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STYROFOAM SIMULATION OF BOILING AND TEMPERATURE
EFFECTS IN THE EBWR COLD CRITICAL EXPERIMENTS

by

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ABSTRACT

Styrofoam was used successfully as a void material in the representation of hot reactor conditions during the EBWR zero power experiments.

The void requirements were determined from available heat transfer data and then Styrofoam strips were designed and manufactured by special equipment. These strips were inserted in the fuel element water channels and the reactivity changes noted. The data were then converted to boiling and temperature coefficients.

The nuclear properties of the material were excellent, and its use proved economical. The experimental accuracy was good, but probably could be improved by sealing the surface of the material against water absorption.

I. INTRODUCTION

A boiling water reactor requires considerable excess reactivity, i.e., additional fuel, to compensate for changes in reactivity occasioned by boiling voids, temperature coefficient, and xenon buildup. The importance of these effects in EBWR led to a decision that a way should be found to measure the reactivity required by the first two effects in the course of the cold critical experiments. The xenon buildup, of course, could only be measured at full power and therefore is not included here. In the case of the temperature coefficient, the reactivity change results from the variation in moderator density with temperature. For the boiling condition, the effective moderator density is inversely proportional to the amount of steam present. Therefore, a dimensionally stable method had to be found to vary the moderator density in the fuel assembly water channels in a way that conformed to the temperature and boiling characteristics of the reactor.

Several methods were considered; among these were: bubbling of gas through the water channels, controlled introduction of gas into water-filled tubes inserted in the fuel assembly water channels, and, finally, use of some low-density expanded solid. The first method was inexpensive, but had the major disadvantage of poor control, which constitutes not only a hazard to reactor operation, but also makes it difficult, if not impossible, to distribute the voids in the proper way. The second method overcomes the objections to the first and would probably lead to high experimental accuracy. However, the fabrication of a tube arrangement for each water channel becomes expensive if 560 such channels must be filled.

The third method, that of using a low-density expanded solid, is really a variation of method two, with no means for circulating the gas within the solid. It also appeared to be an expensive method, because of fabrication problems. However, the use of expanded polystyrene or Styrofoam for float controls was noted, and Styrofoam was suggested as a possibility. The problems and costs of fabricating this material were investigated and found to be reasonable, and Styrofoam was selected for the experiment.

II. STYROFOAM - A MODERATOR VOID

Styrofoam is a white, multicellular structure, manufactured first by bubbling gas into melted polystyrene and then permitting the foam mixture to cool and solidify. Its density is only about 0.03 gm/cm^3 , which is suitable for production of large voids in water. Measurements of the rate of water absorption for the material gave values far greater than that for polystyrene, which is very low. This is explained by the presence of ruptured cells at or near the surface which slowly fill with water. As shown in Fig. 1, the rate of absorption of water is fairly rapid for the first two days, slowing up considerably at the end of that time. Also, the initial value of the displacement fraction is less than one, because many of the surface cells fill with water immediately. The original or starting value of displacement fraction is a function of the ratio of volume to surface area, being larger as the ratio is increased.

The mechanical properties of the material in the strip form were found suitable for strips greater than about $1/4$ in. thickness. For smaller thicknesses, the loss in rigidity, as well as strength, leads to considerable breakage. The machinability by sawing or sanding is good, although care must be used to avoid crushing. It should be pointed out that the melting point limits the usefulness of this material to low-temperature experiments. The low-melting point characteristic was used to good advantage in the manufacturing operations which will be described later.

FIG. 1
DISPLACEMENT FRACTION FOR STYROFOAM STRIPS

The nuclear properties of Styrofoam were investigated, since the void material would occupy a region of high importance in the reactor (fuel assembly water channels). A spectrochemical analysis was made to determine if any materials with objectionable nuclear cross sections were present. The results were negative (Table I). The nuclear purity of the material was further verified by examining its effect on the multiplication of a sub-critical Argonaut assembly.¹ Irradiation of the material in the Argonne Research Reactor CP-5 for 15 min at a flux of $\sim 2 \times 10^{12}$ n/(cm²)(sec) produced no significant change in the water absorption or mechanical properties, and only short-lived activation occurred.

¹D. H. Lennox, C. N. Kelber, "Summary Report on the Hazards of the Argonaut Reactor," ANL-5647, (December, 1956).

TABLE I
SPECTROCHEMICAL ANALYSIS OF
POLYSTYRENE (STYROFOAM)

(% Element in Ash After Ignition in Platinum)

Sample Weight: 2500 mg
Weight of Ash: 33 mg

Ag <0.01	Fe 0.15	Pb <0.01
Al 0.8	Gd <0.05	Sb <0.01
B 0.001	K 0.1	Si Very Strong
Ba 10	La <0.01	Sn <0.01
Be <0.01	Li 0.0002	Sr 0.02
Bi <0.01	Mg 0.2	Th <0.1
Ca 30	Mn <0.01	Ti 0.05
Cd <0.01	Mo <0.1	V <0.02
Co <0.01	Na <0.3	Y <0.01
Cr 0.01	Ni <0.01	Zn <0.1
Cu 0.02	P <0.1	Zr <0.1

III. VOID VOLUME CALCULATIONS

The void calculations were done in two parts. The first dealt with the temperature effect. The amount of void required to represent the decrease in density of the EBWR moderator between 60F and 475F (respectively, the critical experiment temperature and the saturation temperature for the operating pressure of 600 psia) is 20% of the total water volume in the core. This void was distributed within the fuel assembly water channels only. A symmetrical loading of alternate thick and thin fuel assemblies² was assumed (see Fig. 2). Further, it was assumed that the control rods were withdrawn at least 80 or 90%, which gives little or no rod displacement by water. One cell of nine fuel assemblies, bounded at each of its four corners by a control rod, was used to calculate the total water volume in the core.

The void value was allocated between thick and thin fuel assembly water channels on a percentage basis, channels with more volume being assigned more void. This was deviated from only slightly to permit the use of the same type of Styrofoam strip in both the thick and thin fuel assemblies by loading one less strip in the thick assembly. Allowance was made for the density of the Styrofoam by increasing the void by 3%. No attempt was made to simulate conditions external to the circumference of the core loading.

²ANL-5607. "The Experimental Boiling Water Reactor - As Constructed."
To be published.

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KN THICK NATURAL URANIUM
 KE THICK ENRICHED URANIUM
 NN THIN NATURAL URANIUM
 NE THIN ENRICHED URANIUM

FIG. 2
 EBWR UNIFORMLY MIXED LOADING OF 18 NN,
 18 KN, 38 NE, AND 38 KE FUEL ASSEMBLIES

The calculated temperature coefficient void for each of the four types of fuel assemblies is shown in Table II.

The displacement for each average size type of Styrofoam strip was measured. The proper types were then combined to determine the voids as shown in Table III.

The second phase of the void calculations dealt with boiling voids. Several assumptions were necessary. For example: the rods were assumed to be near the "all-out" position so that boiling could be represented for a full-length core. Uniform steam distribution was assumed along a boiling length equal to the upper 60% of each channel.

Figure 3 shows the radial variation of power density (reported by Lottes)² modified for the 60% boiling length. The curves correspond to the flux distribution obtained when the core is loaded with a uniform mixture of the four types of fuel assemblies as shown in Fig. 2.

It was decided that a better simulation of voids would be obtained by dividing the core into two zones and assigning an average power density to each zone. As shown in Fig. 3, Zone No. 1 extends from the center of the core out to a radius of 1.1 ft and includes the central 6 x 6 square of 36 elements, with the exception of the four elements at each corner of the square. The latter elements are included in Zone No. 2, which represents the balance of the assemblies external to Zone No. 1.

The average power densities assigned were: 30 kw/liter for Zone No. 1, and 18 kw/liter for Zone No. 2. The average power density for each of the four types of fuel assemblies was then determined and the data used to calculate the void volumes (Table II). The voids measured with average sized Styrofoam strips are listed in Table III.

FIG. 3
RADIAL VARIATION OF POWER DENSITY
AND STEAM VOID FRACTION

TABLE II
SUMMARY OF CALCULATED VOIDS

	Voids Per Fuel Assembly Type, in ³			
	<u>KN</u>	<u>NN</u>	<u>KE</u>	<u>NE</u>
Temperature Coefficient	118.5	140.5	118.5	140.5
Boiling Voids - Zone No. 1	50.3	36.9	57.5	57.5
Boiling Voids - Zone No. 2	29.2	20.0	33.9	33.9

TABLE III
SUMMARY OF AVERAGE MEASURED VOIDS

	Voids Per Fuel Assembly, in ³			
	<u>KN</u>	<u>NN</u>	<u>KE</u>	<u>NE</u>
Temperature Coefficient	108.8	129.7	108.8	129.7
Boiling Voids - Zone No. 1	45.8	33.3	48.4	51.3
Boiling Voids - Zone No. 2	19.0	16.3	40.1	40.3

It should be pointed out that the boiling void and temperature coefficient effects were combined in a second set of strips rather than adding a set of boiling void strips to the set of temperature coefficient strips used in the first part of the experiment. This was necessitated by the relatively large voids required in the boiling sections of the channel and the requirement that the voids be discontinuous, if possible, to help reduce neutron streaming. The effect was to reduce the accuracy of boiling voids, since they were the differences of two large numbers. A further contribution to the differences shown in the tables was the necessity for limiting the number of types of strips by using multipurpose standardized strips in different combinations.

IV. MECHANICAL DESIGN OF STYROFOAM STRIPS

The design of the strips was governed largely by the dimensions of the fuel assembly water channels and the desire to distribute the voids

the length of the channel to minimize neutron streaming. With one exception, the strips were 54 in. long (the same length as the fuel plates) and 3 in. wide. It was later found necessary to cut the strips for the two outermost channels to 2-1/4 in. wide in order to clear identification straps welded in the inside corners of the fuel assembly loading bracket. A thickness of 0.281 in. was selected for all but two strips after trial calculations. The two exceptions were made 0.343 in. thick to accommodate large boiling voids. The above dimensions gave the strips reasonable strength so that they could be handled with little breakage. Good channel clearances were obtained and the volume to surface ratio was such as to give a good displacement fraction.

The temperature coefficient strip was designed with 1.315-in. diameter holes to permit hole offset to stop neutron streaming, to make the number of holes feasible, and to keep the structure as strong as possible. The void volume was compromised slightly to permit use of the same strips in both thick and thin plate fuel assemblies. This was accomplished by loading all five channels in the thin, and only four channels in the thick, fuel assemblies. The loading was independent of enrichment; hence, only two types of strip were required for the entire temperature coefficient core loading. These were designated A and A', and are shown in Fig. 4, which displays all the types manufactured.

NOT SHOWN - G AND G'

FIG. 4
STYROFOAM VOID STRIPS

The boiling voids were included with temperature coefficient in a second set of strips. The hole size of 1.315 in. was retained and the holes were grouped in such a way that the same punches and punch groupings as were used in the temperature coefficient strips could be used again with as little alteration as possible. Since the boiling voids were confined to the upper 60% of the channel, the lower 40% is temperature coefficient only and looks just like the A strips. To permit a reduction of types of strips, use was made of one short strip (designated C in Fig. 4), which equalled the 60% boiling length. This permitted adjustment of total boiling void per fuel assembly without altering the temperature coefficient in the lower 40% of length. Table IV is a summary of the types of strips used in loading each fuel assembly, with one strip used per water channel.

TABLE IV
SUMMARY OF FUEL ASSEMBLY LOADINGS

<u>TYPE OF VOID</u>	<u>Fuel Assembly Type</u>			
	<u>KN</u>	<u>NN</u>	<u>KE</u>	<u>NE</u>
Temperature Coefficient	3A, 1A'	3A, 2A'	3A, 1A'	3A, 2A'
Boiling plus Temperature Coefficient				
Zone No. 1	3G, 1B', 1C	3B, 2B'	3G, 1G', 1C	3G, 2G'
Zone No. 2	3F, 1F', 1C	3F, 2F'	3E, 1E', 1C	3E, 2E'

One very important aspect of the design was to provide a safe loading scheme which would guarantee that the strips could not shift from the proper loaded position. It was essential that the strips not be allowed to escape upward out of the fuel assembly, since their buoyancy provides very large acceleration which would lead to rapid reactivity increase. The solution to this problem was to insert into the fuel assembly loading bracket a thin stainless steel sheet bent almost double, so that its spring action held it securely in place, thus effectively blocking off the end of the assembly. The sheet was wrapped with tape to prevent scratching of the fuel assembly, which could lead to corrosion. Downward movement of the strips was prevented by the use of a specially designed pin. Similar to a safety pin, it was thrust through the top edges of all strips in an assembly and then locked in place (see Fig. 5).

FIG. 5
METHOD OF CONTAINING STYROFOAM
STRIPS WITHIN FUEL ASSEMBLY

V. MANUFACTURE

The fabrication of the Styrofoam required the development and application of semi-production techniques to produce the required number of strips uniformly and inexpensively. The Styrofoam was obtained from the manufacturer in the form of $5/16 \times 3 \times 54$ in. and $3/8 \times 3 \times 54$ in. strips. The manufacturer's sawing tolerance was $\pm 1/32$ in., which is equivalent to a void error of $\pm 10\%$, or more. Therefore the thickness was increased by $1/32$ -in. to permit finishing to the correct size. A method of sanding was developed for this purpose. As shown in Fig. 6, it consisted basically of a disc sander with a special fixture which channelled the strip against the sanding wheel. The sanding forces exerted by the wheel draw the strip through, thus eliminating the need for a feeding mechanism.

Requirements for strips of width and length other than indicated above were met by sawing to size on a large band saw using a special fixture (Fig. 7).

FIG. 6
DISC SANDER AND FIXTURE USED TO MACHINE
STYROFOAM STRIPS TO DESIRED TOLERANCE

FIG. 7
SAWING JIG

The most difficult problem to solve was that of producing void distribution through the length of the channel. The use of distributed holes in the strips was made feasible by the development of a method to produce large numbers of holes rapidly. Basically the method uses a hot cup, similar to a cookie cutter, which melts through the Styrofoam very rapidly when pressed against it. The cups were heated by soldering irons. The heating of the irons was controlled to give uniform hole production. A total of 48 cups were mounted on a framework which pivoted in such a way that all the cups were pressed into the Styrofoam simultaneously (Fig. 8). The maximum production was about 10 strips per minute.

FIG. 8
MULTI-HOLE PRESS

VI. ZERO POWER EXPERIMENT

The EBWR void experiment was conducted in three parts:

- (1) Temperature voids were gradually added to core loading No. 26 starting at the center and working radially outward. The purposes were to provide data on the temperature void coefficient as a function of radial position and to ensure that the void coefficient was negative at all points.
- (2) Temperature voids were used with core loading No. 33 to obtain reactivity as a function of void volume. The data were then used to calculate the temperature-void coefficient.
- (3) Boiling voids were used with core loading No. 33 to measure the boiling void coefficient. Boric acid was also used to enable a rod withdrawal consistent with the assumption that boiling takes place only in the upper 60% of the water channel.

Figures 9, 10, and 11 are condensations of the data from experiments (1), (2), and (3), respectively. The abscissa in all figures is the average void volume expressed as a percent of the water channel volume, without regard to axial distribution. Uniform radial distribution of voids is assumed in Figs. 10 and 11. The void coefficients shown were computed by the relationship:

$$\text{Void Coefficient} = \frac{\Delta k}{\Delta V} ,$$

where

Δk = reactivity change in percent caused by ΔV ;

ΔV = change of void volume in the fuel assembly water channels expressed as a percent of the total no-void volume of the channels.

The varying slope in Fig. 11 shows that control rod insertion affects the results. This would be expected since it was necessary to size the voids in accordance with an assigned core height. The height, of course, will vary with control rod position, and thus error will be introduced. The data should be most accurate for the largest rod withdrawal.

FIG. 9
RADIAL VARIATION OF VOID COEFFICIENT - CORE
LOADING NO. 26. CONTROL RODS IN UPPER 67% OF CORE

FIG. 10
TEMPERATURE VOID ADDITION
TO CORE LOADING NO. 33

FIG. 11
BOILING VOID REMOVAL FROM
CORE LOADING NO. 33

VII. CONCLUSION

The usefulness of Styrofoam to produce voids for zero power reactor representation of hot reactor conditions was proven out in the course of the EBWR zero power experiments outlined herein. An important consideration is that it was an economical solution which sacrificed some flexibility. More flexibility of void placement would be attained, for example, by the use of a more expensive, water-filled tube system that could be emptied and filled at will. Such a system might prove more desirable where long-term experiments are to be run. The experimental accuracy of the Styrofoam method could be improved by developing a method of sealing the surfaces to prevent the absorption of water which occurs. This not only would eliminate the need for correcting data, but would permit re-use of the material in succeeding experiments.

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