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Studsvik Report

DATA AND RESULTS FOR KRITZ EXPERIMENTS ON REGULAR H_2O/FUEL PIN LATTICES AT TEMPERATURES UP TO 245°C

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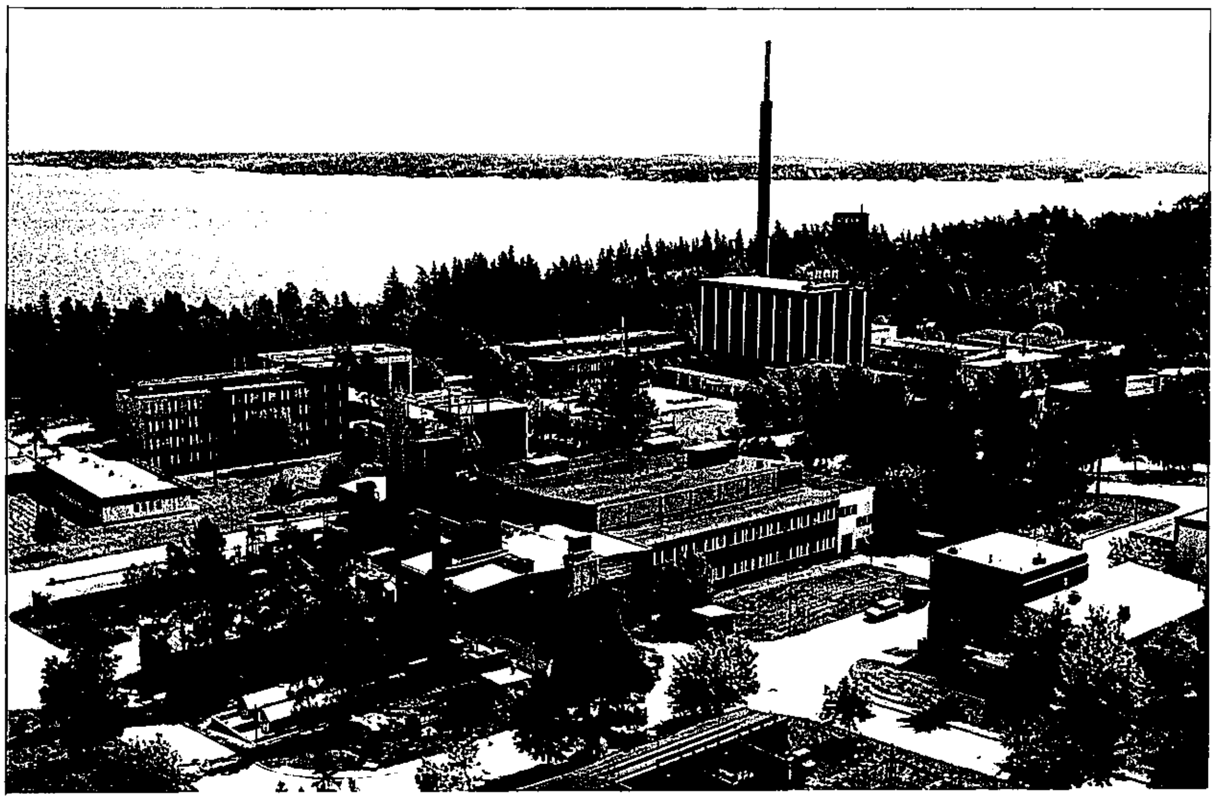

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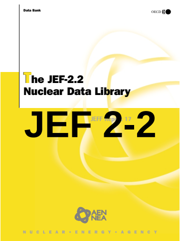

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Erik Johansson

DATA AND RESULTS FROM KRITZ EXPERIMENTS ON REGULAR H_2O/FUEL PIN LATTICES AT TEMPERATURES UP TO 245 °C

Abstract

The measurements in the KRITZ reactor at Studsvik, performed during the first half of the seventies, include a series of light water moderated lattices with uranium rods or plutonium rods or both. Data and experimental results for three regular cores, two of which with uranium rods and one with plutonium rods, from this series are presented. The experiments, performed at temperatures up to 245 °C, concern the critical state. Measurements of fission rate distributions are included. A uranium core from an earlier series is also presented.

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1 Overview

The KRITZ reactor, operated at Studsvik during the first half of the seventies, was used in physics measurements for many types of light water moderated configurations, including cases with burnable absorbers or plutonium rods. The experiments, performed at temperatures up to 245 °C, mainly concern criticality and fission rate distributions.

A vertical cross section of the reactor is shown in figure 1. The lattice to be studied, a UO_2 case in the figure, is located inside a square-shaped inner part of an insert vessel. The side length of this square part is about 1 metre. The pressure tank is high enough to accommodate full-size BWR rods and assemblies, a property utilized in many cases. Outside the square-shaped part is a dump region, empty on normal reactor operation. In case of a scram signal the shutters shown in the figure would open quickly and the reactivity would decrease because of the redistribution of the water. Furthermore, due to the reactivity effects in case of flashing following a pressure release, safety aspects required restrictions for certain parameters of the cores to be used.

Criticality was attained by choice of a suitable boron content in the water and, finally, by adjustment of the water level. The value of that content and the height of that level are important parameters in the measurements. Also valuable are the flux and fission rate distributions. Thus, with regard to the axial buckling, measurements on activated copper wires as well as gamma

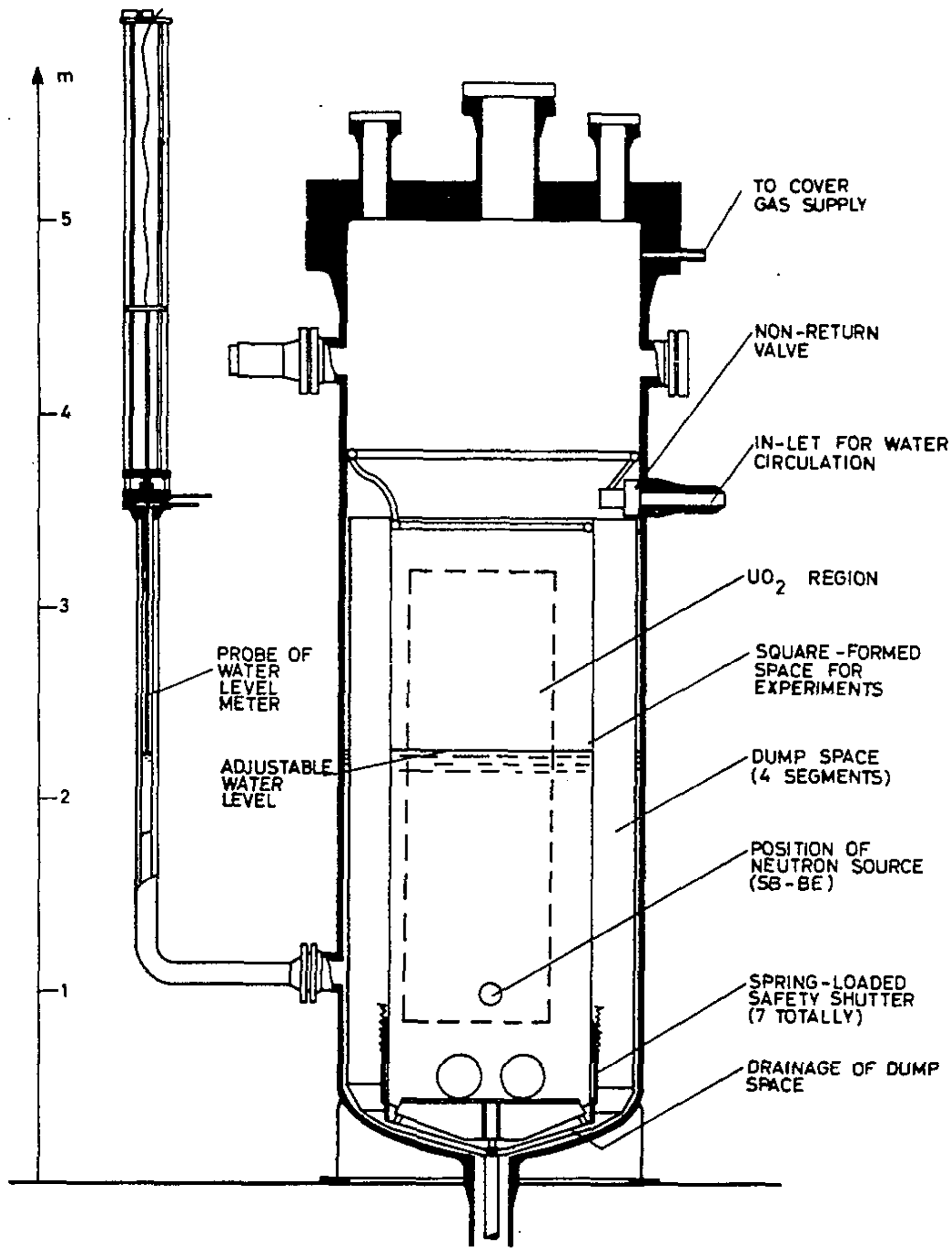


Figure 1

Vertical cross section of the KRITZ reactor with its inner square-shaped space for the experimental configuration.

scans of irradiated fuel rods were performed for some of the cores. Furthermore, gamma measurements were made rod by rod in the radial direction for several cores. These measurements are of a particular value for cores with more than one cell type. However, also for single-cell cores such scans could be valuable in studies of the near-reflector region, in addition to possible use in the buckling context.

Some of the KRITZ measurements are still not openly accessible. Recently, however, data and results for cores from a series, which we may call KRITZ-2 to conform with other presentations, have been released. This series includes geometrically regular lattices of uranium rods or plutonium rods or both, all lattices being moderated with light water. Two uranium cores and one plutonium core, labelled 2:1, 2:13, and 2:19, respectively, from this series will be considered in this report. In addition, a core from an earlier series, KRITZ-1, for which data and results have been openly available since long ago, will be presented briefly.

2 KRITZ-2

2.1 Fuel rods

Two types of fuel rods, containing UO_2 as pellets or vibrocompacted PuO_2UO_2, respectively, were used in the experiments. The PuO_2UO_2 rods were obtained on loan from the USAEC. Data for the rods, in the rest of the report labelled U rods and Pu rods, respectively, are given in table 1.

Table 1

Data for fuel rods used in KRITZ-2.

Parameter	U rod	Pu rod
Fuel material	UO_2	PuO_2UO_2*
Fuel density, g/cm^3	10.145*	9.58*
U235 in U, wt%	1.86*	0.16
PuO_2, wt% in fuel	-	1.50
Pu composition:		
Pu239, at%	-	91.41
Pu240, at%	-	7.83
Pu241, at%	-	0.73*
Pu242, at%	-	0.03
Fuel diameter, mm	10.58	9.45
Fuel length, mm	3650	1232
Canning material	Zircaloy-2	Zircaloy-2
Canning thickness, mm	0.74	
Canning, outer diameter, mm	12.25	10.79*

* The following additional information can be given for the fuel rods:

- The average grain size for PuO_2 in the Pu rods is 25 µm. This size is large enough to require self-shielding corrections in accurate calculations on these experiments.

- The density given for the U rods is an average value obtained when the material and the dishing volume of the pellets are homogenized.

- Tests at Studsvik for the Pu rods, using fission neutrons emitted on thermal neutron irradiation as well as tests using natural gamma radiation, indicated density deviations as large as 5 percent from the average value in a few cases. However, most of the test results were much closer to the average value.

- There is also a certain amount of U234 in the U rods. In this context it can be mentioned that the CASMO code has a default content of U234 expressed in wt% as 0.008·(wt% of U235).

- The Pu composition values refer to the date of analysis which is June 1962 - whereas the KRITZ measurements were done in the period September 1972 through February 1973, meaning a considerable decay of Pu241. Whether Am stripping has been performed in the meantime is not known by the author. Probably it has not.

- The outer diameter of the canning for the Pu rods varied from 10.70 to 10.90 mm. The average value 10.79 mm is given in the table.

- All dimensions and densities given in the table as well as elsewhere in the report refer to room temperature. Thermal expansion effects should be included in calculations at elevated temperature.

2.2 Core configurations

A vertical cross section of the reactor, indicating a Pu rod and a few U rods, without reference to any particular measured core, is shown in figure 2. The U rods, being ordinary

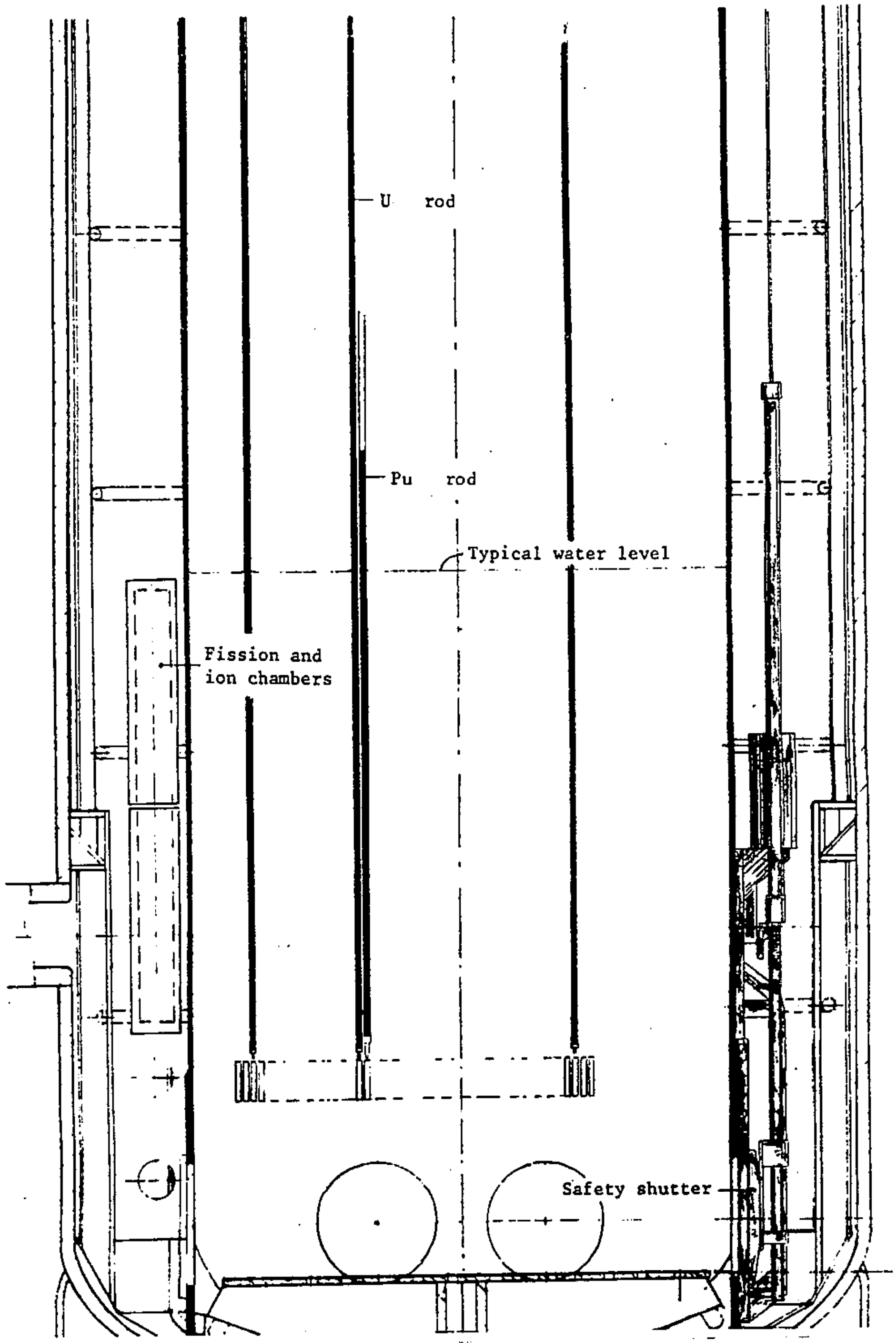


Figure 2

A vertical cross section of the reactor with a few fuel rods indicated.

BWR rods, are very long going through all three spacer grids - as is more clearly shown in figure 3. The Pu rods, for which the upper end

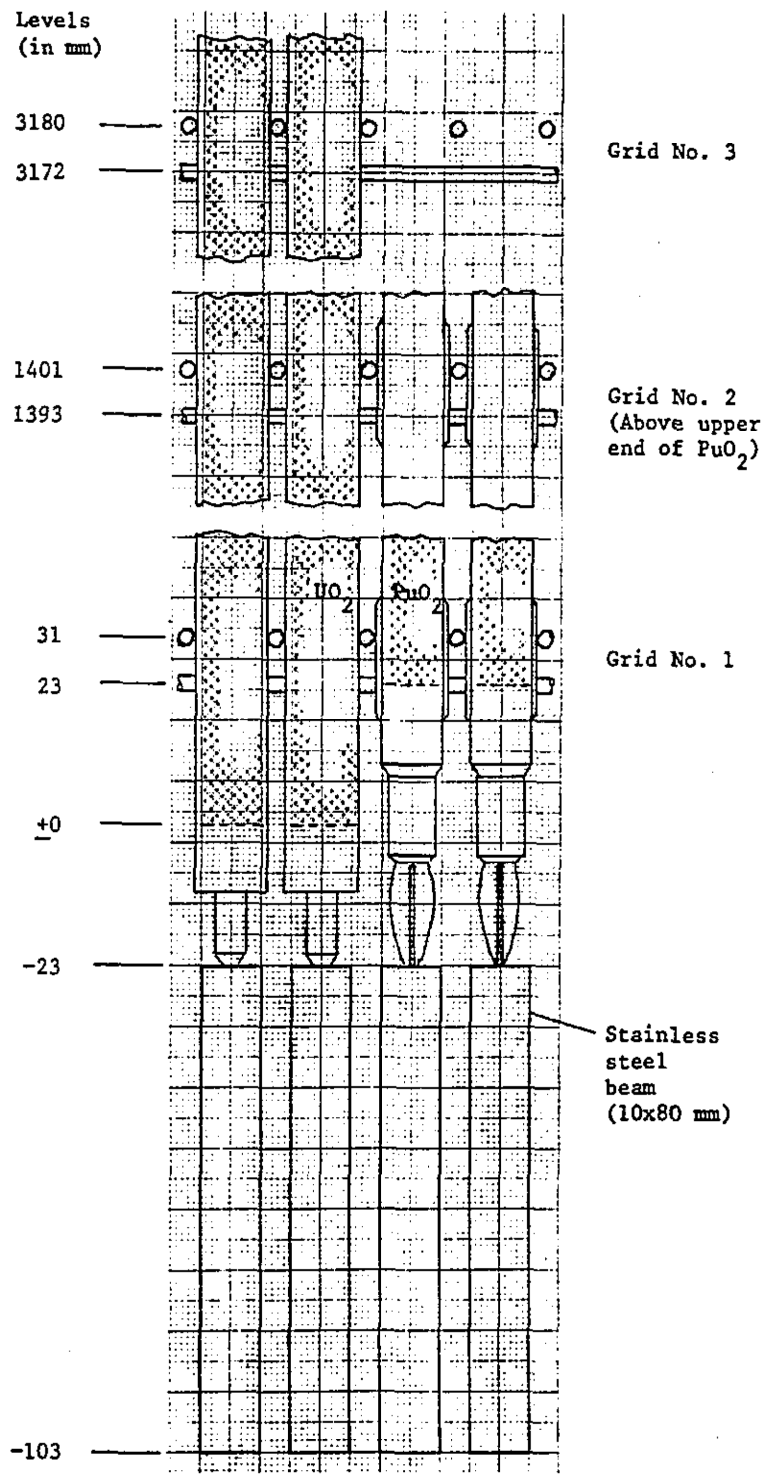


Figure 3

Axial positions of the spacers and of the lower ends of the fuel.

is located a little above spacer grid 2, have their upper fuel end at the level 1232+23 = 1255 mm, as obtained from data in table 1 and figure 3. This is well below grid number 2. The lower end region for the fuel rods is clearly shown in figure 3. For cores containing Pu rods the critical water level is throughout well below the upper end of the active fuel for such rods. Also, for all three cores from KRITZ-2 considered here, this level is clearly below grid number 2.

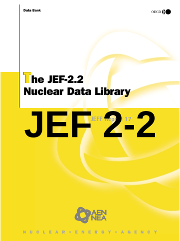
As shown in figure 3 each spacer grid consists of two layers of wires. These wires are made of stainless steel (SS-316). Those in one layer are perpendicular to the ones in the adjacent layer. Three different values for the fuel rod pitch were used in the regular lattices in KRITZ-2, each corresponding to a certain diameter of the grid wires as is summarized in table 2.

Table 2

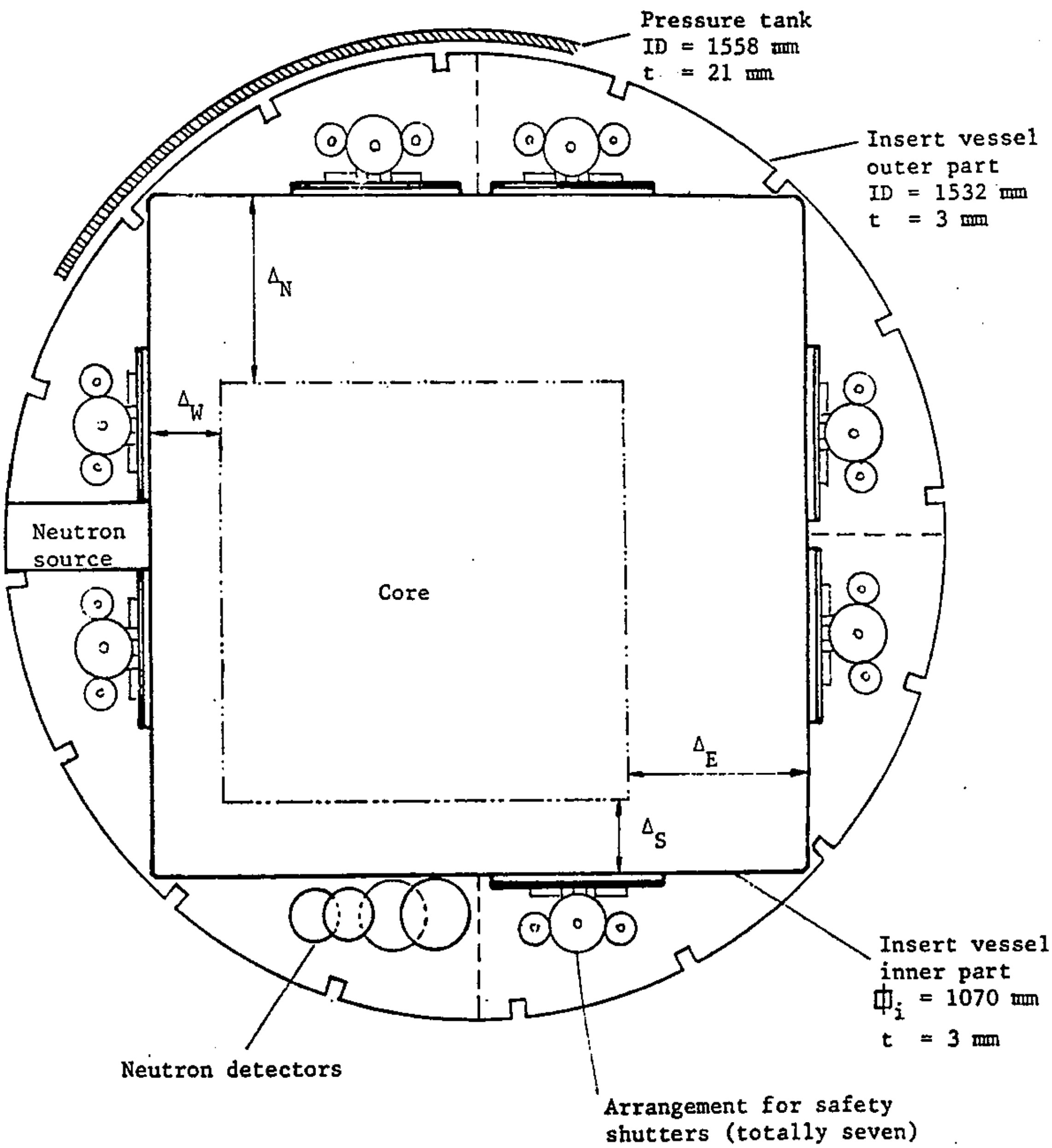
Fuel rod pitch and grid wire diameter.

Pitch, mm	Diameter, mm	P-D, mm
14.85	2.5	12.35
16.35	4.0	12.35
18.00	5.65	12.35

P-D is just 0.1 mm larger than the outer diameter of the canning for the U rods. For a well-defined positioning also of the Pu rods, which have a smaller outer diameter than the U rods, special short tubes were attached as shown in figure 3. Possibly the lattices might be slightly perturbed because rods could be bent, especially Pu rods.



A horizontal cross section of the reactor is shown in figure 4. The experimental core is located in the insert vessel made of stainless steel. As mentioned earlier, the space between the inner and outer parts of this vessel is empty on normal operation of the reactor. One



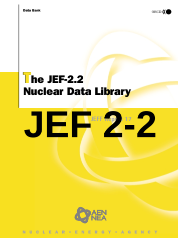
<u>Figure 4</u>

A horizontal cross section of the reactor.

should rather say that it contains gas - at high temperature essentially saturated steam. Between the insert vessel and the pressure tank, made of Fortiweld and supplied with a 2 mm thick stainless steel lining, is a thin region containing water up to the same height as the core and the tube for water level measurement shown in figure 1. The pressure tank was located within a concrete shield in a space with square-shaped horizontal cross section. Detailed data for this shield are not given here. Neither are any data presented for the shutters. Both these parts play a minor role in the utilization of the experiments in test calculations.

As shown in figure 4 the experimental core is eccentrically placed. This is because one wanted to build up this core close to the neutron source and close to the neutron detectors.

The reflector layers, marked by the Δ values in figure 4, extend from the boundary of the outer pin cells of the regular lattice to the steel wall. Δ_S and Δ_W are always equal but can differ from one core to the other. As most cores are square-shaped, Δ_N and Δ_E are also equal. However, one of the cores, the Pu core 2:19, to be discussed later is not square-shaped. The thermal expansion of the Δ values is probably insignificant for the reactivity calculations. If included it should be based on the expansion coefficient for steel - as should also the expansion of the pin pitch - which should be considered in accurate calculations.



2.3 The measurement procedure

As mentioned earlier, criticality was attained by adjustment of the water level. The measurement of this level, carried out in the side tube shown in figure 1, proved to have a reproducibility at room temperature of ± 0.1 mm. At high temperature the uncertainty in the level measurement is larger, being 1 to 2 mm. The typical height, HK, for fuel under water is about 1 metre. It can be mentioned also that critical levels were often measured at a reactor power as low as 10 W - to avoid unnecessary activation of the rods. Especially in such cases it was important to withdraw the neutron source, indicated in figure 4, before the critical level was finally determined.

The boron content in the core was determined by analysis of samples taken from the water. This analysis has an uncertainty of 1 %. Below a content of about 100 ppm the uncertainty is somewhat larger, being 1.5 %. It is important to observe that the boron content of a sample taken at room temperature can not be used directly also at high temperature, because some of the water in the system turns into steam, leading to a higher boron content. This effect was taken into account by calculational corrections verified by analysis of samples taken at high temperature.

The temperature in the reactor was measured with thermocouples. The accuracy in the determination is better than 1 % absolutely seen.

For use in the buckling determination copper wires were activated in an axial thimble. The wires were then cut into pieces whose activity was measured giving essentially the axial thermal neutron flux distribution.

The KRITZ experiments also include a large number of gamma scanning measurements on irradiated fuel rods. A special experimental setup, in which a rod could be moved axially, and simultaneously also rotated, between two opposite NaJ(Tl) scintillation counters, was built for this work. The measurements were done integrally from a low energy limit of 0.6 MeV. Axial scans were taken along the whole irradiated length for use in the buckling determination. Gamma measurements were also done rod by rod to give the radial fission rate distribution. Axial scanning was used also in these measurements but only along an 11 cm high part of the rods. One of the rods was chosen as a reference and was measured repeatedly to give the decay correction. The 1σ uncertainty in the radial fission rate distribution measurement is below 1 % for a set of U rods as well as for a set of Pu rods. However, for some rods the error could be much larger than 1 %, not only due to statistics but for instance due to bent rods or inhomogeneities of the material. As mentioned earlier the Pu rods do have such inhomogeneities but a complete examination was not carried out and the results are given without corrections for such effects. It can be mentioned finally that gamma measurements for cores with both U rods and Pu rods require special intercalibration factors for determination of the complete fission rate distribution. However, this point will not be further discussed here as each of the cores for which results will be given only contains one rod type.

2.4 Treatment of measured results

The treatment of the primary measured results included a lot of computer work both with regard to criticality and to fission rate distributions. However, this work need not be described here.

Concerning criticality the results could be presented and utilized in various ways. To start with one has the critical level which can be given as the height of active fuel under water, HK. With sufficient information for geometry and composition one can then utilize the results in criticality test calculations by applying a 3-dimensional method. This should be possible on the basis of the data given in this report. Measured flux or fission rate distributions (axial and radial) give additional test possibilities. As an alternative one can give the axial buckling B_z^2 in which case a 2-dimensional core calculational model is sufficient in the tests. In the KRITZ-2 work B_z^2 was obtained as $\pi^2/(HK+\lambda_z)^2$, where λ_z is the total axial extrapolation length, i.e. the sum of top and bottom contributions. Values of λ_z basically rest upon the measured axial distributions of the flux and the fission rate. Details of that particular analysis are not given here. Results for B_z^2 will be quoted in the next paragraph. Using also radial distributions one can obtain the total critical buckling. In such a case a cell code can be tested directly without any calculations for the whole reactor. No such buckling values will, however, be presented in this paper.

Finally, the effect of the spacer grids is small in the cases for KRITZ-2 presented in this report. However, in very accurate reactivity calculations one should consider grid number 1 (see figure 3).

2.5 Results for the three cores selected

The criticality results for the three regular cores 2:1, 2:13, and 2:19 from KRITZ-2 are given in table 3. This table shows results more or less directly obtained in the measurements. As is seen the temperatures are fairly close to 20 °C or to 245 °C. For practical applications, e.g. for tests of calculational methods, it might be advantageous to deal with only two temperatures. Therefore a set of adjusted results referring to 20 °C or to 245 °C has also been produced - on the basis of more primary results like the ones in table 3. The adjusted results are given in table 4. The procedure for the adjustment need not be described. However, the results in table 4 are practically as accurate as those in table 3.

The results in tables 3 and 4 can be used for comparison of calculated and measured k_{eff} values, the latter being equal to unity. In the comparison one should attach an experimental uncertainty to this value because of uncertainties in parameters involved, such as the boron content. Values for the uncertainty of this parameter as well as of the temperature and the critical level HK have been given in the preceding paragraph. It can be added that the uncertainties for B_z^2 can be as large as 2 % in some cases. The resulting experimental uncertainty of k_{eff} has not been examined in detail and so far only a typical 1σ value of ±80 pcm presented in earlier work can be quoted.

Table 3

Measured results at criticality for the temperature, the boron content, the axial buckling, and the height of active fuel under water for the three cores selected from KRITZ-2.

Core	Rod type	Number of rods	Pitch, mm	Δ_S, Δ_W, mm	Temp, °C	Boron, ppm	$B_z^2 \cdot 10^4$, cm^{-2}	HK, mm
2:1	U	44x44	14.85	81	19.7	217.9	14.75	652.8
					248.5	26.2	6.25	1055.2
2:13	U	40x40	16.35	113	22.1	451.9	8.01	961.7
					243.0	280.1	5.98	1109.6
2:19	Pu	25x24	18.00	99	21.1	4.8	16.37	665.6
					235.9	5.2	7.70	1000.1

Table 4

Measured results at criticality adjusted to the temperatures 20 °C and 245 °C for the three cores selected from KRITZ-2.

Core	Rod type	Number of rods	Pitch, mm	Δ_S, Δ_W, mm	Temp, °C	Boron, ppm	$B_z^2 \cdot 10^4$, cm^{-2}	HK, mm
2:1	U	44x44	14.85	81	20	217.9	14.75	652.8
					245	26.2	6.67	1015.0
2:13	U	40x40	16.35	113	20	451.9	8.04	959.7
					245	281.0	5.80	1129.4
2:19	Pu	25x24	18.00	99	20	4.8	16.37	665.6
					245	5.2	7.15	1042.8

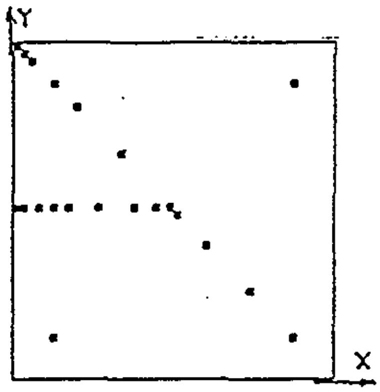
Radial fission rate distributions for the three cores are presented in table 5. Three of the values, which are clearly outside the 1σ uncertainty ±1 %, have been supplied with question marks in the table. The choice of origin for the coordinate system might be strange but we prefer not to change.

Table 5

Radial fission rate distributions from gamma measurements on irradiated fuel rods.

Core 2:1

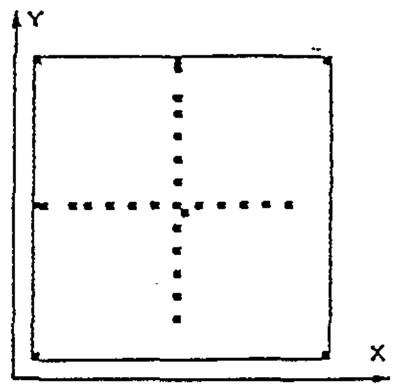
U rods
44x44
Pitch 14.85 mm



X	Y	248.5°C
1	23	0.7133
1	44	0.4309
2	23	0.5899
2	43	0.3431
3	42	0.3140
4	23	0.5689
6	6	0.3763
6	23	0.6231
6	39	0.3954
8	23	0.7074
9	36	0.5653
12	23	0.8602
15	30	0.7902?
17	23	0.9670
20	23	0.9868
22	23	1.0000
23	22	0.9965
27	18	0.9679
33	12	0.7071
39	6	0.3832
39	39	0.4025

Core 2:13

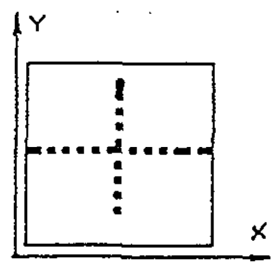
U rods
40x40
Pitch 16.35 mm



X	Y	22.1°C	243.0°C
3	3	0.1570	0.2601
3	23	0.4167	0.5427
3	42	0.1554	0.2563
4	23	0.3846	0.4858
8	23	0.5573	0.5929
10	23	0.6646	0.6903
13	23	0.8021	0.8214
16	23	0.9228	0.8951
19	23	0.9608	0.9519
22	8	0.5653	0.6048
22	11	0.7174	0.7332
22	14	0.8347	0.8563
22	17	0.9192	0.9145
22	20	0.9859	0.9640
22	23	0.9656	0.9784
22	26	0.9522	0.9375
22	29	0.8907	0.9085
22	32	0.8129	0.8405
22	35	0.6667	0.6960
22	37	0.5647	0.5983
22	41	0.3802	0.4763
22	42	0.4032	0.5406
23	22	1.0000	1.0000
25	23	0.9640	0.9628
28	23	0.9256	0.9177
31	23	0.8196	0.8218
34	23	0.7140	0.7469
37	23	0.5711	0.5985
42	3	0.1536	0.2555
42	42	0.1547	0.2609

Core 2:19

Pu rods
25x24
Pitch 18.00 mm



X	Y	21.1°C	235.9°C
2	14	0.5571	0.6953
3	14	0.5360	0.5985
5	14	0.6412	0.6535
7	14	0.7648	0.7644
9	14	0.8688	0.8583
11	14	0.9731	0.9297
13	14	0.9774	0.9486
14	6	0.7697?	0.7354
14	8	0.8493	0.8216
14	10	0.9275	0.8917
14	12	0.9772	0.9384
14	14	1.0000	1.0000?
14	15	0.9970	0.9459
14	17	0.9367	0.9230
14	19	0.8522	0.8329
14	21	0.7369	0.7277
14	22	0.6641	0.6856
14	23	0.5941	0.6435
16	14	0.9591	0.9217
18	14	0.9344	0.9015
20	14	0.8359	0.8170
22	14	0.7063	0.7045
23	14	0.6406	0.6511
25	14	0.5265	0.6054
26	14	0.5580	0.6898

3 KRITZ-1

Data for the UO_2 rods used in KRITZ-1 are given in table 6.

Table 6

Data for the UO_2 rods used in KRITZ-1.

Fuel material	UO_2
Fuel density, g/cm^3	10.26*
Uranium composition	
U234 wt% in U	0.0115**
U235 wt% in U	1.3532
U236 wt% in U	0.0095
U238 wt% in U	98.6258
Fuel diameter, mm	12.38
Fuel length, mm	2194
Canning material	Zircaloy-2
Canning thickness, mm	0.63
Canning, outer diameter, mm	13.86

* The density given is an average value obtained when the material and the dishing volume of the pellets are homogenized.

** The uranium composition was obtained in a mass-spectrometer check performed in 1985. The check was done because of uncertainty about wt% or at% for U235.

The arrangement of the rods and spacers for KRITZ-1 is shown in figure 5. The vertical distance ℓ shown in the figure is 360 mm for the particular core treated in this paper. The spacer wires, made of stainless steel (SIS-2343 containing 17.2 % Cr, 11.5 % Ni, and 2.7 % Mo), have a diameter of 3.99 mm. The lattice pitch is 18.0 mm.

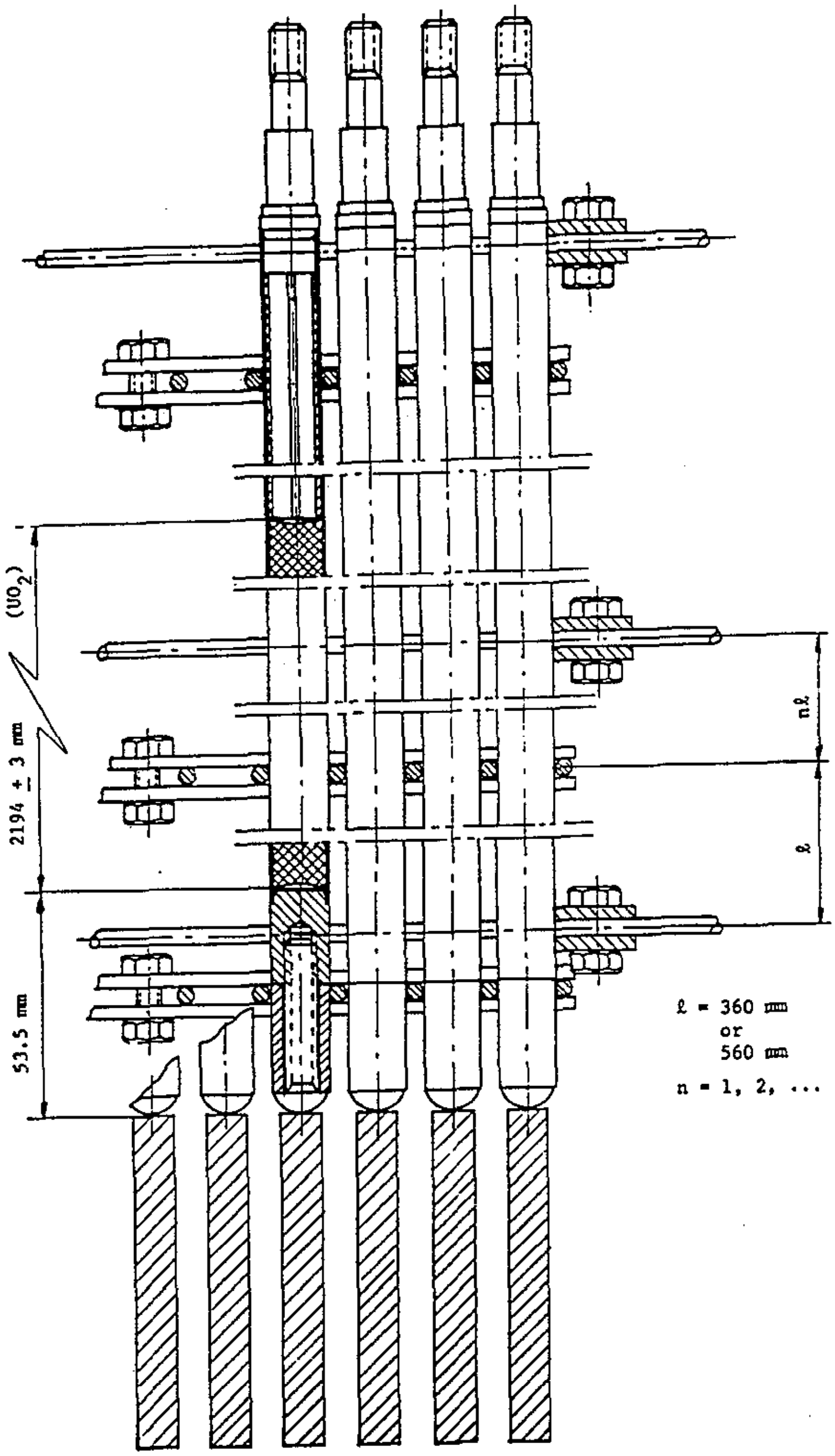


Figure 5

The arrangement of fuel rods and spacers for KRITZ-1. The distance ℓ for the core treated here is 360 mm.

A horizontal cross section of the reactor with an approximate representation of the pressure tank and the insert vessel is shown in figure 6. It can be mentioned also that the steam in the dump region (see figures 1 and 4) has been neglected in figure 6.

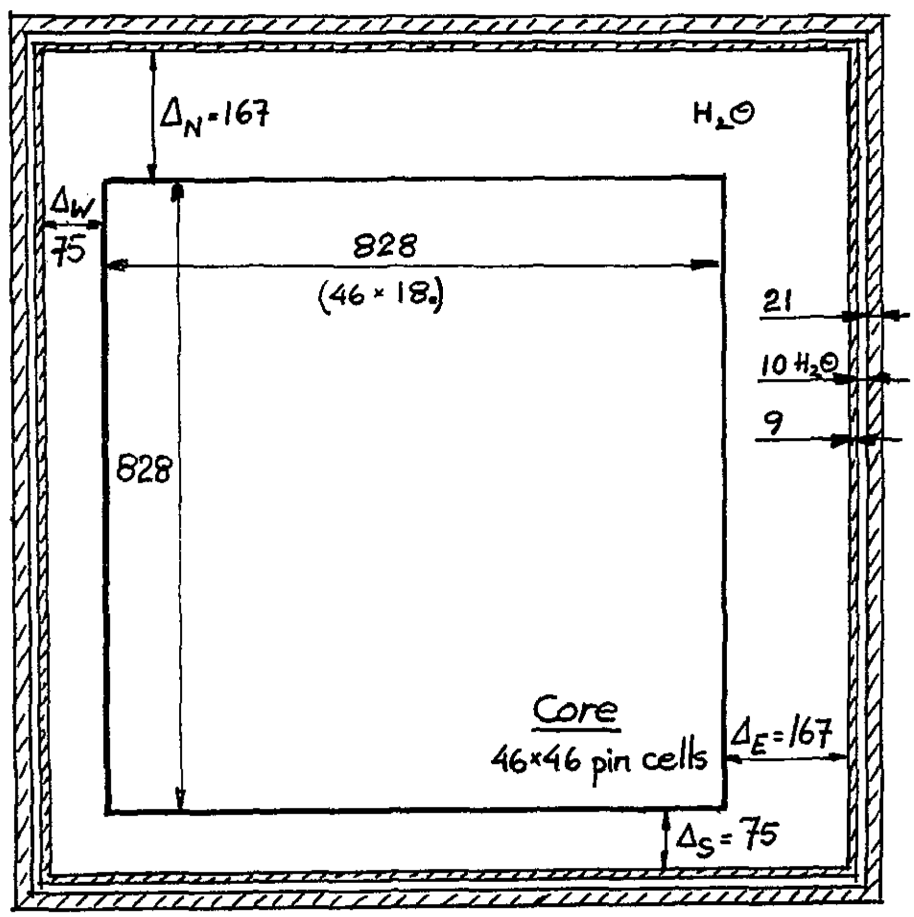


Figure 6

The selected core in a simplified reactor geometry. Dimensions (in mm) refer to 20 °C.

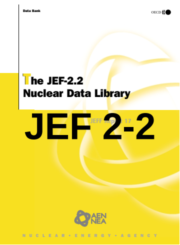
Measured results at criticality for the KRITZ-1 core selected are given in table 7. The axial extrapolation length (top+bottom) is about 180 mm.

Table 7

Measured results at criticality for the core selected from KRITZ-1.

Number of rods	Pitch, mm	Δ_S, Δ_W, mm	Temp, °C	Boron, ppm	$B_z^2 \cdot 10^4$, cm^{-2}	Spacer correction, pcm
46x46	18.0	75	20	175	9.07	-440
			90	175	7.15	-484
			160	177	4.33	-528
			210	181	1.88	-559

The spacer corrections, obtained in a combination of calculation and measurement, should be applied to k_{eff} values from 2-dimensional core calculations using the B_z^2 values. It is also possible to carry out new spacer reactivity calculations on the basis of information given in this paper. Finally it can be mentioned that the experimental k_{eff} value, nominally unity, has a 1σ uncertainty of ±100 pcm, mainly associated with the boron content. The uncertainty is smaller for the value at one temperature relative to that at another temperature.



Acknowledgement

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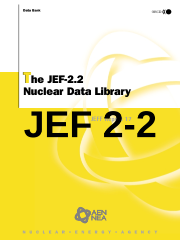

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