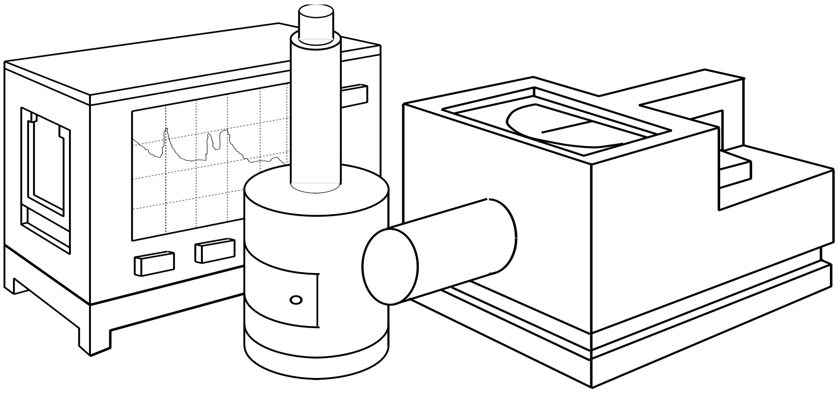
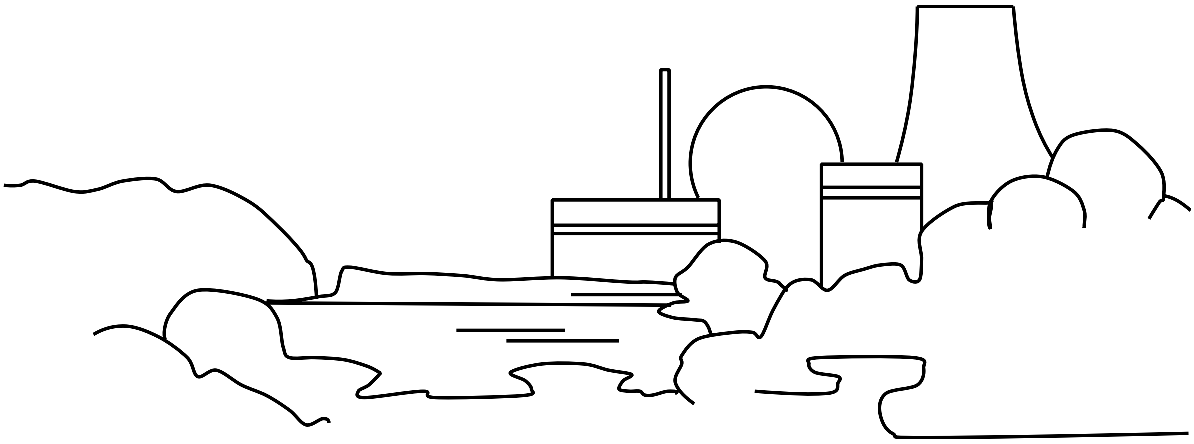
TECHNICAL UNIVERSITY DRESDEN
Institute of Power Engineering
Training Reactor



Reactor Training Course

Experiment

"Critical Experiment"



Instruction for
Experiment "Critical Experiment"

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(issued: March 2015)

1. Motivation

The critical experiment is a procedure for checking experimentally the correct core loading of a nuclear reactor with nuclear fuel. It is carried out in case of the initial commissioning of a nuclear reactor or in case after modification of the reactor core (geometry and/or material changes) if the critical mass and the critical control rod positions are only known from calculations.

The critical experiment ensures
- that, on the one hand, the reactor is actually loaded with sufficient fuel for obtaining criticality and
- that, on the other hand, the reactor core does not contain too much nuclear fuel to avoid that the permitted excess reactivity would be exceeded or that the reactor could even become prompt supercritical.

The reactor must be controllable by the control rods at any time, i.e. control rod movements must guarantee that both, multiplication factors $k>1$ and (for safety reasons even more important) $k<1$ can be adjusted.

For example, it may never happen that due to a too high fuel loading the AKR becomes critical or even supercritical already while the core sections still approach one to another, because in that case, control by the control rods would be impossible.

The critical experiment requires profound professional knowledge regarding the physical processes in a nuclear reactor and also a high level of responsibility of the operating staff. The critical experiment needs to be performed with special caution and care.

The training experiment aims at conveying the **measurement and analysis methods** for a critical experiment which enable
- an always safe approach to criticality and
- the reliable predetermination of the critical reactor parameters.

At the AKR, a critical experiment can be carried out in two ways:
- enlarging the amount of fuel in the reactor core by stepwise adding fuel-element plates or
- stepwise approach of the core sections to each other with having a fixed fuel loading in each of the sections.

For the initial commissioning of the AKR, the critical mass was adjusted by stepwise adding of fuel plates.

Because the manipulation of nuclear fuel requires a lot of effort and additional comprehensive precautions and prescriptions and is very time consuming, in the training procedure the critical experiment will be carried out by stepwise approach of the lower core section to the upper one.

2. Tasks

1. From the increase of the neutron density n which is caused by the stepwise approach of the lower core section of the AKR to the upper one, the distance x_{crit} that corresponds to criticality has to be determined by extrapolation.

2. From the measured neutron count rates N for the neutron density n, determine and plot the relation between the position x of the lower core section and
   - the multiplication factor $k(x)$,
   - the subcritical amplification $M(x)$, and
   - the reactivity ρ(x).

3. General Remarks

For every new-build reactor facility or after considerable modifications of its components, those parameters with a direct influence on the criticality have to be experimentally determined. In principle, this concerns all those quantities z_i which affect the neutron balance and correspondingly the criticality of the system:

$$k = f(z_1, \ldots , z_n)$$

The nuclear fuel itself as well as the moderator, the reflector, the control rods, the neutron detectors, the experimental facilities, and all other materials being located in the core belong to those quantities.

The level of influence is given by the material characteristics as well as by the installed masses and the geometric arrangement.

For the initial commissioning of a reactor, the starting point usually is an almost completed system with only one free parameter z_i. In the so-called "critical experiment", the system is led to criticality by variation of this single free parameter z_i, i.e. for $z_i \rightarrow z_{krit}$ follows $k \rightarrow 1$ (Fig. 1).

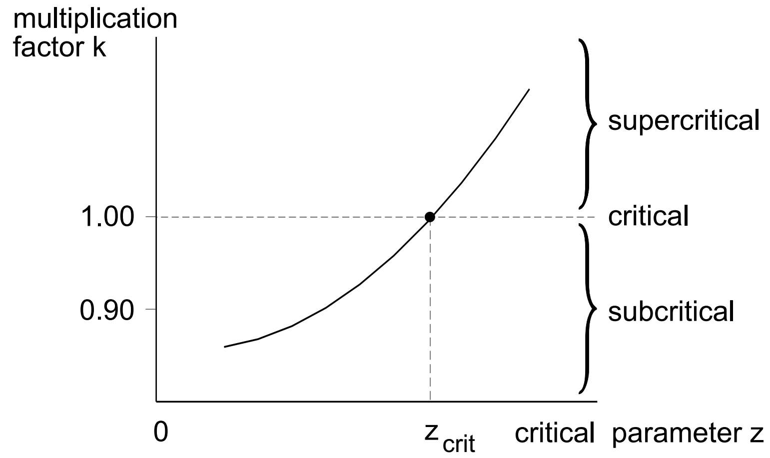

Fig. 1, Dependence of the multiplication factor k on the critical parameter z of the critical experiment

For achieving criticality of a reactor for the first time, mostly the fuel mass ($z = m_{fuel}$) is chosen as the free parameter in the critical experiment. Starting from a subcritical loading, the amount of fuel is enlarged stepwise until the reactor is critical or supercritical.

Another feasible procedure is to approach cautiously two subcritical masses which would give together a critical mass. In this case, the distance between the two subcritical masses represents the critical parameter. This alternative is applied in the given experiment (the critical parameter z_i is the position of the lower core section).

4. Theoretical Background

At the beginning of the experiment, the lower core section of the AKR is in its lowest position, the reactor is reliably subcritical (x = 0). The arrangement is shown schematically in Fig. 2.

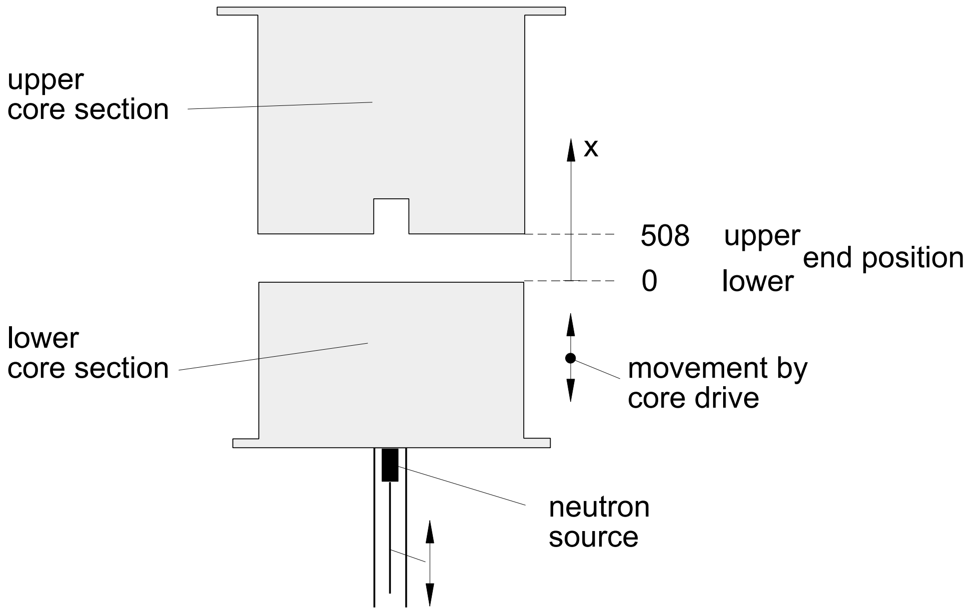

Fig. 2, Schematic arrangement of the experiment

A subcritical reactor contains almost no free neutrons. By inserting the neutron source, which has a source strength *S* and emits neutrons into the reactor core, the neutron density is increased to such level that
- a sufficient count rate at the neutron detectors is available, and
- therefore statistically safe measurements of the reactor state are possible.

For determining the reactor state, the neutron density $n(t\rightarrow\infty)$ is used, which is the result of the **subcritical amplification of the neutron source**. Theoretically, it is reached only after infinitely long time. The neutron density *n* is proportional to the neutron flux density Φ in the reactor, proportional to the reactor power P as well as proportional to the count rates N measured by the neutron detectors.

The asymptotic neutron density n after infinitely long time is

$$n_{(t\to\infty)}(\sim\Phi,\sim P,\sim N) = S\cdot l + S\cdot l\cdot k + (S\cdot l\cdot k)\cdot k + ... \tag{1}$$
$$= S\cdot l\,(1 + k + k^2 + k^3 + ...)$$
$$= S\cdot l\cdot\frac{1}{1-k} \quad \text{(limit value of the geometric series with k<1)}$$

with S source strength of the neutron source
l neutron generation time
k multiplication factor of the (subcritical) reactor

The time dependence for approaching the asymptotic neutron density is

$$n(t) = \frac{S\cdot l}{1-k}\left(1 - e^{-\frac{(1-k)}{l}\cdot t}\right) \tag{2}$$

After infinitely long time, equation (2) results in equation (1). As it can be seen from equation (2), the nearer the system is to the critical state ($k \to 1$), the slower the approach to the asymptotic value continues $n\ (t\to\infty)$.

At the beginning of the experiment and for $t < 0$, the distance between the two core sections be x_0 and the entire arrangement has the multiplication factor $k(x_0) = k_0$.

At $t = 0$, the distance between the core sections is reduced by the value Δx. The resulting multiplication factor corresponding to the new position x shall be $k(x)$. The neutron density n increases according to equation (2). After a sufficient time period ($t \to \infty$), the neutron density has virtually reached its asymptotic value $n\ (t\to\infty)$ (equation (3)):

$$n(x, t\to\infty) = S\cdot l\cdot\frac{1}{1-k(x)} \tag{3}$$

The factor

$$M(x) = \frac{1}{1-k(x)} \tag{4}$$

is also known as the **subcritical amplification**.

Fig. 3 shows the relation between the discussed quantities *x, k(x), and n(x,t)*.

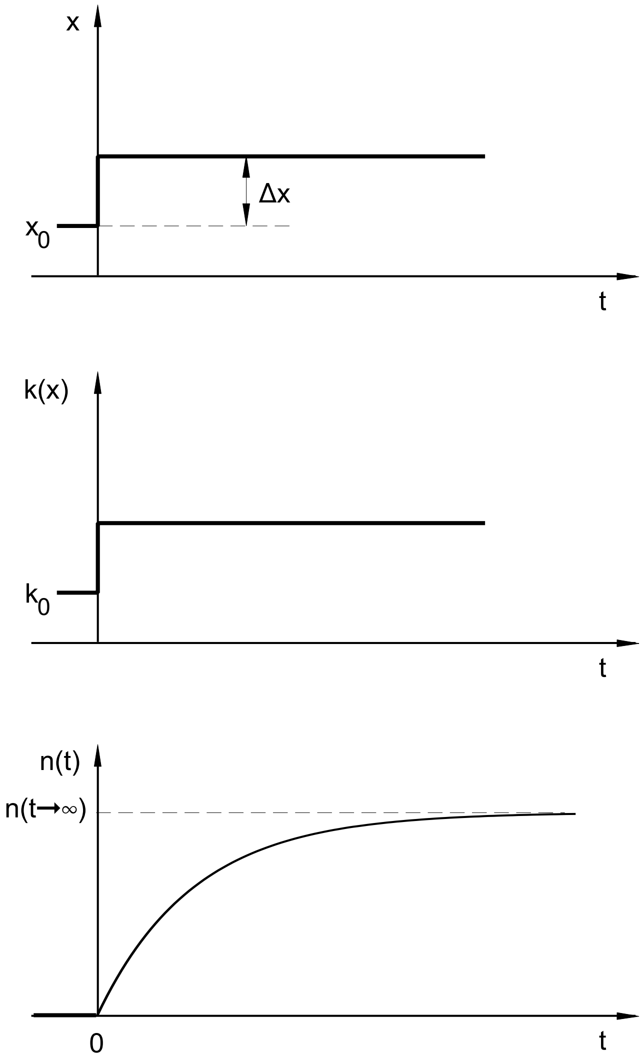

Fig. 3, Neutron density over time with approaching to the asymptotic value for reduction of the distance between the two core sections

In the experiment, the distance between the core sections is reduced stepwise.

If waiting until the asymptotic value is nearly reached, then for ($k \to 1$) the subcritical amplification and the neutron density n ($t \to \infty$) as well goes to infinity:

$$\lim_{k \to 1} n(t \to \infty) = \infty \tag{5}$$

Hence, for ($k \rightarrow 1$), the reciprocal value of the neutron density $1/n(t \rightarrow \infty)$ tends to zero:

$$\lim_{k \to 1} \left(1/n(t \to \infty) \right) = 0 \qquad \textbf{(6)}$$

Since the pulse rate N of a neutron detector of the reactor instrumentation is directly proportional to the neutron density n, it can also be written:

$$N \sim n \qquad \text{resp.} \qquad N = C \cdot n \qquad \textbf{(7)}$$

The constant C depends on the positioning and on the sensitivity of the neutron detector.

After approaching the asymptotic value $n(t \rightarrow \infty)$, the **inverse pulse rate** of a channel $1/N$ is:

$$1/N(x) = \frac{1}{C \cdot n(t \to \infty)} = \frac{1 - k(x)}{C \cdot S \cdot l} \qquad \textbf{(8)}$$

If plotting $1/N(x)$ over x, the point of intersection of the resulting curve with the abscissa axis gives the position x_{crit} of the lower core section that marks exact criticality (Fig. 4).

$$1/N(x_{krit}) = 0 \qquad \textbf{(9)}$$

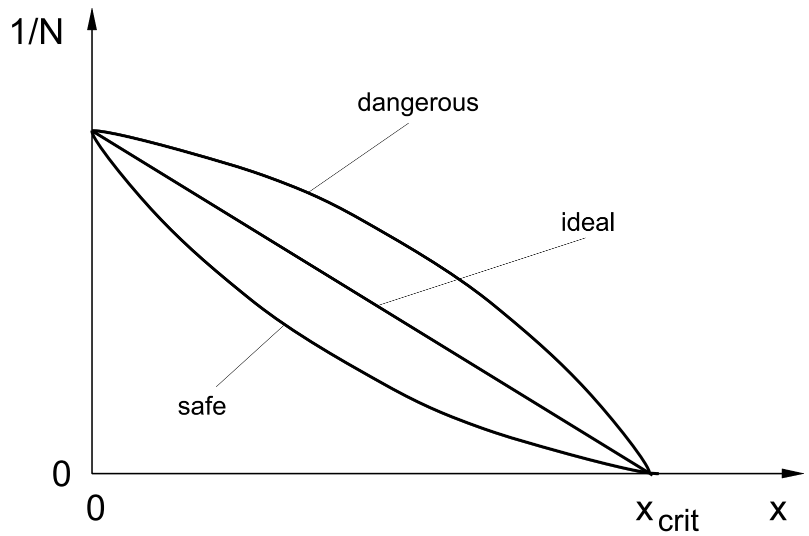

Fig. 4, Reciprocal pulse rate $1/N$ over position x of the lower core section for the determination of x_{crit} by extrapolation

In principle, three shapes of the curve $1/N(x)$ are possible:
- ideal shape (linear),
- dangerous (concave with respect to abscissa), and
- safe (convex with respect to abscissa).

The shape of the measured curve depends essentially on the positions of the neutron source and the neutron detector.

For the stepwise movement of the lower core section by steps of the distance Δx, the neutron pulse rate N increases by an amount ΔN:

$$\Delta N = N(x+\Delta x) - N(x) = C \cdot S \cdot l \, \frac{k(x+\Delta x) - k(x)}{(1-k(x+\Delta x)) \cdot (1-k(x))} \qquad \textbf{(10)}$$

Division by $N(x)$ eliminates the unknown constants and gives

$$k(x+\Delta x) = 1 + \frac{N(x)}{N(x+\Delta x)} \, (k(x) - 1) \qquad \textbf{(11)}$$

Thus, using the known previous value of the multiplication factor the next respective value can be calculated iteratively. The initial value $k_0 = k(x_0)$ must be known for this procedure. At the AKR, the multiplication factor for completely separated core sections is $k_0 = 0.945$.

If $k(x)$ is known then also the subcritical amplification M as a function of x can be calculated:

$$M(x) = \frac{1}{1 - k(x)} \qquad \textbf{(12)}$$

The reactivity ρ is defined on basis of the multiplication factor k. From known values $k(x)$, ρ can be calculated as follows

$$\rho(x) = \frac{k(x) - 1}{k(x)} \qquad \textbf{(13)}$$

The change in reactivity $\Delta\rho(x)$ is given by

$$\Delta\rho(x) = \left(\frac{d\rho}{dx}\right) \cdot \Delta x \qquad \textbf{(14)}$$

with

$$\left(\frac{d\rho}{dx}\right)_x = -\frac{\rho(x)}{N(x)} \cdot \frac{N(x+\Delta x) - N(x)}{\Delta x} \qquad \textbf{(15)}$$

Because the function *d*ρ*/dx* may occasionally be increasing tremendously in the vicinity of criticality (dangerous shape in Fig. 4) the approach to criticality has to be carried out with continuously decreasing step width Δx in order to avoid the increase in reactivity $\Delta\rho(x)$, i.e. the product $(d\rho/dx)\cdot\Delta x$, to become too high.

5. Procedure of the Experiment

5.1. A prerequisite for carrying out the critical experiment through stepwise movement of the lower core section is an experimentally secured facility status. The excess reactivity of the reactor must not exceed the limit of 0.3 % for completely joined core sections.

5.2. First, the facility is checked in the same way as for a normal restart (i.e., among others, by movement of the lower core section by about 30 digits and by subsequent total shut-down by activating the push-button "Hand-RESA" (SCRAM)).

Additionally, the correct drop-off of the control rods has to be checked:

- For this purpose, the limit switch "Kernhälften zusammen" (core sections joined) has to be bridged by turning the key-switch "Simulation Kernhälften zusammen" (simulation of joined core sections). The key-switch administratively ensures that this operational state can be intentionally set only.
- The control rods are moved from their inner end position consecutively. The movement is interrupted, when the control-panel display shows that the respective control rod left its lower end position.
- A manual SCRAM ("Hand-RESA") signal is released at the control panel.
- The drop-off of the control rods has to be checked on the monitor screens of the control desk (confirmation by indication of the lower end position).

After this check, the facility must not be shut down until the end of the critical experiment.

The correct operation of the partial and the total shut-down systems is a condition for the start of the critical experiment.

5.3. When starting the experiment, the core sections are completely separated. Then, the start neutron source is moved in and the signal "Kernhälften zusammen" (core sections joined) is bridged via the key-switch "Simulation Kernhälften zusammen" (simulation of joined core sections). Subsequently, all control rods have to be withdrawn out of the reactor core up to their end positions.

5.4. Using the wide-range channels i (i=1,2), the pulse rates N_{out} (1,i) are measured for the completely separated core sections. The control rods are drawn in and the pulse rates N_{in} (1,i) are measured. The measured values of the wide-range channels are displayed directly on the monitor screen of the control desk or indirectly from the presented graphical diagram. These values have to be recorded according to the protocol sheet in the appendix of this instruction. For improving the reliability of the output values, the average of three measurements is used.

5.5. The lower core section is lifted by 10 mm (100 digits). The control rods are pulled out and the pulse rates N_{out} (2,i) are measured. The control rods are drawn in, again, and the pulse rates N_{in} (2,i) are measured. For improving the reliability of the measurement, the average values of two measurements each are used.

For each wide-range channel i the ratios W_{out} (2,i) = N_{out} (1,i) / N_{out} (2,i) and W_{in} (2,i) = N_{in} (1,i) / N_{in} (2,i) are calculated and recorded in the protocol sheet.

The resulting values W_{out} (2,i) and W_{in} (2,i) are plotted versus the position x of the lower core section and connected each via a straight line with the points W_{out} (1,i) and W_{in} (1,i) [W_{out} (1,i) = N_{out} (1,i) / N_{out} (1,i) = 1 and W_{in} (1,i) = N_{in} (1,i) / N_{in} (1,i) = 1]. The extrapolation of both the lines to the abscissa gives the estimated positions $x_{crit, out}$ (i) and $x_{crit, in}$(i) for the critical reactor with drawn out control rods and drawn in rods (Fig. 5). The difference between $x_{crit, out}$ (i) and $x_{crit, in}$ (i) is a measure for the control range of the rods expressed in terms of lower core section positions for the critical reactor. For a successful end of the critical experiment, the technically possible maximum position x_{max} (position for joined core section) must range between $x_{crit, out}$ (i) und $x_{crit, in}$ (i).

5.6. The smallest of the values $x_{crit, out}$ (i) is set as the estimated critical position. In the next step, the lower core section is lifted by the half of the difference between the current position and the minimal critical position, but not more than 10 mm (100 digits), i.e.

$$\Delta x_{\max} = \frac{x_{crit,\min} - x}{2} \leq 100 \ digit \qquad \textbf{(16)}$$

Then, new pulse rates N_{out}(3,i) and N_{in}(3,i) are measured with control rods drawn out and in. The ratios W_{out}(3,i) = N_{out}(1,i) / N_{out}(3,i) and W_{in}(3,i) = N_{in}(1,i) / N_{in}(3,i) are calculated and plotted in the diagram. A straight line is drawn between the points W_{out} (2,i) and W_{out} (3,i) as well as between W_{in} (2,i) and W_{in} (3,i). The extrapolation of the resulting straight lines to the abscissa gives new (more precise than before) critical positions $x_{crit, out}$(i) and $x_{crit, in}$ (i) of the lower core section.

5.7. Item 5.6 is repeated as long as the extrapolation intersections with the abscissa do reliably fulfil the condition $x_{crit, out}$ (i) < x_{max} < $x_{crit, in}$ (i). Fig. 5 corresponds to the expected result of the experiment.

5.8. If $x_{crit, out}$ (i) > x_{max}, the reactor core contains too less fuel, i.e. the reactor will not become critical. If $x_{crit, in}$ (i) < x_{max}, the reactor core contains too much fuel. The reactor has to be shut down immediatly and fuel has to be removed.

5.9. After providing the condition in item 5.7, the distance between the two core sections has to be reduced to zero using smaller steps for finishing the critical experiment (core sections completely joined). The gain in reactivity has to be compensated by drawing in the control rods.

5.10. By turning back the key-switch "Simulation Kernhälften zusammen" (simulation of joined core sections) the bridge of the limit switch "Kernhälften zusammen" (core sections joined) is interrupted. The critical experiment ends with record of the critical control rod position and the time of achieving the critical state in the operation logbook.

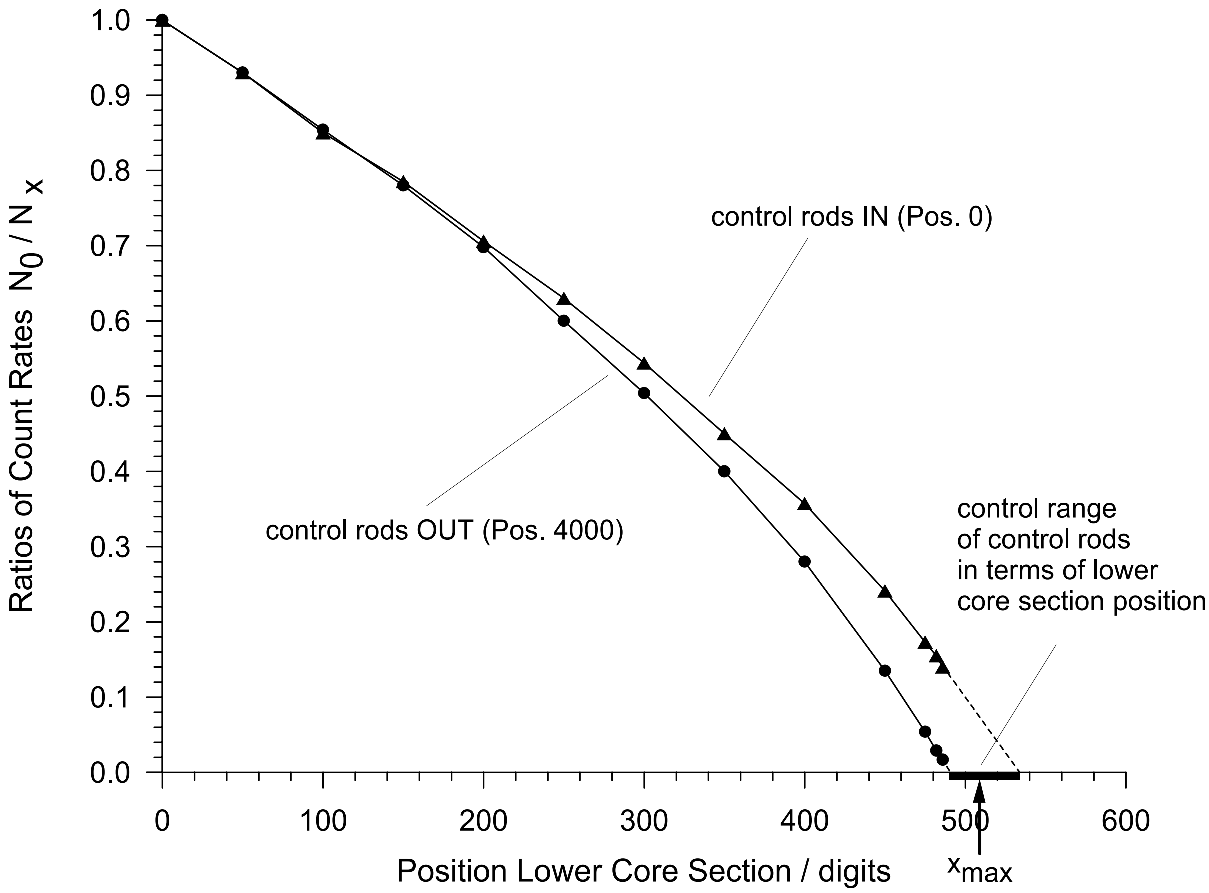

Fig. 5, Expected result of the critical experiment

6. Further Comments on the Experiment

The graphical representations of the measurements for determining the critical positions have to be prepared during the experiment.

For this purpose, the following items are needed:
- millimetre paper (see also appendix)
- rulers
- pocket calculator

The following values have to be recorded in a table or calculated (each for drawn in or drawn out control rods).

Position of lower core section x_i / digits	Control rod position in / out	Count rates N(x,i)	Ratios W(x,i)	Multiplica-tion factor k(x)	Subcritical amplification M(x)	Reactivity ρ(x) / %

An example for the table is provided in the appendix.

7. Questions to Answer

1. Why is it mandatory to carry out a critical experiment before initial commissioning of a nuclear reactor ?

2. Give some quantities that affect the criticality of a nuclear facility!

3. What are the possible operational states of a nuclear reactor ? What operational states are allowed and what operational states must be avoided in any case? Justify the answers!

Appendix: Protocol Sheet of the Critical Experiment

Equations:

$$k_i = 1 + \frac{N_{i-1}}{N_i}(k_{i-1} - 1) \qquad \text{with } k_0 = 0.945 \tag{1}$$

$$M_i = \frac{1}{1 - k_i} \tag{2}$$

$$\varrho_i = \frac{k_i - 1}{k_i} \tag{3}$$

Maximum permitted step for the movement of the lower core section:

$$\Delta x_{max} = \frac{x_{crit,min} - x}{2} \leq 100 \text{ digit} \tag{4}$$

Wide-Range Channel 1 (WB 1)	Wide-Range Channel 2 (WB 2)
Pulse rates of fission chamber	Pulse rates of fission chamber
Name:	Name:

Determination of start values N_0 :

	Control rod position	Measure-ment 1	Measure-ment 2	Measure-ment 3	**Average value N_0**
WB 1	in (0)				
	out (4000)				
WB 2	in (0)				
	out (4000)				

No. of wide-range channel (WB1 / WB2) : ....

Position of lower core sect. x_i / digits	Control rod position	Count rates			Ratios $N_0 / \bar{N}_i$	Multiplication factor k_i	Subcritical amplification M_i	Reactivity ϱ_i
		$N_{i,1}$	$N_{i,2}$	$\bar{N}_i$				
0	in				1.00	0.945	18.18	-0.0582
	out				1.00	0.945	18.18	-0.0582
100	in							
	out							
	in							
	out							
	in							
	out							
	in							
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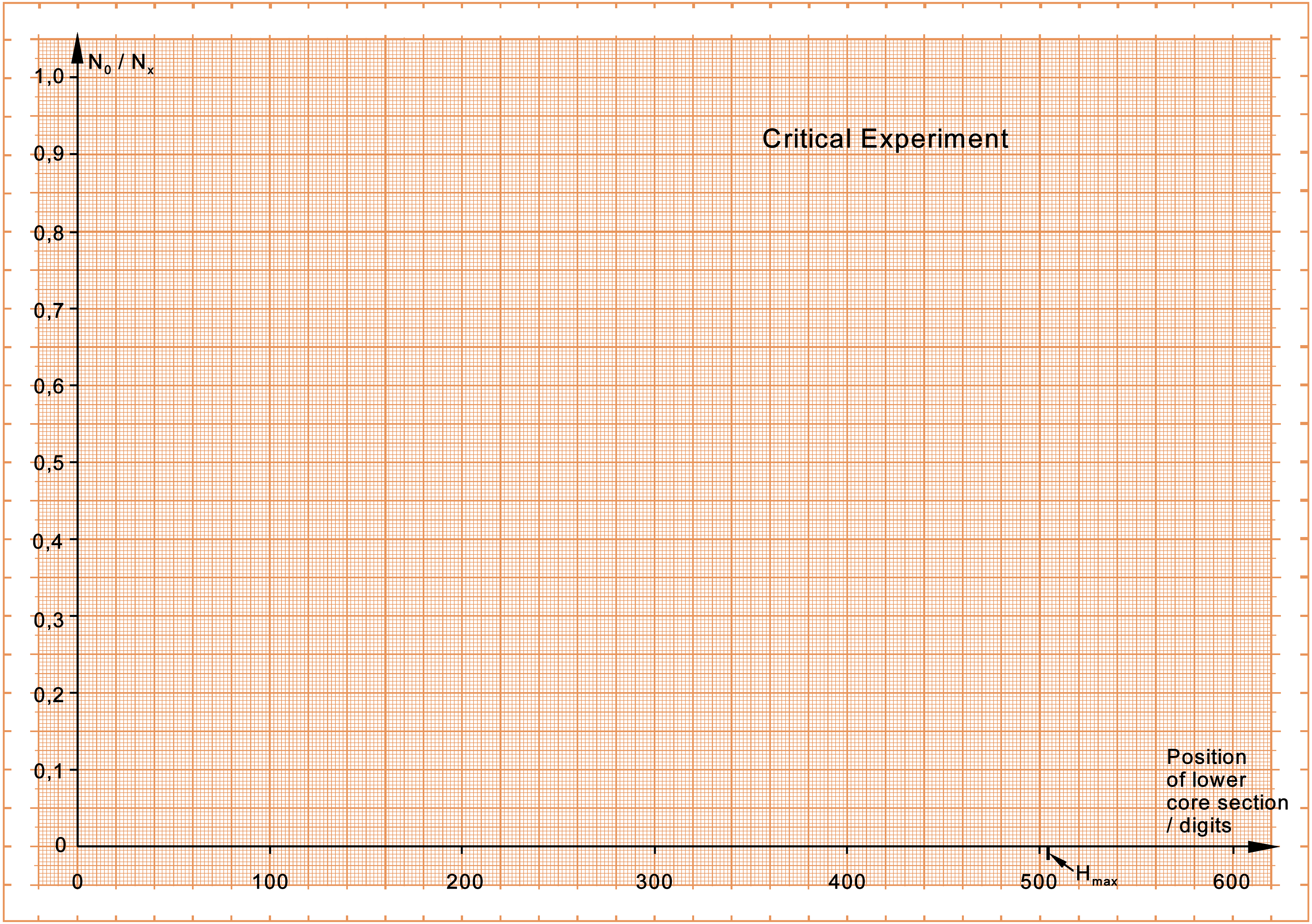

Critical Experiment
N0 / Nx
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
100
200
300
400
500
600
Hmax
Position of lower core section / digits