

CRITICAL AND SUBCRITICAL EXPERIMENTS USING THE TRAINING NUCLEAR REACTOR OF THE BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS

É. M. Zsolnay

*Department of Nuclear Techniques,
Budapest University of Technology and Economics*

1. Introduction

A knowledge of the source multiplication characteristics of a subcritical assembly is important for many reasons. It is required for safe approach to criticality by power and research reactors, and subcritical assemblies can be used to measure important reactor parameters. Measurements will be made with the Training Nuclear Reactor (TNR) of the Budapest University of Technology and Economics to obtain such information. The experiment will be started with measurements on the reactor operated as a subcritical system, then the reactor will be made first critical, then slightly subcritical and the excess reactivity will be determined.

2. Theory

Criticality is defined by

$$k_{eff} = 1$$

where

$$k_{eff} = k_{\infty} P_{NL} = \eta \varepsilon p f P_{NL} \quad (1)$$

using standard notation for k_{∞} , η , ε , f and p , and P_{NL} is the non-leakage probability of the core. The average number of fission neutrons, η , emitted as a result of the capture of one thermal neutron in the fuel, and the fast fission factor, ε , are fixed by the fuel material and size. The thermal utilization, f , and the resonance escape probability, p , depend on the relative concentration of the various reactor materials. The non-leakage probability P_{NL} , determines the fraction of neutrons that do not escape from the reactor core and is dependent on the core size and composition and the properties of the reflector.

During the criticality experiment the volume to surface ratio of the reactor is increased step by step, until P_{NL} , which increases with increasing volume to surface ratio, has obtained such a value that the effective multiplication factor (k_{eff}) is at least equal to unity; i.e., the reactor is critical. In the subcritical state, $k_{eff} < 1$, the strength of an extraneous neutron source is multiplied by the active lattice. If the neutron source emits S neutrons per second, there will be Sk_{eff} new neutrons at the end of the first generation, $(Sk_{eff})k_{eff}$ neutrons at the end of the second generation, etc. Thus, the subcritical multiplication, M , is

$$M = \frac{S + Sk_{eff} + Sk_{eff}^2 + Sk_{eff}^3 + \dots + Sk_{eff}^n}{S} = 1 + k_{eff} + k_{eff}^2 + k_{eff}^3 + \dots + k_{eff}^n \quad (2)$$

Since the expansion of $(1-x)^{-1} = 1 + x + x^2 + x^3 + \dots + x^n$ (3)

$$M = \frac{1}{1-k_{eff}} = 1 + k_{eff} + k_{eff}^2 + k_{eff}^3 + \dots + k_{eff}^n \quad (4)$$

The subcritical multiplication M defined by Eq. (4) can theoretically be reached only after an infinite time period. The real multiplication approaches this value asymptotically (see Figure1). However, in practice a certain finite time T_s can be defined to reach the asymptotic value. The magnitude of the time period T_s depends on the number of terms can be ignored in Eq. (2). Obviously, the less is k_{eff} , the more strongly decrease the terms in the expansion of Eq. (2), and as a result the less terms have to be taken into account to remain within the required error limit, therefore, the less time is necessary for the multiplication to reach its value defined by Eq. (4).

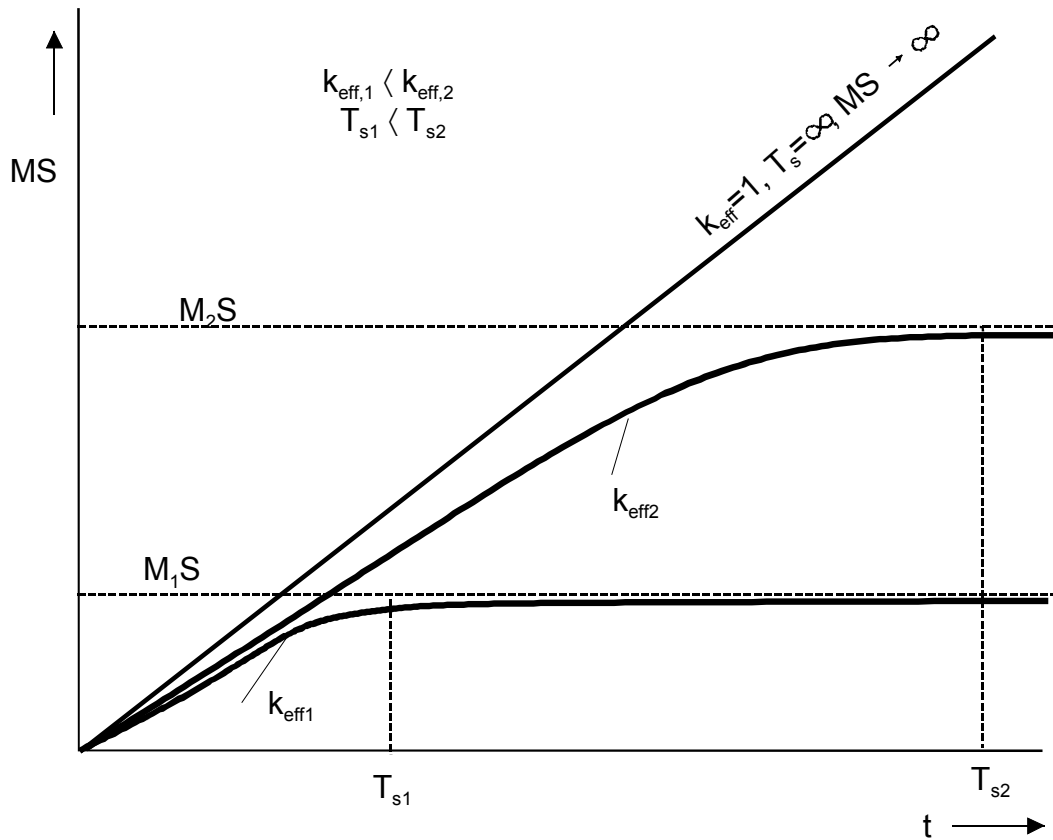


Figure 1. Time dependence of the source strength

If the number of neutrons from the extraneous neutron source which enter the core per second is S then the number of neutrons which are present in the core at any second is

$$MS = S \frac{1}{1-k_{eff}} \quad (5)$$

As k_{eff} in the present case is between 0 and 1 (but smaller than 1), the denominator of Eq. (5) is always smaller than 1, therefore, $M > 1$ will be obtained. The larger is k_{eff} , the larger will be M as well, and at $k_{eff} = 1$, M will become infinite (see also Figure1).

Equation (5) describes the integral effect of all neutrons in the reactor core. These neutrons will create a spatial neutron flux distribution $\phi(x,y,z)$ in the core. If one then places a neutron detector near the core at position x , then the count rate of the detector (N) will be some fraction of the neutrons present in the core and proportional with the neutron flux at the place of the detector:

$$N \text{ (cpm)} = c \cdot \phi(x) = \frac{c}{1 - k_{\text{eff}}} \cdot S \quad (6)$$

where c is a constant, depending on the geometry and material composition of the core (determining the neutron flux distribution), furthermore, it involves the counting efficiency of the neutron detector, applied in the experiment, as well.

Knowing the value of c and S , furthermore, by measuring the count rate of the detector N , the effective multiplication factor can be calculated:

$$k_{\text{eff}} = 1 - \frac{c \cdot S}{N} \quad (7)$$

If we take the reciprocal of the count rate

$$\frac{1}{N} = \frac{1 - k_{\text{eff}}}{c \cdot S} \quad (8)$$

and make a plot versus the amount of fuel, it is seen that when $k_{\text{eff}} = 1$, the parameter $1/N$ will be zero. k_{eff} will increase with the number of added fuel elements; i.e., with the mass of ^{235}U which is loaded into the active lattice. From a plot of the reciprocal count rates versus the amount of fuel in the reactor the additional amount of fuel required for criticality can be continuously estimated by extrapolating the curve plotted. After each extrapolation procedure only a small fraction of the amount of fuel predicted to be necessary for the criticality is loaded into the core. Thus the critical condition is approximated step by step.

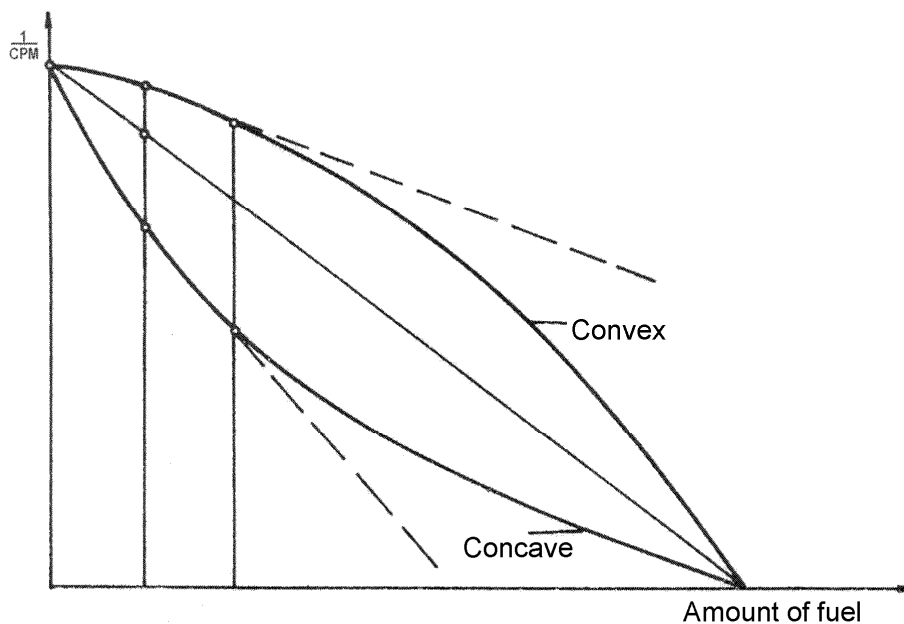


Figure 2. Extrapolation of the critical mass

Figure 2 shows three types of curves which are possible to obtain with this type of experiment. Ideally one would like to have the linear curve since, once one would have two points on the curve, the exact amount of fuel required for criticality would be known. If the value of reactivity of a fuel element was independent of its position in the active lattice, the reciprocal count rate would be proportional to the added number of fuel elements, and if the detector were located and working properly the ideal curve would be obtained.

However, because the worth in reactivity of any fuel element is dependent on the relative magnitude of the flux present, the reactivity worth is dependent on the position in the reactor where the element is added and on the sequence of this addition relative to the addition of other elements.

If the position of the detector relative to the source and the fuel is such that the detector is not sensitive to the small increase in count rate with the addition of the first few fuel elements, then the convex curve probably would be obtained. This convex curve can occur if the loading is such that the elements, which add the largest increments of reactivity, are loaded last instead of first. Note that with a convex curve one would always extrapolate a much greater amount of fuel than is actually necessary for criticality, which could lead to dangerous conclusions as to the amount of fuel to be added.

If all counting equipment is operating properly and the elements are added judiciously, the concave curve can be obtained. Note that this curve always predicts a conservative amount of fuel required for criticality, which should not lead to dangerous misinterpretation of the amount of fuel which can be added.

At the beginning of the experiment the reactor will contain a number of fuel elements, which are insufficient for criticality. A source of neutrons will be placed on one side of the core while the neutron detector will be located on the opposite side of the core from the neutron source. This is to ensure that the detector does not see the source neutrons directly, but will see the neutrons coming from the core and indicate the subcritical multiplication of the source neutrons.

In the practice, at the criticality experiments more neutron detectors are used, and the average of their responses is evaluated.

3. Object of the experiment

In this experiment instead of the number of fuel pieces required to obtain criticality, the position of the manual control rod necessary for the critical condition of the reactor is determined, to illustrate the approach-to-critical technique. At the end of the experiment the reactor will be taken also supercritical and the excess reactivity of the core will be determined using the power doubling time method.

4. Equipment needed for the experiment

- Reactor.
- Reactor control desk
- Neutron detector (BF₃ or ³He counter) and electronics with pulse counting system.

5. Procedure

5.1. Initial condition

Since frequent manipulation and movement of the fuel assemblies may lead to mechanical failures, the assemblies are not moved during the experiment. Instead, the critical condition of the core is approached by gradually withdrawing the control rods from the core. In this experiment the manual control rod position required to obtain criticality is determined

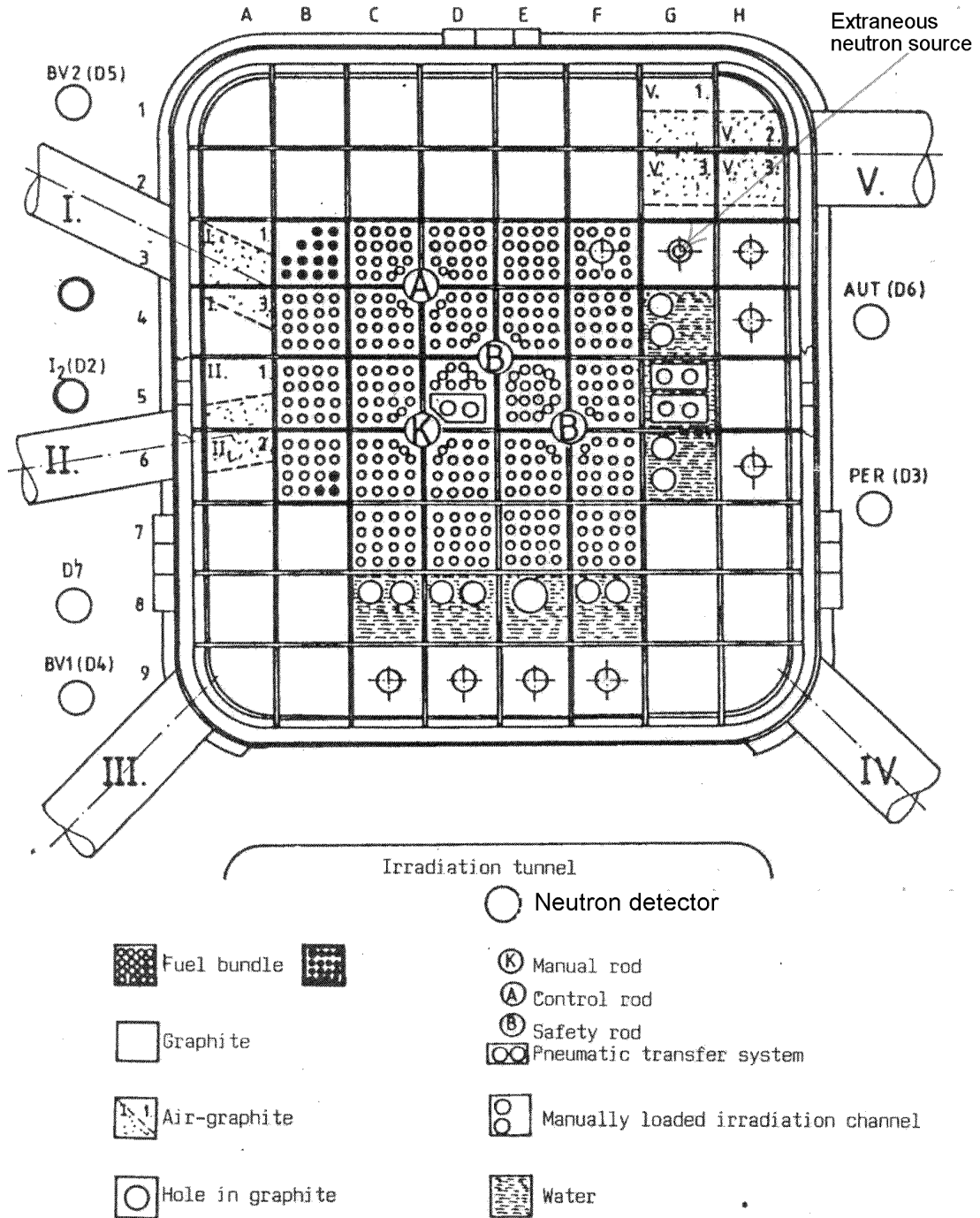


Figure 3. The horizontal section of the reactor core

to illustrate the approach-to-critical technique. The automatic control rod is in a fixed position during the procedure. At the end of the experiment the reactor will be taken also supercritical and the excess reactivity of the core will be determined using the reactor power doubling time method.

The core configuration of the reactor can be seen in Figure 3. The reactor contains more fuel elements than the amount needed for criticality. The excess reactivity of the core $\Delta\rho_{exc}$ is compensated by the safety (B) and control rods (K and A) inserted in the core. The composition of the manual control rod (K) is Boron carbide (B_4C) and its reactivity worth is $\rho \sim 186$ cent, while the automatic one (A) is made of Iron (Fe) and its reactivity worth is $\rho \sim 80$ cent. The criticality experiment will be carried out to obtain at the end a core with an excess reactivity of $\Delta\rho_{exc} \sim 10-12$ cent. The selection of the suitable rod positions will be done using the result of the criticality experiment and the control rod calibration curves.

As it has already been mentioned above in the theoretical part, the technique used to safely load a reactor with fuel, requires several neutron counters to detect the neutron population in the core and hence to determine the inverse multiplication after each step of loading. In this experiment only one neutron detector - a 3He counter will be used to illustrate the method.

The neutron detector (BF_3 or 3He counter) will be located in the first channel of the irradiation tunnel of the reactor in the centreline of the core. This is on the opposite side of the core from the neutron source (Figure 3).

At the beginning of the experiment the reactor will be taken deeply subcritical, inserting the control rods in the active core (the safety rods are out). The control rod positions needed to reach the required subcritical condition depend on the excess reactivity of the core, and these positions can be adjusted using the control rod calibration curves. The position of the automatic control rod will not be changed during the experiment, instead, the manual control rod will be withdrawn from the core step by step, and the critical condition will be approximated by the extrapolation procedure described in the theoretical part.

5.2. Approach to criticality

1. Reactor checkout

To assure safe operation of the reactor, a prescribed sequence of operations must be followed to start the reactor. Each day before the reactor is brought to critical a daily reactor checkout is performed to confirm by actual tests that all safety circuits are operating properly and that the reactor is in perfect, mechanical operating order. The standard checklist is available at the Reactor Operator.

2. Detector adjustment and measurement of the γ -background

After the checkout of the reactor is finished, all the safety (B) and control rods (A and K) are inserted in the core, and the neutron source is withdrawn from the core. Then the neutron detector is inserted to the first channel of the irradiation tunnel. The detector and the counting instrument are now adjusted. The discriminator base level of the counting apparatus has to be chosen in a way that it should cut the background deriving from the γ -radiation of the active core. The neutron detector is surrounded by lead shielding in order to decrease the intensity of the γ -radiation reaching its active volume. After adjusting the detector parameters, measure the γ -background and record it, to be taken into account later, during the measurement of the neutron intensities, if necessary.

3. Control rod positioning

Remove the safety rods (B) from the core, and adjust the manual (K) and automatic (A) control rods (with aid of the calibration curves of the control rods and the excess reactivity of the reactor core) in a way that the reactor should be deeply subcritical (ρ should be between -110 cent and -130 cent). The adjusted position of the automatic control rod (A) will not be changed during the experiment. Record the control rod positions and measure again the γ -background with the neutron detector. Compare the data with the value obtained in the former case! Draw conclusions!

4. Initial core

Leaving the control rods in the position adjusted in point 3, put the neutron source in the core and after waiting for the steady state condition, record the counting rate of the initial core (N_0). Compare it with the value of the background measured previously at the same rod positions, but without the neutron source. Draw the conclusions!

5. Approach to criticality

Draw back the neutron source from the core and wait while the neutron intensity decreases to a negligible value. Then draw back the manual (K) control rod from its former position by 100 mm and put the neutron source in the core again. Measure the neutron intensity, and after the steady state condition has been reached, record the counting rate (N_1) and convert it to inverse count rate relative to the initial count data (N_0/N_1). Then plot the data (obtained with the initial manual rod position and with the present one) on a diagram as a function of the manual rod position, and perform linear extrapolation to estimate the critical rod position. Thereafter draw back the neutron source from the core and wait while the neutron intensity decreases again to a negligible level. Then adjust a new manual rod position, put the neutron source in the core, and repeat the counting and extrapolation procedure as it has been done before. Thus approximate the critical manual rod position gradually. After each step in the experiment wait for the steady state, then record the counting data and convert them to inverse count rate relative to the initial count data (N_0/N_i , where N_i is measured in the i^{th} control rod position). Each time, when a new data point is obtained, use that point and the previous point to predict, by linear extrapolation, the critical control rod position. The manual control rod position should always be changed by the third or fourth value of the difference between the extrapolated critical rod position and the actual rod position in the topical step of the experiment!

5.3. Excess reactivity measurement

In the last step of the experiment the reactor will be made slightly supercritical. This condition can be adjusted based on the result of the criticality experiment and using the calibration curve of the manual control rod. Remove the neutron source. The excess reactivity is measured by observing the positive period of the reactor. Record the counts of the neutron detector until they show saturation character (the dead time of the counting apparatus is about 17 μs). Monitoring the rise of the neutron flux level and determining the doubling time of the reactor power level will make measurement of the positive stable reactor period.

6. Data analysis

1. Calculate the inverse multiplication of the subcritical core after each manipulation with the manual control rod and plot it versus the manual rod position. Make extrapolations step by step to predict the critical manual rod position.
2. Determine the excess reactivity of the supercritical assembly obtained after the last step of the experiment. The doubling time T_2 of the reactor power level is related to the stable asymptotic period T of the reactor by the following expression:

$$T = \frac{T_2}{\ln 2}$$

These asymptotic periods are related to reactivity by reactor kinetic equations and the usual inhour equation. The chart of reactivity versus the doubling time of the reactor power level will be available.

References

- [1] S. E. Livergant: Elementary Introduction to Nuclear Reactor Physics. John Wiley & Sons, Inc. New York, 1960.
- [2] S. Glasstone, A. Sesonske: Nuclear Reactor Engineering, Van Nostrand, New York, 1967.
- [3] G. J. Bell and S. Glasstone: Nuclear Reactor Theory, Van Nostrand, New York, 1970.
- [4] J. J. Duderstadt, L. J. Hamilton: Nuclear Reactor Analysis, Wiley, New York, 1976.