Comparison of Critical and Subcritical ρ^{28} Measurements*†

Measurements of ρ^{28} in a critical facility have been performed by the NORA Project staff under the auspices of the international IFA-IAEA NORA Project, and have been reported in Refs. 1, 2, and 3. Two of these experiments pertain to low-reactivity lattices and one to a subcritical lattice. In these experiments measurements have been carried out in the central zone (containing respectively 85 and 133 fuel rods in the two cases made use of in this work) of a two-zone core. Checks on the validity of the two-zone ρ^{28} experiments are obtained by inference from the adequacy of buckling measurements on these cores as demontrated in Ref. 3. A more direct check is available from measurements performed at Babcock & Wilcox Co. by the Small Lattice Experimental technique[9]. The conclusion in both instances is that ρ^{28} as measured in the two-zone cores is representative of the corresponding critical lattice.

Later, measurements of ρ^{28} have been performed by the authors in a strongly subcritical reflected facility, with the purpose of investigating to what extent such a small assembly is useful for experimental evaluation of the physics parameters characteristic of a critical core. These experiments are also a part of the NORA Project.

The experimental technique is identical in all measurements and is based on the thermal-activation technique. The activity determinations made use of a chemical Np-extraction technique developed at IFA[1]. The subcritical experiments were performed in the miniature 'satellite' facility JEEPNIK[4]. The lattices in this experiment were composed of approx 90 rods with a height of 57 cm and with equivalent core radii in the range 9 to 21 cm, reflected by D_2O and H_2O. In both NORA and JEEPNIK experiments, fuel was 3%-enriched UO_2 rods 1.13 cm diam with 0.7 mm stainless-steel clad. Moderator was 99.4% D_2O.

JEEPNIK is basically a right cylindrical tank, 45 cm i.d. and 66 cm high. Thermal neutrons (from the JEEP reactor) are fed into the tank from the bottom.

Experimental results are given in Table I, lines 2 and 3, taking

$$\rho^{28} = \frac{\text{epicadmium } U^{238}\text{-absorptions}}{\text{subcadmium } U^{238}\text{-absorptions}} .$$

On comparing critical and subcritical experimental values it is seen that agreement for open lattices is fairly good. As the lattice becomes tighter, a systematically increasing difference between critical and subcritical values is evident. As justified below we have good reason to believe that the calculated critical value for the 2.31-cm pitch will be representative for the experimental critical value. One can conclude from the critical and subcritical experimental values that JEEPNIK measurements of ρ^{28} will not give results representative for critical lattices similar to our two tightest examples.

In a JEEPNIK-type experiment the influence of direct thermal-source neutrons is a possible source of error in the ρ^{28} measurements. We have tried to eliminate this by performing our experiments in a region of the core where the copper cadmium ratio was axially constant, and where total, epithermal and thermal fluxes, as measured by copper activations, showed a purely exponential axial decline.

Physically the discrepancy between critical and subcritical experimental results must be caused by differences in neutron spectra. One physically reasonable explanation of the observed values is found from the following three characteristics of the experiment and their influence on the neutron-spectrum formation:

1) the smallness of the core, resulting in a very high neutron leakage—this is seen to increase ρ^{28} by depletion of the thermal-neutron population;
2) the very effective reflector (in most lattices practically infinite)—this is seen to increase the thermal-neutron population thereby decreasing ρ^{28}, provided the core is small enough that the spectral distortion permeates the core to the point of measurement;

*This paper is based on experimental work performed as part of a thesis for the Cand. Real. degree at the University of Oslo.

†This report covers work carried out as part of the NORA Project, a joint undertaking between the International Atomic Energy Agency and Institutt for Atomenergi. Acknowledgment is given to the USAEC for its support of the joint project.

[1]J. A. THOMASSEN and H. H. WINDSOR, "Measurements of Resonance Absorption in U^{238} using a Chemical Separation Technique for Isolation of Np^{239}." Kjeller Report KR-44 (1963).

[2]S. O. LARVIN *et al.*, "Methods for the Determination of ρ^{28} and δ^{28} Based on Chemical Separation of Np^{239} and Mo^{99} from Uranium and Fission Products." Paper SM-42/75, IAEA Sympsoium on Exponential and Critical Experiments, (1963).

[3]E. ANDERSEN *et al.*, "Experimental and Theoretical Studies of Uranium Oxide Lattices Moderated by Light and Heavy Water." Third U. N. Geneva Conference, P/669, (1964).

[4]H. H. WINDSOR, "JEEPNIK, the Kjeller Miniature Exponential Facility." Kjeller Report KR-46 (1963).

TABLE I[a]

Calculated and Experimental Results

Lattice Pitch (cm)	4.908	3.272	2.310	1.636
ρ^{28} crit exp (Refs. 1 & 3)	1.292	2.893	-	14.3
ρ^{28} subcrit exp	1.24 ± 0.06	2.74 ± 0.1	5.50 ± 0.15	8.2 ± 0.2
ρ^{28} crit calc (Ref. 3)	1.25	3.00	7.40	(18.1)[b]
ρ^{28} bare subcrit calc	1.99	3.90	11.3	29.2
Φ_3/Φ_4 crit	0.572	1.27	2.74	(5.9)[b]
Φ_3/Φ_4 bare subcrit	0.853	1.65	3.35	6.79
Φ_3/Φ_4 reflected subcrit	0.715	1.49	2.08	2.40
B^2 crit exp m^{-2} (Ref. 3)	20.10	16.87	2.99	-11.25
B^2 geom JEEPNIK, m^{-2}	89	100	112	118

[a]The ρ^{28} values in Ref. 3 and in this table differ from those of Ref. 2. A reevaluation of the experiments reported in Ref. 2 has been undertaken. It turned out that thermal irradiations of Dy-Al and UO_2 foils were performed with a Cd cover that could easily create strong flux gradients across the foil positions. Other irradiations with a half-closed Cd tube were found to be more satisfactory and have been used both in our experiments and in reevaluating data from Ref. 2.

[b]These values are calculated for $B^2 = 0$.

3) connected with 2) is a spatially variable distortion of the spectrum, making ρ^{28} space-dependent.

Other effects that have been found small compared to these are the Cd-cutoff effect and the distortion of the thermal spectrum by leakage and reflector effects. Approximate theoretical evaluations show that effect 3) is probably less than 2% in our ρ^{28} values.

Thus the spectrum distortions 1) and 2) will dominate, and they have counteracting influences on ρ^{28}. On this basis one may expect, on the one hand, that ρ^{28} is too low from a highly reflected small subcritical assembly, and on the other hand, that ρ^{28} is too high from a poorly reflected high leakage subcritical assembly, both when compared to the 'true' or critical ρ^{28}. Obviously a cancellation of effects may take place. This then may explain the acceptable subcritical-critical correlation in our two widest lattices. On the two tightest lattices it is probable that the reflector effect dominates.

Support for the above simple model has been derived from studies of the experiments with our standard criticality-calculation scheme. This is based on the DATAPREP-BIGG system[5,6], which is of the SOFOCATE-MUFT type. DATAPREP is a lattice homogenizer constructing U^{238}-resonance integrals based on Hellstrand's measurements with the Levine interaction shielding approach[7]. In addition, the code also evaluates a 10-group Brown & St. John thermal spectrum and produces one-group spatially averaged (by the Amouyal-Benoist method) thermal data. These are used in BIGG with the B-1 approximation and extended Greuling-Goertzel slowing down, together with a special treatment to get an approximately correct energy distribution of resonance fission and absorption in U^{235} and U^{238}. The resulting 40-group neutron spectrum is used to evaluate criticality parameters and few-group diffusion constants. Aiming at qualitative evaluations rather than high-accuracy design calculations, energy-independent bucklings were used in these spectrum calculations. Also applied was a few-group one-dimensional diffusion-theory code[8]. Four neutron-energy

[5]J. O. BERG *et al.*, "DATAPREP, a Lattice Homogenization and Data Preparation Computer Programme." Kjeller Report KR-78 (to be issued 1964).

[6]O. P. TVERBAKK and J. M. DØDERLEIN, "BIGG-I a Multigroup Neutron Spectrum and Criticality Code." Kjeller Report KR-77 (1964).

[7]M. M. LEVINE, *Nucl. Sci. Eng.* **16**, 3 (1963).

[8]S. LINDE, "The Multigroup Neutron Diffusion Equations in One Space Dimension." AB Atomenergi Report AE-36 (1960).

groups with the cuts 10^7, 2.7×10^5, 9.1×10^3 and 0.625 eV were used. The good agreement with critical ρ^{28} experiments obtained with this theory, both for these and a number of other lattices, encourages us to use the theoretical values where no critical ρ^{28} measurements were available (2.31-cm pitch) and, as pointed out above, to accept the comparison theory-subcritical experiment as corroborating evidence.

Some of the calculated results are listed in Table I together with the experimental results. Using the geometric buckling of the BIGG-calculation, an approximate value of the ρ^{28}, which would probably be observed in an unreflected subcritical assembly, is found. This is given in Table I as "ρ^{28} bare subcrit calc". The values bear out the leakage influence on ρ^{28} (compared with the critical values) as postulated in 1) above. The same effect is evidenced by the high value of "Φ_3/Φ_4 bare subcrit" deduced from the same calculation, where Φ_3 and Φ_4 are group 3 and 4 fluxes at core center respectively, (group 4 = thermal).

A calculation of ρ^{28} for the actual reflected subcritical setup has not been performed, but the behavior proposed in 2) above is borne out by the values of "Φ_3/Φ_4 reflected subcrit" which have been calculated with one-dimensional diffusion theory. For the two widest lattices, where a reasonable agreement between subcritical and critical ρ^{28} is found, Φ_3/Φ_4 is slightly higher than the critical values, whereas for the tightest examples substantially lower values are found. This is taken to indicate the enhanced thermal flux from the reflector in these situations.

To conclude then, for one of the lattices widely different experimental ρ^{28} values have been found in identical lattices in a critical and a strongly reflected small subcritical assembly, whereas in one other lattice the subcritical ρ^{28} is substantially different from a presumably fairly correctly calculated critical value. An explanation is proposed, accounting for both the proposed fortuitous critical-subcritical agreement in two of the lattices, and for the substantial disagreement observed in the tightest lattices.

If the proposed explanation of the experimental results is basically correct, a subcritical facility for ρ^{28} measurements should preferably 1) be as large as possible, minimizing leakage effects, and 2) be unreflected to minimize perturbation of relative thermal-neutron population, possibly utilizing a thermal-neutron shield around the core.

J. M. Døderlein
J. A. Thomassen

Kjeller Research Establishment
Institutt for Atomenergi (IFA)
Kjeller, Norway

T. H. Johansen

University of Oslo
Oslo, Norway

Received May 4, 1964
Revised September 8, 1964

[9] T. C. ENGELDER *et al.*, "Measurement of k_∞ and Other Lattice Parameters by the Small Lattice Experimental Technique." BAW-1283 (1963).