illustrated with thehigh-efficiency re-entrant channel. Consequently, current nuclear data evaluations may not be suitable for modelling the Canadian SCWR. In this work, a simplified sensitivity and uncertainty analysis of the SCWR-64 elements lattice cell with fresh fuel was investigated at the inlet and the outlet of the channel using TSUNAMI-2D Code which is a part of the SCALE 6.1.3.

1. Introduction

Advanced Generation-IV (GEN-IV) reactor concepts are being developed through an international collaboration, the GEN-IV International Forum (GIF), in order to provide future nuclear energy systems with enhanced safety, improved resource sustainability, improved economic benefit and enhanced proliferation resistance. Canada's primary contribution to the GIF is the Canadian SCWR concept, which is a heavy water moderated, pressure tube reactor that uses supercritical light water (SCW) as a coolant. Regardless of the modelling approach, the accuracy of a nuclear reactor physics model is ultimately limited by the accuracy of the nuclear data used in it. The development of accurate models of any advanced reactor systems therefore requires an assessment of the sensitivity of calculations to the nuclear data as well as the quality of the data itself.

The goal of this study to perform a 2D sensitivity and uncertainty analysis of the nuclear data library for the SCWR-64 elements lattice cell with fresh fuel at the inlet and the outlet of the channel in order to determine which isotopes and which reactions make the largest contributions to the sensitivity and uncertainties in the key reactor physics parameters. Moreover to investigate the effects of position and temperature on such calculations.

The TSUNAMI-2D (Tools for Sensitivity and Uncertainty Analysis Methodology Implementation) codes in SCALE (Standardized Computer Analyses for Licensing Evaluation) 6.1.3 are used to study the effects of nuclear data on calculations for SCWR fresh fuel lattice cell at the inlet and the outlet channel. These results are used to determine the isotopes and reactions that make the largest contributions to the nuclear data sensitivities and uncertainties.

2. Modelling Methods

For this study, a single fuel lattice cell loaded with fresh fuel is modelled. Examination of a fresh fuel assembly facilitates the isolation of major contribution to uncertainties in neutron multiplication factor k and reactivity coefficients without the complication of fission and activation products. A cross-sectional view of the fuel channel and surrounding high-efficiency re-entrant channel (HERC) is shown schematically in Fig.1, with geometric specifications and material compositionsreferred to [1]. The fuel assembly contains 64 fuel elements with a central flow tube which enable the re-entrance of the coolant through the channel. Estimated values of temperatures for the components at bottom and the top of the vertical channel are listed in Table 1.

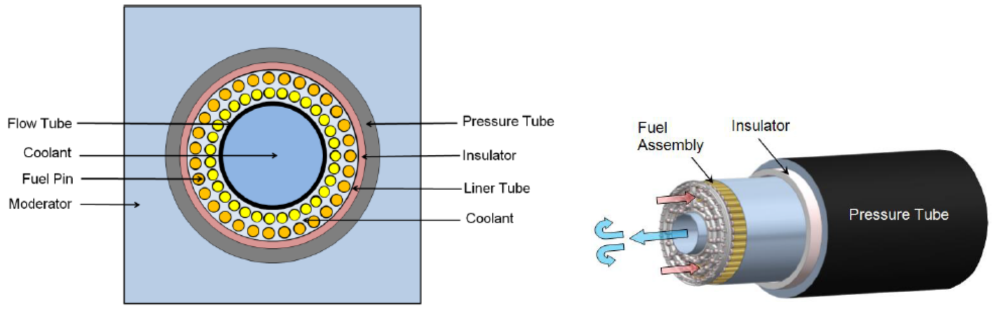

Fig.1 (Left) Cross-sectional view of the 64-element Canadian SCWR fuel bundle design, channel, and lattice cell. (Right) Cut-away view of the 64-element Canadian SCWR fuel bundle design High Efficiency Re-entrant Channel (HERC), and illustration of coolant flow [1]

The analysis presented in this work was performed using the code TSUNAMI-2D which can be used to perform sensitivity and uncertainty analysis of 2-D geometries. TSUNAMI-2D is a code sequence in SCALE that executes TRITON (Transport Rigor Implemented with Time-Dependent Operation for Neutronic Depletion) to generate the forward and the adjoint neutron transport solutions followed by SAMS (Sensitivity Analysis Module for SCALE) to produce sensitivity coefficients and the uncertainty in k_{eff}. Sensitivity and uncertainty analysis were performed for the various scenarios listed in Table 2.

Table 1: Downward and upward coolant density, ρ_{dc} and ρ_{uc}, and component temperatures, T_{dc}, T_{uc}, T_F, T_{Cl}, T_L, T_{Ins}, T_{PT}, and T_M for the downward coolant, upward coolant, fuel, cladding, liner, insulator, pressure tube and moderator, respectively versus distance from the bottom of the vertical channel z.

z (mm)	ρ_{uc}	T_{uc}	T_{Cl}	T_L	T_{Ins}	T_{PT}	T_{dc}	ρ_{dc}	T_F
250	0.51702	647.40	683.04	640.78	537.68	410.38	636.45	0.57896	1117.36
4750	0.07014	890.62	1006.99	859.82	673.29	452.28	625.81	0.61903	1539.91

Case name	Description
Reference	Nominal temperatures and densities of different lattice cell components
Inner Coolant Voided (ICV)	Coolant density in the central flow tube (Inner tube) decreases to 0.001g/cm^3
Outer Coolant Voided (OCV)	Coolant density in the outer flow tube decreases to 0.001g/cm^3
Total Coolant Voided (TCV)	Coolant density in both tubes (Inner and outer) decreases to 0.001g/cm^3

Table 2: Channel condition scenarios modelled in TSUNAMI-2D

3. Results and discussion

The neutron multiplication factor k obtained for the reference case at the bottom and at the top of the channel were 1.289201 and 1.287231 respectively. The sensitivities calculated from TSUNAMI-2D for the reference case at the bottom and the top of the vertical channel was investigated. Only the nuclides with the 10 highest sensitivity contributions are included in the tables. These contributions are integrated over all energies but are broken down into contributions from various cross-section components. The sensitivity of k to nuclear data was combined with a nuclear data covariance and the uncertainty in k due to uncertainties in nuclear data library was found to be ±6.96 mk at the bottom of the channel and ±6.89 mk at the top of the channel. The sensitivities calculated at the top and the bottom of the channel for the ICV (Inner Coolant Voided), OCV (Outer Coolant Voided) and TCV (Total Coolant Voided) are shown in Tables 3-10.

Table 3: The ten top nuclides for which the k calculation is sensitive, along with their components at 25 mm from the bottom the channel for the reference case

Nuclide	nubar	fission	n,gamma	capture	elastic	scatter	Total
239Pu	0.71068	0.30942	-0.20704	-0.20704	-0.00024422	-0.00027119	0.10211
240Pu	0.0053792	0.0031613	-0.082285	-0.082285	0.0010032	0.00098999	-0.078133
241Pu	0.27523	0.12592	-0.049665	-0.049665	-0.00010494	-0.00009864	0.076155
232Th	0.0053486	0.002478	-0.082713	-0.082713	0.0061969	0.0059199	-0.074315
2H			-0.00061228	-0.00061228	0.061479	0.063305	0.062693
56Fe			-0.023088	-0.023137	-0.0018303	-0.0019701	-0.025107
58Ni			-0.01164	-0.012607	-0.0011165	-0.0011497	-0.013757
91Zr			-0.014504	-0.014507	0.0011737	0.0011508	-0.013356
1H			-0.035327	-0.035327	0.026358	0.026357	-0.0089698
53Cr			-0.0085343	-0.0085364	-0.00007556	-0.00008434	-0.0086208

Table 4: The ten top nuclides for which the k calculation is sensitive, along with their components and 4750 mm from the bottom the channel for the reference case

Nuclide	nubar	fission	n,gamma	capture	elastic	scatter	Total
239Pu	0.70537	0.30764	-0.20312	-0.20312	-0.00033671	-0.00036746	0.10415
2H			-0.0005992	-0.0005992	0.082943	0.084904	0.084305
232Th	0.0057684	0.0026717	-0.089652	-0.089652	0.00729	0.0069587	-0.080022
241Pu	0.2792	0.12713	-0.050177	-0.050177	-0.00013172	-0.00012565	0.076827
240Pu	0.0059492	0.0034961	-0.079031	-0.079031	0.00091639	0.00090164	-0.074633
56Fe			-0.021738	-0.021791	-0.0021792	-0.0023349	-0.024126
58Ni			-0.010942	-0.01199	-0.0013193	-0.0013557	-0.013346
91Zr			-0.014129	-0.014132	0.0017718	0.0017457	-0.012386
1H			-0.034911	-0.034911	0.025939	0.025938	-0.0089731
53Cr			-0.0079998	-0.008002	-0.00010231	-0.00011204	-0.0081141

Table 5: The ten top nuclides for which the k calculation is sensitive, along with their components at 25 mm from the bottom the channel for the ICV

Nuclide	nubar	fission	n,gamma	capture	elastic	scatter	Total
239Pu	0.69935	0.31104	-0.19936	-0.19936	-0.00030515	-0.00035462	0.11133
2H			-0.00081132	-0.00081132	0.098362	0.10044	0.099624

232Th	0.0061408	0.0029128	-0.10069	-0.10069	0.0095553	0.0087708	-0.089008
241Pu	0.28401	0.13356	-0.049301	-0.049301	-0.00013093	-0.00013151	0.084127
240Pu	0.0064207	0.0038337	-0.085898	-0.085898	0.0013168	0.0012944	-0.08077
56Fe			-0.021193	-0.021248	-0.0010036	-0.0012413	-0.02249
91Zr			-0.019234	-0.019237	0.0016895	0.0016389	-0.017598
58Ni			-0.01065	-0.011747	-0.00063258	-0.00068782	-0.012435
1H			-0.0077939	-0.0077939	0.017378	0.017378	0.009584
242Pu	0.0015231	0.00091363	-0.0091638	-0.0091638	0.00012943	0.00011894	-0.0081313

Table 6: The ten top nuclides for which the k calculation is sensitive, along with their components and 4750 mm from the bottom the channel for the ICV

Nuclide	nubar	fission	n,gamma	capture	elastic	scatter	Total
2H			-0.00084618	-0.00084618	0.14897	0.15122	0.15038
239Pu	0.68911	0.3081	-0.19126	-0.19126	-0.00048235	-0.00053633	0.1163
232Th	0.0067867	0.003241	-0.11615	-0.11615	0.01201	0.011224	-0.10169
241Pu	0.2919	0.13622	-0.050184	-0.050184	-0.00018692	-0.00018761	0.085849
240Pu	0.007444	0.0044624	-0.079098	-0.079098	0.0012446	0.0012211	-0.073414
56Fe			-0.020395	-0.020455	-0.0020917	-0.0023395	-0.022794
91Zr			-0.020132	-0.020135	0.0029906	0.0029371	-0.017198
58Ni			-0.010215	-0.011426	-0.0012664	-0.0013231	-0.012749
238Pu	0.0030097	0.0017364	-0.00939	-0.00939	-5.5836E-05	-0.00005774	-0.0077114
242Pu	0.0017479	0.0010527	-0.0086646	-0.0086646	0.00008582	0.00007477	-0.0075372

Table 7: The ten top nuclides for which the k calculation is sensitive, along with their components

Nuclide	nubar	fission	n,gamma	capture	elastic	scatter	Total
239Pu	0.70102	0.30415	-0.19943	-0.19943	-0.00028645	-0.00031532	0.10441
241Pu	0.28352	0.12795	-0.050633	-0.050633	-0.00012479	-0.00011769	0.077196
2H			-0.00060682	-0.00060682	0.075122	0.077156	0.076549
232Th	0.0057558	0.0025834	-0.082953	-0.082953	0.0053224	0.0050463	-0.075323
240Pu	0.0059457	0.0034253	-0.078976	-0.078976	0.00090512	0.00089097	-0.074659
56Fe			-0.021657	-0.021712	-0.0021405	-0.0022943	-0.024006
58Ni			-0.010945	-0.012025	-0.0013298	-0.0013656	-0.013391
91Zr			-0.014389	-0.014392	0.0017182	0.0016942	-0.012698
238Pu	0.0023314	0.0012698	-0.0093904	-0.0093904	-0.00002785	-0.00002872	-0.0081493
53Cr			-0.0080026	-0.0080049	-0.00009601	-0.00010544	-0.0081104

at 25 mm from the bottom the channel for the OCV

Table 8: The ten top nuclides for which the k calculation is sensitive, along with their components at 4750 mm from the bottom the channel for the OCV

Nuclide	nubar	fission	n,gamma	capture	elastic	scatter	Total
239Pu	0.70228	0.30514	-0.20076	-0.20076	-0.00030195	-0.00033112	0.10405
2H			-0.00059771	-0.00059771	0.078055	0.080072	0.079474
241Pu	0.28227	0.12762	-0.050544	-0.050544	-0.00012331	-0.00011637	0.076958
232Th	0.0057698	0.0026179	-0.084223	-0.084223	0.0055188	0.005236	-0.07637
240Pu	0.0059537	0.0034527	-0.078322	-0.078322	0.00084059	0.00082637	-0.074043
56Fe			-0.021619	-0.021673	-0.0022801	-0.0024331	-0.024107
58Ni			-0.010919	-0.011991	-0.0014063	-0.001442	-0.013433
91Zr			-0.014159	-0.014162	0.001774	0.0017499	-0.012412
1H			-0.034665	-0.034665	0.023214	0.023213	-0.011452
53Cr			-0.0079828	-0.0079851	-0.00010284	-0.00011223	-0.0080973

4. Conclusion

Sensitivities of the different fuel isotopes are the dominants in the reference case and the void cases as expected. And it increases generally in the voided cases compared to the reference case which reflects the effects of the fuel isotopes on calculation in the voided cases. The sensitivities of Pu-238 and Pu-242 starts to appear in the top ten nuclides with high sensitivity which reflects the importance of the fast fission events took place in the voided cases especially at the channel outlet with high fuel temperature. The sensitivities of H-1 and H-2 also appear in the top ten nuclides due to the role of the moderator and the coolant in neutron thermalization processthrough scattering. The sensitivity of H-2 increases in the voided cases as it becomes the only moderating material which is responsible on the neutron slowing down phenomena. Moreover, the sensitivity of H-2 at the channel outlet at the ICV case becomes comparable to the H-2 sensitivity at the channel inlet at the TCV case because the coolant density decreases tremendously at inner channel at the channel outlet to behave close to the voiding case. The Zirconium is the main material of the insulator, outer liner and the pressure tube which reflects its high sensitivity. The same for the Fe-56, Ni-058 and Cr-53 which are the main components of the central flow tube.

Table 9: The ten top nuclides for which the k calculation is sensitive, along with their components at 25 mm from the bottom the channel for the TCV

Nuclide	nubar	fission	n,gamma	capture	elastic	scatter	Total
2H			-0.00084718	-0.00084718	0.14486	0.14715	0.14631
239Pu	0.68514	0.3045	-0.18746	-0.18746	-0.0004773	-0.00052824	0.11651
232Th	0.0067772	0.0031707	-0.11366	-0.11366	0.010923	0.01022	-0.10027
241Pu	0.29575	0.13616	-0.050908	-0.050908	-0.00020174	-0.00020102	0.08505
240Pu	0.0074974	0.0044356	-0.077997	-0.077997	0.0013022	0.0012799	-0.072281
56Fe			-0.020554	-0.020615	-0.0024218	-0.0026605	-0.023276
91Zr			-0.020278	-0.020281	0.0030637	0.0030143	-0.017267
58Ni			-0.01033	-0.011563	-0.0015104	-0.0015647	-0.013127
238Pu	0.0030819	0.0017524	-0.0098158	-0.0098158	-0.00005457	-0.00005632	-0.0081196
53Cr			-0.007497	-0.0074996	-0.00011752	-0.00013316	-0.0076328

Table 10: The ten top nuclides for which the k calculation is sensitive, along with their components at 4750 mm from the bottom the channel for the TCV

Nuclide	nubar	fission	n,gamma	capture	elastic	scatter	Total
2H			-0.00084801	-0.00084801	0.15089	0.15318	0.15233
232Th	0.006832	0.0032252	-0.123	-0.123	-0.0011483	-0.0018693	-0.12164
239Pu	0.68581	0.30711	-0.18821	-0.18821	0.00006935	0.00001756	0.11892
241Pu	0.29495	0.13669	-0.050722	-0.050722	-0.00002256	-0.00002208	0.085941
240Pu	0.0075584	0.0044949	-0.078747	-0.078747	0.00046056	0.00043797	-0.073814
56Fe			-0.020409	-0.02047	-0.0026366	-0.0028782	-0.023348
91Zr			-0.020382	-0.020386	0.002127	0.0020764	-0.018309
58Ni			-0.010242	-0.011475	-0.0014837	-0.0015387	-0.013014
238Pu	0.0030807	0.0017686	-0.0096606	-0.0096606	-0.00001301	-0.0000148	-0.0079068
242Pu	0.0017721	0.0010595	-0.0088237	-0.0088237	-0.00005299	-0.00006366	-0.0078279

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