1. CRITICAL EXPERIMENT ON ZERO POWER LIGHT WATER REACTOR

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1.1. INTRODUCTION

The critical experiment on a zero power light-water-moderated reactor is described in the lesson. Necessary theory, technical equipment and measurement procedures used on LR-0 reactor, including an example of real experimental data measured on LR-0, are presented.

The LR-0 reactor located in Řež near Prague (Czech Republic, operated by Research Center Řež ltd.) is an experimental zero power light-water-moderated reactor. It was originally designed for the research of the VVER-1000 and VVER-440 fuel lattice cores. The LR-0 fuel elements are in radial direction identical while they are axially shortened relative to VVER NPPs fuel. Available fuel assemblies have 2.0–4.4 wt.% ^{235}U enrichment. Experiments are realized at atmospheric pressure and room temperature. The moderator can be demineralized water or water with diluted boric acid. The change of the moderator level or control-cluster position is used to control reactor power. Continuous maximal nominal power is nominally 1 kW with neutron thermal flux density $\approx 10^{13}$ $cm^{-2}s^{-1}$.

The main objective of projects that are being solved on the LR-0 reactor is to create experimental data bases, which could be utilized for verification of codes and libraries used for neutronic calculations in safety analyses of criticality of cores, storage and transport-cask lattices for VVER type reactors. The first criticality was reached in December 1982. The general LR-0 reactor scheme is shown on Figure 2.

1.1.1. Theoretical background

The critical experiment is the measurement with defined procedure of the reactor staff activities and reactor systems operations, whose aim is to determine parameters of the critical core. The core is critical when effective multiplication factor k_{eff} =1.0 and fission reactions are maintained spontaneously. Reaching a critical state can be achieved in several ways: by adding fuel (increase number of the fuel assemblies), change of the moderator level, change of the neutron absorption either due to the insertion of control rods or due to the change of boron acid concentration in the moderator. The method of the criticality determination is based on the neutron flux measurement (multiplication of the neutron generations) in response to the changes to parameter affecting core state (critical condition?).

In a simple point kinetics model it is supposed that the reactor can be described as one-point. It means that the thermal neutron flux density in the core and in the reflector are proportional to each other and neutron detector at any point in the reactor measures the value which is directly proportional to the reactor power.

Time dependent neutron distribution is described in point kinetics theory [1] as

$$\frac{dn}{dt} = \frac{\rho - \beta}{\Lambda} n + \sum_{g=1}^{G} \lambda_g C_g + S \qquad (1)$$

$$\frac{dC_g}{dt} = \frac{\beta_g}{\Lambda} n - \lambda_g C_g \qquad (2)$$

where n is average neutron density at time t, C_g is average density of delayed neutron precursor group G at time t, S is the external neutron source density emission in per second, ρ = reactivity, Λ= neutron generation time, λ_g = decay constant for precursors group G, β_g = delayed fraction for precursors group G.

$$\rho = \frac{k_{eff} - 1.0000}{k_{eff}} = \frac{\delta k}{k_{eff}}$$

Effective multiplication factor (k_{eff}) is defined as

$$k_{eff} = \frac{production}{absorption + leakage}$$

Coefficient k_{eff} within critical experiment depends on core parameters that change at each measurement step. Coefficient k_{eff} determines whether the neutron density within a reactor will remain constant or it will change.

Power is directly proportional to neutron density
k_{eff} = 1.00 → critical reactor (power constant)
k_{eff} < 1.00 → subcritical reactor (power decreasing)
k_{eff} > 1.00 → supercritical reactor (power increasing)

The core is assembled before the start of the critical experiment, i.e. required number of fuel assemblies with pre-defined enrichment ^{235}U is inserted to the reactor vessel without moderator. Reaching the critical state of experimental light water reactors is carried out by sequential addition of moderator.

Then as the zero step, neutron source is inserted to the position under the core and moderator is pumped into the vessel up to the level where core remains highly subcritical (the effective multiplication coefficient k_{eff} << 1.0 at this initial state). In the zero step there is moderator level H_0 and neutron detectors measured values, which are proportional to the total number of neutrons in core (n_0).

After i^{th} addition of moderator (step i), the change of the moderator level will increase neutron multiplication as well as coefficient k_{eff}. For number of neutrons holds

$$n_1 = n_o + n_o * k_{eff} + n_o * (k_{eff})^2 + n_o * (k_{eff})^3 + ... n_o * (k_{eff})^m \quad (3)$$

where m is number of neutron generations (step of moderator addition).

From relation (3)3) follows for subcritical reactor with external neutron source (k_{eff} <1) that number of neutrons is described as

$$n_i = n_o * \frac{1}{1 - k_{effi}} \quad (4)$$

Solving the system of equations (1) and (2) for steady state with external neutron source leads also to the relation (4).

This relation is used to estimate coefficient k_{eff} from number of neutron measured at i^{th} step as

$$k_{effi} = 1 - \frac{n_0}{n_i} \qquad (5)$$

As follows from relations (4) and (5) the more the critical state is approached the more numbers of neutrons increase and coefficient k_{eff} is close 1.0. When variable parameter is close to its critical value measured count rate will increase beyond all limits and as illustrated on Figure 2 inverse count rate is close to zero. Thus, the variable core parameter (moderator level) at the time of the criticality (k_{eff} =1.0) can be predicted by extrapolating this function to zero.

1.1.2. Experimental theory

Criticality of the experimental light-water reactor must be reached only by adjusting the moderator level in order to measure basic critical core parameter, critical moderator level. The core must be without any perturbation (no absorption rod is inserted into the core) to ensure this measurement. The time-dependent neutron-flux measurement during the experiment is performed using 2–4 neutron detectors with related nuclear instrumentations. The detectors are placed in dry channels in the reflector. The count rate is measured by counters controlled by a PC-based data-acquisition system. The data of moderator level are transferred simultaneously with neutron count rates to the data-acquisition PC system.

The measurement of reactivity as a function of moderator level in the vicinity of the estimated critical moderator level is used to determine exact critical moderator level together with its uncertainty. Estimated critical moderator level is determined by calculations which are carried out before start of the experiment. The critical moderator level (H_{cr}) depends on core material and geometry parameters (the core map specifying fuel assembly positions and enrichments, see Figure 1).

Using a one-group diffusion model the relation for the effective multiplication factor is following

$$k_{eff} = \frac{k_\infty}{1 + B^2.M^2}$$

where k_∞ is infinite multiplication factor, B^2 is material buckling and M^2 is migration area.

At critical state holds that material buckling is equal to geometry buckling. Thus for moderator levels slightly under or over H_{cr} reactivity may be expressed from above relation as

$$\rho(H) = \frac{C}{\left(H_{cr} + \lambda_z\right)^2} \left[\frac{1}{\left(1 + \frac{H - H_{cr}}{H_{cr} + \lambda_z}\right)^2} - 1 \right] \qquad (6)$$

where C is constant and λ_z is the axial extrapolation length.

If the reactivity is less than 0.001875 (25 ¢), the relation (7) resulting in a Taylor expansion around Hcr may be used.

$$\rho(H) = f(H, a_1, a_2) = a_1 (H-a_2) \left(1 - \frac{3}{2} \frac{H - a_2}{H_{cr} + \lambda_z} \right), \quad (7)$$

where reactivity level coefficient $\delta\rho/\delta H = a_1$ and critical moderator level $H_{cr} = a_2$.

This approximation or its linearization was used to determine critical parameters (a_1, a_2). Reactivity for various moderator levels around critical height is evaluated by the inverse kinetics method with time-dependent neutron counts input. The exact critical level by regression analysis is determined from reactivity values corresponding to three to seven supercritical moderator levels.

The reactimeter and data acquisition are implemented on LR-0 reactor using an independent EWS computer system [2]. More details regarding application of such method can be found in [3], material details of LR-0 reactor fuel and other structures are in [4].

An example of experimental values for critical moderator level H_{cr} and the moderator level reactivity coefficient are listed in the chapter 1.10.

1.2. PURPOSE

Knowledge of the exact critical core parameters is important not only during initial start-up of the reactor, but also within any period of reactor exploitation. It determines the level of safety of any measurement and irradiation at the reactor. The critical experiment is also experimental verifications of material and geometric parameters of the core predetermined by the calculation. A comparison of the results of critical experiment and calculation can adjust calculation methods and models, used constants and data libraries.

The purpose of this lecture is to provide all participants an overview of the critical experiment carried out on critical reactor.

1.3. SAFETY MEASURES

Even that the students stay mainly in the control room (where very low radiation dose rate is during experiment), standard regulations for control of radiation exposure in the laboratory for health and safety should be demonstrated to the experimenters. The general radiation protection safety measures for each student during this experiment are:

- Personal dosimeter for each course participant provided by the health physics group;
- Use of lab coat, and boots;
- Spend as little time as possible in the control area;
- Each course participant should check for possible contamination using a hand-foot monitor when leaving controlled area.

1.4. INSTRUMENTS AND MATERIALS

The neutron flux time distribution is measured with experimental detection system. It needs the following equipment:

- LR-0 reactor with an operating power of 0.01–10 W for this experiment
- An appropriate number (2–4) of special experimental neutron detectors located in dry tube in lateral reflector (See Figure 1)

- Special neutron counting electronics
- Precise moderator level meter with output on control panel and data storage on PC
- A PC based data control and storage system – reactimeter (ESW at LR-0 reactor)
- PC for data evaluation.
- A contamination monitor

1.5. EXPERIMENTAL PROCEDURE

Critical experiment on light-water moderated experimental reactor has following sequence of steps and activities that follow core assembling:

a) The determinations of the multiplication factor k_{eff} and critical moderator level for successive moderator levels. The end of the critical experiment is when condition k_{eff} =0.995 has been met.
b) Determination of reactivity moderator level coefficient $\delta H/\delta\rho$, absorption cluster integral worth and diferential reactivity coeficient, i.e. reactivity measurement for several parameters changes (moderator level, cluster insertion) at known critical moderator level (known core).

The time delay is required at each succesive step of measurement to decrease the transition process caused by change of the variable parameter. When neutron flux is stabilized, numbers of neutron counts are sampled and recorded in the log book. Neutron inverse count rate and parameters (H_{cr}, k_{eff}) estimations are shown on an ESW display and they are also written to ESW disk for archiving and subsequent analysis.

In all stages of a critical experiment the conditions for reactivity change rate must comply with pre-set values. It is also necessary to carefully monitor values especially of these parameter that affect change of reactivity, neutron channel signals and other core parameters data. Proper function of safety and control systems and other technologies and experimental systems are also monitored.

Requirements of the critical experiment and correct and safety approaching the critical state, i.e. the choice of the next changes in moderator level or clusters insertion that ensure nuclear safety within all steps, are caried out in accordance with standard procedures to reach an unknown critical state

At the beginning of each criticality measurement, the moderator level is stepwise increased and steady neutron flux (counts) is measured for every step. Measured count rate increases depending on the moderator level change (see relation (4) and illustration on Figure 3). Effective multiplication coefficient and critical moderator level are estimated after each moderator addition (change).

General procedure for determining the critical parameter within critical experiment on light water moderated experimental reactor is the following.

(1) Initial core state (described by fuel composition, moderator and reflector data and other structural components) is set not to exceed 2/3 of the expected critical value parameter being changed within critical experiment. This parameter has to be determined by validated code. (Conservatively this parameter value can be selected so that initial $k_{eff} \leq 0.5$). It is not permitted to change more than one parameter in the core at any given time. This should be ideally monitored continuously and remotely by safety and control system. The changes must be reversible and sufficiently precise to monitor. The changes are performed step by step, so that extrapolation of the monitored parameter can be sufficiently accurate in determination of the expected criticality.

(2) The second and subsequent parameter changes should be made in steps corresponding to a maximum of 1/5 of the difference between $k_{eff} = 1.0$ (expected critical parameter value) and estimated k_{eff}, corresponding parameter value realized in previous steps.

(3) The values of measuring neutron channels N_i and the value of the changed core parameter are recorded in each step.

(4) After each step, parameters defining the expected critical value are estimated and refined. It is presumed that the value of the parameter showing the smallest critical value with acceptable accuracy is the correct one.

(5) When the criticality of the core compared to the expected critical parameter is $7\,\beta_{eff}$ ($k_{eff} \approx 0.950$), next reactivity changes are allowed to perform by moderator level increase in one step corresponding to the reactivity change less than $0.7\,\beta_{eff}$.

(6) The critical experiment ends when core subcriticality compared to the expected criticality is less than $0{,}7\,\beta_{eff}$. Subsequent parameter changes can be performed by a standard method of the aproach to the known reactor critical state.

If the moderator level is then stepwise decreased to a subcritical level, and if all moderator level changes would be used for Hcr determination, two parallel lines are obtained for the water level dependence of reactivity, crossing zero reactivity at two points corresponding to water levels varying by 0.15–0.3 cm. The moderator level changes used for the Hcr determination are those that keep fuel elements always dry above the moderator level (only those in the upward direction). This procedure eliminates the water meniscus-shape effect found in dense fuel elements lattices. The neutron flux has to be reduced after the 2 or 3 supercritical states as soon as neutron count rates measured by the experimental detectors are in the interval 4×10^4 to 10^5 s^{-1}. At the light water reactor it is done by the insertion of an absorption cluster or by decreasing the water level to a subcritical level. The water level returns to the dry lattice in the next increase of water level.

The relation (7) is used for the criticality measurement when there are between three to seven supercritical water levels.

Function of inverse count rate cross the x-axis when the critical state (critical moderator level) is reached (see Figure 3). Thus, we can predict the variable parameter (moderator level) at the time of the criticality ($k_{eff} = 1.00$) extrapolating this frequency curve to zero.

1.6. MAIN PARAMETERS MEASURED

Moderator level - measured by means of an experimental water measuring unit (electric needle contact type level meter) with output on the digital display. According to technical data the uncertainty of the LR-0 experimental contact level meter is 0.3 mm (unit tolerance) within the whole measuring interval up to 1600 mm, and 0.12 mm within an interval of 500 mm and 0.03 mm within an interval of 40 mm in the vicinity of the critical level. The level meter output is displayed at control system screen and stored to the ESW system.

The neutron flux sampled steady value measured by the neutron detector located in dry tube in lateral reflector. After adding defined moderator amount, moderator increases to new level. Steady neutron flux is then measured after some time interval (delay) to suppress the transition effects caused by moderator level change. Neutron counts are displayed on the control system screen and stored to the ESW system.

1.7. TYPICAL REAL DATA COLLECTED

The example of the collected data for critical experiment performed on LR-0 reactor on core are illustrated on Figure 3 and shown on Table 1. Neutron number at each step is measured (sampled) for selected time interval. An average count rate of sampled neutron counts is taken.

Table 1 The example of the critical experiment on LR-0 reactor experimental neutron detectors count rate and estimation of effective multiplication coefficient

H	**M1**	**M2**	**M3**	$\mathbf{k_{eff}}$ **(M1)**	$\mathbf{k_{eff}}$ **(M2)**	$\mathbf{k_{eff}}$ **(M3)**
[mm]	[s^{-1}]	[s^{-1}]	[s^{-1}]			
100.20	0.213	0.228	0.033	-	-	-
240.00	**0.943**	**0.453**	**0.067**	N_0 (H=240)		
291.10	5.350	0.860	0.123	0.8237	0.4733	0.4553
430.30	23.960	15.299	1.989	0.9606	0.9704	0.9663
550.00	44.750	68.606	10.222	0.9789	0.9934	0.9935
600.00	70.550	141.601	18.856	0.9866	0.9968	0.9965
640.00	106.690	258.161	37.744	0.9912	0.9983	0.9982
665.70	143.050	367.356	54.744	0.9934	0.9988	0.9988
685.20	202.870	514.226	77.999	0.9954	0.9991	0.9991
700.15	226.670	557.049	83.151	0.9958	0.9992	0.9992
710.20	262.110	689.269	105.700	0.9964	0.9993	0.9994
716.25	342.920	852.991	135.889	0.9973	0.9995	0.9995
719.12	384.880	932.533	150.444	0.9976	0.9995	0.9996

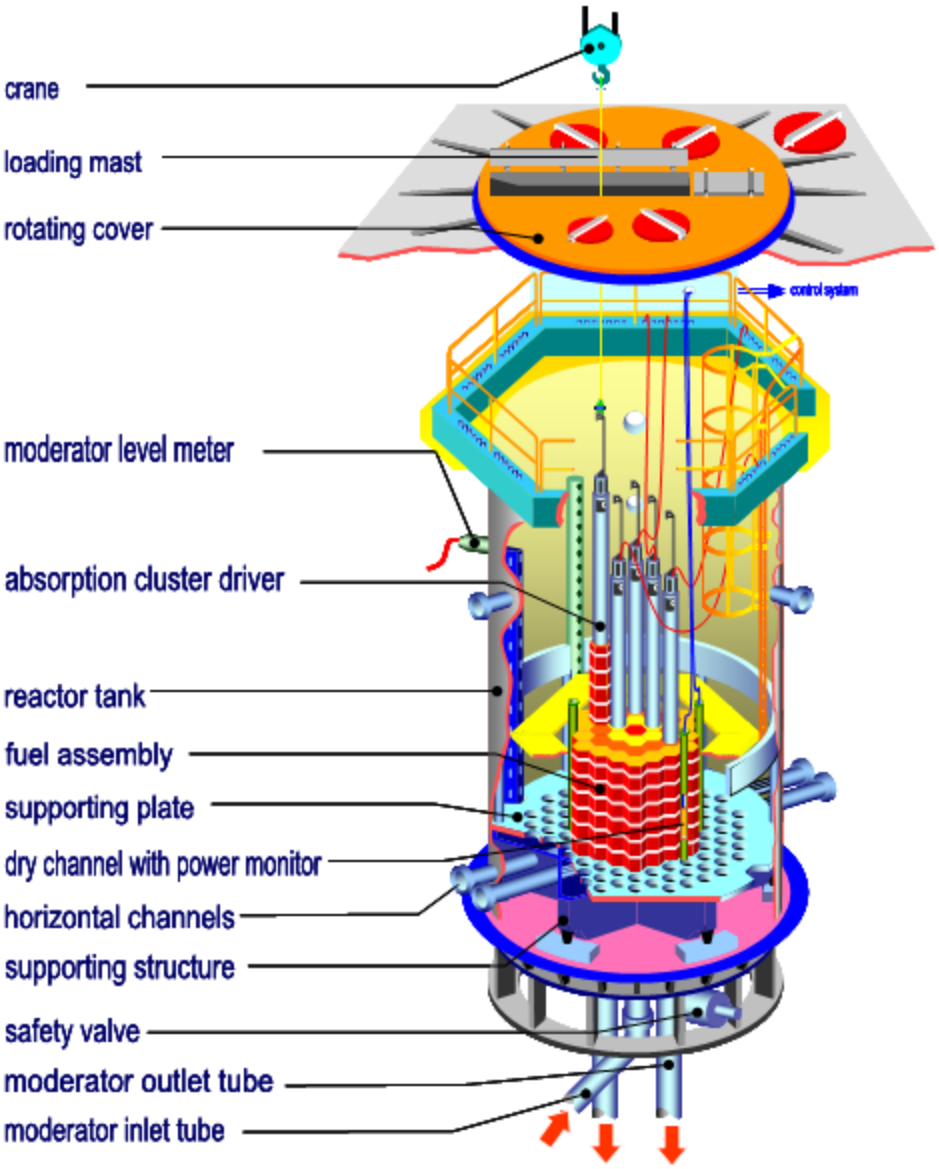


Figure 1. The scheme of LR-0 reactor

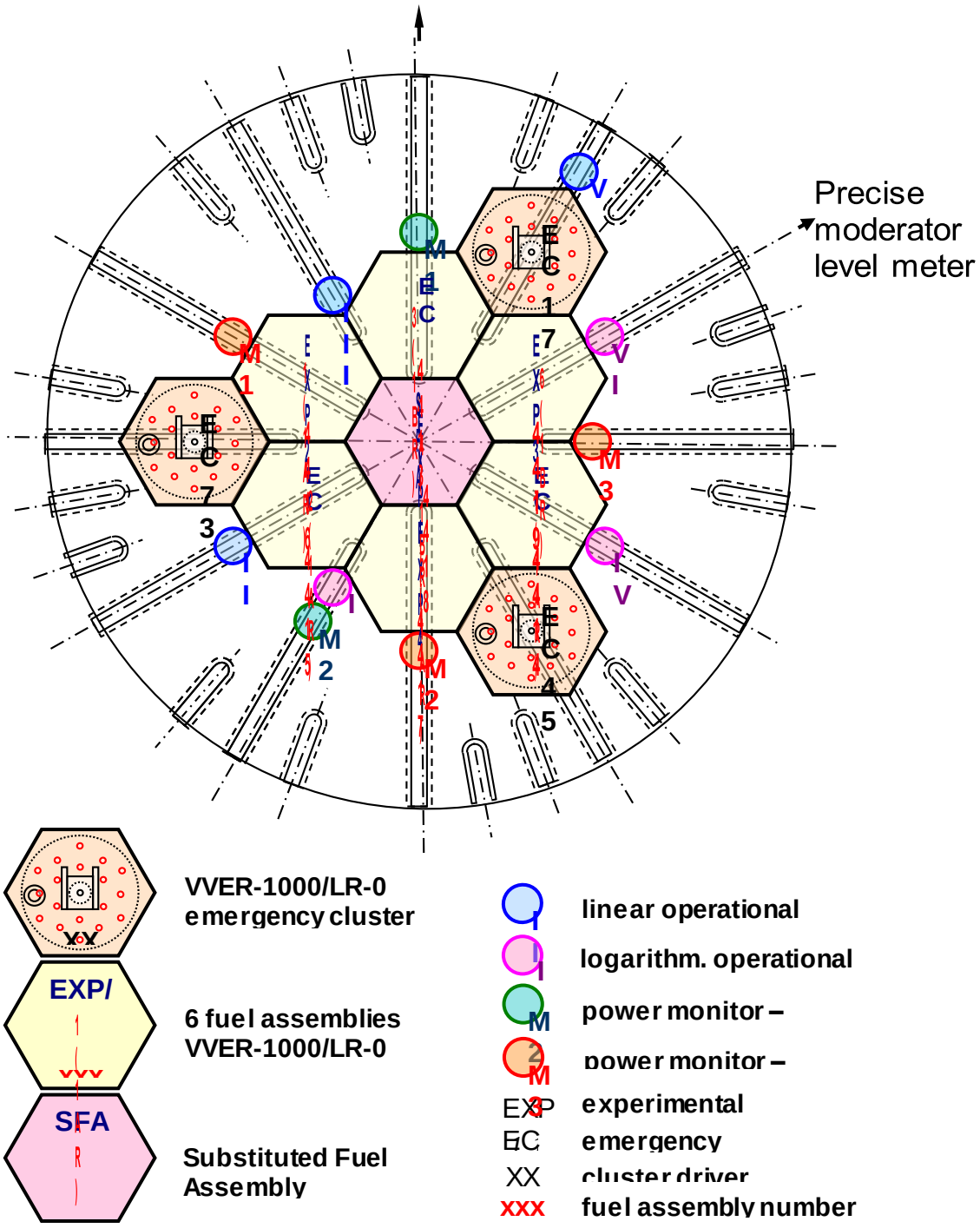


Figure 2. LR-0 reactor with VVER-1000 type core and neutron flux (power) monitoring system. An example of LR-0 reactor core map with special experimental neutron detectors.

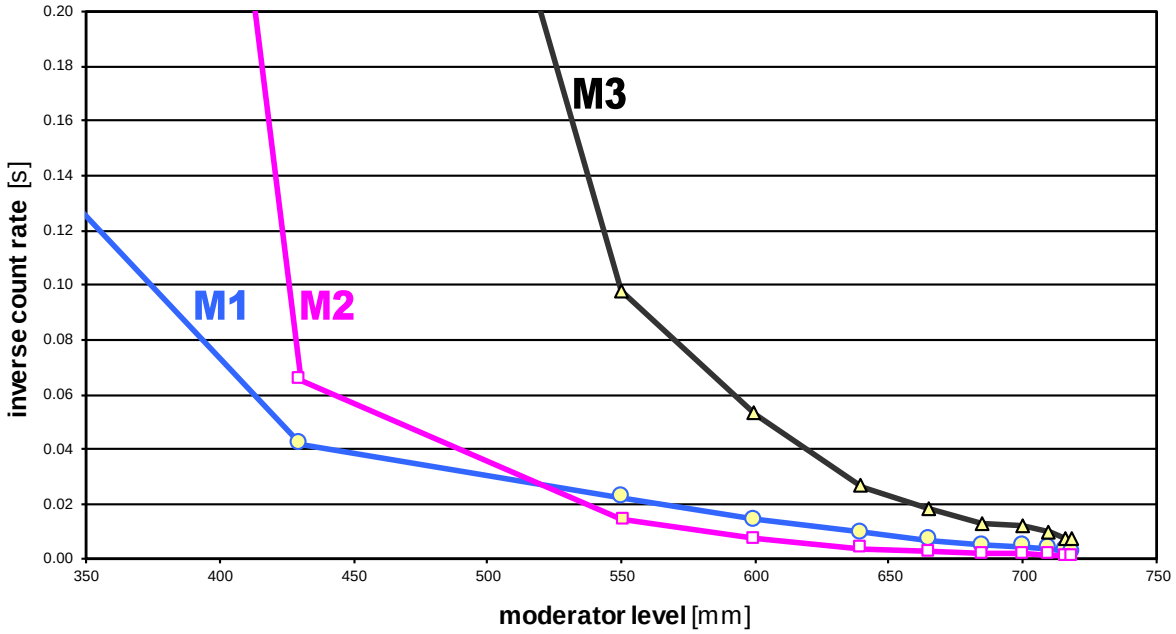


Figure 3. Critical experiment on LR-0, Inverse neutron count rate, 15.11.2004. M1, M2, M3 – reactor power monitors (see Figure 2)

1.8. DATA ANALYSIS, ASSUMPTIONS AND EQUATIONS

To estimate effective multiplication formula and critical moderator level in individual step of the criticality measurement the following formulae are used:

The estimation of effective multiplication parameter is determined from relation (5). From relation (4) follows, that at critical moderator level inverse neutron count rate goes to zero (see Figure 3).

$$H_{cr} = H(\frac{1}{n_i} \to 0) \tag{8}$$

The estimation of the critical moderator level is determined from count rate inverse function extrapolation to zero or from its linear function ($1/n_i = A_0 + A_1 * H_i$) regression.

$$H_{cr} = -\frac{A_0}{A_1} \tag{9}$$

The estimation of the exact critical moderator level and its uncertainty are also determined from reactivity function (7) or its linearization regression analysis.

1.9. PRE-KNOWLEDGE REQUIRED FROM STUDENTS

Students should possess a basic knowledge in

- Nuclear physics: the different types of cross sections and nuclear reactions, radiation decay and the half-life
- Reactor physics: the nuclear fission, point neutron kinetics, one-group diffusion theory, multiplication factor

The participants should have an understanding about radioactive decay, dose rates and limits, activity and basic aspects regarding radiation physics and protection

1.10. RESULTS

Using the relations (7) and (9), with the measured neutron count rates referred to in CHAPTER 1.7, the estimation of the critical moderator level listed on Table 2 were obtained. Figure 3 shows inverse thermal neutron counts during critical experiment.

Table 2. Critical moderator level and reactivity level coefficient estimations

detection system	H_{cr} [cm]	σH_{cr} [cm]	$\delta\rho/\delta H$ [pcm/cm]	$\sigma\ \delta\rho/\delta H$
M1	72.14	0.06	190.39	2.77
M2	72.17	0.06	203.41	4.72
M3	72.18	0.06	207.36	3.36
average	72.16	0.06	200.39	3.21

1.11. CONCLUSIONS

The critical experiments on the LR-0 reactor (experimental zero-power light-water moderated) in Řež are performed by validated procedure using the change of moderator level. The illustration on Figure 3 shows dependence of neutron counts during the critical experiment. It can be noticed that using neutron counts and one-point theory with simple extrapolation or regression analysis can be used to fit critical moderator level.

REFERENCES

[1] D.L. Hetrick, 1993. Dynamics of Nuclear Reactor. American Nuclear Society, Illinois, USA, ISBN 0-89448-453-2

[2] V. Juricek, Experimental workstation “EWS” in the LR-0 reactor control room, UJV Rez Report No. 13044, 2009

[3] M. Košťál, V. Rypar, V. Juříček, The criticality of VVER-1000 mock-up with different H3BO3 concentration, Annals of Nuclear Energy, Vol. 60, October 2013, pp 1-7, ISSN 0306-4549, doi:10.1016/j.anucene.2013.04.014

[4] J. Kyncl, V. Rypar, E. Novák, LEU-COMP-THERM-087 „VVER Physics Experiments: Hexagonal Lattices (1.22 cm Pitch) of Low Enriched U(3.6, 4.4 wt.% ^{235}U) O_2 Fuel Assemblies in Light Water with Variable Fuel Assemblies Pitch”, 2008, NEA/NSC/DOC/(95)03/IV Volume IV