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Critical Experiments with 4.31 Wt% ^{235}U Enriched UO_2 Rods in Highly Borated Water Lattices

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ABSTRACT

A series of critical experiments were performed with 4.31 wt% ^{235}U enriched UO_2 fuel rods immersed in water containing various concentrations of boron ranging up to 2.55 g/ℓ. The boron was added in the form of boric acid (H_3BO_3). Critical experiment data were obtained for two different lattice pitches wherein the water-to-uranium oxide volume ratios were 1.59 and 1.09. The experiments provide benchmarks on heavily borated systems for use in validating calculational techniques employed in analyzing fuel shipping casks and spent fuel storage systems that may utilize boron for criticality control.

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SUMMARY

The results from the seventh in a series of criticality experiments funded by the United States Nuclear Regulatory Commission are presented in this paper. The purpose of these experiments is to provide a data base for benchmarking computational methods used in the criticality analysis of fuel transportation and storage systems.

This experiment program explored the effect on criticality of adding large amounts of boric acid to undermoderated arrays of 4.31 wt% ^{235}U enriched UO_2 fuel rods in water. Boron concentrations ranging up to 2.55 g/ℓ were achieved in two lattices, one having a square pitch of 1.89cm and the other 1.715cm (water-to-fuel volume ratios of 1.59 and 1.09 respectively).

It is apparent that if the concentration of boron in the water moderator of two different lattices be the same, the lattice with the larger spacing (and water-to-uranium ratio) will have a higher ratio of boron to uranium. In addition, as the spectrum is harder in the lattice of least water, the boron also can be expected to have a smaller effect on the criticality of that lattice.

It also is apparent that compacting a lattice of fuel rods from optimum spacing in water (reducing the separation between fuel rods in the assembly) can result in a larger critical size and number of fuel rods for criticality, and lead to a safer condition. The data reported here on heavily borated lattices show that it is possible for the reverse to occur, i.e., with the absorber present, compacting th[illegible]ce spacing can result in a smaller critical size or volume and num[illegible] fuel rods for criticality.

Adding a given amount of boron to the water moderator of either of the above two lattices results in a larger critical size and mass (number of rods for criticality). The boron-to-uranium atom ratio is smaller, however, in the smaller lattice for a given concentration of boron in the water. This implies (and the data on these two lattices show) that as the concentration of boron in the water of the two lattices is equally increased there will be a boron concentration point at which the smaller lattice has the smaller critical size, though in the absence of the boron this was not the case. If the concentration of boron in g/ℓ is increased in the smaller lattice so as to maintain the same boron-to-uranium atom ratio in the two lattices this does not appear to be the case (see Figure 5). This point should be considered in the use of soluble absorbers for criticality prevention and control.

CONTENTS

FIGURES

TABLES

CRITICAL EXPERIMENTS WITH 4.31 WT% ^{235}U ENRICHED UO_2 RODS IN HIGHLY BORATED WATER LATTICES

INTRODUCTION

A research program was begun in 1976 at the Pacific Northwest Laboratory Critical Mass Laboratory (CML) to provide experimental criticality data on conditions simulating light water reactor fuel shipping and storage configurations. The program, which is funded by the Nuclear Regulatory Commission, has provided data to date which supports criticality analyses of both fuel element handling and storage facilities.

Six previous experiment programs under this program have explored a wide variety of phenomena affecting the criticality safety of fuel rod storage, such as the effect of neutron absorber plates between interacting clusters of rods in water and the effect of heavy metal reflector walls on critical separation distances between fuel rod clusters.[1-7] This report details the results of the experiments which evaluate the effect of a soluble neutron absorber, boric acid, on the criticality of water moderated fuel rod arrays.

Boric acid is a widely used neutron poison in both shipping casks and storage pools. The poison is added as an additional precaution against accidental criticality. Although many experiments have been performed on water flooded arrays containing less than 1 g/ℓ boron, no data exist for the high concentrations of boron which might be used for criticality control (∿2 - 5 g/ℓ B in solution). Large amounts of boric acid can significantly alter the neutronics of a system. For example, Marotta showed in calculations relating to the recriticality of the TMI-2 core, that the infinite multiplication factor, k_∞, is higher for a tighter pitched system at the same boron concentrations.[8]

This should not be confused with the fact that adding a "neutron absorber" to any given lattice (providing this absorber does not of itself substantially moderate neutrons or displace the moderator that does) will always render that lattice assembly further subcritical.

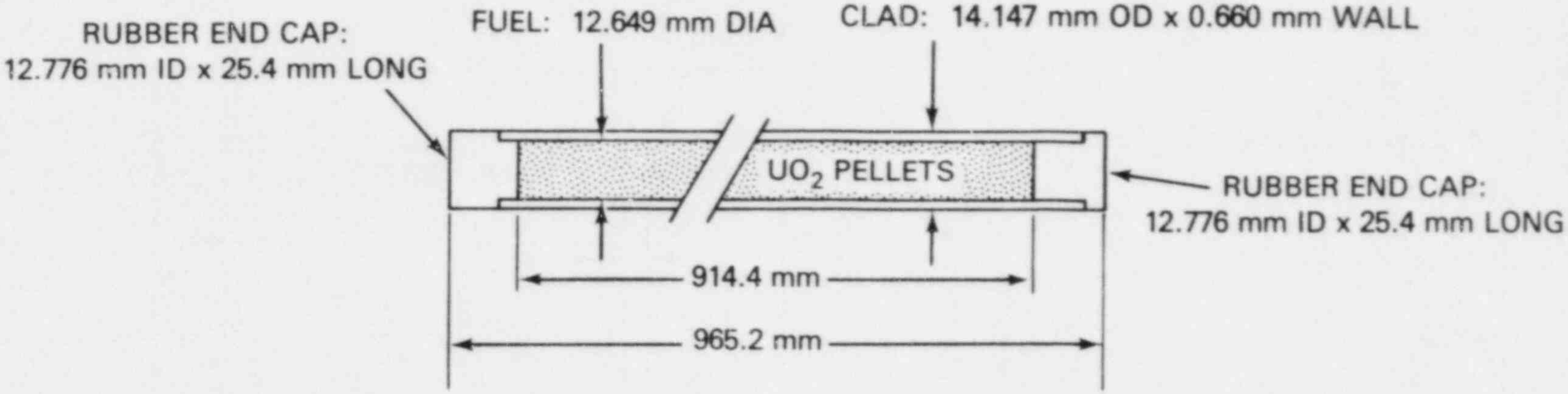
EXPERIMENTAL PROCEDURE

The experiments utilized 4.31 wt% ^{235}U enriched UO_2 rods available at the Critical Mass Laboratory in square pitched, water moderated lattices, poisoned with varying amounts of boric acid (H_3BO_3). Data were obtained for two different lattice pitches, 1.890cm ± .002 and 1.715cm ± .005. This corresponds to water-to-fuel volume ratios of 1.59 and 1.09 respectively.

The fuel rods are described in Figure 1. The experimental setup is shown in Figures 2 and 3. Fuel rods were loaded into polypropylene lattice templates [density of 0.904 g/cm], securely fastened inside a plexiglas container. The container was surrounded on all four sides by a full water reflector. Beneath the container, a 15.2cm thick plexiglas slab elevated the fuel off the tank bottom. The soluble absorber was restricted to the water within the container, while the outside reflector region was left unpoisoned. An analysis of the water prior to boron additions is given in Table I.

Critical arrays were constructed using the critical approach method to obtain criticality. That is, arrays were built up in a rectangular fashion. With the array width remaining fixed at 40 or 44 rods, depending on pitch, the array length was gradually increased symmetrically. An experiment was performed at one boric acid concentration, poisoned water samples were taken and then additional boric acid was added prior to the next fuel loading. Water was progressively removed from inside the container as more fuel was added to keep the water level inside constant as shown in Figure 2.

4.31 WT% ^{235}U ENRICHED UO_2 RODS



CLADDING: 6061 ALUMINUM TUBING

LOADING:

ENRICHMENT - 4.31 ± 0.01 WT% ^{235}U
FUEL DENSITY - 94.9 ± 0.55% OF THEORETICAL DENSITY
URANIUM ASSAY - 88.055 ± 0.261 WT% OF TOTAL FUEL COMPOSITION
UO_2 - 1203.38 ± 4.12 g/ROD

END CAP:

DENSITY - 1.321 g/cm^3
COMPOSITION -C-58 ± 1 WT%
H-6.5 ± 0.3 WT%
Ca-11.4 ± 1.8 WT%
S-1.7 ± 0.2 WT%
0-22.1 WT% (BALANCE)
Si-0.3 ± 0.1 WT%

Figure 1. Description of Fuel Rods

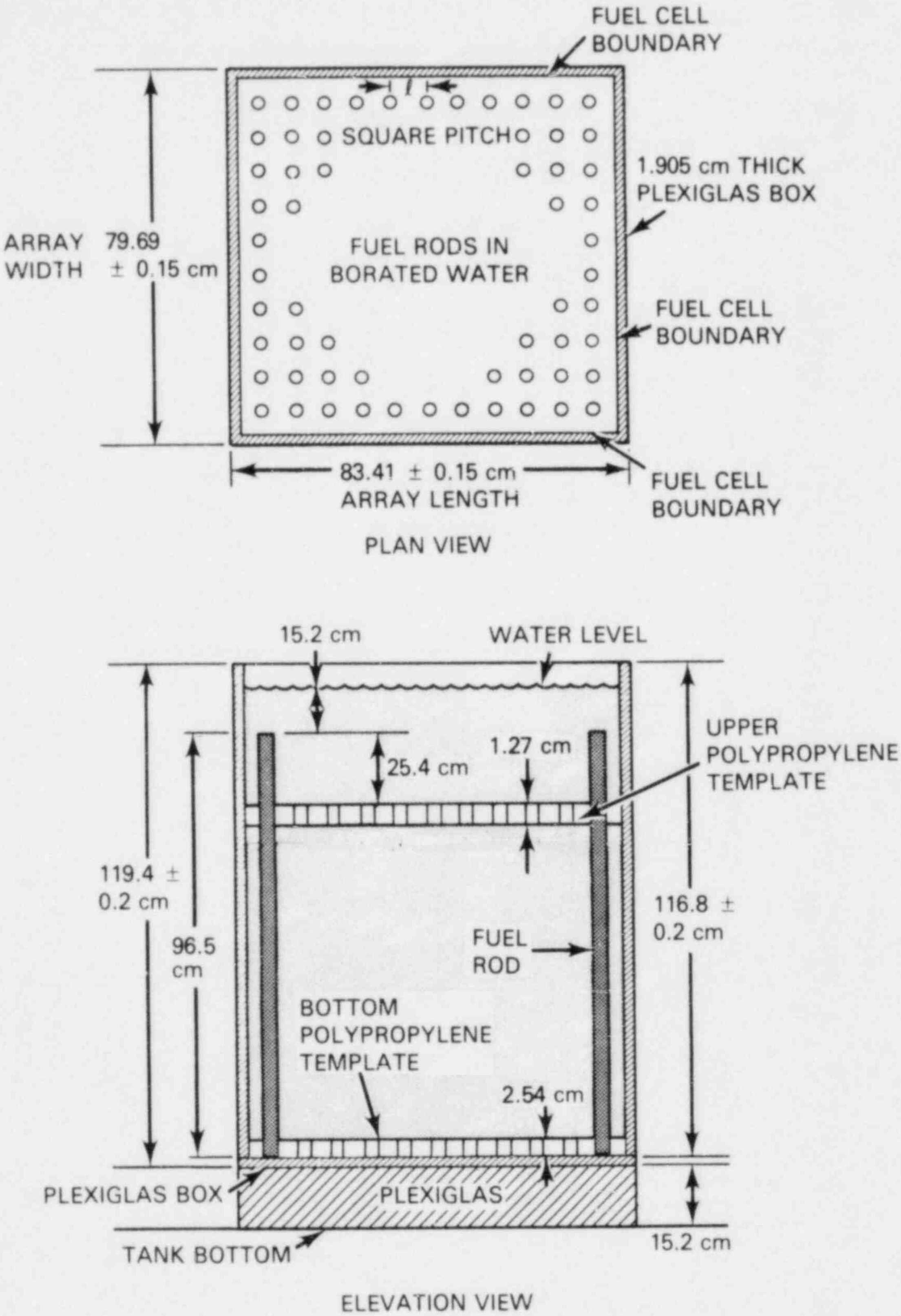


Figure 2. Experimental Setup

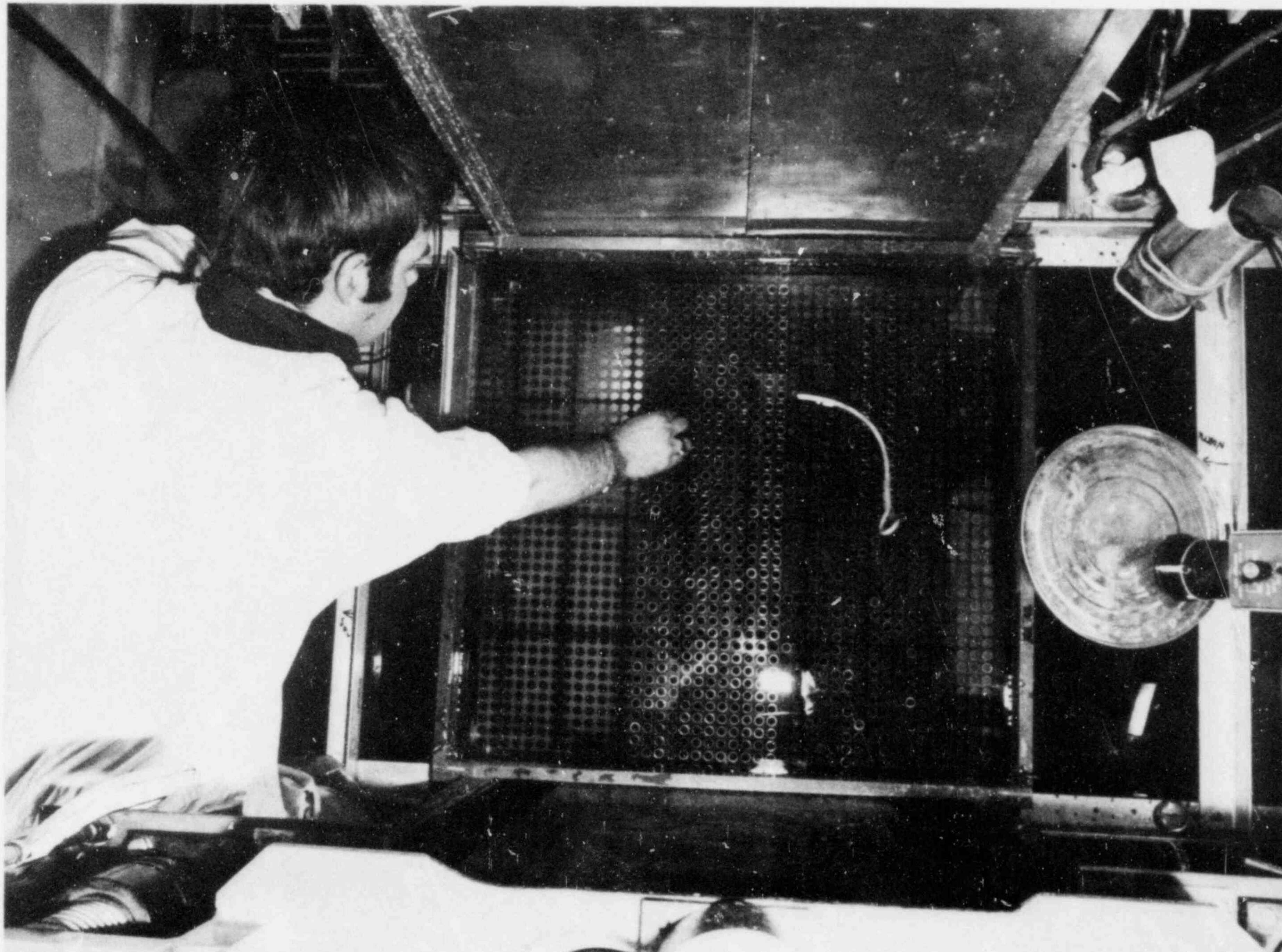


Figure 3. Photograph of Lattice Assembly

TABLE I

WATER IMPURITIES

COMPONENT	CONCENTRATION g/m^3 (ppm)
Cl	≤ 5
NO_3	0.02
Cr^{+6}	<0.01
Zn	16
Mn	<0.01
Pb	<0.005
F	0.18
Fe	24
Cu	<0.01
Cd	0.001
SO_3	14.5
DISSOLVED SOLIDS	61 ± 3

RESULTS

The results of the experiments are summarized in Table II and Figure 4. The largest critical array constructed for the 1.89cm - pitched lattice was a 40 x 30.92 array (∿1237 rods), having a boron concentration of 2.55 g/ℓ. For the 1.715cm lattice, the largest array constructed was 44 x 27.09 (∿1192 fuel rods) also at a concentration of 2.55 g/ℓ B. This amount of boron is substantial in terms of hold down as in both lattices the assemblies contained more than twice the number of rods required for criticality in the absence of the boron.

The lattice with the 1.715cm pitch had a water-to-fuel volume ratio of 1.09 and that of the 1.89cm lattice is 1.59. The smaller lattice was less well moderated and in the case of no boron required a larger number of rods for criticality (509 vs. 357). As noted above, however, for the case of 2.55 g/ℓ B in the water, the critical rod number was 1192 for the 1.715cm lattice compared with 1237 for the 1.89cm lattice, i.e., the smaller lattice with the absorber had the smaller critical number, not larger. This may be misleading, but consideration must be given to the fact that if the boron concentration in the water moderator is the same, the lattice with the smaller water-to-fuel volume ratio also will have a smaller boron-to-uranium ratio, or less boron absorber per atom of uranium.

The experimental arrays were buckling corrected to square arrays to account for geometric differences and Figure 5 presents rod numbers plotted vs. the boron-to-uranium oxide weight ratios in the two lattices. With comparable amounts of absorber present, the smaller lattice does indeed have the larger critical number of rods.

The implication is important. It means that the boron concentration in terms of g/ℓ B may have to be substantially increased in the less well moderated lattice to ensure the same degree of subcriticality for a given assembly size.

TABLE II

RESULTS OF EXPERIMENTS

Experiment Number	Square Pitch (cm)	Boron[a] Concentration g/ℓ	Critical Array Width No. of Rods	Critical[b][c] Array Length No. of Rods	Total Rods[d] for Criticality
SSC-4.3-000-173	1.890	0.0	40	8.92	357
174	1.890	0.49 ± 0.06	40	10.72	429
175	1.890	1.25 ± 0.21	40	14.05	562
176	1.890	2.15 ± 0.35	40	23.07	923
177	1.890	2.55 ± 0.07	40	30.92	1237
178	1.715	0.0	44	11.57	509
179	1.715	1.03 ± 0.05	44	16.75	737
180	1.715	1.82 ± 0.30	44	20.84	917
181	1.715	2.55 ± 0.21	44	27.09	1192

(a) Boron added in the form of H_3BO_3.

(b) This has the same interpretation as all experiments performed before in this program. A fraction of a row is a row which extends full width but is thinner in length. This is the best interpretation for computer modeling.

(c) The cell boundary of the first fuel row is next to the plexiglas wall of the box.

(d) The error in critical rod number is <0.5%.

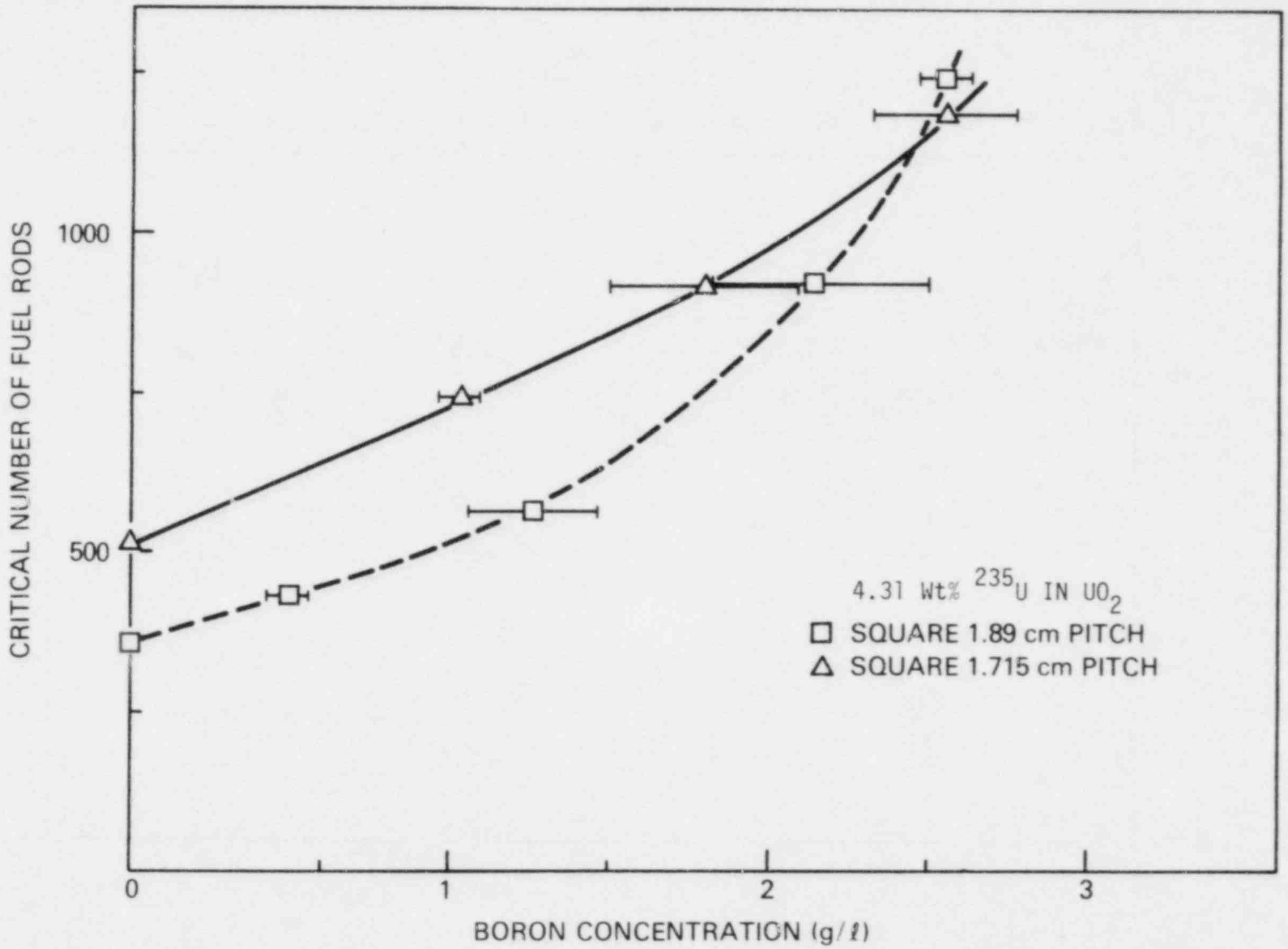


Figure 4. Critical Rod Number as a Function of Boron Concentration

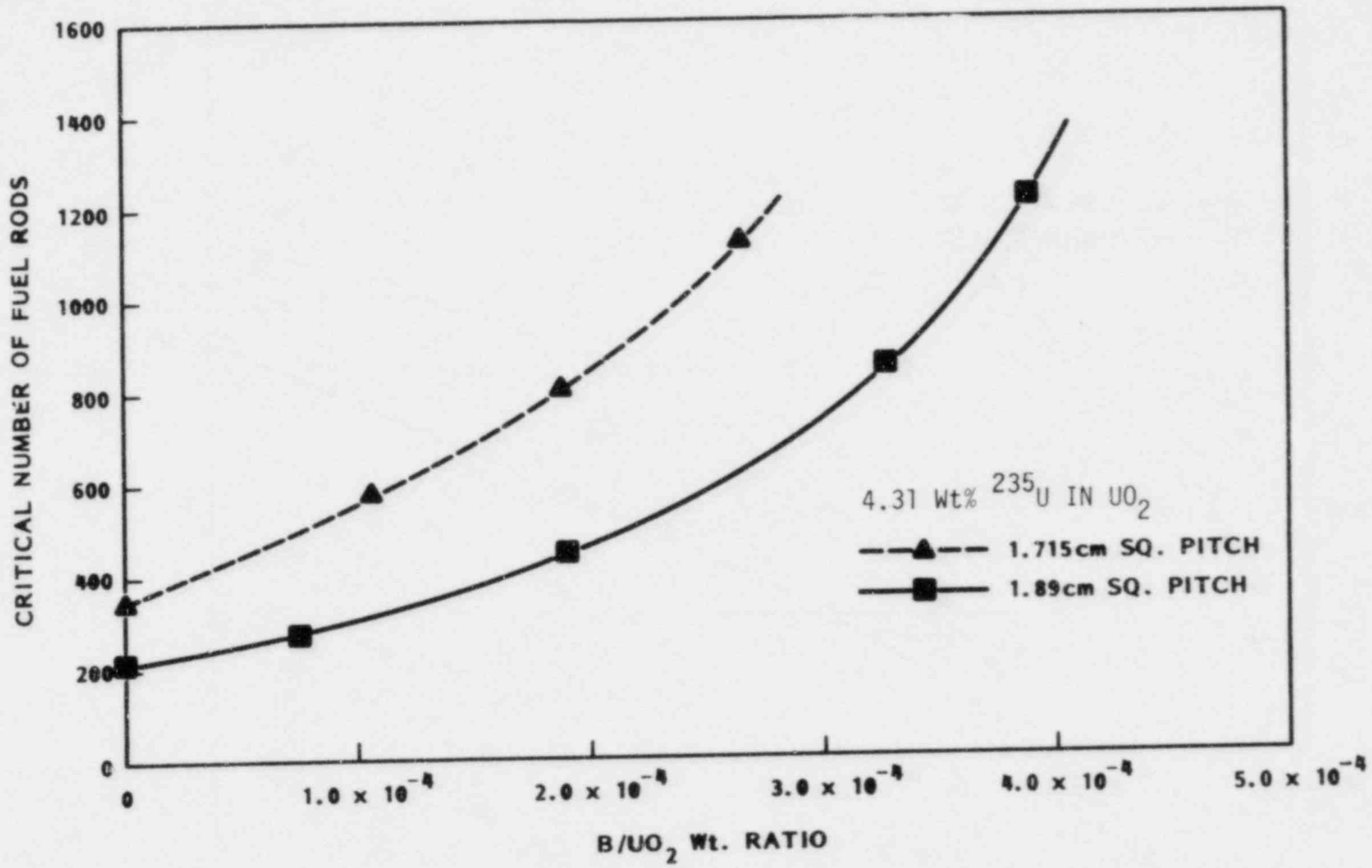


FIGURE 5. ESTIMATED CRITICAL NUMBER OF RODS vs B/UO_2 Wt. RATIO

CONCLUSIONS

Experiments have been performed with LWR-type fuel rods for evaluating criticality in highly borated lattices under high reactivity hold down conditions with boron concentrations in the water ranging up to 2.55 g/ℓ.

It is well known that compacting a lattice of fuel rods from optimum spacing in water (reducing the separation between fuel rods in the assembly) can result in a larger critical size and number of fuel rods, and lead to a safer condition. The data reported here on highly borated lattices show that it is possible for the reverse to occur, i.e., after adding boron to the lattice, compacting the lattice spacing might then result in a smaller critical volume and number of fuel rods for criticality.

The implication is important. It means that the boron concentration in terms of g/ℓ B (but not necessarily the B/U atom ratio) may have to be substantially increased in the less well moderated lattice to ensure the same degree of subcriticality for a given assembly size.

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