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Sensitivity Studies of the TRIGA Benchmark Critical Experiment

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Abstract: On the basis of critical benchmark experiments performed on the TRIGA Mark II reactor in Ljubljana, a benchmark model was proposed. To estimate effects of various uncertainties in the effective multiplication factor, extensive sensitivity studies were performed. Sensitivity studies included geometry sensitivity studies, where the effects of geometry simplifications and geometrical inaccuracies were investigated and material sensitivity studies, where effects of fuel composition of fresh and burned fuel as well as other materials were investigated. The MCNP Monte Carlo code and WIMSD2 and ORIGEN4 codes were used in these studies. Results showed that one of the largest uncertainties of the effective multiplication factor arises from inaccurately known fresh fuel composition. For burned fuel, WIMS and ORIGEN2 gave similar results, which indicates that the calculated burned fuel composition may be used reliably. Another important uncertainty in the effective multiplication factor arises from fabrication tolerances and material composition of stainless steel cladding of fuel elements.

1. Introduction

One of the key features of any benchmark evaluation is an accurate model of the benchmark geometry, including composition of the materials used. Ideally, such geometry would be exactly known. However, because of various uncertainties, connected with the geometry itself and material composition and densities, extensive sensitivity analyses have to be performed. The sensitivity analyses should enable reasonable estimation of how much the uncertainties reflect in the final result.

On the basis of critical benchmark experiments performed on the TRIGA Mark II reactor in Ljubljana in 1991 [1], a benchmark model was proposed [2]. To estimate effects of various uncertainties in the effective multiplication factor, extensive sensitivity studies were performed. Sensitivity studies were divided into two parts. In the first part, suitability of different benchmark geometries for a benchmark model was studied. In the second part, fuel composition uncertainties and uncertainties in other material composition data were examined. In 1998, a similar benchmark experiment was performed, this time with burned fuel [3]. For this reason, a detailed analysis of burned fuel composition, using two different computer codes, WIMS and ORIGEN2, was made in addition. The effect of cooling was also investigated because it may significantly affect material composition of burned fuel.

2. Geometry sensitivity studies

Geometry sensitivity studies were performed to estimate which parts of the TRIGA reactor geometry need to be described, and which can be omitted without a substantial loss of accuracy of the model in terms of effective multiplication factor (k_{eff}) results. The geometry simplifications were done in two steps. In the first step the geometry was simplified in radial

direction. The following structures were omitted or simplified: surroundings, irradiation channels, graphite of the thermalizing and thermal column and end caps of fuel elements and control/transient rods. In the second step, in addition to the radial simplification, the geometry was simplified in axial direction as well. Control rods were replaced with fuel elements (only the fueled follower part without the absorber part was assumed) and the transient rod was replaced with an empty element. In this way, the model geometry had a mirror symmetry and was thus similar to a 2D model.

The influence of all simplifications was investigated using a series of MCNP models with different simplification levels compared to the complete TRIGA reactor model. In the complete model, description of the vicinity of the core was very detailed and no simplifications were assumed. It was hard to estimate the contribution of a particular simplification (below statistical errors of Monte Carlo simulations). For that reason, more simplifications were done and a combined effect was estimated. The total change in k_{eff} because of the geometry simplifications in radial direction was an increase in k_{eff} of $+150 \pm 30$ pcm (0.15%). It is likely that this error is mainly due to omitted void regions in the close vicinity of the core (irradiation channels). This error was considered to be acceptable for a benchmark model. The complete and radially simplified benchmark models are shown in Figures 1 and 2. On the contrary, the simplifications in the axial direction were found to be too severe for a benchmark model, because they introduced $+470 \pm 60$ pcm (0.47%) systematical error.

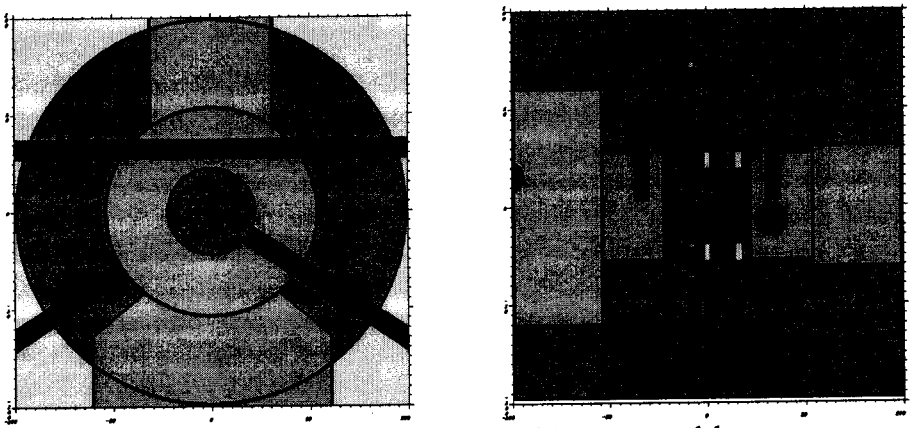

Figure 1: Top (left) and side (right) views of the complete TRIGA reactor model.

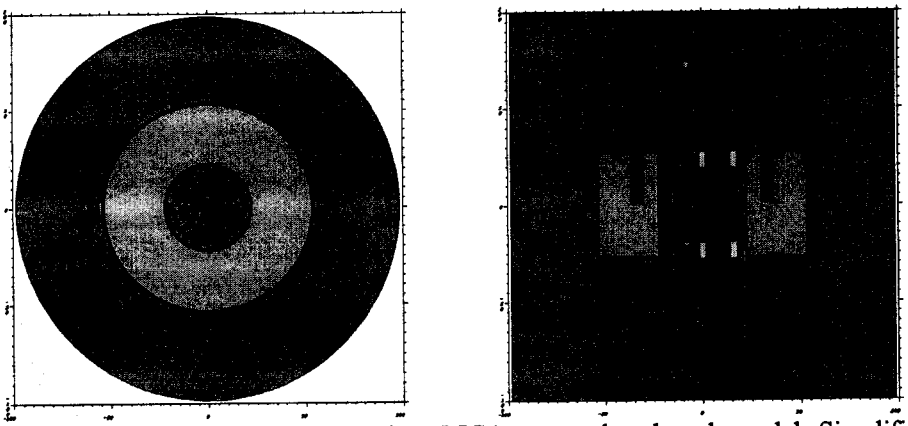

Figure 2: Top (left) and side (right) views of the TRIGA reactor benchmark model. Simplifications of the geometry in the radial direction have only minor effect on the effective multiplication factor, and are acceptable for the benchmark model.

Effect of the source was determined experimentally and confirmed by simulations by calculating two core configurations, one without the source element and one with the source element inserted. The effect was estimated to be $+40 \pm 10$ pcm (0.04%). Because the geometry and materials of the source are not well known, it was decided that the benchmark models do not include the source.

In addition, effects of inaccurate positioning of fuel elements in the rings and control rods in vertical direction were investigated. The analyses showed aproximately $\pm 150 \pm 35$ pcm (0.15%) uncertainty per 1% fuel element displacement. The effect of inaccurate vertical positioning of the control rods was found to be insignificant for the expected maximal 2 cm displacement.

3. Material composition sensitivity studies

Sensitivity studies of the material composition were divided into three parts. In the first part, sensitivity analyses of the fresh fuel composition were performed. Second step included a detailed sensitivity study of the burned fuel material composition as well as the effect of different reactor operation schemes on burnup. Finally, other materials than fuel were considered. Here, the effects of different material compositions, densities and production tolerances on effective multiplication factor were estimated.

3.1 Fresh fuel

The first uncertainty in the fuel description was the total weight of ^{235}U in the core, which was calculated according to the shipment documents. According to these data, the uncertainty of ^{235}U weight in the core should be less than ± 2 g or 10^{-3} relative to the total weight. Uncertainty analysis showed that this yields approximately ± 60 pcm uncertainty in k_{eff}.

An important source of uncertainty is also concentration of uranium in U-ZrH mixture. According to the documentation, the uranium content in the fuel meat was 11.94 wt %. The one percent uncertainty in this data gave approximately ± 150 pcm uncertainty in k_{eff}, which was also considered to be a reasonable estimate of the uncertainty.

Another important source of uncertainty is uncertainty in H/Zr atom ratio. According to the fuel manufacturing documentation, the H/Zr atom ratio was 1.60. However, 1% uncertainty in this data gave approximately ± 200 pcm uncertainty in k_{eff}. The references on fuel fabrication process showed that variations in hydrogen content may be on the order of $\pm$ 2%. For 40 fuel elements used in the experiment this gave for the uncertainty of the mean less than a percent. Thus, the uncertainty in H/Zr ratio was considered to be approximately ± 200 pcm.

Considering all quoted uncertainties in fuel composition data, the fuel material composition inaccuracy was estimated to be approximately $\pm$ 250 pcm (0.25% of k_{eff}).

3.2 Burned fuel

For interpreting the critical benchmark experiment with burned fuel, good knowledge of burned fuel element composition is essential. Since experimental methods are usually too complicated for determination of burnup, calculations are a more common and practical method. Burnup of all fuel elements used in the 1998 experiment were calculated using the in-house developed computer code named TRIGLAV [4]. The isotopic compositions of burned fuel elements used in TRIGLAV were calculated with the WIMSD code [5] for each fuel element at its particular burn-up. However, the isotopic vector was limited to the nuclides defined in the 1981 WIMS library.

To estimate the accuracy of the isotope composition calculations, two different codes were compared. The first one was the WIMSD4 program and the second one was ORIGEN2 with its original data base [6]. Calculations of standard TRIGA fuel element isotopic composition as a function of burnup were performed for 3.34%, 10% and 20% burned ^{235}U. Isotopic composition of 20% burned fuel after one year cooling time was also investigated. Fresh fuel was irradiated at constant power of 5 kW until the requested burnup was achieved. Geometry in the radial direction and material composition of fresh fuel was realistic in the WIMSD calculations, while the geometry in the axial direction was assumed to be invariant. On the other hand, in ORIGEN the structural materials were not taken into account since they have no influence on fuel depletion. Calculated concentrations of most of the important fission products in dependence of burnup are tabulated in Table I. Concentrations of isotopes are expressed in wt % units of the total fuel meat mass. Relative differences in the calculated values are also shown. The values calculated with WIMS were used as the reference values. General agreement is very good, however, large differences in ^{155}Eu, ^{95}Mo, ^{239}Pu and ^{240}Pu isotope concentrations were observed. Differences increase with burnup except for ^{95}Mo. Larger discrepancies were observed also for ^{134}Cs and ^{147}Pm isotope in the cases of 10% and 20% burned fuel.

Influence of a particular fission product on the WIMS calculated unit-cell k_{eff} was investigated for different burnups to estimate relative importances of different isotopes. By excluding a particular isotope from the criticality calculation relative importance of the isotope on k_{eff} was determined. Results of the calculations in dependence of burnup are collected in Table II. Results show that the largest influence on the k_{eff} have ^{135}Xe, ^{149}Sm and ^{239}Pu isotopes (Figure 4). At higher burnups ^{151}Sm and ^{143}Nd become important. All other fission products have no significant influence on k_{eff} (less than 10%). To obtain absolute importances on k_{eff}, the same procedure should be made for criticality calculations of the whole reactor core.

It can be concluded that only ^{135}Xe, ^{149}Sm, ^{239}Pu and ^{151}Sm are important for criticality calculations if burnup of fuel is less than 10%. Neglecting the rest of the fission products gives approximately ± 10% uncertainty in the change of k_{eff} due to burnup. For higher burnups ^{240}Pu and ^{143}Nd must be taken into account as well to achieve the same uncertainty in the change of k_{eff}.

Table I: Isotopic composition of standard TRIGA fuel in wt % calculated for different burn-ups with WIMSD4 and ORIGEN2.

	3.34 % burned fuel		10 % burned fuel		20 % burned fuel		20 % burned fuel + one year cooling time	
Isotope	WIMS [wt %]	ORIGEN [wt %]	WIMS [wt %]	ORIGEN [wt %]	WIMS [wt %]	ORIGEN [wt %]	WIMS [wt %]	ORIGEN [wt %]
KR-83	0.0011	0.0010	0.0030	0.0031	0.0057	0.0059	0.0057	0.0059
MO-95	0.0146	0.0076	0.0422	0.0375	0.0810	0.0792	0.0810	0.0856
TC-99	0.0145	0.0136	0.0422	0.0408	0.0805	0.0810	0.0805	0.0810
RU-101	0.0119	0.0120	0.0346	0.0359	0.0664	0.0716	0.0664	0.0716
RU-103	0.0014	0.0015	0.0013	0.0015	0.0012	0.0015	0.0000	0.0000
RH-103	0.0057	0.0061	0.0189	0.0208	0.0370	0.0416	0.0382	0.0430
RH-105	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
PD-105	0.0021	0.0026	0.0064	0.0080	0.0127	0.0165	0.0127	0.0165
PD-108	0.0003	0.0003	0.0008	0.0009	0.0018	0.0021	0.0018	0.0021
AG-109	0.0001	0.0001	0.0004	0.0005	0.0009	0.0011	0.0009	0.0011
CD-113	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
IN-115	0.0000	0.0000	0.0001	0.0000	0.0002	0.0002	0.0002	0.0002
I-127	0.0007	0.0005	0.0022	0.0015	0.0042	0.0030	0.0042	0.0031
XE-131	0.0089	0.0084	0.0256	0.0254	0.0485	0.0495	0.0485	0.0499
CS-133	0.0206	0.0202	0.0598	0.0611	0.1137	0.1210	0.1137	0.1220
CS-134	0.0000	0.0001	0.0003	0.0006	0.0009	0.0021	0.0007	0.0014
XE-135	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CS-135	0.0158	0.0162	0.0469	0.0484	0.0900	0.0958	0.0900	0.0958
ND-143	0.0192	0.0181	0.0546	0.0557	0.1023	0.1090	0.1023	0.1110
ND-145	0.0129	0.0131	0.0373	0.0391	0.0712	0.0770	0.0712	0.0770
PM-147	0.0066	0.0065	0.0135	0.0211	0.0215	0.0440	0.0177	0.0348
SM-147	0.0007	0.0007	0.0054	0.0055	0.0169	0.0173	0.0219	0.0225
PM-148	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000
SM-150	0.0028	0.0029	0.0095	0.0106	0.0192	0.0221	0.0192	0.0221
SM-151	0.0012	0.0012	0.0023	0.0026	0.0029	0.0033	0.0029	0.0033
SM-152	0.0012	0.0012	0.0045	0.0047	0.0101	0.0108	0.0101	0.0108
EU-153	0.0006	0.0006	0.0017	0.0021	0.0036	0.0048	0.0036	0.0048
EU-154	0.0000	0.0000	0.0001	0.0001	0.0003	0.0005	0.0003	0.0005
EU-155	0.0001	0.0000	0.0001	0.0002	0.0002	0.0004	0.0002	0.0004
GD-157	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
U-234	0.0000	0.0000	0.0000	0.0001	0.0000	0.0002	0.0000	0.0002
U-235	19.3300	19.2400	18.1220	18.0000	16.4350	16.1000	16.4350	16.1000
U-236	0.1102	0.1256	0.3170	0.3720	0.6012	0.7290	0.5465	0.7290
U-238	80.3600	80.0200	80.4680	80.4000	80.4680	80.2000	80.4680	80.2000
PU-239	0.0600	0.0468	0.1671	0.1310	0.3005	0.2320	0.3005	0.2330
PU-240	0.0008	0.0006	0.0058	0.0075	0.0201	0.0263	0.0201	0.0263
PU-241	0.0000	0.0000	0.0004	0.0007	0.0026	0.0049	0.0025	0.0036
PU-242	0.0000	0.0000	0.0000	0.0000	0.0001	0.0002	0.0001	0.0002

Table II: Results of the sensitivity studies of the effective multiplication factor for different burn-up of fuel element (3.34%, 10% and 20%). The relative differences in k_{eff} for a particular isotope are shown. MAT number means the identification number of the selected isotope as used in the WIMS program.

MAT number	Isotope	3.34% burn-up [pcm]	10% burn-up [pcm]	20% burn-up [pcm]
135	XE-135	1015	972	1015
1149	SM-149	679	697	689
3239.1	PU-239	111	332	725
151	SM-151	90	214	285
143	ND-143	62	183	364
236	U-236	30	88	167
103	RH-103	23	80	162
1147	PM-147	21	49	71
131	XE-131	20	58	113
147	PM-147	18	44	64
133	CS-133	17	52	101
145	ND-145	10	31	62
155	EU-155	10	18	24
99	TC-99	10	30	59
113	CD-113	7	8	9
1240	PU-240	6	50	175
152	SM-152	6	25	57
95	MO-95	6	18	36
157	GD-157	5	5	6
83	KR-83	4	12	24
148	PM-148	4	11	16
105	RH-105	4	4	4
150	SM-150	3	12	26
153	EU-153	3	10	22
1135	CS-135	3	9	17
101	RU-101	2	6	12
2147	SM-147	1	9	31
154	EU-154	1	1	4
1105	PD-105	0	1	3
109	AG-109	0	1	3
115	IN-115	0	0	1
1148	PM-148	0	0	0
1103	RU-103	0	0	0
127	I-127	0	0	1
108	PD-108	0	0	1
134	CS-134	0	0	1
242	PU-242	0	0	0
241	PU-241	0	2	11

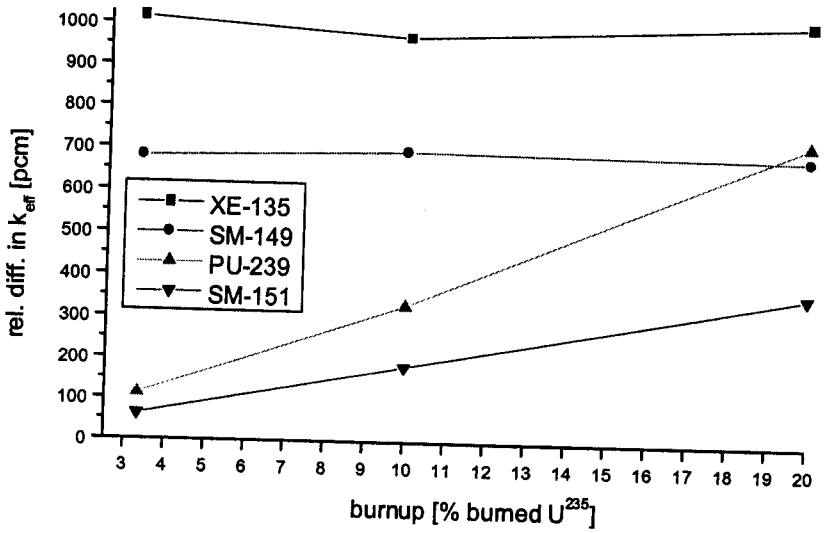

Figure 3: Influence of a particular fission product on the WIMS calculated unit-cell k_{eff}, investigated for different burnups.

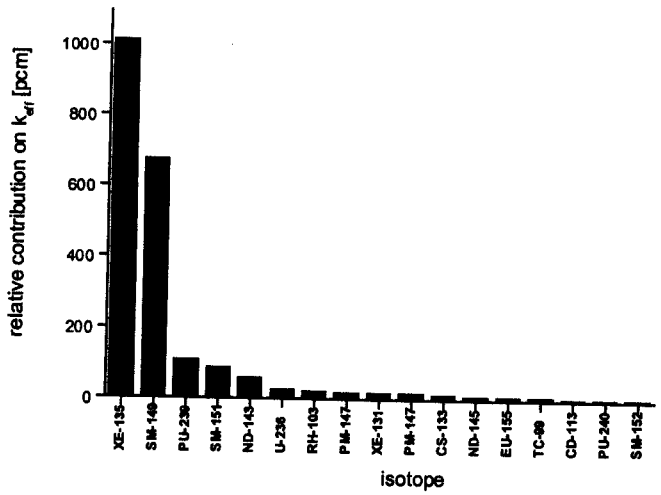

Figure 4: Relative contribution of selected isotope on calculated k_{eff} for 3.34% burned fuel.

3.3 Other Material Composition Data

The stainless steel used for cladding and top and bottom ends of fuel and control elements is standard stainless steel type 304. A sensitivity study using MCNP was done to estimate the effect of stainless steel top and bottom ends of fuel elements on k_{eff}. No significant effect was obtained when top and bottom end diameters were changed to approximately preserve the mass. Sensitivity study on stainless steel density gave approximately ±50 pcm uncertainty in k_{eff} per one percent uncertainty in stainless steel density, which was also the estimated uncertainty. Sensitivity studies on stainless steel composition showed no significance on k_{eff} if the low-content elements (Si, C, P, S) were taken out. However, when the content of other

elements was changed within production tolerances, a rather large effect of approximately 400 pcm was observed. Varying the clad thickness (25 μm) and diameter within fabrication tolerances also had a significant effect of approximately 250 pcm on k_{eff}.

Varying absorber density and material composition had only a minor effect on reactivity of approximately 20 pcm per 1% change. The total uncertainty because of absorber data uncertainties was estimated to be approximately 100 pcm.

Combining all quoted uncertainties on other than fuel material composition data, the total inaccuracy was estimated to approximately ±500 pcm (0.5%).

4. Conclusions

Examinations of simplifications in radial and axial direction showed that radial simplifications (neglecting far vicinity of the core) had only minor effects on k_{eff}, which is still acceptable for a benchmark. On the other hand, simplifications in axial direction were too severe and as such not acceptable for a benchmark model.

Results of material sensitivity studies showed that one of the largest uncertainties in the effective multiplication factor arise from inaccurately known fresh fuel composition. For burned fuel, WIMSD4 and ORIGEN2 gave similar results, which indicates that the calculated burned fuel composition may be used reliably. Another important uncertainty in the effective multiplication factor arises from fabrication tolerances and material composition of stainless steel cladding of fuel elements.

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