REFERENCE 112

S. R. BIERMAN, B. M. DURST, E. D. CLAYTON, R. I. SCHERPELZ, AND H. T. KERR, "CRITICAL EXPERIMENT WITH FAST TEST REACTOR FUEL PINS IN WATER," NUCL. TECHNOL. 44: 141-151 (1979).

nucleartechnology®

VOLUME 44
JUNE, JULY,
AUGUST 1979

AMERICAN NUCLEAR SOCIETY
555 NORTH KENSINGTON AVENUE • LA GRANGE PARK, ILLINOIS 60525 USA

CRITICAL EXPERIMENTS WITH FAST TEST REACTOR FUEL PINS IN WATER

FUEL CYCLES

KEYWORDS: *FTR, fuel pins, criticality, water, lattice parameters, computer calculations, data, comparative evaluations*

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Received September 25, 1978
Accepted for Publication January 9, 1979

A series of criticality experiments with fast test reactor (FTR) fuel pins in water has been performed in support of the Advanced Fuel Recycle Program (AFRP). The objective of these experiments was to provide clean, easily defined criticality data on AFRP-type fuel pins in water for use in verifying calculational techniques and nuclear data used in calculations. Measurement data were obtained on water-flooded square lattices of FTR fuel pins. The number of fuel pins required for criticality was determined at lattice pitches of 7.7, 9.5, 9.7, 12.6, 15.3, and 19.1 mm to be 1268, 605, 580, 279, 205, and 162, respectively. These center-to-center fuel pin spacings correspond to water-to-fuel volume ratios of 1.67, 3.33, 3.49, 6.87, 10.88, and 17.53, respectively, and cover the neutron moderation range from near optimum to the highly undermoderated.

KENO-IV calculations with ENDF data from the AMPX system overestimated the experimental results by 1 to 2% in k_{eff}. *KENO-IV calculations with FLANGE-ETOG-THERMOS-EGGNIT-processed ENDF data resulted in calculated values 1 to 6% high in* k_{eff}.

INTRODUCTION

Criticality experiments for the Advanced Fuel Recycle Program (AFRP) are currently being carried out at the Battelle-operated U.S. Department of Energy Critical Mass Laboratory at Hanford. The objective of these experiments is to provide a reliable technological basis for nuclear criticality control in the AFRP Research and Development Program. The planned critical experiments are designed to serve as benchmarks for validating computer codes and nuclear data used in calculations of mixed plutonium and uranium systems.

The results from a series of experiments in this program are presented in this paper. These experiments were performed with fast test reactor (FTR) fuel pins immersed in water and arranged in square lattices to obtain water-to-fuel-volume ratios ranging from 17.53 to 1.67. A partially loaded lattice is shown in Fig. 1.

FUEL PIN DESCRIPTION

The fuel for the FTR is a mixture of PuO_2 and UO_2. The weight ratio of UO_2 to PuO_2 is normally in the region from 2 to 4, and the uranium is either natural or depleted. Two types of FTR fuel pins were available for use in the critical experiments: Type 3.1 (201 fuel pins) and Type 3.2 (999 fuel pins). Physically, both types of fuel pins are essentially identical. A diagram giving both the common dimensions and those dimensions that differ between the two types of pins is shown in Fig. 2. Both types of fuel pins are 5.842 mm in diameter and ~2.4 m in length. In either fuel pin, the actual fuel region is restricted to a 914-mm length near the bottom of the pin. The remainder of the pin consists of endcaps and other types of hardware.

The primary differences between the two types of fuel pins are in the composition of the PuO_2-UO_2 fuel mixtures. The Type 3.1 fuel pins contain 24.39 wt% plutonium in the PuO_2-UO_2, while the Type 3.2 fuel pins contain 19.84 wt% plutonium. A complete composition breakdown of each type of fuel mixture is given in Fig. 2. The plutonium in either type of fuel pin contained 11.5 wt% ^{240}Pu. The uranium in the PuO_2-UO_2 mixture was natural uranium for both the Type 3.1 and Type 3.2 fuel pins.

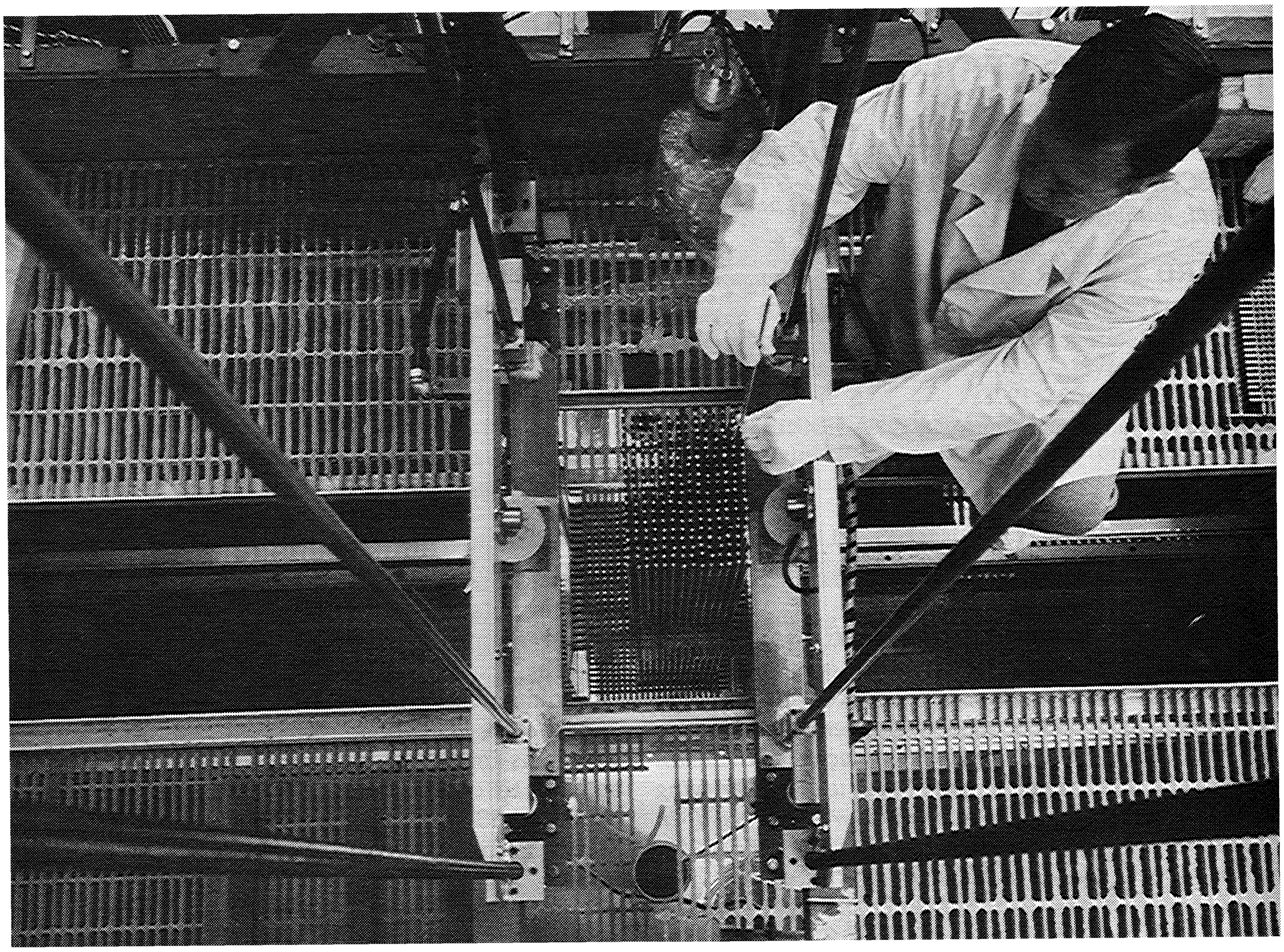


Fig. 1. Partially loaded lattice of FTR fuel pins immersed in water.

TABLE I

Experimental Criticality Data—Water-Flooded Type 3.2 FTR Fuel Pins

Experiment Reference Number[a]	Square Lattice Pitch[b] (mm)	Water-to-Fuel (Volume ratio)	Lattice Width (Fuel pins)	Critical Number of Fuel Pins[b]
003R	7.671 ± 0.127	1.67	36	1037 ± 1[c]
005	9.525 ± 0.127	3.33	28	605 ± 1
029[d]	9.677 ± 0.127	3.49	28	579 ± 1
030[e]	9.677 ± 0.127	3.49	28	579 ± 1
001	12.588 ± 0.127	6.87	18	279 ± 1
004	15.342 ± 0.127	10.88	18	205 ± 1
006	19.050 ± 0.127	17.53	14	162 ± 1

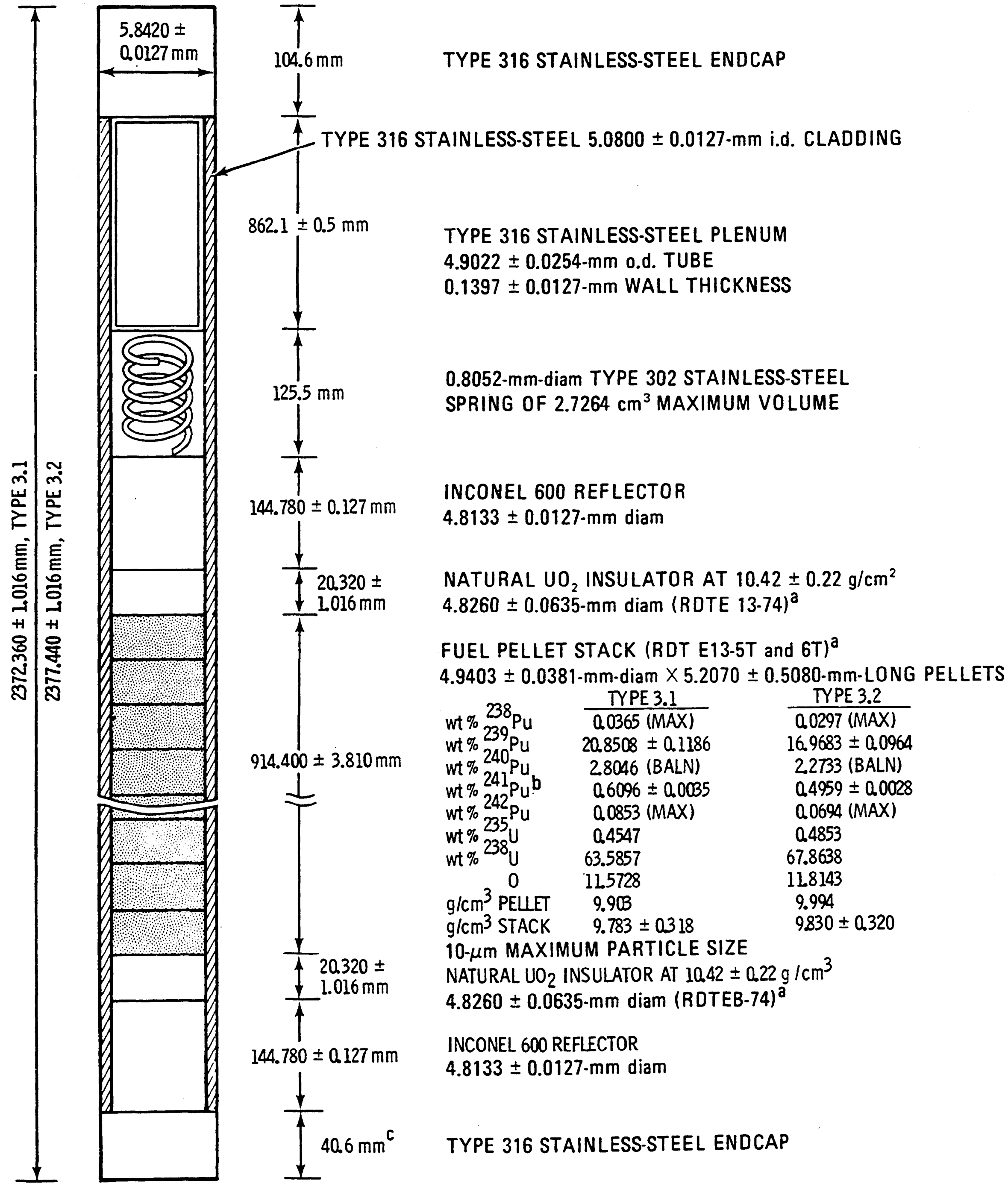
[a] All experiments were performed in February 1978, except 029 and 030, which were performed in December 1978.

[b] Error limits shown are standard deviations and are for the indicated measured parameter only.

[c] Includes 65 Type 3.1 FTR fuel pins on a 15.342-mm lattice pitch positioned on either side (36 on one side and 29 on the other) of a 27 X 36 fuel pin array of Type 3.2 FTR fuel pins at a 7.671-mm square lattice pitch.

[d] Type 304L stainless-steel lattice grids replaced with 13.68 ± 0.04-mm-thick, 0.904 g/cm^3 polypropylene grids.

[e] Same as experiment 029 except different fuel pins of the same type.



	TYPE 3.1	TYPE 3.2
wt % ^{238}Pu	0.0365 (MAX)	0.0297 (MAX)
wt % ^{239}Pu	20.8508 ± 0.1186	16.9683 ± 0.0964
wt % ^{240}Pu	2.8046 (BALN)	2.2733 (BALN)
wt % ^{241}Pu[b]	0.6096 ± 0.0035	0.4959 ± 0.0028
wt % ^{242}Pu	0.0853 (MAX)	0.0694 (MAX)
wt % ^{235}U	0.4547	0.4853
wt % ^{238}U	63.5857	67.8638
O	11.5728	11.8143
g/cm^3 PELLET	9.903	9.994
g/cm^3 STACK	9.783 ± 0.318	9.830 ± 0.320

[a] Referenced division of reactor development and technology standard.

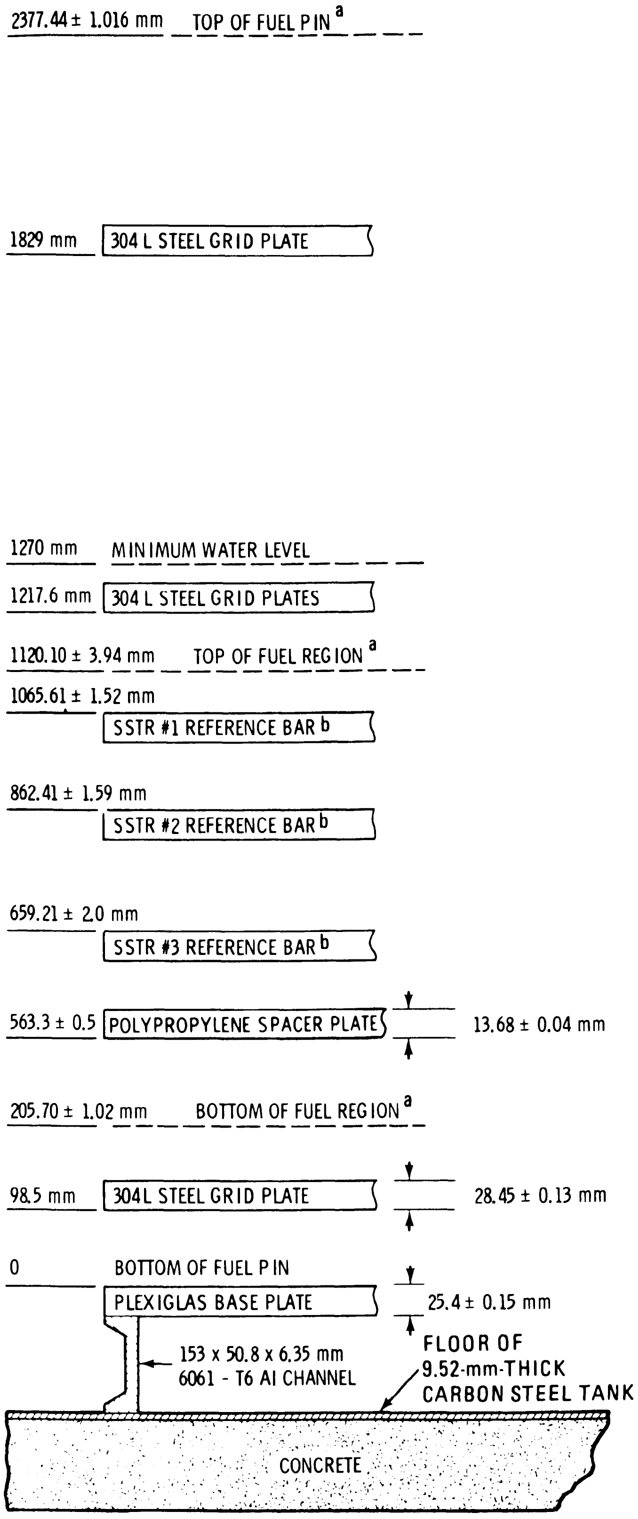
[b] Americium-241 content of total plutonium was measured to be 0.13 wt% during April and May of 1972.

[c] 35.6 mm for Type 3.1 fuel pins.

Fig. 2. Simplified description of FTR fuel pin.

EXPERIMENTS AND DATA

The experimental results obtained for the different lattices are presented in Table I. The fuel region of each lattice is water flooded and fully reflected on all sides by at least 150 mm of water. However, the fuel pins were immersed in water only to a depth of 150 mm above the fuel region, as indicated in Fig. 3. Consequently, the top reflector for each of the assemblies is perforated by the fuel pin hardware



[a] Elevations for Type 3.2 fuel pins. Elevations for Type 3.1 fuel pins are 5 mm less.

[b] Located outside the fuel pin array. Not involved in critical experiments.

Fig. 3. Relative elevations–critical experiments with FTR fuel pins in water.

immediately above the fuel region. Deionized water (500 000-Ω minimum) was used in the experiments.

In all but one lattice, the grid plates used to obtain the desired spacings between the pins were of "egg-crate"-type construction and were made of steel (Type 304L stainless steel) to obtain the structural integrity believed needed. In each lattice, these steel grids were located above and below the fuel region to minimize their reactivity effect on the experimental assembly. A photograph showing one set of steel grid plates mounted in position is shown in Fig. 4. The fuel region of an FTR fuel pin inserted in this assembly would lie between the bottom two grid plates.

To prevent fuel pin deflections over this region, a spacer grid of polypropylene (which has neutron-moderating properties very similar to water) was provided in the fuel region of each lattice, as indicated in Fig. 3. Based on the experience with these polypropylene spacers, it was concluded that the steel grids could be replaced with polypropylene in any future experiments with this fuel. As indicated in Table I, one set of experiments at a lattice pitch of

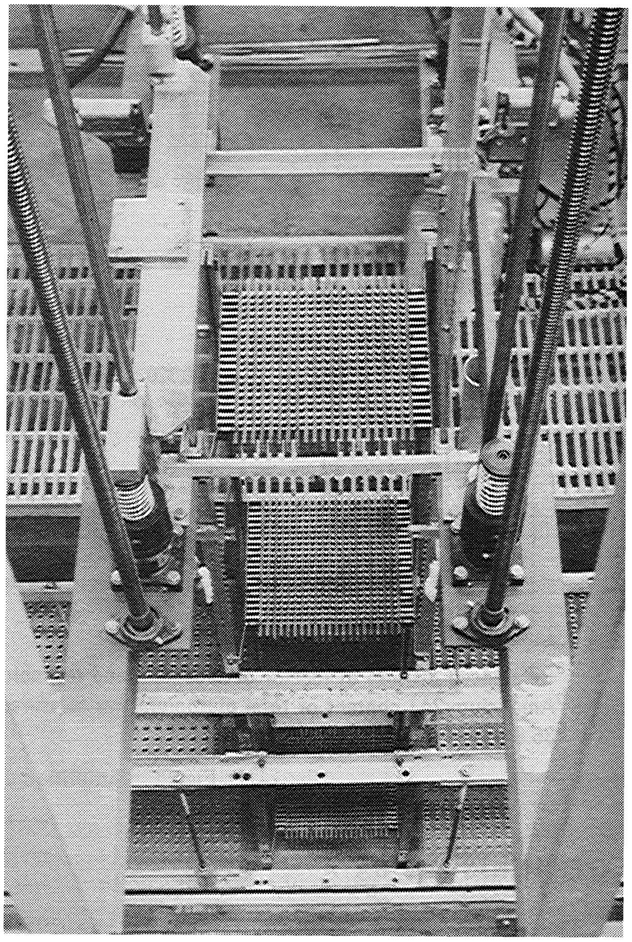
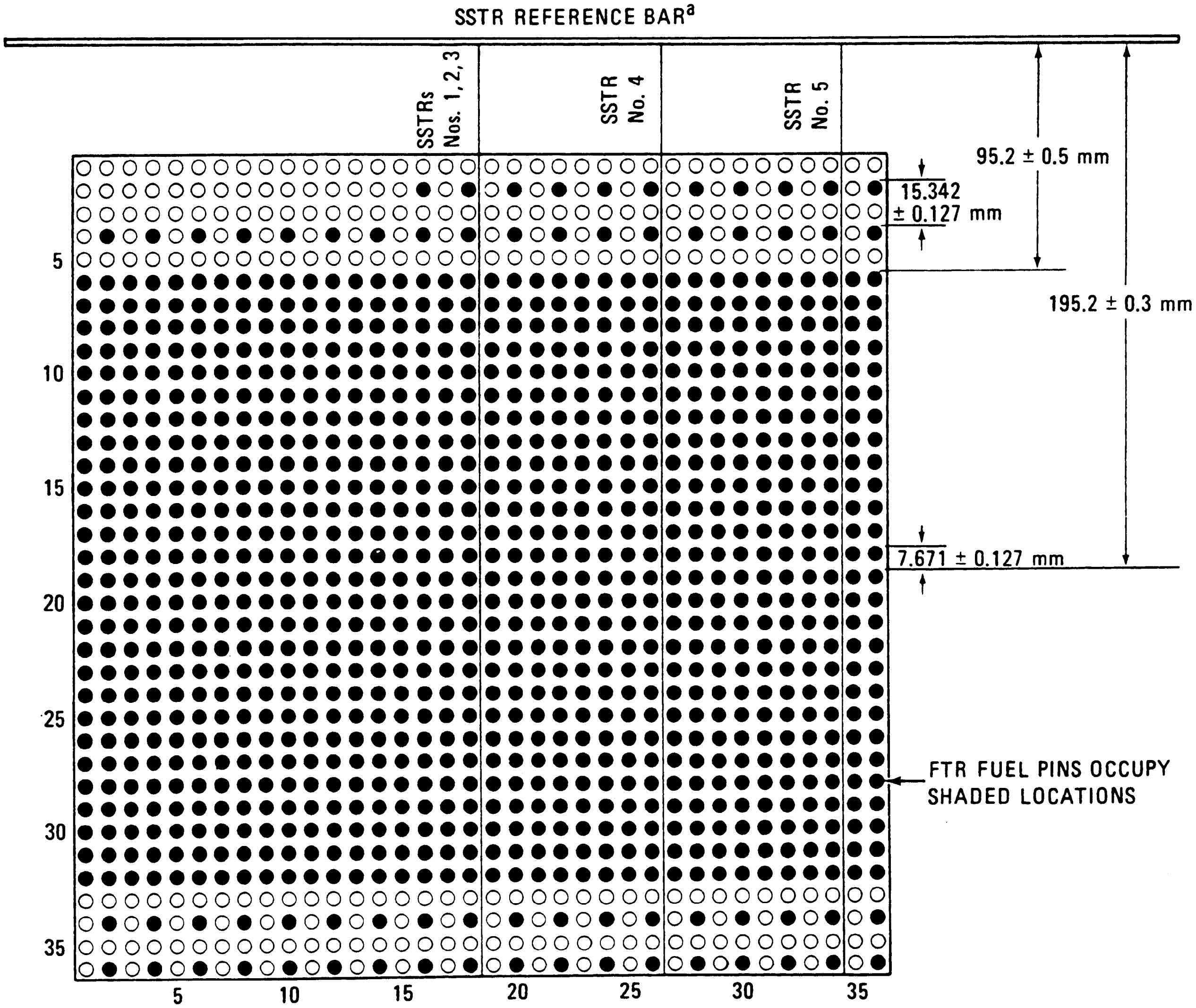


Fig. 4. Typical set of grid plates mounted in position.

~9.7 mm was performed with all the grid plates in the assembly being polypropylene.

Each experimental assembly was provided with a Boral safety blade and a Boral control blade; however, these were fully withdrawn from each assembly during data acquisition. (The safety blade is shown withdrawn and the control blade is shown inserted in Fig. 4.) Although controlled criticality is normally achieved by movement of a control device, this perturbation was avoided in the measurements covered in this paper to obtain clean, well-defined data. The critical condition for each assembly was obtained by extrapolation of subcritical data to the critical condition. For this extrapolation, each experimental assembly was generally taken to within 1% of the critical condition by observing the increase in neutron flux as fuel pins were symmetrically added (with respect to the flux) to each assembly. Whenever 99% of the critical condition was not achieved with a symmetrical loading, the assembly was loaded to a critical condition for the control blade partially withdrawn to verify that the extrapolated critical condition was reasonable. Because of the neutron source indigenous to fuel of this type, no external source was used in any of the experiments.

Except for the 7.671-mm lattice, the critical assemblies in Table I contain only the Type 3.2 fuel pins. At the 7.671-mm center-to-center spacing, the



[a]Elevations of the SSTR reference bars are 1065.61 ± 1.52 mm and 862.41 ± 1.59 mm above the bottom of the fuel pins for SSTRs Nos. 1 and 2, respectively. The reference bar for SSTRs Nos. 3, 4, and 5 is at an elevation of 659.21 ± 2.0 mm above the bottom of the fuel pins. SSTRs not in assembly during approach to critical.

Fig. 5. Layout of critical experiment (experiment No. 003R) FTR fuel pins immersed in water.

number of fuel pins required for criticality exceeded the 999 Type 3.2 fuel pins available for the measurements. Consequently, this lattice contains some Type 3.1 fuel pins. To obtain criticality data for this 7.671-mm spacing, Type 3.1 fuel pins at a more reactive spacing of 15.342 mm were positioned on either side of a 36 X 27 array of Type 3.2 fuel pins having the 7.671-mm center-to-center spacing. The fuel pin arrangement for this assembly is shown in Fig. 5. According to calculations normalized to this mixed assembly, an assembly of only Type 3.2 fuel pins on the 7.671-mm center-to-center spacing would require 1268 fuel pins to achieve criticality. Fuel arrangements for the other lattices are shown in Figs. 6 through 10.

The data from these measurements are summarized in Fig. 11 to obtain a curve for the critical number of fuel pins as a function of lattice pitch. All assemblies were ~270 mm wide except for the

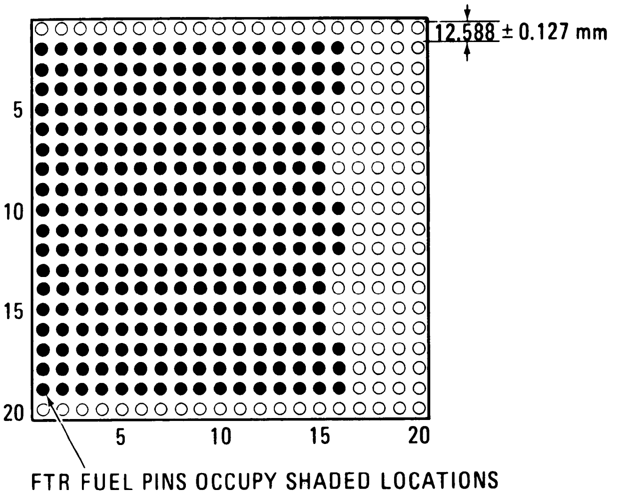


Fig. 6. Layout of critical experiment (experiment No. 001) FTR fuel pins immersed in water.

TABLE II

Summary of Calculational Results: FTR Fuel Pins in Water

Experiment Number	Square Pitch (mm)	Lattice Width (Pins)	Total Number of Pins in Lattice[a]	k_{eff}[b]	
				EGGNIT-THERMOS/ KENO-IV[c]	NITAWL/KENO-IV[c]
003R	7.671	36[d]	1037[e]	1.010 ± 0.005	1.017 ± 0.005
		36	1296	1.014 ± 0.004	
		36	1224	1.004 ± 0.004	
		36	1188	1.001 ± 0.004	
005	9.525	28	605[e]	1.034 ± 0.005	1.016 ± 0.004
029	9.677	28	579[e]	1.035 ± 0.005	1.017 ± 0.005
		28	605	1.043 ± 0.007	
		28	560	1.023 ± 0.005	
		28	504	1.006 ± 0.006	
001	12.588	18	279[e]	1.038 ± 0.004	1.018 ± 0.004
		18	306	1.066 ± 0.004	
		18	252	1.018 ± 0.005	
004	15.342	18	205[e]	1.053 ± 0.005	1.014 ± 0.005
		18	180	1.012 ± 0.006	
006	19.050	14	162[e]	1.044 ± 0.004	1.012 ± 0.004
		14	140	1.016 ± 0.005	
		14	112	0.946 ± 0.005	

[a] Type 3.2 FTR fuel pins unless otherwise noted.

[b] Error limits are one standard deviation on the KENO calculations.

[c] 18-energy-group EGGNIT-THERMOS-averaged cross sections from FLANGE-ETOG-processed ENDF/B-III and ENDF/B-IV data. ORNL 218-neutron-group criticality library collapsed into 27 energy groups using MALOCS module in AMPX.

[d] 65 Type 3.1 FTR fuel pins on a 15.342-mm lattice pitch positioned on either side (36 on one side and 29 on the other) of a 27 X 36 fuel pin array of Type 3.2 pins at a 7.671-mm square pitch.

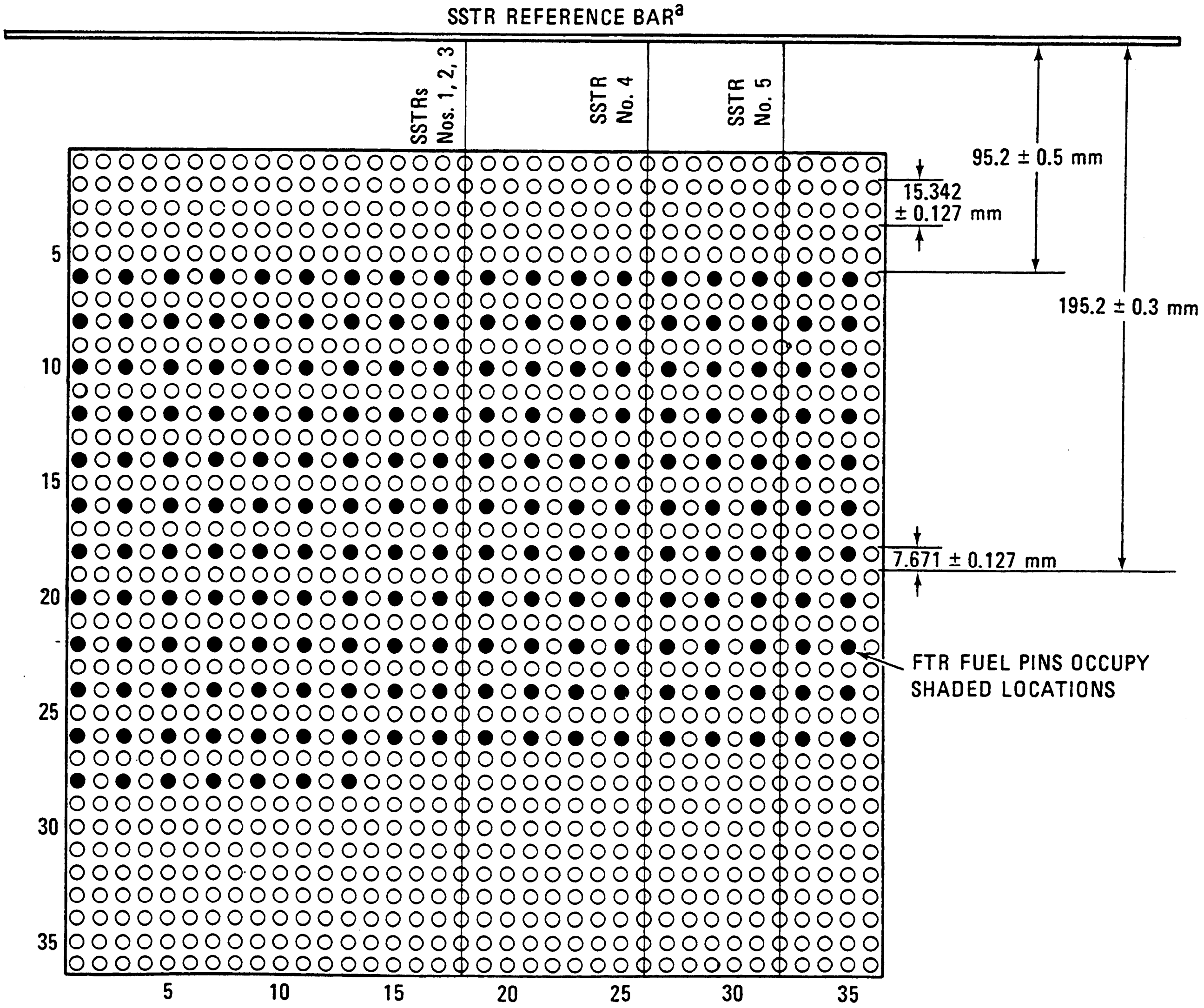
[e] Experimentally determined critical size.

12.588-mm-pitch assembly, which was ~226 mm wide. To put this assembly on a common basis with the others, a buckling conversion was made to the experimental data to obtain the number of fuel rods (294) required for criticality at an assembly width of 270 mm.

It was anticipated that the steel grid plates were positioned such that they would have a negligible effect on the number of fuel pins required in each assembly for criticality. Later experiments with grid plates constructed of polypropylene and having a lattice spacing of 9.677 mm verified this assumption. As can be seen in Fig. 11, the result obtained with the polypropylene lattice grids is in good agreement with the other experimental results. As a further check, steel straps were positioned between the fuel pins on the polypropylene grid just above the fuel region, and no change was observed in the number of fuel pins required for criticality.

Although the curve shown in Fig. 11 indicates the sensitivity of lattice spacing on the number of fuel pins required for criticality, the measurements with the 9.677-mm pitched polypropylene grids provide a direct measure of this sensitivity in the region where it is very pronounced. Both the 9.677- and 9.525-mm pitched lattices were 28 fuel pins wide. As indicated by the data in Table I, this 0.152-mm change in fuel pin spacing resulted in a 4.3% (25 fuel pins) change in the number of pins required for criticality.

Fission rate measurements were carried out on



[a]Elevations of the SSTR reference bars are 1065.61 ± 1.52 mm and 862.41 ± 1.59 mm above the bottom of the fuel pins for SSTRs Nos. 1 and 2, respectively. The reference bar for SSTRs Nos. 3, 4, and 5 is at an elevation of 659.21 ± 2.0 mm above the bottom of the fuel pins. SSTRs not in assembly during approach to critical.

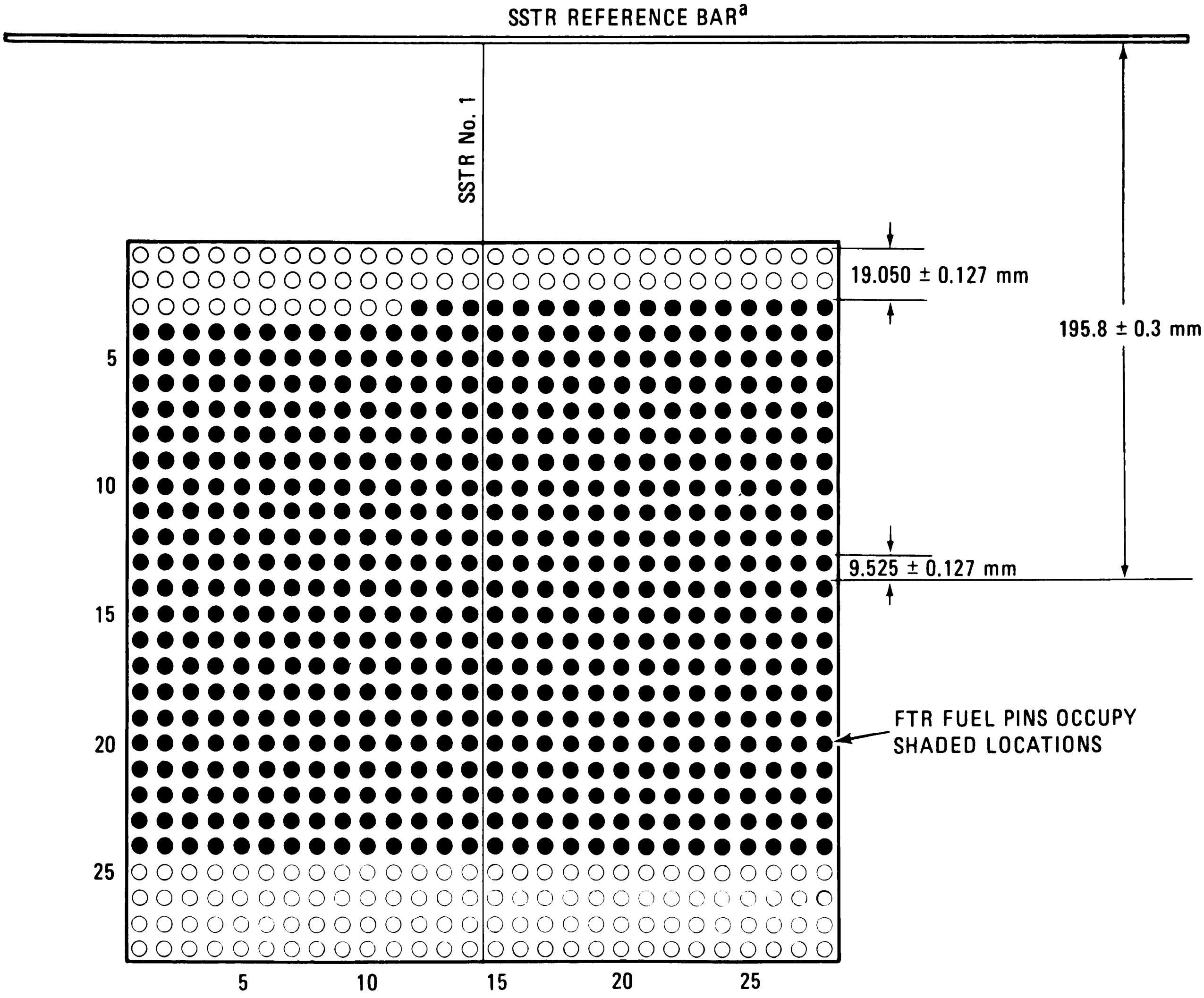
Fig. 7. Layout of critical experiment (experiment No. 004) FTR fuel pins immersed in water.

selected assemblies with solid-state track recorders (SSTRs) (Ref. 1). These measurements are to be reported by others and are not covered in this paper. The SSTR positions are indicated in the appropriate figures for future reference. The SSTRs were not in the assemblies during the criticality measurements.

EXPERIMENT-CALCULATION COMPARISON

Neutron multiplication constants (k_{eff}) were calculated for each of the critical assemblies using the KENO-IV computer code[2] with ENDF data. Initially, calculations were performed with cross sections obtained from FLANGE (Ref. 3)-ETOG (Ref. 4)-processed ENDF/B-III and ENDF/B-IV libraries. The THERMOS computer code[5] was used to generate single-group thermal data from its companion ENDF/B-III library, and the EGGNIT code[6] was used to generate 17-group epithermal data from its ENDF/B-IV library. The results of these calculations are summarized in Table II.

As can be seen in Table II, the calculations with THERMOS-EGGNIT-ENDF data underestimate the critical size of each experimental assembly by 1 to 6% in k_{eff}. Because of these large differences between experiment and calculations, several possibilities were explored in an attempt to resolve the differences. For five of the lattices, k_{eff} calculations were made at loadings other than critical to establish the sensitivity of k_{eff} to errors in the experimentally determined number of fuel pins required for criticality. These



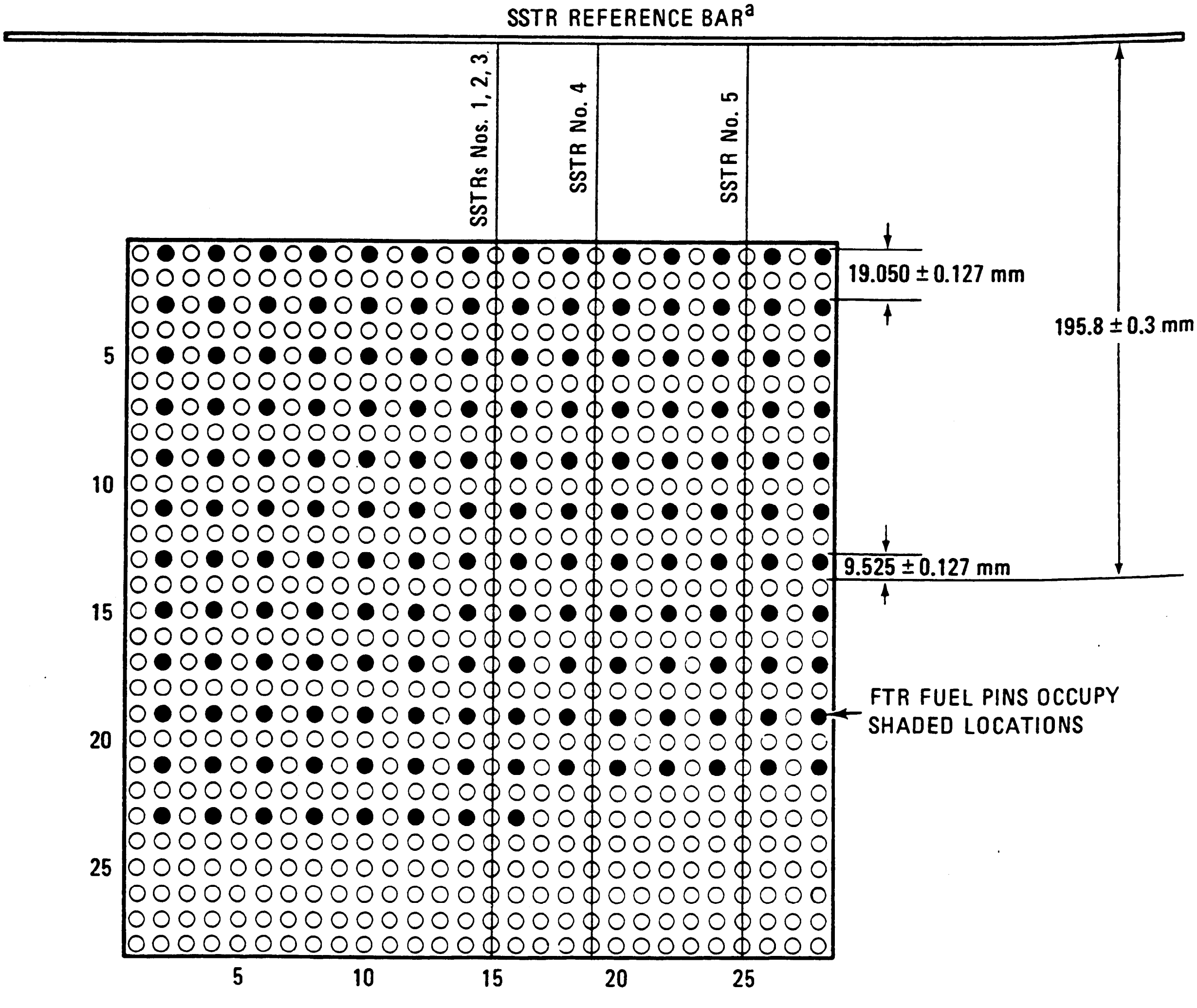
[a]Elevation of the SSTR reference bar is 1065.61 ± 1.52 mm above the bottom of the fuel pins for SSTR No. 1. SSTR not in assembly during approach to critical.

Fig. 8. Layout of critical experiment (experiment No. 005) FTR fuel pins immersed in water.

results are also summarized in Table II and indicate that an error >10% would have to exist in the critical size of each assembly to account for the differences observed between calculations and experiment. Since an error this large in these types of experiments is inconceivable, additional studies were carried out. The cladding thickness was increased to the maximum tolerance of 0.0127 mm. Americium-241 content was assumed to be twice the measured value. Different models of the rod systems were tried. (In one case, individual rods were modeled, while in another instance, cell-averaged microscopics were used in a "smeared" rod model.) The effect of all of the above changes, when considered separately, was within the statistical one sigma error bars shown for the calculations in Table II.

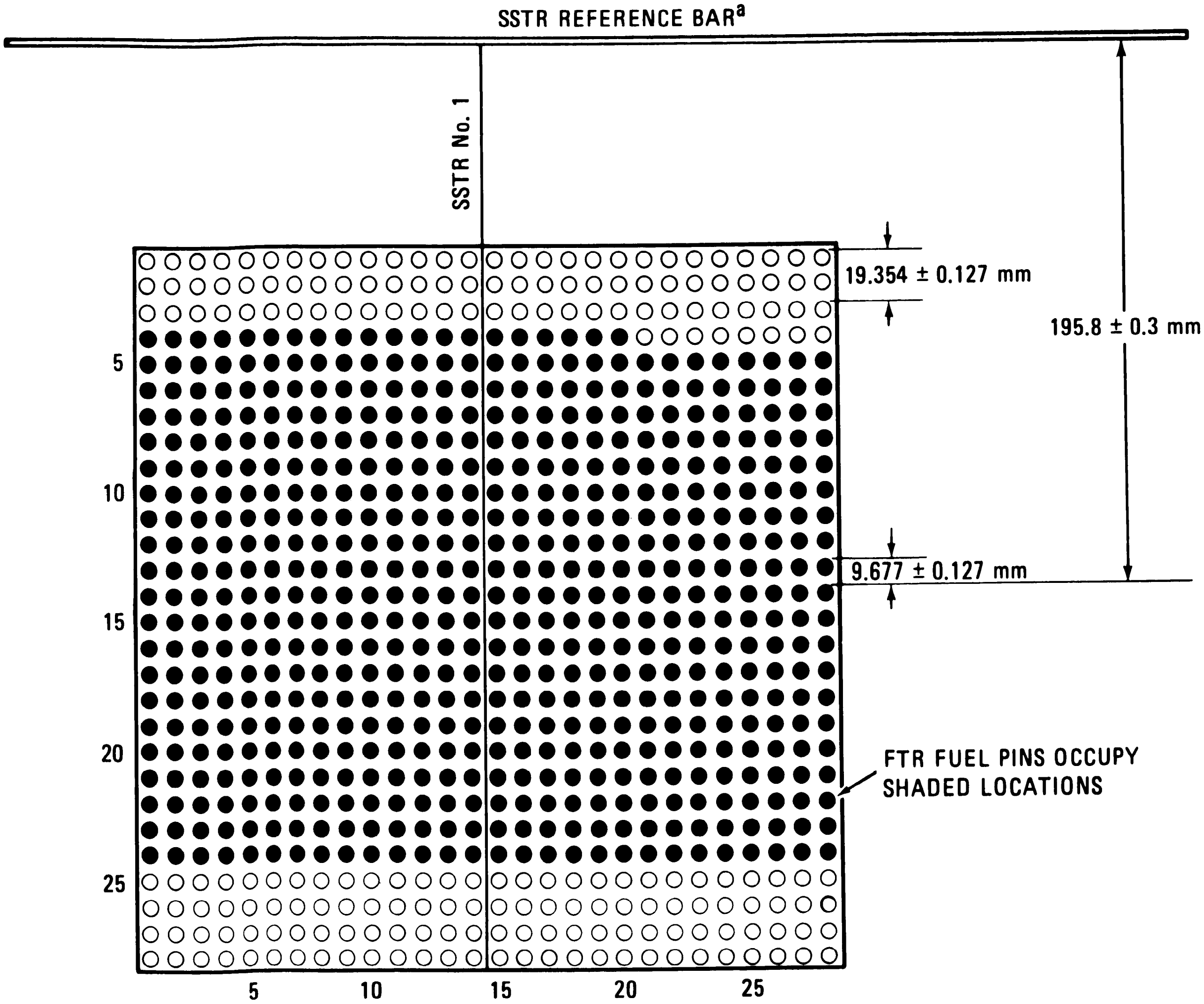
The sensitivity of the calculations to variations in lattice pitch was also investigated. By referring to Fig. 11, which gives the critical number of fuel pins as a function of lattice pitch, it can be seen that the measured variation of ±0.127 mm in lattice pitch would not result in a significant change in the number of fuel pins required for criticality, except for the very undermoderated assembly.

Based on the above, it was concluded that the differences between experiments and calculations were primarily due to errors in the calculations. Consequently, a second set of KENO-IV calculations was performed with different cross sections. The NITAWL module in the AMPX system[7] was used to generate problem-dependent cross sections with ENDF/B-IV data taken from the 218-neutron-group



[a]Elevations of the SSTR reference bars are 1065.61 ± 1.52 mm and 862.41 ± 1.59 mm above the bottom of the fuel pins for SSTRs Nos. 1 and 2, respectively. The reference bar for SSTRs Nos. 3, 4, and 5 is at an elevation of 659.21 ± 2.0 mm above the bottom of the fuel pins. SSTRs not in assembly during approach to critical.

Fig. 9. Layout of critical experiment (experiment No. 006) FTR fuel pins immersed in water.



[a]Elevations of the SSTR reference bars are 1065.61 ± 1.52 mm and 862.41 ± 1.59 mm above the bottom of the fuel pins for SSTRs Nos. 1 and 2, respectively. The reference bar for SSTRs Nos. 3, 4, and 5 is at an elevation of 659.21 ± 2.0 mm above the bottom of the fuel pins.

Fig. 10. Layout of critical experiment (experiment No. 029) FTR fuel pins immersed in water.

Oak Ridge National Laboratory (ORNL) criticality library.[8] The 218-group criticality library data were collapsed to the Westfall 27-energy-group structure using the MALOCS module of AMPX. The results of these calculations are shown in Table II. As can be seen, they are in much better agreement with the experiments than are the previous calculations with the THERMOS-EGGNIT data. The NITAWL-KENO-IV calculations underestimated the critical size of each assembly by only 1 to 2% in k_{eff}, as compared to the 1 to 6% obtained in the initial calculations with THERMOS-EGGNIT data.

Although cross sections generated by the AMPX system appear to yield results that are in better agreement with the experiments than do the THERMOS-EGGNIT data, it should be apparent that the analyses performed are not of sufficient depth to warrant any firm conclusions being made on the causes for the differences. The calculational results are presented for the readers' benefit, should they encounter similar discrepancies and have questions about the relative effects that various parameters may have on their calculations. A systematic study, beyond the scope and interest of the work presented in this paper, would have to be made before any conclusions could be made as to the validity of the cross-section data or the relative accuracy of the processing codes used in generating the cross sections.

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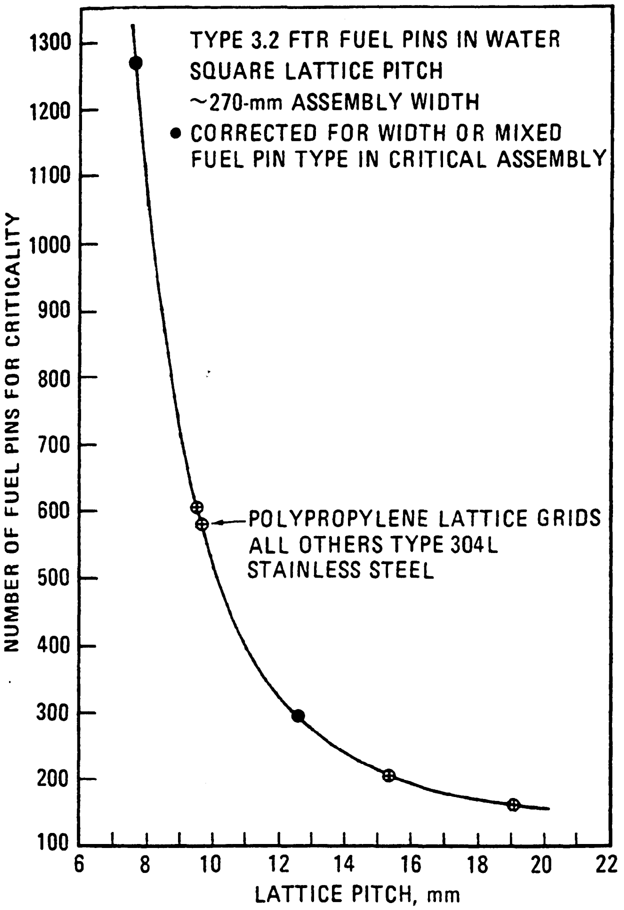

Fig. 11. FTR fuel pins in water—critical number as function of lattice pitch.

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