

TRIGA MARK II REACTOR BENCHMARK

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ABSTRACT

A benchmark experiment on the TRIGA Mark II reactor is described. Experiments performed on fresh fuel during startup tests were done under well-controlled conditions. A benchmark model is proposed on the basis of manufacturer data. Some simplifications, which do not affect k_{eff} significantly, are assumed in the benchmark model.

Results of sensitivity studies of the effects on k_{eff} of geometrical and material uncertainties are given. The results of MCNP and KENO simulations of the benchmark model show very good agreement with the experimental results and are well within the benchmark model uncertainties.

1. INTRODUCTION

The scope of this paper is to present benchmark experiments on the TRIGA Mark II reactor in Ljubljana, Slovenia, their simulation and evaluation. The experiments were performed as a part of startup tests after reconstruction and upgrading in 1991, during which all core components (top and bottom grid plates, fuel, control rods, irradiation channels), with the exception of the graphite reflector around the core, were replaced with new ones. The experiments in steady-state operation were performed with completely fresh fuel (including instrumented elements and fueled followers of control rods) in a compact and uniform core (i.e. all elements including the fueled followers of control rods were of the same type with no nonfuel components in the critical core configuration) at well-controlled operating conditions [1]. Only standard commercial TRIGA fuel elements of 20 wt.% enrichment and 12 wt.% uranium concentration were used. It should be noted that the core lattice does not have a periodic structure. For this reason the benchmark can not be treated as a unit-cell problem with effective buckling but has to be modeled explicitly in 3D geometry.

2. TRIGA REACTOR GEOMETRY

The reactor in which the experiments were performed is a typical 250-kW TRIGA Mark II. It is a light-water reactor with an annular graphite reflector cooled by natural convection. Top and side views of the TRIGA reactor are shown in Figures 1 and 2, respectively.

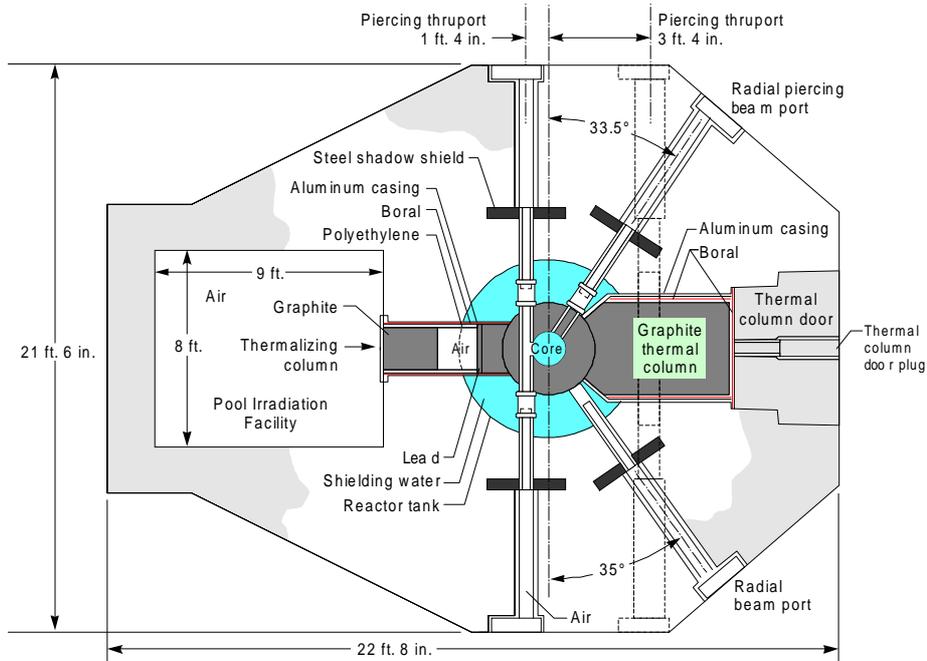


Figure 1. Top View of the TRIGA Mark II Reactor.

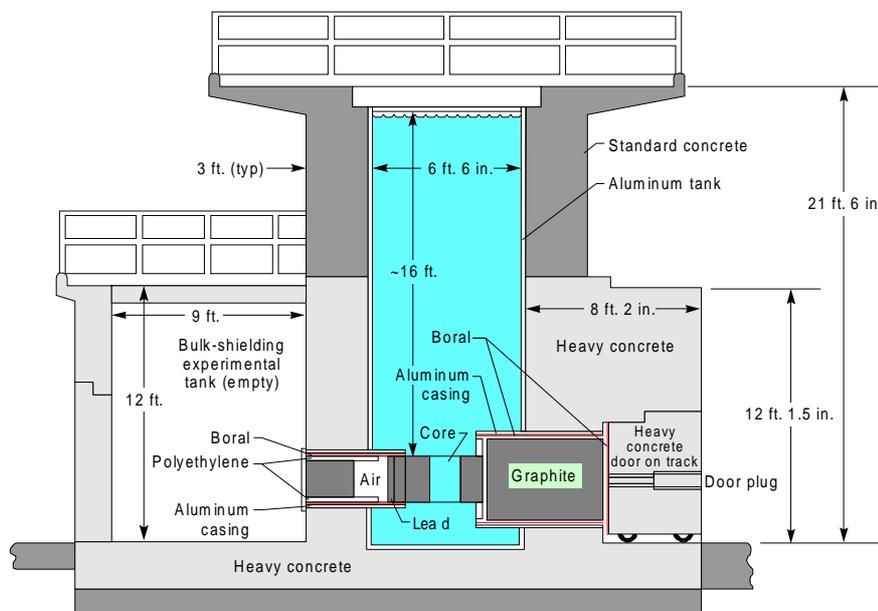


Figure 2. Side View of the TRIGA Mark II Reactor.

In total there are 91 locations in the core, which can be filled either by fuel elements or other components like control rods, a neutron source, irradiation channels, etc. The core lattice has an annular but not periodic structure.

Elements are arranged in six concentric *rings*: A, B, C, D, E and F, having 1, 6, 12, 18, 24 and 30 locations, respectively. Each location corresponds to a hole in the aluminum upper grid plate of the reactor. The distances between adjacent locations in a given ring are equal. A 12-inch-thick *graphite reflector* enclosed in aluminum casing surrounds the core. An annular groove in the upper part of the reflector body is provided to contain a special irradiation facility (rotary specimen rack). The aluminum specimen rack was placed in the groove in the critical experiments. The reflector is positioned symmetrically with respect to the horizontal midplane of the active part of the reactor core. There are two *irradiation channels* running through the graphite reflector. Both irradiation channels are filled with air and are clad with aluminum. A bottom grid plate that in addition provides accurate spacing between the fuel elements supports the core. The *top grid plate* also provides accurate lateral positioning of the core components. They are both made of aluminum of the same thickness but of different diameters. *Fuel elements* are cylindrical rods with stainless steel (SS-304) cladding. Their total length is approximately 28 inches with 1.478-inch diameter. Fuel material in each element is 15 inches long. There are 2.6-inch-long and 3.7-inch-long cylindrical graphite slugs at the top and bottom ends, respectively, which act as axial reflectors. In the center of the fuel material is a 0.25-inch-diameter hole which is filled by a zirconium rod. Between the fuel meat and the bottom graphite end reflector is a 1/32-inch-thick molybdenum disc. The fuel is a homogeneous mixture of uranium and zirconium hydride. In these experiments, only one type of fuel element was used: standard stainless steel-clad fuel elements with 12 wt.% uranium of 20% enrichment (uranium is 20 wt.% ^{235}U). Three *control rods* of fueled-follower type are used in the reactor: regulating (R), shim (C), and safety (S). They are identical in geometry and composition. The control rods are in their fully withdrawn positions during the core excess-reactivity measurement for the critical core configurations presented in this benchmark specification. Similar to the fueled-follower control rods, the *transient rod* (T) consists of the absorber part and the so-called air follower, which replaces the fuel part in the fueled-follower control rods. The purpose of the air-follower, which is in fact an empty tube, is to reduce power peaking that could appear when the transient rod is in its fully withdrawn position. The transient rod has a guide tube that is the only structural component of the reactor that extends into the active volume of the core. Vertical dimensions of the transient rod are approximately the same as of the control rods. The transient rod is in its fully withdrawn position during the core excess reactivity measurement for the critical core configurations presented in this benchmark specification. The *neutron source element* was in some measurements present and in some measurements taken out of the core. It contains a Ra-Be neutron source with activity of 10^6 neutrons/s. The more detailed description of the reactor geometry, including dimension and material specifications, can be found in [2] and [3].

In the critical experiments, two approximately critical core configurations were considered. They both had the same number of fuel elements (40), control rods (3), and a transient rod (1), but differed in loading pattern. The core labeled 132 had 7 fuel elements in the E ring placed on the same side as the transient rod, while Core 133 had them placed on the opposite side (see Figure 3). Both loading patterns show mirror symmetry across the line through the transient rod and the center of the core. It should be noted that the experiments are not independent but are closely correlated.

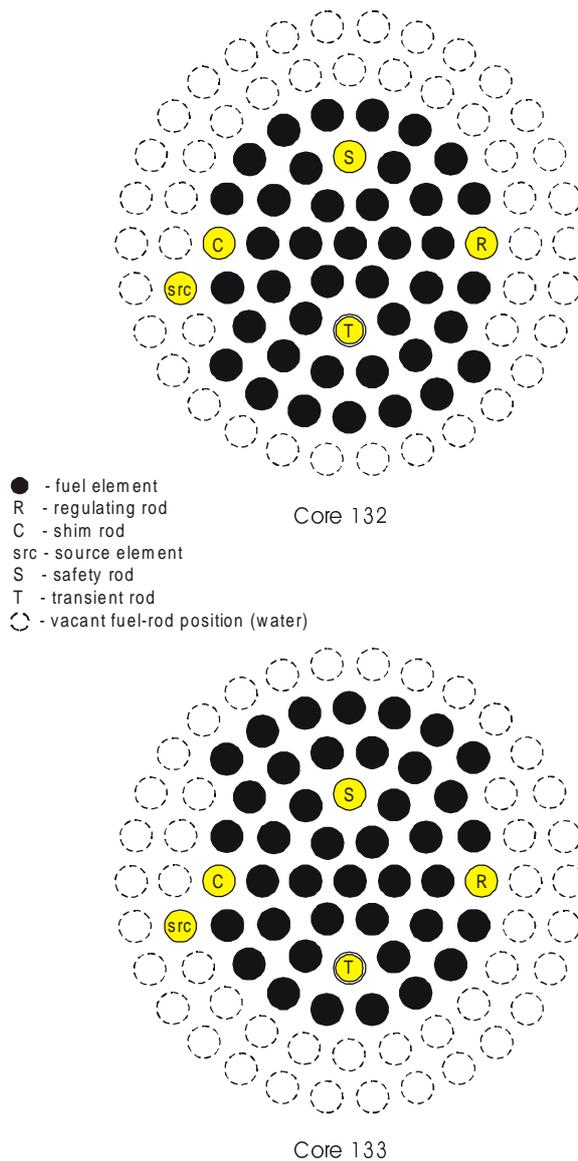


Figure 3. Configurations of the Cores 132 and 133.

3. TRIGA REACTOR MODEL GEOMETRY

Simulations of the TRIGA benchmark experiment were performed with MCNP4B [4] and KENO V.a [5] codes. Our goal in constructing the benchmark model was to prepare a faithful copy of the real TRIGA geometry. However, some simplifications of the geometry were done by simplifying surroundings of the core to an extent that does not affect k_{eff} significantly. The simplifications were done mainly to avoid complex modeling that has a minor or negligible effect on k_{eff} . The following structures were omitted or simplified: surroundings, irradiation channels, graphite of the thermalizing and thermal column, end caps of fuel and control/transient rods and source element. Original and simplified geometries are presented in Figures 4 and 5, respectively.

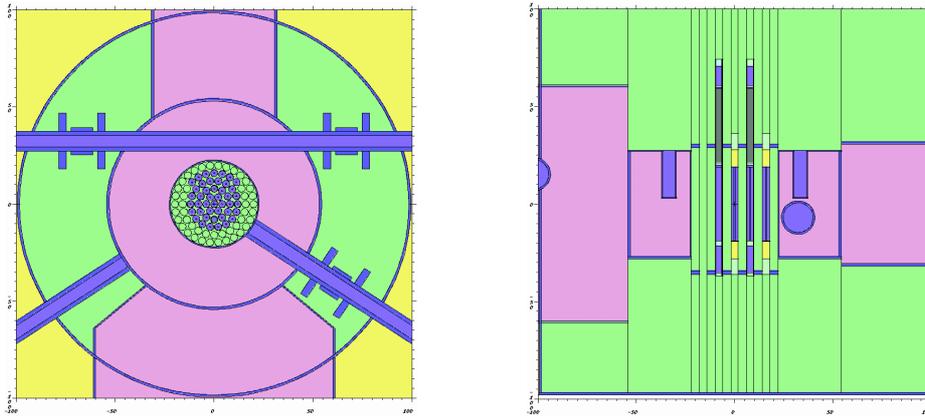


Figure 4. Top and Side Views of the Original TRIGA Reactor Model.

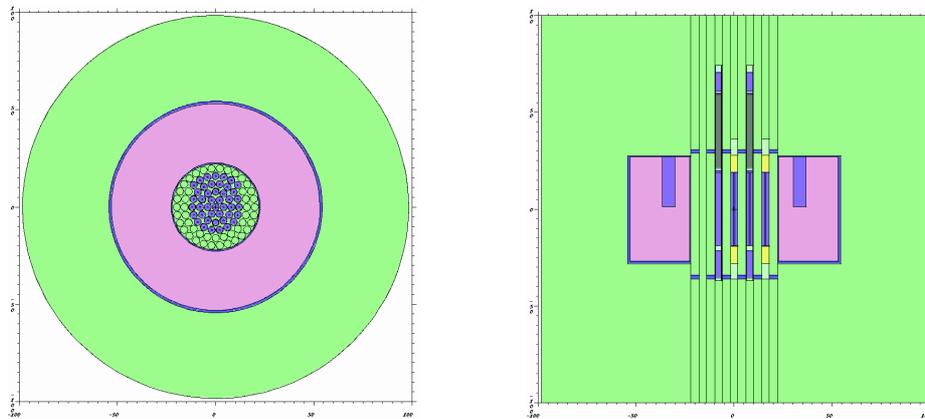


Figure 5. Top and Side Views of the TRIGA Reactor Benchmark Model.
(Simplifications of the geometry in the radial direction have only minor effect on the effective multiplication factor, and are acceptable for the benchmark model.)

4. BENCHMARK MEASUREMENTS

For reactivity measurements, a digital reactivity meter DMR-043 was used. The DMR-043 [6] consists of an electrometer and an IBM/PC-compatible computer and the software. The electrometer measures the neutron flux signal from a compensated ionization chamber, which is placed in the reactor tank outside the reactor core. The electrometer is linked to the computer so that the flux signal can be sampled automatically, as required by the reactivity-meter software. The signal is processed on-line to determine the reactivity by solving the nonhomogeneous integral inverse point-kinetics equations, which include the contribution of the neutron source. The reactivity meter allows dynamic reactivity measurements in the range from -500 pcm to $+300$ pcm^a.

^a 1 pcm = 10^{-5} $\Delta k/k$

Prior to the experiments, its proper functioning was checked by comparing several reactivities (from 10 to 50 pcm) measured by the DMR to the values measured by the doubling-time method. The maximal relative difference between the DMR and doubling-time results was 2.6% or 0.8 pcm absolute. No overshoots, undershoots, or drifts in the DMR reactivity signal were observed, indicating good experimental conditions (stable temperature, no xenon, small gamma background) as well as proper functioning of the DMR.

5. EVALUATION OF EXPERIMENTAL DATA

It is important to note that besides experimental error, which is only about ± 15 pcm (0.015%) [1], there is a large effect from uncertainty in fuel composition data, particularly in the content of uranium in U-ZrH mixture and H/Zr ratio, and from uncertainty about the stainless steel cladding [7]. Despite the large uncertainties, both configurations are acceptable benchmark data [2].

5.1 GEOMETRY SENSITIVITY STUDIES

The influence of all *simplifications* was investigated using a series of MCNP models with different simplification levels compared to the complete model of the TRIGA reactor. In the complete reactor model, the description of the vicinity of the core was very detailed and no simplifications were assumed. By omitting surroundings of the core, including irradiation channels and graphite of the thermalizing and thermal column, and by simplifying end caps of the elements, simplification of the geometry was done to the level which was estimated to be acceptable for a benchmark model. Further simplifications would lead to systematic errors because of too poorly described geometry, which would be unacceptable. 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 estimated. The total change in k_{eff} because of geometry simplifications is 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).

Effect of the *source* was determined experimentally and confirmed by simulations by calculating two configurations of Core 133, one without the source element and one with the source element inserted in the position E12. The effect was estimated to be $+40 \pm 10$ pcm (0.04%). Because the geometry and materials of the source are not well known, the benchmark models do not include the source. A bias of +40 pcm is included in the benchmark-model k_{eff} for Core 132.

In addition, effects of *inaccurate positioning* of fuel elements in the rings and control rods in vertical direction were determined experimentally and verified by calculations. The analyses showed approximately $\pm 150 \pm 35$ 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.

5.2 MATERIAL COMPOSITION SENSITIVITY STUDIES

Fuel Material - The *weight of ^{235}U* in the core was calculated according to the shipment documents, as were average values of the mass of uranium and ^{235}U in the fuel elements and control rods. 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 shows that this yields approximately ± 60 pcm (0.06%) uncertainty in k_{eff} .

A very important source of uncertainty is *concentration of uranium* in U-ZrH mixture. According to the documentation, the uranium content in the fuel meat is 11.94 wt.%. The one percent uncertainty in this data gives approximately ± 150 pcm uncertainty in k_{eff} , which is also considered to be a reasonable estimate of the uncertainty. Thus, the effect from uncertainty in the content of uranium is estimated to be ± 150 pcm (0.15%).

Another very important uncertainty is uncertainty in *H/Zr atom ratio*. According to the fuel manufacturing documentation, the H/Zr atom ratio is 1.60. However, 1% uncertainty in this data gives approximately ± 200 pcm uncertainty in k_{eff} . The references on fuel fabrication process show that variations in hydrogen content may be on the order of $\pm 2\%$. For 40 fuel elements used in the experiment this gives for the uncertainty of the mean less than a percent. Thus, the effect from uncertainty in H/Zr ratio is approximately ± 200 pcm (0.2%).

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

Other materials - 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 (within statistical uncertainty of 30 pcm) 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 is also the estimated uncertainty. Sensitivity studies on stainless steel composition showed no significant effect (within statistical uncertainty of 30 pcm) 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, an effect of approximately 400 pcm (0.4%) was observed. Varying the clad thickness (25 μm) and diameter within fabrication tolerances also has a significant effect of approximately 250 pcm (0.25%) on k_{eff} .

Varying *absorber* density and material composition has a minor effect on reactivity of approximately 20 pcm per 1% change. The total uncertainty because of absorber data uncertainties is thus estimated to be approximately 100 pcm (0.1%).

About 1°C variations in *water and fuel temperatures* were observed, which may contribute approximately ± 5 pcm (0.005%) to reactivity measurement error.

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

6. RESULTS

6.1 EXPERIMENTAL RESULTS

Experimental values of k_{eff} and the uncertainties of the examined cases are presented in Table I.

Table I. Experimental k_{eff} with the Uncertainties.

Case	Experimental k_{eff}
Core 132 (source at E12)	0.99865 ± 0.00015
Core 133 (no source)	1.00310 ± 0.00015

The systematic errors because of geometry simplifications, i.e. omitting surroundings of the core, irradiation channels, graphite of the thermalizing and thermal column, Al cladding of the groove in the graphite reflector, and simplifying end caps of the elements in the benchmark model, were discussed in Section 5.1. The uncertainties in the reported data, especially fuel data, were discussed in Section 5.2. The systematic errors from geometry simplifications contribute a bias of +0.0015 to the benchmark-model k_{eff} 's of both configurations. Omitting the source from Core 132 adds a bias of +0.0004. Results are summarized in Table II.

It should be noted that in neither of the two benchmark-model core configurations was the source element present, although it was present in the experimental configuration of Core 132.

Table II. Benchmark-Model k_{eff} and Errors.

Case	Experimental Error	Material Error	Geometry Error	Benchmark-Model k_{eff}
Core 132	± 0.00015	± 0.0056	$+ 0.0019 \pm 0.0003$	1.0006 ± 0.0056
Core 133	± 0.00015	± 0.0056	$+ 0.0015 \pm 0.0003$	1.0046 ± 0.0056

6.2 SIMULATION RESULTS

The calculated values of k_{eff} are given in Table III for the benchmark model geometry. Results calculated with MCNP were with the material cross-sections from ENDF/B-VI continuous-energy library. In KENO V.a calculations 44-group ENDF/B-V cross sections (CSAS, SCALE 4.4) were used. Although the pitch of fuel rods is not regular, the LATTICECELL option with triangular pitch was used for multigroup cross section preparation. The pitch for the LATTICECELL option was chosen to approximately preserve the water-to-fuel ratio in the first four rings. The uncertainties listed in the Table are the statistical errors of the calculations.

The calculated results are within 1% of the experimental results. The correct scattering kernels for thermal cross sections of water and zirconium hydride are necessary to obtain proper results.

Table III. Sample Calculation Results with Corresponding Statistical Errors.

Code (Cross Section Set) → Case ↓	KENO (44-Group ENDF/B-V)	MCNP (Continuous-Energy ENDF/B-VI)
Core 132	1.0028 ± 0.0004	0.9994 ± 0.0002
Core 133	1.0069 ± 0.0003	1.0042 ± 0.0002

CONCLUSIONS

A benchmark experiment on the TRIGA Mark II reactor is described in this work. Experiments performed after the reconstruction in 1991 during startup tests were done under well-controlled conditions and are thus acceptable as benchmarks. Benchmark models were proposed on the basis of manufacturer data. Some simplifications, which produced only small biases in k_{eff} (0.0019 and 0.0015), were assumed in the benchmark model.

The results of the MCNP and KENO simulations show very good agreement with the experimental results - well within the benchmark-model uncertainties (~560 pcm). However, the KENO results are approximately 300 pcm (0.3%) higher than the MCNP results. It is likely that this discrepancy is mostly due to different cross-section libraries used.

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