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Burn-up TRIGA MARK II Benchmark Experiment

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Abstract

Different reactor codes are used for calculations of reactor parameters. The accuracy of the programs is tested through comparison of the calculated values with the experimental results. Well-defined and accurately measured benchmarks are required. The experimental results of reactivity measurements, fuel element reactivity worth distribution and fuel burn-up measurements are presented in this paper. The experiments were performed with partly burnt reactor core. The experimental conditions were well defined, so that the results can be used as a burn-up benchmark test case for a TRIGA Mark II reactor calculations.

1. Introduction

After the reconstruction and the modification of TRIGA MARK II reactor in Ljubljana in 1991, a set of experiments on the fresh reactor fuel was made. The results were evaluated and may be used as benchmark for fresh fuel of TRIGA MARK II reactor. Seven years later in 1998 we repeated the measurements of some reactor parameters with partly burnt reactor fuel in the same core configuration. The results of the measurements will serve as the verification of the computer program for burn-up calculations.

The scope of this paper is to present the burn-up TRIGA Mark II benchmark experiment. The goal of our TRIGA benchmark measurements was to determine the following:

- the multiplication factor of two core configurations identical as in 1991 benchmark,
- the fuel elements reactivity worth and
- burn-up of some fuel elements.

2. Critical experiment

Well-defined, uniform and compact core with simple geometry is required for testing criticality calculations. The reactor cores described in [1] and labelled 133 and 134 are suitable for testing k_{eff} calculations. 40 fresh standard TRIGA fuel elements with 12 wt% uranium and 20% enrichment were used. The neutron source was in the E-12 position. The core 134 is similar to the core 133, but it has five additional fresh fuel elements in E ring and the neutron source was located in E-7 position. The excess reactivity of both cores was measured using digital reactivity meter DMR-043 [2]. It extends the practical range of the reactivity measurements from $-20\text{x}10^{-5}$ to $300\text{x}10^{-5}$. During the experiments all control rods were withdrawn. The same core configurations were used in the criticality experiment using partly burnt fuel elements (the core 133.1 and 134.1). The calculated burn-up data of all fuel elements from the core 134.1 are presented in Table 1.

For reactivity measurements the source multiplication method was applied [3] because the system was deeply subcritical. A previously determined control rod reactivity $\delta\rho_1$ was inserted into a subcritical reactor system with unknown initial reactivity ρ_0. The value of ρ_0 is determined as a function of three parameters: $\delta\rho_1$, the flux signal level of the initial and of the

final states in a subcritical transient. During the experiment, the flux level was measured with two independent neutron counters to check the influence of the detector position on the measurements. BF_3 neutron counter was located outside of the reactor tank and the fission counter was located near graphite reflector. To check the influence of the control rod position on the measured flux signal the sequence of four independent measurements was made at each core configuration (the reactivity was inserted into the system using the regulating, safety, shim and transient control rods).

Table 1: Burn-up and initial uranium content of fuel elements used in the experiment.

Element number	Uranium (g)	Burn-up (%)	Element number	Uranium (g)	Burn-up (%)
6753	272.94	1.72	7266	276.50	0.94
6574	279.00	0.93	7232	278.45	0.86
6945	278.74	1.04	7233	278.45	3.50
6947	278.98	0.97	7270	276.38	3.45
7251	281.18	1.22	7236	278.45	3.56
6754	273.17	4.10	7225	277.32	3.50
7248	281.18	1.74	7265	277.20	3.32
7255	281.16	4.00	7245	277.04	3.32
7212	277.68	3.91	7218	277.20	0.90
7213	277.97	3.91	7250	281.42	3.91
7214	277.44	3.94	7259	275.13	0.98
7249	281.06	4.01	7254	277.03	1.02
7282	277.39	4.08	7252	278.98	1.06
7217	279.51	1.24	7253	278.98	1.01
7257	280.78	4.16	7258	274.88	0.96
7219	278.74	4.04	7261	275.37	1.72
7220	278.45	4.02	7246	274.77	0.99
7235	280.47	0.93	7241	274.89	1.17
7256	280.11	3.22	7221	276.31	1.68
7223	277.97	3.13	7243	276.43	0.42
7247	279.59	3.24	7234	274.48	1.09
7268	279.24	3.23	7177	232.92	2.85
7228	277.97	3.14	7178	235.62	3.57
7229	277.25	3.28	7179	238.45	3.07

Experiments began with the core 133.1 and the reactivity of the system was measured. The system was deeply subcritical. The core 134.1 was established in six steps. In the first step the core 133.1 was rearranged. Then fuel elements were inserted in E13, E14, E15, E2 and E3 in five additional steps to establish the core 134.1. The reactivity was measured after each step using the source multiplication method. The system was critical when three fuel elements were added. To determine inserted control rods reactivity, the control rod reactivity worth was measured by the rod exchange [2] and by the rod insertion methods [4]. The results are presented in the Table 2. The results obtained by rod insertion method were used in k_{eff} measurements.

Some corrections of the measuring flux signal were needed to eliminate the influence of the control rods position regarding to detector position [4]. The measured flux signal consists of two contributions: the nonhomogeneous part presents the disturbance caused by inserted control rod while the homogeneous part belongs to the basic, undisturbed solution. When the transient was performed with regulating or with shim control rods, the flux signal measured with fission counter was corrected. When the transient was performed with safety or transient control rods, the flux signal measured with BF_3 counter was corrected. The multiplication factors calculated with corrected flux signals are presented in Fig. 1.

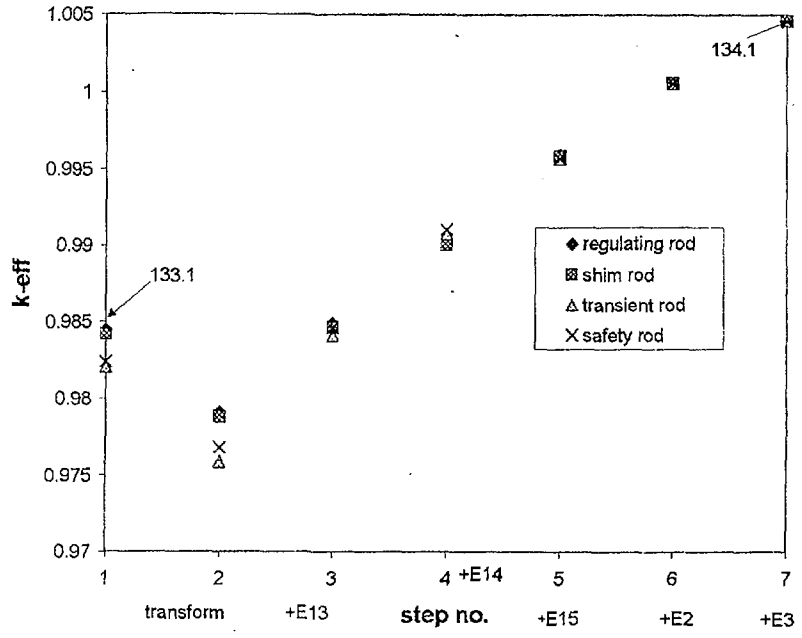

Figure 1: The multiplication factor for different core configuration, starting with the core 133.1. The fuel elements in positions E13, E14, E15, E2 and E3 were added to establish the core 134.1.

Table 2: Integral control rod worth measured by the rod-exchange method and by rod insertion method.

Control rod	Rod-exchange (pcm)*	Rod insertion (pcm)
Regulating	2116	2602
Shim	3238	2645
Safety	3684	3470
Transient	2280	2320

* pcm or "per centenas millias" equals $10^{-5} \cdot \Delta k/k$.

3. Fuel element reactivity worth distribution

Examination of the fuel reactivity worth distribution is useful to provide the information about the flux distribution in the core. Fuel element worth for a well-thermalized, small and uniform core is approximately proportional to the square of the thermal flux, integrated over the entire fissile volume of the fuel element [1]. The fuel element reactivity worth was determined experimentally from the difference in reactivity before and after the fuel element was removed from the reactor core.

The experiments were performed in the reactor core 134.1 with 467 pcm excess reactivity. The fuel elements in position A1, B4, C8, D11, E14 and E15 were chosen for measurements (the same position as in the experiment with the fresh fuel elements). Before the experiment

the measured element was removed from the core and the the core reactivity change was measured. The reactivity worth of the elements in inner rings of the core is about 1000 pcm or more so the system was subcritical when a fuel element was withdrawn from the core. The method of source multiplication described in the previous section was used for subcritical

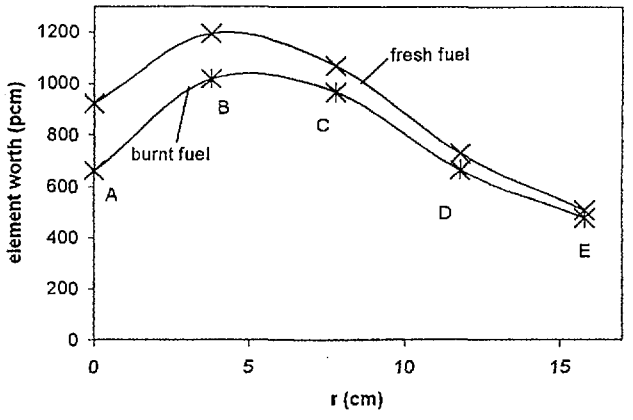

Figure 4: Averaged fuel element reactivity worth by rings.

measurements. The regulating or safety control rods were used to insert the negative reactivity change in the system and flux was measured with fission chamber. The subcriticality of the core was determined to the flux ratio when the control rod was fully inserted in the core and when it was withdrawn. Results for fuel elements reactivity worth are presented in the Table 3 together with the measurements of the fresh fuel elements. The average element worth in a certain ring is presented in Fig. 4.

The fuel element reactivity worth in A ring is lower than in B and C rings. This indicates that the flux in the centre is lower than in B or C rings. The reactivity worth of the elements in outer rings decreases with increasing radius of the core. The results were confirmed by the flux distribution measurements [5]. The difference between reactivity worth of fresh and burnt fuel depends on the burn-up history of the element. The large difference is observed for element in A ring (burn-up of this element is 1.76%), the smallest for element in D and E ring (0.82 and 1.19 % burnt).

Table 3: Fuel element reactivity worth for different positions in the core 134.1.

Position in the core, (element number)	Burn-up (%)	Element worth fresh fuel (pcm)	Element worth burnt fuel (pcm)
A1 (6753)	1.76	922	662
B4 (7251)	1.25	1194	1016
C8 (7217)	1.26	1070	966
D11 (7232)	0.82	729	665
E14 (7241)	1.19	508	453
E15 (7221)	1.71	Not measured	502

4. Fuel element burn-up measurements

Fuel element burn-up was measured with the reactivity method. The reactivity method [6] is based on the fact that the reactivity worth of the fuel element is a known function of burn-up. If we measure the reactivity worth of the fuel element we can calculate its burn-up. But because the absolute criticality calculations are not very accurate it is better to rely only on relative differences between reactivity worth of elements, which are proportional to differences in burn-up. When the burn-up of at least two measured fuel elements is known we can determine the absolute value of burn-up for all elements.

The measurements were performed in the core 161 loaded only with standard 12 wt% uranium, 20% enriched, burnt fuel elements. The system of elements was slightly supercritical. Location C6 was chosen for measurement position. In this location the reactivity worth of the element is high and the gradient of neutron flux is approximately constant. The measurements are relative so the configuration of the reactor core was constant during the experiment. The control rods were withdrawn during the reactivity measurements with digital reactivity meter to eliminate the redistribution effect of the control rods.

Nine standard, 12 wt % uranium, 20% enriched TRIGA fuel elements included in the core 134 were selected for measurements. Four of them (elements 7213, 7243, 7247 and 7258) spent most of their lives in the vicinity of the control rods, near irradiation channel or in the outermost ring. The elements 6945, 7219, 7220 and 7228 were identified to have a relatively simple and well-defined burn-up history. The element 7215 was almost fresh (0.02 MWd) and served as reference element for absolute burn-up determination. Measurements started with the element with the highest burn-up value (element 7219). It was inserted into the selected measuring position and the core reactivity was measured. After that the reactor was shut down and the element was replaced by the next fuel element. At the end of the measurements the element 7219 was measured again to determine reproducibility of the reactivity measurements (± 1 pcm difference in 97 minutes interval).

The first set of the measurements was performed only 20 hours after the reactor was shut down. Reactor worked one day at full power (250 kW) and produced 6.378 MWh energy. The strong effect of Xe on measured reactivity was observed (the variation of reactivity measurement of the element 7219 is 7 pcm in 132 minutes). We repeated all measurements again next day (40 hours after shut down of the reactor) to estimate the Xe influence on measured reactivity. We also estimated the effect of burn-up gradient of the fuel element to rotate it around its vertical axis.

The results of measurements of nine standard TRIGA fuel elements are presented in Fig. 5. Measured burn-up values were also compared to the calculations using burn-up program TRIGLAV [7]. The whole operating history of the reactor from 1991 to today was recalculated. The accuracy of calculated burn-up of a particular fuel element depends on its position in the core and on the precision of the operational records. It is estimated to ± 0.5% ^{235}U [8]. The results are presented in Table 5.

Three types of errors can occurr in the measured reactivity: the first is the uncertainly in the fuel material composition with respect to initial uranium, zirconium, and hydrogen content in the measured fuel elements. Reactivity correction due to difference in uranium content is calculated for each element, assuming a linear dependence on uranium weight [8]. We supposed that the calculated burn-up of fuel element 6945 is too low due to uncertainty in initial hydrogen and zirconium content (different batch of fuel elements). The second source of the errors is the orientation of the fuel element. When the fuel element was rotated around its axis, the difference in measured reactivity was observed. Measurements of elements 7228 and 7258 showed that the effect contributes about ±8 pcm to reactivity measurements.The

uncertainty of radial and axial location of the element and errors of the digital reactivity meter were estimated to ±5 pcm [8].

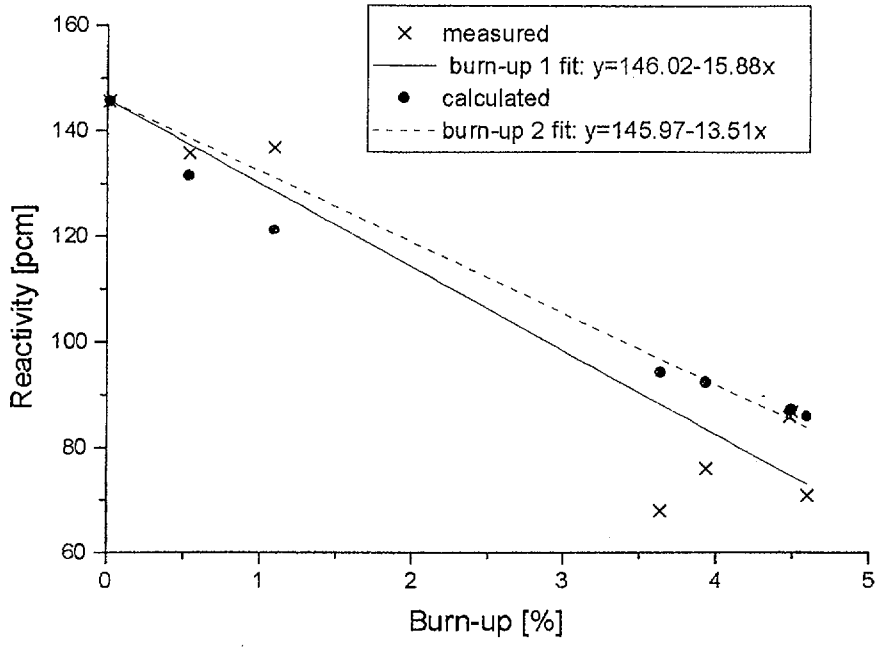

Figure 5: Results of reactivity measurements and calculations as a function of calculated burn-up.

Table 5: Measured and calculated reactivities. Measured burn-up 1 values were obtained by weighted linear fit of measured reactivity and measured burn-up 2 values by weighted linear fit of calculated reactivity.

Element	Reactivity calculation (pcm)	Measured reactivity (pcm)	Calculated burn-up (%)	Measured burn-up 1 (%)	Measured burn-up 2 (%)
7219	33.4	96.8	4.50	3.74	4.37
7220	32.0	94.8	4.49	3.80	4.46
7228	37.5	74.9	3.64	4.93	5.76
6945	65.0	92	1.27	4.04	4.72
7213	29.1	77.8	4.60	4.74	5.55
7247	41.5	89	3.94	4.42	5.17
7258	51.3	130.9	1.10	0.59	0.69
7243	67.8	135.8	0.54	0.66	0.77
7215	80.9	144.7	0.02	0.03	0.02

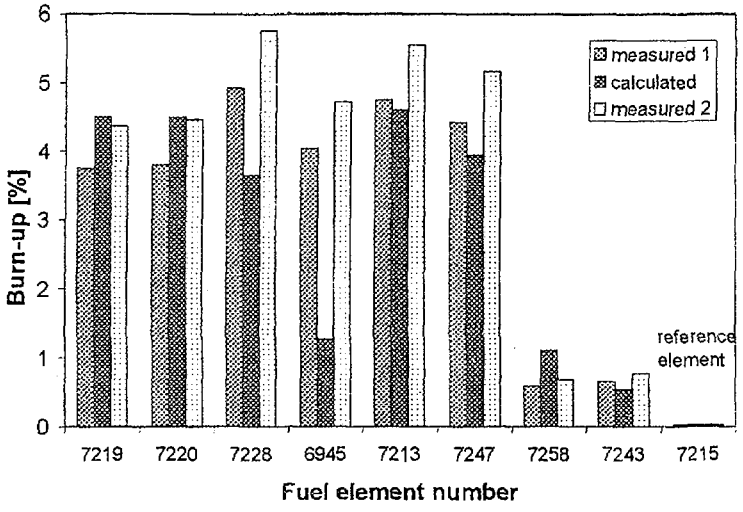

Figure 6: Calculated burn-up values and values measured by the reactivity method.

4. Conclusion

The results of experiments including reactivity measurements, control rods measurements, element reactivity worth distribution and burn-up measurements are presented and discussed in this paper. Reactivity was measured for two TRIGA Mark II core configurations including burnt fuel elements. The systems were subcritical. Criticality was determined using source multiplication method. Two independent flux detectors were used in the experiments to determine the influence of the detector position. Fuel element worth was measured for six burnt fuel elements at different location in the core. The effect of fuel element burn-up on measured reactivity worth was observed.The burn-up measurements of nine standard TRIGA fuel elements using reactivity method are presented. Comparison with the calculated values shows good agreement within ±1% burn-up for almost all investigated fuel elements. The measurements of reactivity show that before the experiment the reactor must be shut down for at last 50 hours to reduce xenon effects (clean reactor condition). The orientation of fuel element is also important for the measurements.

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