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Critical Experiments with Lattices of 4.75-wt%-^{235}U-Enriched UO_2 Rods in Water

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The development of pressurized water reactors and boiling water reactors in the world necessitates complete critical experiments on this type of fuel for the validation of the methods used in criticality calculations and to resolve the various related problems. This paper presents the first results obtained at the Critical Mass Laboratory at Valduc during critical approaches achieved with lattices of 4.75-wt%-^{235}U-enriched UO_2 rods in water. Four square pitches (12.6, 16.0, 21.0, and 25.2 mm) and three triangular pitches (13.5, 17.2, and 22.6 mm) have been studied, and various configurations with fuel rods removed were investigated. Benchmark calculations are presented.

INTRODUCTION

Many problems of nuclear criticality safety arise all through the industrial cycle of the fuel elements for pressurized light water reactors (PWRs). We can mention, for example,

1. in-pool storage
2. dry storage with the hypothesis of accidental moderation
3. shearing and dissolution of the irradiated elements
4. packing and shipping casks design.

If satisfactory solutions are to be reached, it is necessary to carry out critical experiments allowing both the analysis of the phenomena and the validation of the available calculation codes.

Some calculational and experimental results for metallic and oxide rods containing uranium of low

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^{235}U enrichment have been published by various laboratories.[1-5] For its own part, the Commissariat à l'Energie Atomique Department of Nuclear Safety has undertaken an important testing program carried out in the Valduc Critical Mass Laboratory, the result of which are analyzed by the Criticality Service at Fontenay-aux-Roses, near Paris.

The first part of this program, which has just been completed, includes

1. the study of the criticality in water of square lattices for different pitches
2. the study of the criticality in water of triangular lattices for pitches equivalent to those of the square lattices
3. the effect of the removal of rods from an undermoderated square lattice having a pitch of 12.6 mm.

The second part of this program consists in studying the interaction of four PWR-type assemblies in water and in low-hydrogen-density media. Several types and several shield arrangements are used to reproduce storage or transport conditions.

DESCRIPTION OF THE FUEL RODS

The fissile material for these experiments comprised 1300 fuel rods, manufactured by the SICN Company, with the characteristics given in Table I (see Fig. 1).

MODE OF OPERATION

The experiments carried out consisted in determining the critical water heights of the various fuel lattices by extrapolating the inverses of the counting rates recorded during a progressive rise of the water around the rods, with the water acting as the moderator and reflector. They have been carried out in a device called "Apparatus B," which includes (see Fig. 2):

1. a 1.40-m-high experimental tank of square cross section (1.20 m) equipped with two rapid discharge exhaust valves and fed at the bottom by the water pumping system located on the lower floor

TABLE I

Characteristics of the 1300 Fuel Rods

Fuel	
Material	UO_2 sintered pellets
Pellet diameter, cm	0.790 ± 0.002
Pellet height, cm	1.495 ± 0.007
Height of the fuel, cm	90.0 ± 0.1
Average weight of UO_2 per rod	457.5 g
Enrichment of the uranium	4.742 ± 0.001%
Oxide density, g/cm^3	10.38 ± 0.04
Sum of the impurities in boron equivalent,[a] g/cm^3	5.19×10^{-6}
Cladding	
Material	Aluminum alloy (AG5)
Composition, wt%	Al = 98.85, Mg = 0.47, Si = 0.43, Fe = 0.22, Zn = 0.03
Outside diameter, cm	0.94
Inside diameter, cm	0.82
Total length of the element, cm	100

[a]The main impurities (nuclear poisons = B, Cd, N, etc.) are converted into boron equivalent considering their absorption cross section for thermal neutrons and using the formula

$$B \text{ equivalent} = \frac{B\sigma_B + I_1\sigma_{I_1} + \ldots + I_n\sigma_{I_n}}{\sigma_B} .$$

2. an auxiliary container (3.20 m long, 2.10 m wide, and 1.50 m high) enclosing the above tank, to receive the moderator/reflector water upon opening the safety valves.

The fuel rods to be tested were supported in a stainless-steel (Type Z2 CN 18 10) basket by two grids of pitch appropriate to the experiment, attached by four rods to a support plate (see Fig. 3).

The main dimensions of the fuel rods and of the stainless-steel basket are given in Fig. 1. In the analysis, we have neglected the effect of the upper grid, which was in the air, and of the four rods, which were more than 20 cm from the fuel.

Although for operational convenience, the position of the water surface was measured from the upper surface of the support plate, the values of the critical height given in this paper are distances from the lower end of the fuel pellet column.

EXPERIMENTAL RESULTS

During the various experiments we have carried out, the value of the critical height of water was obtained by linear extrapolation of the last two points of the subcritical approach curve. It is an

[1]H. K. CLARK, "Critical and Safe Masses and Dimensions of Lattices of U and UO_2 Rods in Water," DP-1014, Savannah River Laboratory (1966).
[2]E. B. JOHNSON, *Trans. Am. Nucl. Soc.*, **10**, 190 (1967).
[3]E. B. JOHNSON, *Trans. Am. Nucl. Soc.*, **11**, 674 (1968).
[4]E. B. JOHNSON, *Trans. Am. Nucl. Soc.*, **13**, 379 (1970).
[5]B. M. DURST, S. R. BIERMAN, and E. D. CLAYTON, *Trans. Am. Nucl. Soc.*, **28**, 300 (1978).

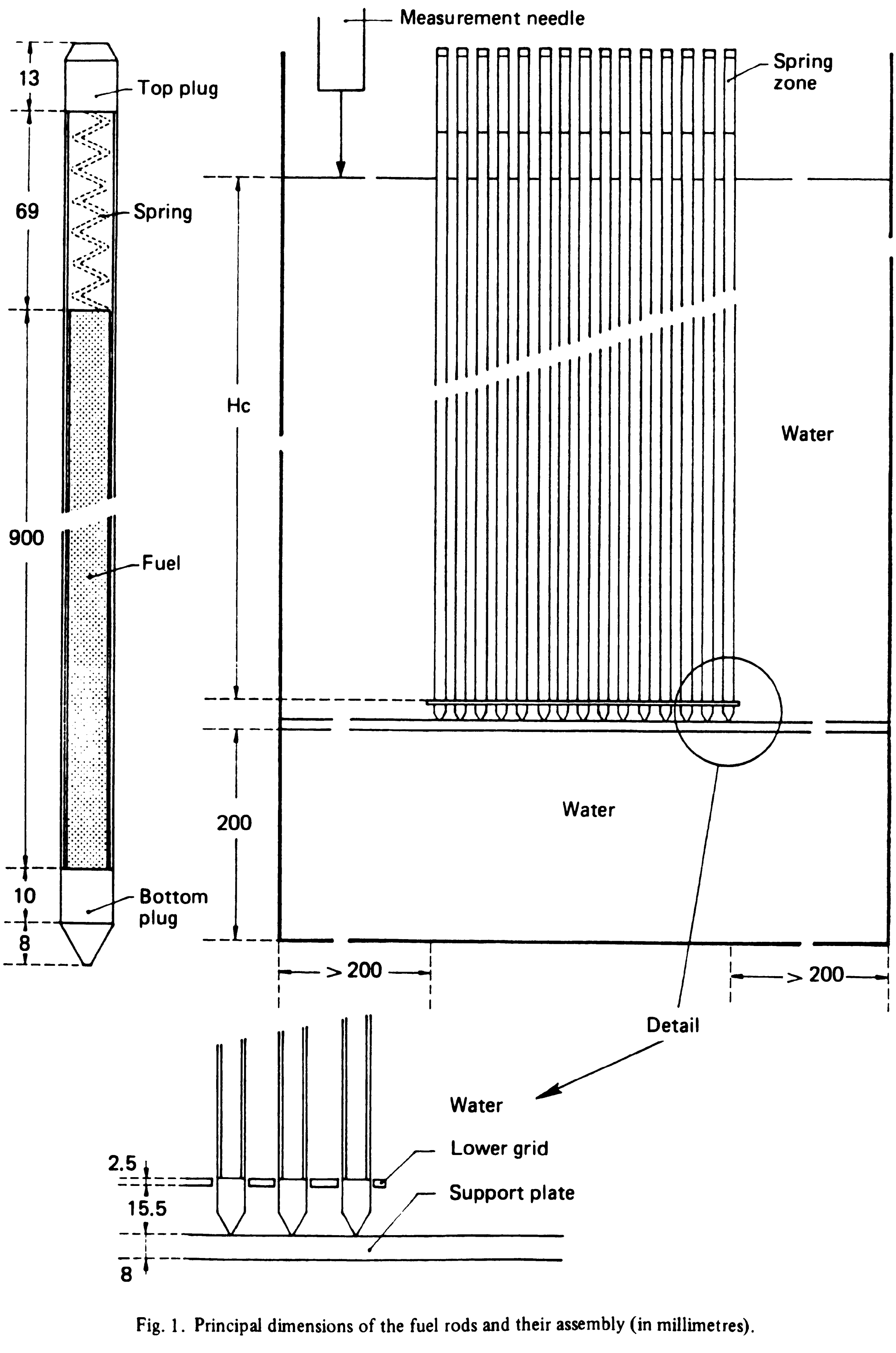


Fig. 1. Principal dimensions of the fuel rods and their assembly (in millimetres).

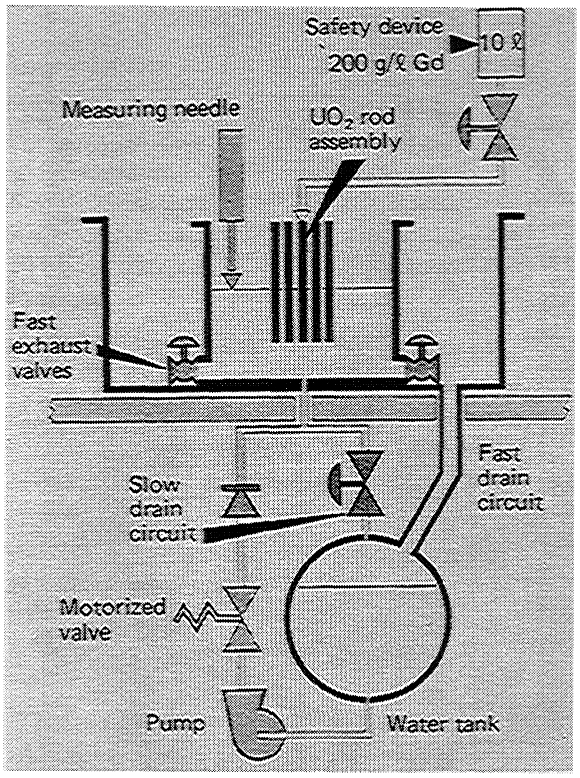


Fig. 2. Experimental criticality installation.

average value based on the indications supplied by five counting channels (BF3), four of them placed vertically at the four corners of the experimental tank and one placed horizontally at the bottom.

The last two points of the subcritical approach were generally between 0.25 and 0.40 dollar from delayed criticality. The uncertainty in the measured critical heights includes

1. a variable uncertainty, which is the standard deviation between the extrapolations and their average value and which is always <0.5 mm
2. a systematic uncertainty of 0.5 mm which results from the accuracy of the measurement needle.

That means that the critical water height was obtained with an accuracy better than ±1 mm. All the experiments have been carried out at a temperature of 22°C.

Experiments Carried Out Without Removal of Rods

First, we successively studied the following lattices:

TABLE II

Experimental Data on Complete Lattices Not Fully Water Moderated and Reflected

Type	Pitch (mm)	Number of Rods		Critical Water Height (cm)
Square	12.6	22 X 22	484	90.69 ±0.10
	16.0	16 X 17	272	73.53 ±0.10
	21.0	15 X 15	255	77.98 ±0.06
	25.2	17 X 18	306	79.85 ±0.01
Triangular (hexagonal shape)	13.5	14 Each side	547	60.93 ±0.06
	17.2	10 Each side	271	68.06 ±0.06
	22.6	9 Each side	217	79.50 ±0.06

1. Square pitch lattices:
   a. 12.6 mm (undermoderated lattice at the nominal pitch of the PWR elements)
   b. 16.0 mm (optimum moderation)
   c. 21.0 mm (overmoderated lattice)
   d. 25.2 mm.
2. Triangular pitch lattices:
   a. 13.5 mm (undermoderated lattice at the nominal pitch of PWR elements)
   b. 17.2 mm (optimum moderation)
   c. 22.6 mm (overmoderated lattice).

By optimum moderation, we mean the moderation corresponding to the maximum value of B_m^2 (i.e., the optimum moderation for the geometry, see Table VI below). The obtained results are shown in Table II.

These data were used to draw the curve of Fig. 4 giving the critical number of completely immersed rods in relation to the pitch of a square lattice. The number of rods was obtained by extrapolation of the measured critical height.

We then studied, for triangular pitch lattices, three irregular hexagonal configurations and three pseudo-cylindrical configurations. The corresponding values of critical water height are shown in Table III. These lattices were not fully moderated and reflected.

The number of rods on the sides of the irregular hexagonal configurations is given in the first part of

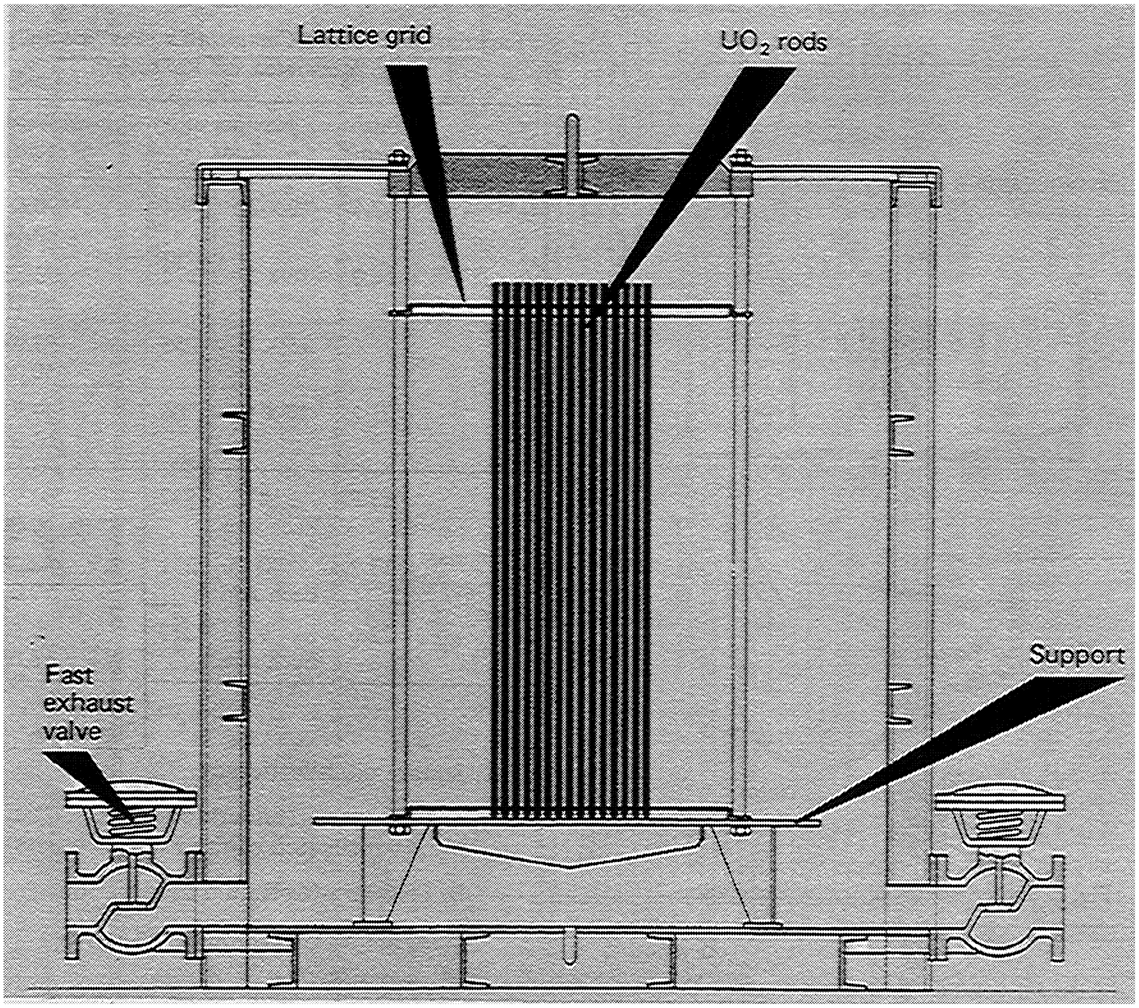


Fig. 3. Rod assembly in the experimental vessel.

TABLE III

Experimental Data on Complete Lattices Not Fully Water Moderated and Reflected

Type	Pitch (mm)	Number of Rods	Number of Rods on Each Side	Critical Water Height (cm)
Triangular with irregular hexagonal shape	13.5	519	13/13/15/13/13/15	69.50 ±0.06
		505	15/12/15/12/15/12	75.79 ±0.07
		495	14/14/12/14/14/12	82.43 ±0.06
Triangular with pseudo-cylindrical shape	13.5	484	See Fig. 5	85.21 ±0.06
	17.2	277	See Fig. 5	61.99 ±0.06
	22.6	225	See Fig. 5	70.44 ±0.07

Table III, and the description of the pseudo-cylindrical configurations is given by the three diagrams of Fig. 5.

Experiments Carried Out After Removal of Rods

The aim of these experiments was to determine the effects of "water holes" in an assembly. Rods were removed in a regular pattern from two of the 12.6-mm-pitch square lattices (e.g., alternate rods in both directions, or every third rod, etc.). The lattices of 21 X 21 and 22 X 22 rods were undermoderated. The pattern was

1. systematic in the whole lattice (see the example in Table IV)
2. by limiting this removal to a small zone, which was then moved from the center of the lattice to one of its angles by following a diagonal (see Fig. 6).

Tables IV and V give the results obtained in the two cases.

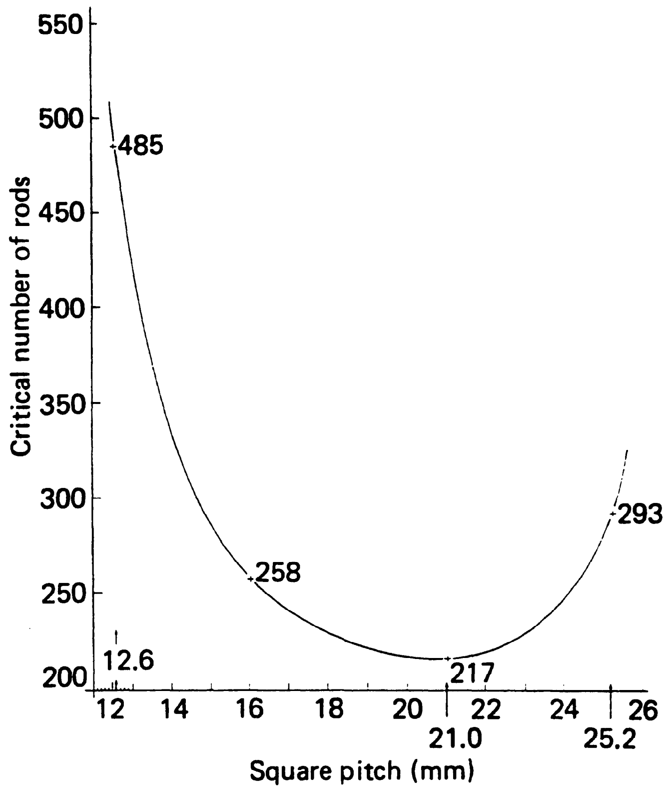


Fig. 4. Curve giving the critical number of completely immersed rods as a function of the pitch of a square lattice.

DATA ANALYSIS AND CONCLUSIONS

These calculations are carried in two phases using the APOLLO (Ref. 6) and MORET (Ref. 7) codes:

1. calculation of the neutron constants of fissile materials by APOLLO
2. calculation of k_{eff} by MORET.

The APOLLO code is used with the "transport" option to calculate the material buckling, B_m^2, and the k_∞ of an infinite lattice of rods in its ambient medium (water or air) and to determine the macroscopic cross sections of the homogenized lattice based on the 16 energy groups of Hansen and Roach. We assume that the cell is cylindrical.

The cross-section library used in the code is ENDF/B-III (Ref. 8). The cross sections are divided into 99 groups (52 fast groups and 47 thermal groups).

The MORET code is a Monte Carlo code that calculates the k_{eff} of any configuration. It is a three-dimensional code that treats the collision isotropically, but anisotropy is taken into account by means of the transport correction. For the structure (pure water and steel), it uses the Hansen and Roach[9] 16-group cross sections as modified by Knight. For the lattice, it uses the cross sections calculated by APOLLO. The results undergo a statistical dispersion equal to twice the standard deviation: "2σ" (i.e., 96% confidence interval).

The code also calculates the average group of fission, which is a "spectral index," the group "16" being the most thermal:

$$\bar{G}_F = \frac{\sum_{i=1}^{i=16} iF(i)}{\sum_{i=1}^{i=16} F(i)} ,$$

in which $F(i)$ is the total number of fission neutrons.

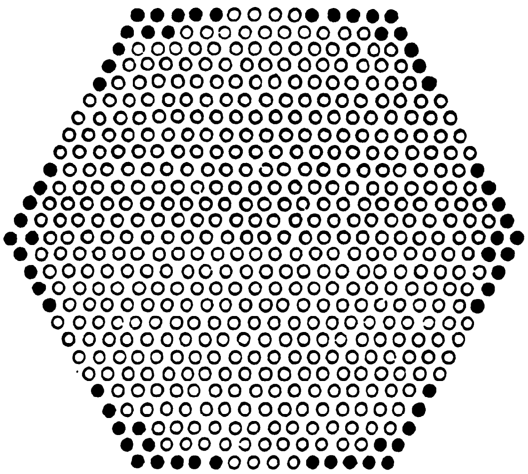
The configuration calculated by the MORET code is deduced from the experimental configuration, including the following simplifications and approximations:

[6] "APOLLO—Code multigroupe de résolution de l'équation du transport pour les neutrons thermiques et rapides," CEA-N 1610, Centre d'Etudes Nucléaires, Saclay (1973).

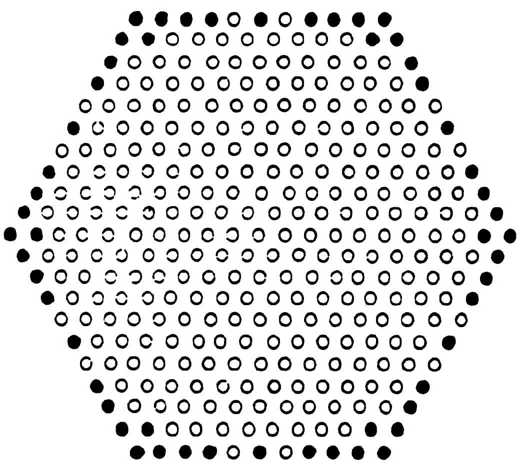
[7] "MORET—Un programme Monte-Carlo pour le calcul rapide de coefficients de multiplication effectifs de milieux fissiles de géométrie complexe," CEA-R 4752, Centre d'Etudes Nucléaires, Saclay (1976).

[8] "Evaluated Nuclear Data File (ENDF/B-III)," National Neutron Cross Section Center, Brookhaven National Laboratory.

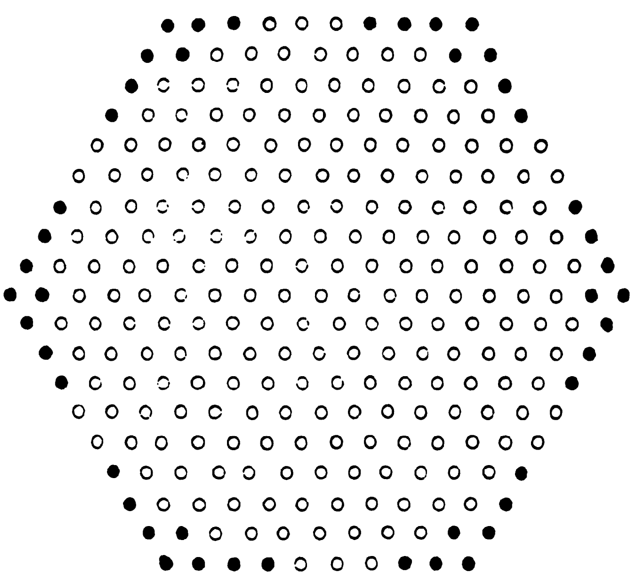
[9] G. I. BELL, J. J. DEVANEY, G. E. HANSEN, C. B. MILLS, and W. H. ROACH, "Averaged Cross Sections," LAMS-2941, Los Alamos Scientific Laboratory (1963).



Pitch = 13.5 mm
Rods = 484
Holes = 63
Critical water height = 85.21 cm



Pitch = 17.2 mm
Rods = 277
Holes = 54
Critical water height = 61.99 cm



Pitch = 22.6 mm
Rods = 225
Holes = 48
Critical water height = 70.44 cm

Fig. 5. Diagram of the three pseudo-cylindrical configurations. Rods = white dots; holes = black dots.

TABLE IV

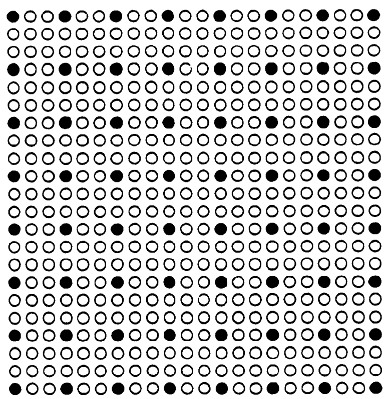
Experimental Data Showing the Effect of Holes Distributed in a Lattice

(The lattices were not fully moderated and reflected.)

Square Pitch (mm)	Pattern	Number of Rods	Number of Holes	Frequency of Hole	Critical Water Height (cm)
12.6	22 X 22	459	25	1 in 5 spaces	81.36 ±0.07
		448	36	1 in 4 spaces	77.69 ±0.07
		420[a]	64	1 in 3 spaces	73.05 ±0.06
		363	121	1 in 2 spaces	58.77 ±0.06
	21 X 21	392	49	1 in 3 spaces	89.07 ±0.07
		320	121	1 in 2 spaces	84.37 ±0.06

[a]Example

22 X 22
1 hole in 3 spaces
420 rods (white dots)
64 holes (black dots)



1. Some structural elements were neglected due to their small sizes and their position apart from the rods, such as the steel tie rods of the basket, the upper guide, the lattice grid, the tank, and the support feet. Other elements were homogenized on the volume owing to their locations and their small effect on the reactivity.

2. The lower lattice grid was taken to be a 0.25-cm-thick slab in which the steel, the aluminum of the lower plug, and the water between the rods and the grid are mixed.

3. The lower plugs were considered as a single slab, 1.55 cm thick, including the aluminum of the plugs and the water between the rods. The dimension a of the homogenized lattice section is equal to $N \cdot P$ for a square section and $P(N_T/3)^{1/2}$ for the triangular (hexagonal) section, in which

P = pitch

N = number of rods according to one side

N_T = total number of rods.

As an example, the results obtained for completed triangular and square lattices are presented in Table VI. The results obtained on the completed lattices are in good agreement with the experiment, except for the overmoderated, 21.0- and 25.2-mm square pitch, for which the k_{eff} values (0.986 and 0.975) are rather low. This is perhaps due to the small validity of the cylindrization hypothesis.

FUTURE PROGRAM

The following experiments are proposed for this program:

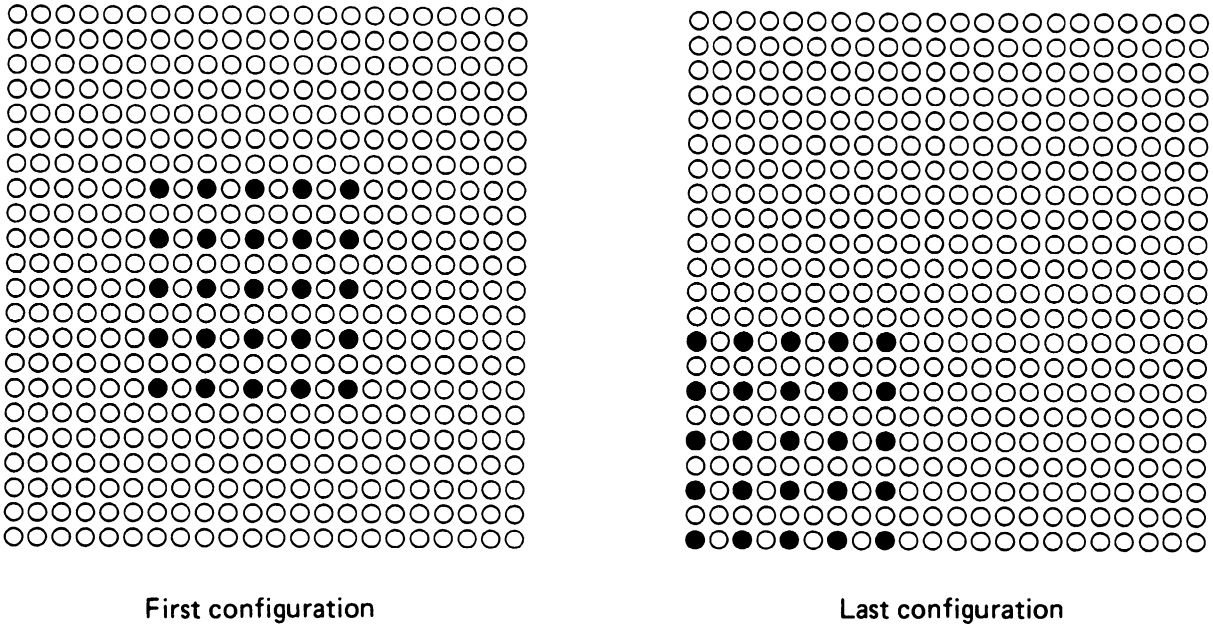


Fig. 6. First and last configurations in the case of holes distributed in a square zone, with 459 rods (white dots) and 25 holes (black dots). Critical water heights were 68.75 and 81.34, cm, respectively.

TABLE V

Experimental Data Showing the Effect of Holes Distributed in a Square Zone

(The lattices were not fully moderated and reflected.)

Pitch (mm)	Pattern	Number of Rods	Number of Holes	Frequency of Holes
12.6	22 X 22	459	25	Alternate rods removed

Configuration (See Fig. 6)	Locations of the Holes[a] Row Number ↓	Locations of the Holes[a] Column Number →	Critical Water Height (cm)
	8-10-12-14-16	7-9-11-13-15	68.75 ±0.06
	9-11-13-15-17	6-8-10-12-14	69.40 ±0.06
	10-12-14-16-18	5-7-9-11-13	69.88 ±0.06
	11-13-15-17-19	4-6-8-10-12	71.14 ±0.06
	12-14-16-18-20	3-5-7-9-11	72.52 ±0.07
	13-15-17-19-21	2-4-6-8-10	75.38 ±0.07
	14-16-18-20-22	1-3-5-7-9	81.34 ±0.06

[a]Rows and columns are numbered from the upper left corner.

TABLE VI

Results of Experiments and Benchmark Calculations for Complete Lattices of 4.75-wt%-^{235}U-Enriched UO_2 Rods in Water

Type	Pitch (mm)	Number of Rods		Critical Water[a] Height (mm)	Calculated Results			
					APOLLO Code		MORET Code	
		Along Edge	Total		B_m (cm^{-2})	k_∞	$k_{eff} \pm 2\sigma$	$\overline{G}_F$
Square	12.6	22 X 22	484	906.9	0.0118	1.479	1.004 ± 0.014	14.48
	16.0	16 X 17	272	735.3	0.0141	1.506	1.009 ± 0.012	15.04
	21.0	15 X 15	225	779.8	0.0116	1.393	0.986 ± 0.013	15.33
	25.2	17 X 18	306	788.5	0.00753	1.256	0.975 ± 0.010	15.45
Triangular	13.5	14	547	609.3	0.0118	1.479	1.004 ± 0.012	14.43
	17.2	10	271	680.6	0.0141	1.506	0.995 ± 0.012	15.05
	22.6	9	217	795.5	0.0116	1.393	0.996 ± 0.012	15.36

[a]Measured from the bottom of the fuel.

1. A study of the poisoning effect of various amounts of gadolinium on the critical water heights obtained for the various lattices.

2. A study of the interaction between four assemblies of 18 X 18 rods at the 13.5-mm pitch; these assemblies have a neutron spectrum equivalent to the spectrum of PWR assemblies. This interaction will be studied in four cases:

   a. simulation of an in-pool storage configuration without neutron absorbing shields

   b. simulation of a dry storage configuration assuming interspersed water from a sprinkler; simulation will be by placing low-hydrogen-density media, like polystyrene, between the various assemblies

   c. simulation of an in-pool storage configuration by placing sheets of various materials (cadmium, copper, hafnium, boron, etc.) between the assemblies.

   d. simulation of a shipping cask with a lead side reflector of more than a 10-cm thickness.