Reevaluation and uncertainty analysis of criticality experiments on water-uranium assemblies of “Rosa” facility

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Determination of uncertainties

Every critical experiment has numerous uncertainties. For instance, the exact contents of the assembly (the masses and compositions of constituents) and the geometry (dimensions, relative positions or array pitch) are never known perfectly.

Although the **exact** experimental configuration is unknowable, the attainable goals are an estimate of how well the configuration and its neutronic state are known.

Benefits:

- Estimates of physical quantities are of little use if there is no information about how reliable the estimates are.
- Qualifying codes and cross sections used in critical assessments.
- Improving state of art of criticality safety. Firm knowledge of the uncertainties provides a foundation for setting appropriate safety margins (smaller safety margins can be justified).

The uncertainty analysis

Best-estimate parameter values and uncertainties are needed. Both overestimation and underestimation of the uncertainties should be avoided

- to exclude existing bias hiding or indication of unexciting bias

Even if the experimenters provide a thorough uncertainty analysis for the experimental configuration, it should be extended to the benchmark model

- as-build experimental configuration should be converted to the practical benchmark model
- transformation-related bias and uncertainty added should be estimated.

Benchmark model Keff and uncertainty ΔKeff =

as-build experiment Keff and uncertainty *combined with* transformation-related Keff and ΔKeff .

Graded approach

- Little effort for small uncertainties, careful consideration of large contributor.

Experiments overview

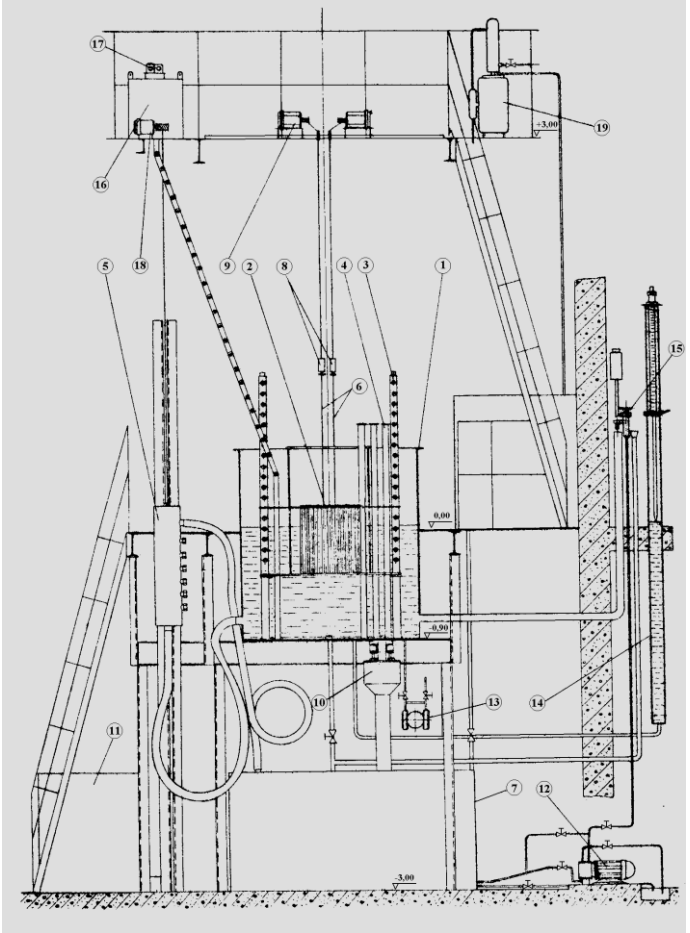
Critical experiments on water-uranium assemblies were performed at “Roza” critical facility (Institute for nuclear power engineering of BSSR Academy of sciences) in 1972.

Critical assemblies had the light water moderated cores made of hexagonal (triangular) lattices fuel rods with 21% enriched dioxide uranium fuel meat in stainless steel cladding. Four pitch sizes were studied: 10.50; 18.19; 21.00 и 27.78 mm.

“Roza” critical facility

Designed for experiments on light water moderated critical assemblies

1 –tank; 2 – core; 3 – supporting structure; 4 – detector channels; 5 – movable vessel; 6 – emergency protection control rods; 7 – emergency drainage tank; 8 – emergency control rod magnets; 9 – servomotors; 10 – emergency drainage valve; 11 – moderator storage tank; 12 – moderator pump; 13 – differential level gauge; 14 – precision level gauge; 15 – flooding control panel; 16 –Po-Be-source container; 17 – servomotor for Po-Be-source; 18 – servomotor for movable vessel; 19 – electric distillation facility



Critical assembly core layout

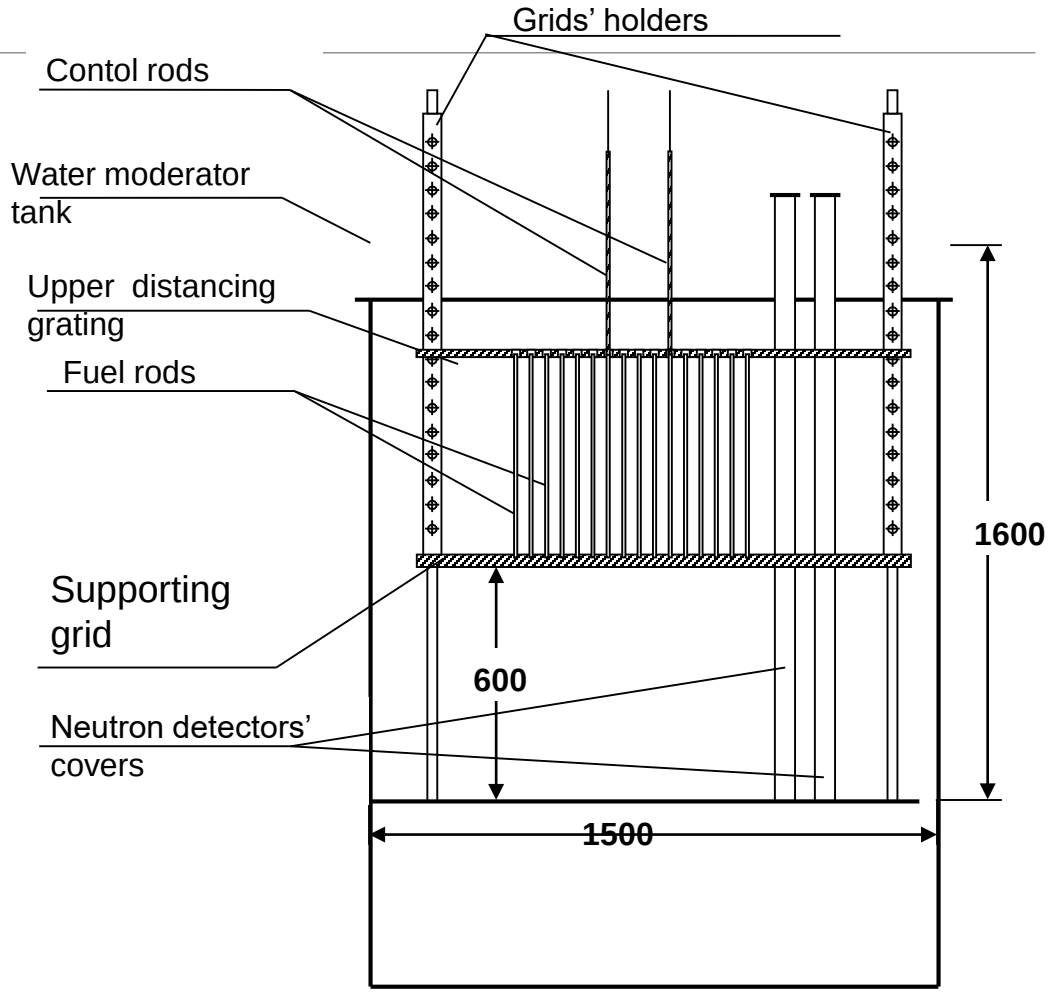
Top reflector was composed of rods' top end cups distancing grating and 100 mm water reflector.

Bottom reflector consisted of bottom rods' end cups. supporting grid and plate. 600 mm water reflector.

Side water reflector was more than 250 мм.

Thus side. top and bottom water reflectors were physically infinite.

Fuel rod is filled with fuel tablets made of uranium dioxide.



Fuel elements. Material data

Parameter	Mean value ± standard uncertainty (1σ)	Comments
Fuel meat mass. g	(109.83 ± 0.04)	UO_2 + impurities
Uranium mass. g	(96.40 ± 0.04)	Averaged over 622 tvels
Impurities. % mass.	0.108	
U-235 mass. g	(20.46±0.01)	Averaged over 622 tvels
U-234 mass. % mass.	(0.1650±0.0029)	Extracted from the published data on isotopic content of U supplied by Russian Federation
Enrichment. %	(21.224±0.013)	
Oxygen content in UO_2. g	(13.311±0.056)	Mass balance

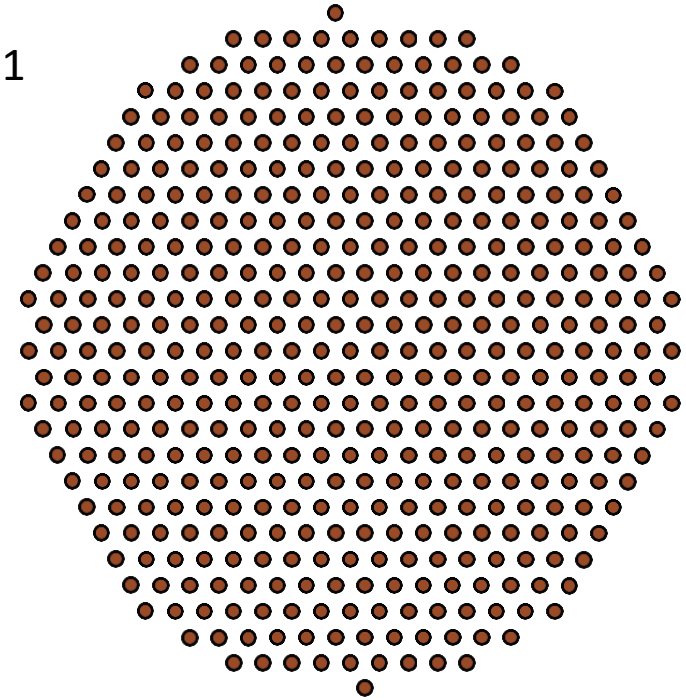
Fuel elements. Geometry.

Parameter	Mean value ± standard uncertainty (1σ)	Comments
Clad outer diameter. mm	(6.20±0.04)	0X16H15M3Б steel clad
Clad inner diameter. mm	(5.4±0.1)	
Fuel lattices' pitches. cm	1.050; 1.819; 2.100; 2.778 (1σ) = 3.2 10^{-4} cm	Four critical core configurations with different pitches are investigated
Fuel pellet diameter. mm	(5.230±0.046)	
Fuel column height. cm	(50.00±0.25)	
Water moderator temperatures. °C	17.6; 19.0; 17.8; 17.0	Order corresponds fuel pitched Temperature was controlled up to 1 °C

Number of fuel rods in the critical configuration is established up to the single rod.

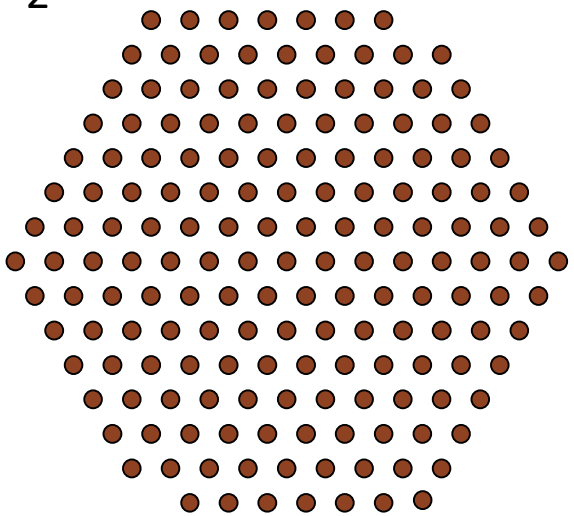
Critical core configurations

1



Pitch 1.050 cm; 453 rods

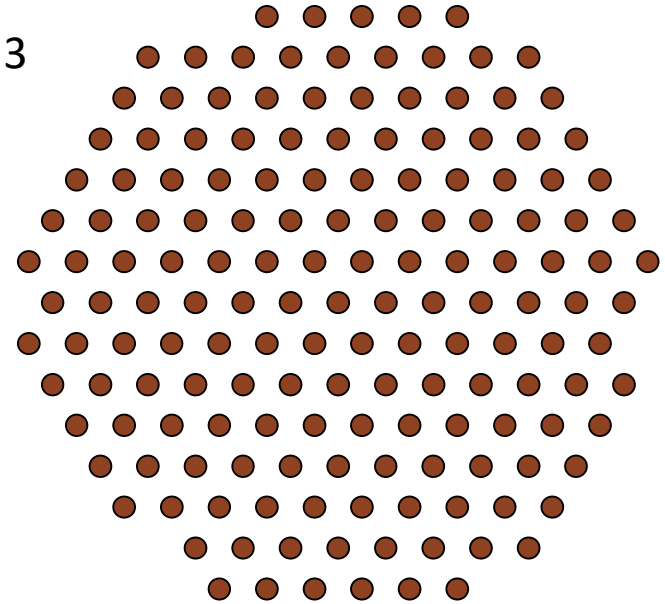
2



Pitch 1.819 cm; 167 rods

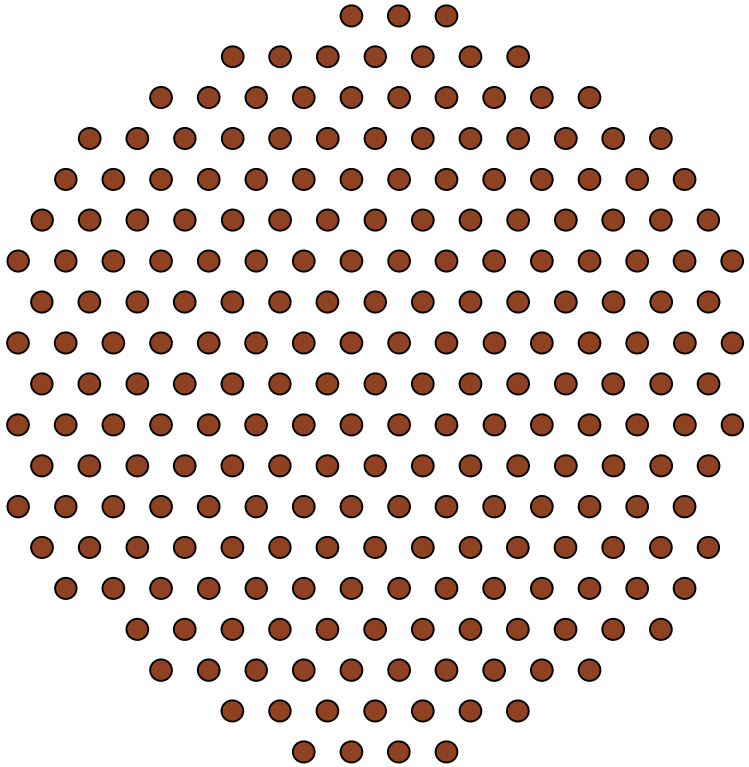
Critical core configurations (cont.)

3



Pitch 2.100 cm; 160 rods

4



Pitch 2.778 cm; 232 rods

The code and cross section libraries used.

MCU-PD Monte Carlo code with MCUDB50 cross section libraries.

Unresolved resonances' energy range:
301-group library MULTIC for U-238. U-235 and 26-group library BNAB/MCU for other resonance nuclides.

Energy range of resolved resonances: LIPAR library

Thermal neutron energy range (bellow 1 eV): VESTA library (continuous neutron energy change. S(α.β) probability tables)

MCU-PD simulation results

Assembly No	Pitch. cm	Keff	β_{eff}
1.	1.05	0.999045±0.000296	0.008307±0.000002
2.	1.819	0.996988±0.000262	0.008204±0.000002
3.	2.100	0.999979±0.000282	0.008053 ±0.000002
4.	2.778	1.000424±0.000277	0.007600±0.000002

Nominal experimental Keff value = 1.0

Uncertainty analysis

One-variable-at-a-time strategy is adopted to evaluate uncertainties.

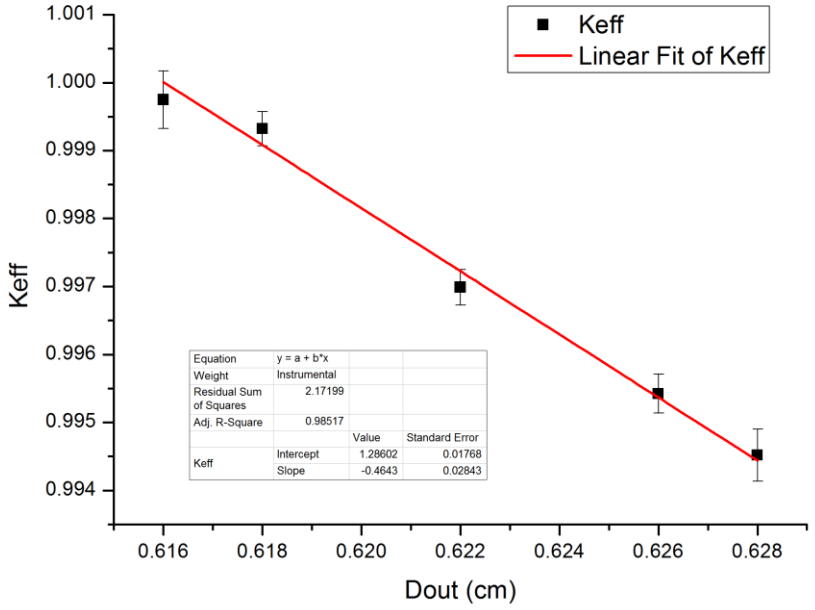
Least square method is used to evaluate sensitivity coefficients and corresponding “uncertainties of the uncertainties”.

Some parameters are correlated! Correlations are taken into account as follows

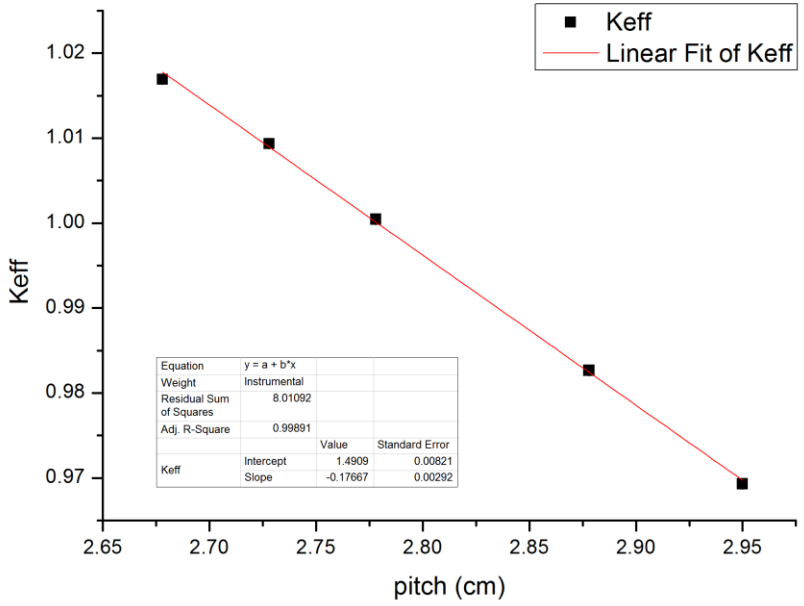
$$(\Delta k)^2 = \sum_{i=1}^{N} \left[\frac{\partial k}{\partial x_i} \right]^2 u_i^2 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial k}{\partial x_i} \frac{\partial k}{\partial x_j} r_{ij} u_i u_j$$

Examples: Sensitivity coeff. evaluation

KEFF DEPENDENCE ON ROD CLADDING OUTER DIAMETER. PITCH 1.819 CM

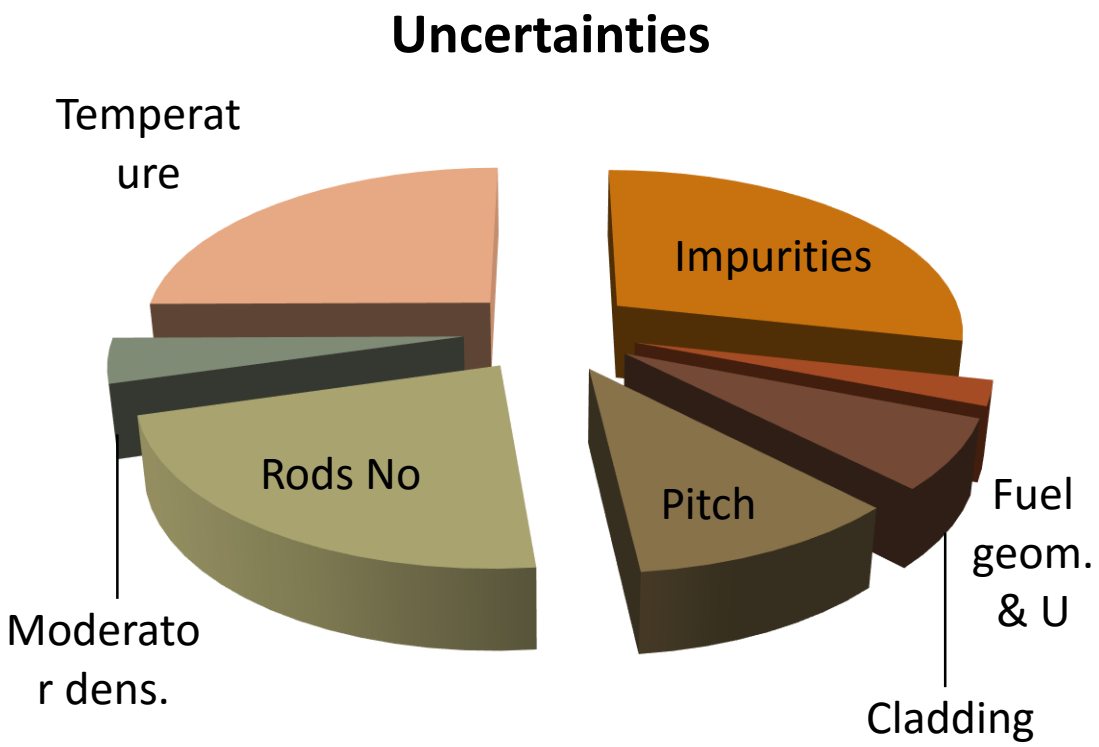


KEFF DEPENDENCE ON ROD PITCH VARIATION AROUND 2.778 CM PITCH VALUE



Critical assembly having pitch 1.050 cm (Keff=1)

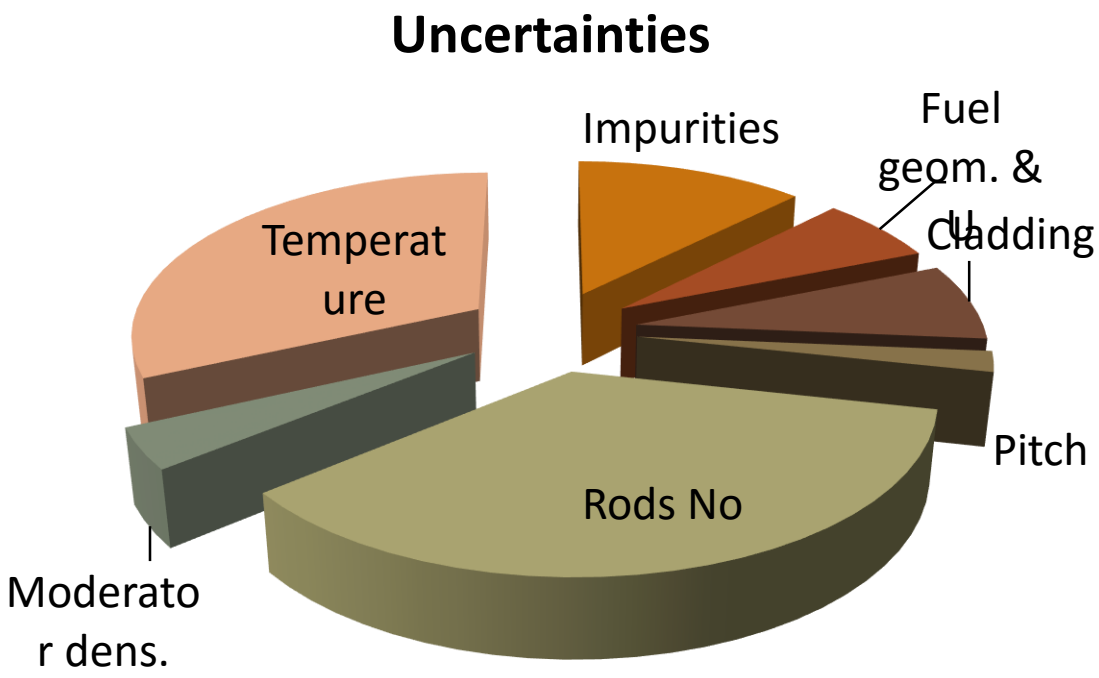
KEFF TOTAL UNCERTAINTY = 0.00095



Parameter	Sens. Coeff.	Std. uncertainty
Impurities	-	0.00059
U-235, 10^{-24} 1/см^3	17.94±0.72	0.00005
U-238, 10^{-24} 1/см^3	-(0.496±0.033)	
Pellet D, 1/cm	0.384±0.034	
Fuel height, 1/cm	(1.90±0. 09) 10^{-3}	
Clad inner D, 1/cm	0.138±0.028	0.00014
Clad outer D, 1/cm	-(0.867±0.004)	
Clad density, cm^3/g	-(6.83±0.66)10^{-3}	
Fuel rod pitch, 1/cm	0.6929±0.0273	0.00022
Num. of rods	(7.98±1.58) 10^{-4}	0.00046
Moder. dens. , cm^3/g	0.5055±0.0115	0.00009
Assembly T, 1/K	(8.73±0.25)10^{-5}	0.00052

Critical assembly having pitch 1.819 cm (Keff=1)

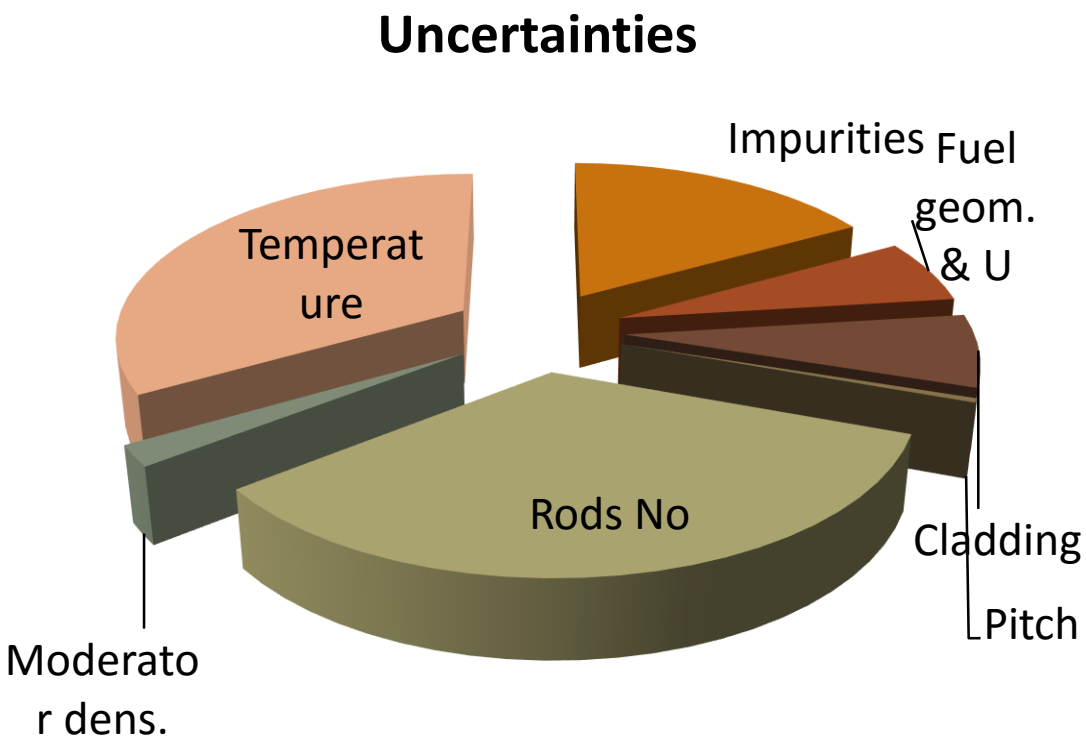
KEFF TOTAL UNCERTAINTY = 0.00102



Parameter	Sens. Coeff.	Std. uncertainty
Impurities	-	0.00025
U-235, 10^{-24} 1/см^3	24.81±0.34	0.00013
U-238, 10^{-24} 1/см^3	-(0.486±0.020)	
Pellet D, 1/cm	0.679±0.019	
Fuel height, 1/cm	(2.01±0.16) 10^{-3}	
Clad inner D, 1/cm	0.3247±0.0173	0.00015
Clad outer D, 1/cm	-(0.464±0.028)	
Clad density, cm^3/g	-(4.7±2.6) 10^{-3}	
Fuel rod pitch, 1/cm	0.112±0.006	0.00004
Num. of rods	(1.25±0.08) 10^{-3}	0.00072
Moder. dens. , cm^3/g	0.394±0.019	0.00008
Assembly T, 1/K	(1.24±0.05)10^{-4}	0.00064

Critical assembly having pitch 2.100 cm (Keff=1)

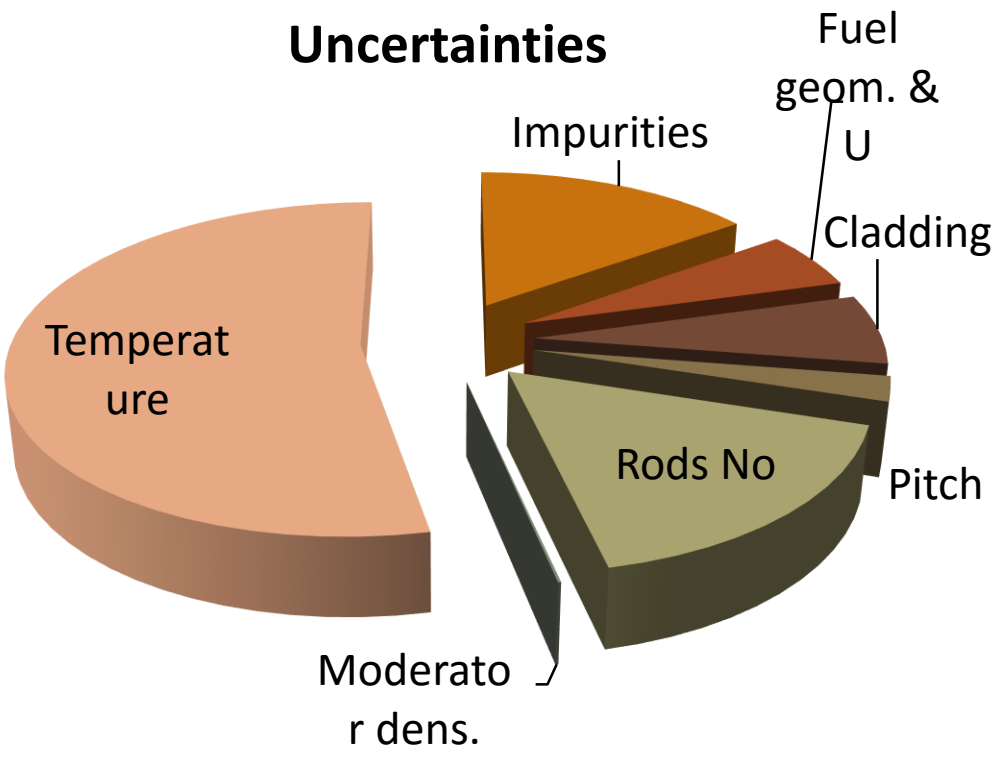
KEFF TOTAL UNCERTAINTY = 0.00125



Parameter	Sens. Coeff.	Std. uncertainty
Impurities	-	0.00041
U-235, 10^{-24} 1/см^3	28.18±1.03	0.00015
U-238, 10^{-24} 1/см^3	-(0.512±0.016)	
Pellet D, 1/cm	0.771±0.026	
Fuel height, 1/cm	(1.89±0.09) 10^{-3}	
Clad inner D, 1/cm	0.332±0.007	0.00017
Clad outer D, 1/cm	-(0.428±0.033)	
Clad density, cm^3/g	-(4.7±2.8) 10^{-3}	
Fuel rod pitch, 1/cm	-(1.96±0.44) 10^{-2}	0.00001
Num. of rods	(1.44±0.12) 10^{-3}	0.00083
Moder. dens. , cm^3/g	0.289±0.013	0.00005
Assembly T, 1/K	(1.393±0.039)10^{-4}	0.00081

Critical assembly having pitch 2.778 cm (Keff=1)

KEFF TOTAL UNCERTAINTY = 0.00147



Parameter	Sens. Coeff.	Std. uncertainty
Impurities	-	0.00038
U-235, 10^{-24} 1/см^3	35.254±0.895	0.00014
U-238, 10^{-24} 1/см^3	-(0.553±0.025)	
Pellet D, 1/cm	0.916±0.014	
Fuel height, 1/cm	(2.06±0.05)10^{-3}	
Clad inner D, 1/cm	0.367±0.010	0.00017
Clad outer D, 1/cm	-(0.273±0.023)	
Clad density, cm^3/g	-(6.18±1.67)10^{-3}	
Fuel rod pitch, 1/cm	-(1.767±0.029)10^{-1}	0.00006
Num. of rods	(7.20±0.52)10^{-4}	0.00042
Moder. dens. , cm^3/g	-(1.79±0.90) 10^{-2}	0.000003
Assembly T, 1/K	(2.141±0.058)10^{-4}	0.00134

Conclusion

Criticality experiments on water-uranium assemblies of "Rosa" facility performed in 1972 at the Institute for Nuclear Power Engineering of Academy of Sciences of BSSR are reevaluated and uncertainty analysis is performed.

Four triangular lattices with the 21% enriched uranium dioxide fuel rods and 1.050. 1.819. 2.100 and 2.778 cm pitches are studied.

Results of calculations are in good agreement with the experiment. Uncertainty analysis performed demonstrates that the four evaluated experiments satisfy the criteria of the International Criticality Safety Benchmark Evaluation Project (ICSBEP) and thus can be considered as benchmarks and submitted further for the international review.

Thank you for attention!