ANL-6772
Reactor Technology
(TID-4500, 30th Ed.)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60440

MEASUREMENT OF WATER-CHANNEL GAPS IN EBWR CORE-I FUEL ELEMENTS

by

C. F. Reinke and W. N. Beck

Metallurgy Program 7.9.8

Part of the material in this report has appeared in the following Metallurgy Division Progress Reports:

Report No.	Pages	Date
ANL-6330	112-113	1960
ANL-6516	156-157	1961

March 1964

Operated by The University of Chicago
under
Contract W-31-109-eng-38
with the
U. S. Atomic Energy Commission

DISCLAIMER

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

MEASUREMENT OF WATER-CHANNEL GAPS IN EBWR CORE-I FUEL ELEMENTS

by

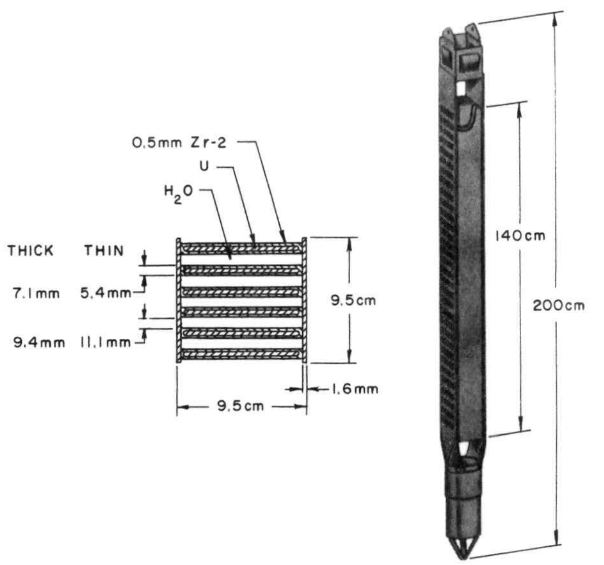
C. F. Reinke and W. N. Beck

ABSTRACT

An eddy-current technique was developed for measuring water-channel gaps on EBWR Core-I fuel elements under water in the EBWR reactor vessel. Actual measurements were made with a modified commercial eddy-current detection device before and after 100-Mw operation of the EBWR. Before high-power operation, the channels ranged from about 8.4 mm (0.330 in.) to greater than the reference value of 11.1 mm (0.438 in.). After 100-Mw operation, the minimum water gap was found to be about 10.2 mm (0.400 in.). The data indicate that swelling (if any occurred) was negligible and masked by a loss of oxide from the fuel-plate surfaces.

INTRODUCTION

The EBWR is a complete, direct-cycle-loading, reactor power plant.[1] Core-I was fueled with plates of U-5 w/o Zr-1.5 w/o Nb alloy jacketed with Zircaloy-2. The fuel elements (shown in Figure 1) are rectangular, box-like structures 200 cm (77.625 in.) long and 9.5 cm (3.75 in.) square. Each assembly contains six plates, 140 cm (54 in.) long, 9.2 cm (3.625 in.) wide, and either 5.4 mm (0.212 in.) or 7.1 mm (0.280 in.) thick. The plates, separated by nominal water channels of 11.1 mm (0.438 in.) or 9.4 mm (0.370 in.), are held in place by perforated side plates.



111-7279

Figure 1. EBWR Core-I Fuel Element

The condition of the Core-I fuel elements in the EBWR after operation to approximately 0.4 a/o burnup and before modification of the reactor for 100-Mw operation has been determined.[2] As part of the program to determine the condition of the fuel elements, annealing studies were conducted of sections of irradiated EBWR fuel plates. The data from these studies indicated that at the 0.4 a/o burn-up level, significant volume increases resulted within 45 hours at 600°C.

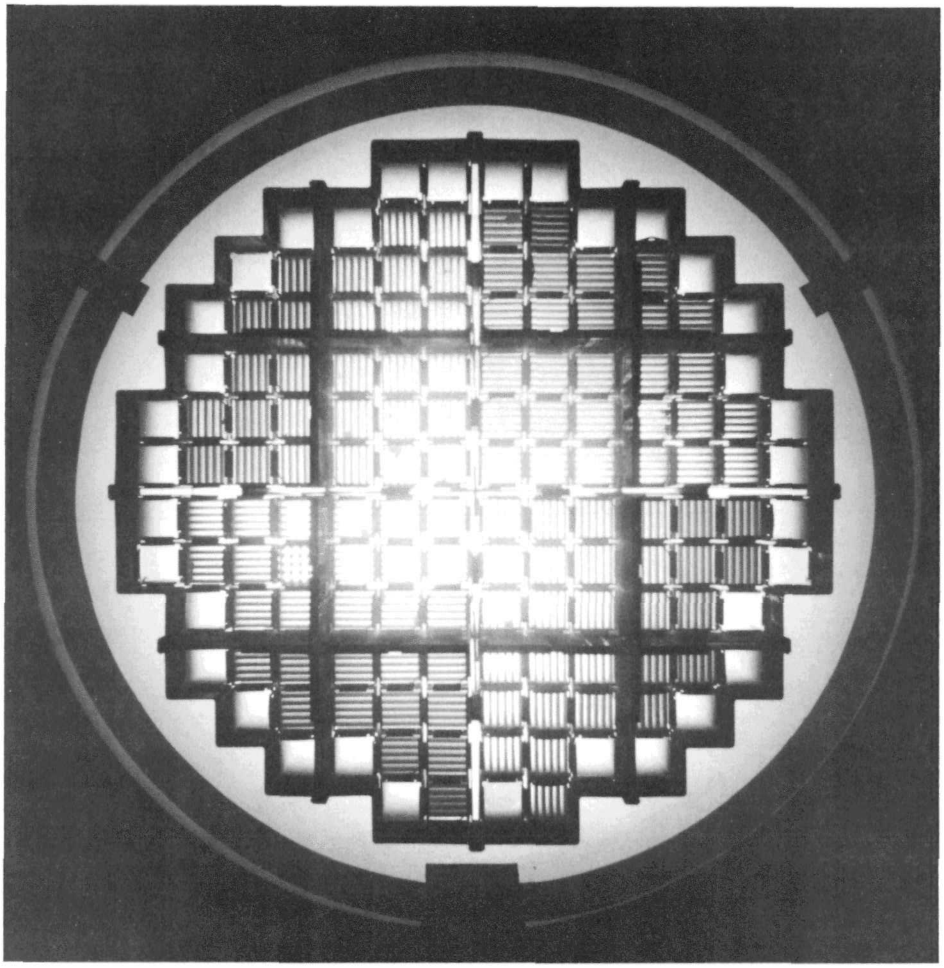
Information on the nature and extent of scale deposits on the fuel-plate surfaces also has been obtained.[2,3] An evaluation of the X-ray diffraction and wet-chemical analyses indicates that the scale was primarily boehmite (Al_2O_3-H_2O). The thermal conductivity of the scale has been measured as 0.0076 ± 0.0016 watts/cm-°C.[3] Calculations of the maximum fuel-plate temperatures during 100-Mw operation varied. Some calculations indicated these temperatures to be 600°C or above,[3] depending on the thickness and condition of the boehmite scale deposits. The effect of the scale on the fuel-plate temperatures, when considered in conjunction with the fuel-swelling data, indicated a condition of possible difficulty during 100-Mw operation of the EBWR.

It was expected that fuel-element difficulties, should they occur, would manifest themselves primarily by decreasing the water channel between fuel plates. It was thus thought advisable to develop a simple and rapid procedure for detecting any change in water-channel thickness in the fuel elements. Because of the expense and time involved in examining a fuel element in a hot cell, it was decided that any examination should be performed in the reactor tank. Thus, a probe was desired that could be indexed over, and driven into, the channel to be measured. The signal from the probe as it traversed a channel was to be continuously recorded. Relative variations along each channel would be immediately apparent, and actual water-channel spacings could be obtained by comparing the chart values with a known standard. The measurements were to be taken before 100-Mw operation, and then periodically throughout the remainder of Core-IA life as necessary.

DESCRIPTION OF EQUIPMENT

The design considerations in performing the channel-gap inspection of the EBWR fuel elements were centered around the accessibility of the channels to be measured and the desired accuracy of the measurement. Figure 2 shows the fuel elements in position in the core, as viewed from the top of the reactor vessel. An irradiated fuel element could be withdrawn from the reactor core to within 150 cm (60 in.) of the surface of the water. The water level could be raised to within 140 cm (54 in.) of the top of the centering ring. The portion of the fuel element which was to be inspected measured 140 cm (54 in.) in length. This meant that a remotely operated probe would have to be handled at a maximum distance of 4.3 meters (14 ft.). A water-channel gap which had been reduced to near 7.6 mm (0.300 in.) was considered critical, and an accuracy of ±0.02 mm (±0.001 in.)

was desired within the range of 7.6 to 8.1 mm (0.300 to 0.320 in.). The tolerance for the range 8.1 to 10.7 mm (0.320 to 0.420 in.) could be greater.



111-7369

Figure 2. EBWR Core-I Fuel Elements in Position in Core, as Viewed from Top of Reactor Vessel

Various techniques perhaps applicable to the inspection were:

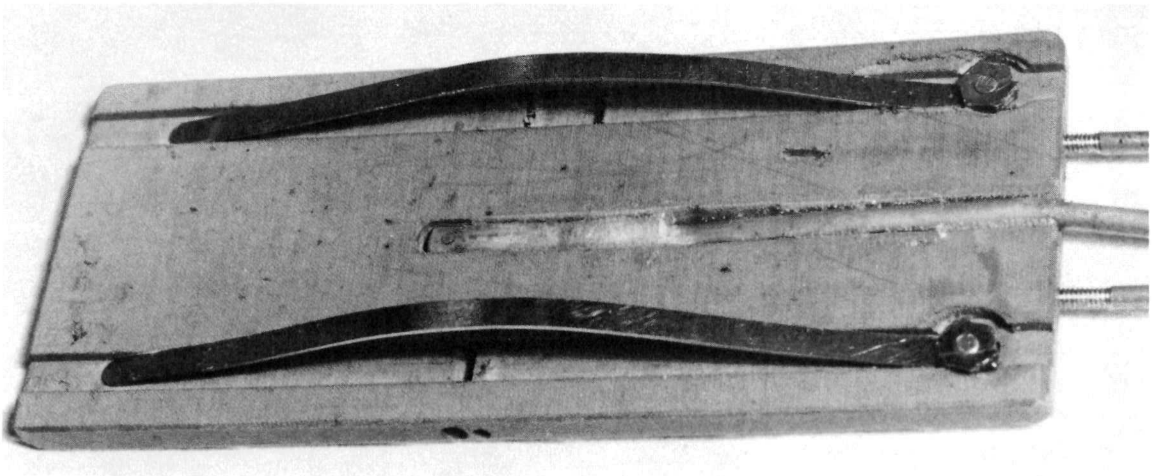
1. Ultrasonic pulse echo
2. Surface-contacting measuring devices
   a. Manually operated extension micrometer
   b. Hydrostatically operated bellows located within channel
   c. Go-no-go gauges
3. Eddy-current techniques
4. Capacitance plate probe
5. Strain-gauge probe

The permissible probe thickness, as well as the calculated accuracy, eliminated some techniques. The environmental conditions and a provision that a continuous full-length scan of the channel be made precluded the use of others. The method which appeared feasible was an eddy-current technique using a small coil imbedded in a waterproof housing.

For this application, a commercial instrument was procured and modified to operate with a coil having 6.1-meter (20-ft.) extension leads. The coil, which was 3.2 mm (0.125 in.) in diameter, formed one leg of an LR bridge, and could be selectively oscillated between the frequencies of 55 and 170 kilocycles. The principle of operation was the change in the impedance of the coil in the presence of a conductor, which affected the balance of the bridge circuit. This, in turn, caused a change of current flow in the circuit, which was detected by a meter and a strip chart recorder. The initial evaluation of the test method was performed on variable-spacing channel gaps assembled from unirradiated sections of EBWR fuel plates. The coil was affixed to one plate surface, and the effect of the plate spacing in relation to oscillator frequency was measured. These tests were made in air as well as under water.

The characteristics of a coil in this application are such that the impedance will vary with changes in environmental temperature. The bulk-water temperature within the reactor vessel was known to be relatively uniform, but gamma heat from an irradiated fuel element could produce a temperature gradient which would vary over the length of the channel. A sheathed thermocouple attached to an extension rod and a potentiometer permitted remote measurements of channel-gap temperatures. A calibration curve was made of the probe temperature in relation to the percentage error of the measurement.

The swelling or bowing of the particular fuel plates was expected to be accentuated in the middle of a channel. The sensing coil was therefore centrally located in a 6.4-mm-thick Micarta block of sufficient width to guide against the side plates of the fuel element. (The probe is shown in Figure 3.) Two leaf springs forced the probe against one side on the channel. The measurement was, in essence, the water gap separating the sensing coil from the opposite plate. The leading and trailing edges of the probe were tapered to override undulations or scale formation on the plate. A ferrite disc 0.5 mm (0.020 in.) thick, was used to isolate the coil from the plate contacting the probe surface. This disc served as a magnetic flux guide and minimized the lift-off effect if the probe straddled scale formations.



106-5772 1.5X

Figure 3. View of Probe Holder, Showing Spacer Springs, Guide Rods, and Sensing Probe

The probe was driven vertically into the channels by two guide rods attached to a motor-driven scanner. The scanner (shown in Figure 4) was designed to be mounted over a hole in the reactor indexing shield plug, as shown in Figure 5. The two-directional motion was accomplished by a chain drive operating a yoke assembly on two guide bars. The yoke was the attachment for the probe extension rods. Positioning of two limit switches governed the length of travel and was preset to include the fueled portion of the plates which approximates 130 cm (51 in.). The scanner was fastened to a slide base plate and could be indexed horizontally over the desired channel to be probed.

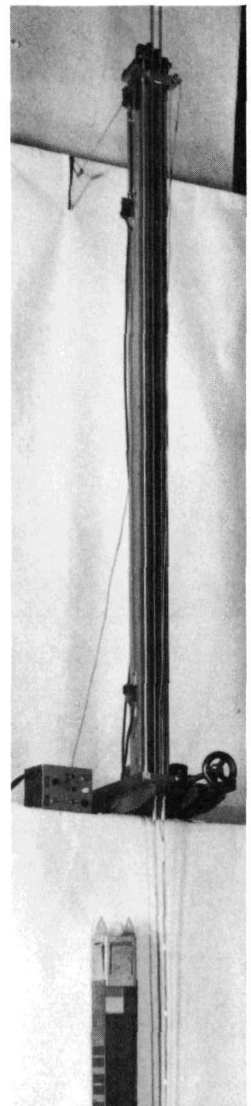
To verify the performance of the test apparatus, a full-scale unirradiated fuel element was inspected. The fuel element was immersed in water, and the channels were scanned under conditions of variable probe-driving speeds, water temperatures, and probe-spring pressures. The recorded channel gaps were verified by using inside micrometers inserted in the web openings of the element side plates. The scanning rate determined to be most suitable for the equipment was 2.5 cm (1 in.) per second. The chart speed selected was 1.3 cm (0.5 in.) per second. Reproducibility of the recordings was within 2.5% when repeated scans were made of the same channel at different times. The electronic equipment was operated with a stabilized power supply. Drift was only a minor problem as the circuit maintained calibration for periods in excess of four hours. A dummy standard probe was coupled to the circuit, and by periodically switching to this probe the calibration could be ascertained.

Inspection of the full-size element and graduated mock-up channel gaps enabled the limits of confidence in the measured values to be established. The probe was designed to provide maximum accuracy within water channels of approximately 7.6 mm (0.299 in.). Within the range of 7.3 to 8.1 mm (0.290 to 0.320 in.), the accuracy was within ±0.02 mm (0.001 in.). From 8.1 to 9.4 mm (0.320 to 0.370 in.), the error was ±0.1 mm (0.005 in); and from 9.4 to 11.4 mm (0.370 to 0.450 in.), it was ±0.6 mm (0.025 in.). A series of ten calibration runs with water temperatures between 18 and 25°C indicated that within that temperature range the response of the probe was constant.

EXPERIMENTAL PROCEDURE

When performing the measurements in the reactor, an element was withdrawn from the core and placed in a rack adjacent to the interior wall of the reactor vessel. The response of the measuring probe was temperature-dependent; consequently, the temperature within a channel was first measured with a chromel-alumel thermocouple. As there was no detectable gradient along a channel, the probe was then calibrated at the measured temperature by means of a micrometer standard. The standard consisted of two sections of EBWR fuel plate that could be adjusted for known separation between the plates.

After calibration, the equipment was mounted on the indexing plug at a point above a positioning rack holding the EBWR fuel element to be examined. The probe holder was indexed over, and driven into, the channel to be measured. The signal from the probe, as it traversed a channel, was continuously recorded. Recordings were made only when the probe was traveling in an upward direction so that the drive rods were pulling the probe through the channel. On the first elements, a go-no-go gauge was introduced into the channel to verify a minimum dimension recorded by the probe. (An irradiated element mounted in the rack is shown in Figure 6.) Duplicate runs on some channels indicated that



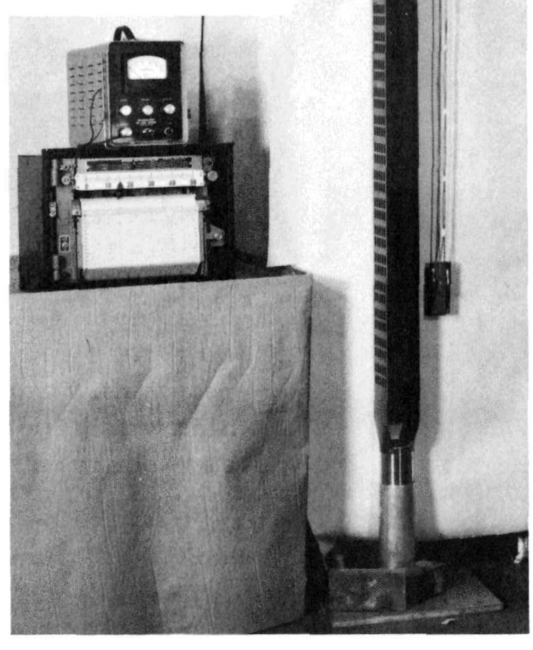


Figure 4

Channel-measuring Device and Associated Recording Equipment. (A mockup fuel element is shown in position relative to the probe.)

106-5770

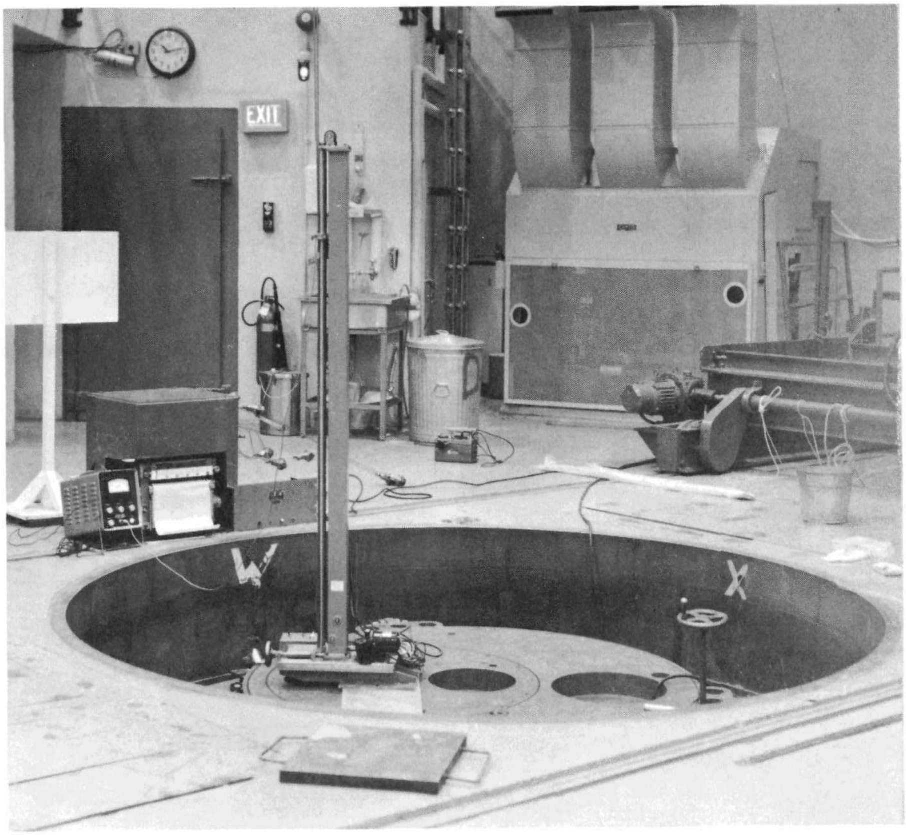


Figure 5
Scanner Mounted on Index Plug of EBWR Reactor Vessel

EI-1092

EI-1096

Figure 6. EBWR Core-I Fuel Element Mounted in Submerged Rack Inside Reactor Vessel. (Probe can be seen entering channel.)

reproduction of the measurements was within 2.5% on channels having gaps of about 10.2 mm. Relative variations along each channel were immediately apparent, and actual water-channel spacings were obtained by comparing the chart values with values obtained from the known standard.

The probe was recalibrated after each fuel element was scanned, or after a four-hour period of operation. As a test, the probe was permitted to remain within a channel for 14 hours. In rescanning this channel, it was found that the measurements could be duplicated.

RESULTS AND DISCUSSION

The application of an eddy-current probe technique to the measurement of channel gaps was demonstrated to be simple and capable of meeting the design requirements. The desired maximum accuracy was preset within an anticipated range which did not actually fall within channel-gap measurements of the irradiated elements. However, relocation of the coil could have yielded accuracies of ±0.025 mm (0.001 in.), within any specified 0.76-mm (0.030-in.) range.

The water-channel gaps on EBWR fuel elements ET-2, ET-5, ET-11, ET-15, ET-31, and ET-43 were measured. The ET designation identifies these assemblies as enriched thin elements. The enrichment was a nominal 1.4% U^{235}. Figure 1 gives the nominal fuel-plate and water-channel thicknesses of the elements. These elements were selected for testing because they represented the maximum burn-up condition existing within the core before 100-Mw operation and would operate at the highest temperature during Core-IA operation. At least one such element was selected from each quadrant of the reactor. The channel measurements are tabulated in Tables I through VII. The values were determined at 5-cm (2-in.) increments along the channel length by comparing the chart values for each element with values obtained from the known standard. Before 100-Mw operation, the channels ranged from 8.4 mm (0.330 in.) to greater than the reference value of 11.1 mm (0.438 in.). This sizable variation in channel spacing has been observed before.[2] It is attributed to misalignment between fuel plates and perforated side plates during welding of the element.

After the fuel elements were measured, but before operation of Core-IA, the inside of the reactor vessel was modified and instrumented experiments were installed. These changes made it impractical to remove elements ET-15, ET-25, and ET-43. Therefore only fuel elements ET-2, ET-5, ET-11, and ET-31 could be remeasured after 100-Mw operation. The minimum water gap on the elements remeasured was found to be about 10.2 mm (0.400 in.). The before-and-after measurements of these elements are compared in Tables I to IV. The data indicate that the general increase in water-channel thickness agreed with observations by reactor personnel[4] that oxide spalling occurred during 100-Mw operation. Thus, the data indicate that swelling (if any occurred) was negligible and was masked by a loss of oxide scale from the fuel-plate surfaces.

Table I

WATER-CHANNEL DIMENSIONS ON EBWR FUEL ELEMENT ET-2 (in mm)

Dist. from Top (cm)	Channel 1		Channel 2		Channel 3		Channel 4		Channel 5	
	Before	After	Before	After	Before	After	Before	After	Before	After
10	≥11.0	≥11.0	≥11.0	=10.9	10.9	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
15	≥11.0	≥11.0	10.6	10.8	10.8	10.8	≥11.0	≥11.0	≥11.0	≥11.0
20	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
25	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
30	≥11.0	≥11.0	≥11.0	≥11.0	10.9	10.8	≥11.0	≥11.0	≥11.0	≥11.0
35	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0	≥11.0	≥11.0
40	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
45	≥11.0	≥11.0	10.6	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
50	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
55	≥11.0	≥11.0	10.9	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
60	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
65	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.7	≥11.0	≥11.0	≥11.0	≥11.0
70	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0	≥11.0	≥11.0
75	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.4	≥11.0	≥11.0	≥11.0	≥11.0
80	≥11.0	≥11.0	≥11.0	10.5	10.5	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
85	≥11.0	≥11.0	≥11.0	10.9	10.5	10.8	≥11.0	≥11.0	≥11.0	≥11.0
90	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
95	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
100	10.9	≥11.0	≥11.0	≥11.0	10.5	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
105	≥11.0	≥11.0	≥11.0	≥11.0	10.3	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
110	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
115	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
120	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
125	≥11.0	≥11.0	10.9	≥11.0	10.9	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0

Table II

WATER-CHANNEL DIMENSIONS ON EBWR FUEL ELEMENT ET-5 (in mm)

Dist. from Top (cm)	Channel 1		Channel 2		Channel 3		Channel 4		Channel 5	
	Before	After	Before	After	Before	After	Before	After	Before	After
10	10.1	≥11.0	10.0	10.9	10.9	≥11.0	10.5	≥11.0	9.8	10.5
15	10.1	≥11.0	9.6	10.9	≥11.0	≥11.0	10.1	≥11.0	9.6	≥11.0
20	10.5	≥11.0	9.8	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.0	≥11.0
25	≥11.0	≥11.0	10.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.7	≥11.0
30	≥11.0	≥11.0	9.5	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.1	≥11.0
35	≥11.0	≥11.0	9.3	10.0	≥11.0	≥11.0	≥11.0	≥11.0	10.1	≥11.0
40	10.9	≥11.0	9.5	10.7	≥11.0	≥11.0	≥11.0	≥11.0	10.3	≥11.0
45	10.9	≥11.0	9.5	10.9	≥11.0	≥11.0	10.9	≥11.0	10.0	≥11.0
50	10.5	≥11.0	9.5	10.5	≥11.0	≥11.0	≥11.0	≥11.0	10.1	≥11.0
55	10.9	≥11.0	9.5	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	9.8	≥11.0
60	10.9	≥11.0	10.6	≥11.0	≥11.0	≥11.0	10.5	≥11.0	10.3	≥11.0
65	≥11.0	≥11.0	10.4	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	9.9	≥11.0
70	≥11.0	≥11.0	9.9	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
75	≥11.0	≥11.0	9.8	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
80	≥11.0	≥11.0	10.3	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	9.9	≥11.0
85	≥11.0	≥11.0	10.2	10.9	≥11.0	≥11.0	≥11.0	≥11.0	9.9	≥11.0
90	≥11.0	≥11.0	9.8	10.7	≥11.0	≥11.0	≥11.0	≥11.0	10.5	≥11.0
95	≥11.0	≥11.0	9.6	10.9	≥11.0	≥11.0	≥11.0	≥11.0	9.6	≥11.0
100	≥11.0	≥11.0	9.7	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	9.8	≥11.0
105	≥11.0	≥11.0	10.8	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	9.6	≥11.0
110	≥11.0	≥11.0	9.8	≥11.0	≥11.0	≥11.0	10.4	≥11.0	≥11.0	≥11.0
115	10.5	≥11.0	9.8	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.6	≥11.0
120	10.6	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
125	10.3	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.5	≥11.0

Table III

WATER-CHANNEL DIMENSIONS ON EBWR FUEL ELEMENT ET-11 (in mm)

Dist. from Top (cm)	Channel 1		Channel 2		Channel 3		Channel 4		Channel 5	
	Before	After	Before	After	Before	After	Before	After	Before	After
10	10.4	≥11.0	10.5	10.6	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
15	≥11.0	≥11.0	10.4	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.5	≥11.0
20	≥11.0	≥11.0	10.9	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
25	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
30	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
35	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
40	≥11.0	≥11.0	10.9	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
45	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.7	≥11.0
50	10.6	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
55	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
60	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
65	10.9	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
70	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
75	10.4	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
80	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
85	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.7	≥11.0
90	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.3	≥11.0
95	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0
100	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0
105	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.1	≥11.0
110	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.0	≥11.0
115	≥11.0	≥11.0	10.9	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.6	≥11.0
120	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.2	≥11.0
125	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.0	≥11.0

Table IV

WATER-CHANNEL DIMENSIONS ON EBWR FUEL ELEMENT ET-31 (in mm)

Dist. from Top (cm)	Channel 1		Channel 2		Channel 3		Channel 4		Channel 5	
	Before	After	Before	After	Before	After	Before	After	Before	After
10	9.9	≥11.0	10.2	≥11.0	10.5	≥11.0	10.7	≥11.0	≥11.0	≥11.0
15	9.8	≥11.0	10.3	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0	≥11.0
20	10.1	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
25	10.2	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
30	10.5	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
35	10.5	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
40	10.9	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
45	10.6	10.9	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
50	10.1	10.5	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
55	9.6	10.1	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
60	9.6	10.7	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
65	9.6	10.2	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
70	9.6	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
75	10.1	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
80	10.7	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
85	10.0	10.9	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
90	10.2	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
95	10.9	10.8	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
100	10.9	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
105	10.7	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
110	10.6	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
115	10.6	10.2	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
120	10.2	10.5	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0
125	9.7	10.4	≥11.0	≥11.0	≥11.0	≥11.0	≥11.0	10.9	≥11.0	≥11.0

Table V

WATER-CHANNEL DIMENSIONS ON EBWR FUEL ELEMENT ET-15
BEFORE 100-Mw OPERATION (in mm)

Dist. from Top (cm)	Channel*					Dist. from Top (cm)	Channel*				
	1	2	3	4	5		1	2	3	4	5
10	>11.1	11.1	>11.1	10.7	>11.1	70	9.6	9.6	10.3	10.6	>11.1
15	10.8	10.5	11.1	10.3	>11.1	75	9.3	9.8	10.0	10.0	>11.1
20	10.5	10.5	11.0	10.2	>11.1	80	9.3	9.3	10.0	10.2	>11.1
25	11.1	10.7	10.8	10.3	>11.1	85	9.3	9.4	9.9	10.0	>11.1
30	11.0	10.5	10.6	10.3	>11.1	90	9.2	9.3	9.9	10.0	>11.1
35	10.5	10.3	10.8	10.3	>11.1	95	9.2	9.2	10.1	10.1	>11.1
40	10.4	10.3	10.7	10.4	>11.1	100	9.2	9.4	10.1	10.1	>11.1
45	10.9	10.3	11.0	10.4	>11.1	105	9.1	9.3	10.0	10.0	>11.1
50	10.3	10.1	10.8	10.5	>11.1	110	9.4	9.8	10.1	10.0	>11.1
55	10.1	10.0	10.8	10.3	>11.1	115	9.2	9.3	10.1	9.8	>11.1
60	9.8	9.8	10.7	10.5	>11.1	120	9.7	9.6	10.3	10.3	>11.1
65	9.8	9.7	10.6	10.6	>11.1	125	9.6	9.4	10.3	10.1	>11.1

*Channel 5 was designated as the one below the identification tab in the top end fitting. The other channels are referenced from channel 5.

Table VI

WATER-CHANNEL DIMENSIONS ON EBWR FUEL ELEMENT ET-25
BEFORE 100-Mw OPERATION (in mm)

Dist. from Top (cm)	Channel*					Dist. from Top (cm)	Channel*				
	1	2	3	4	5		1	2	3	4	5
10	>11.1	8.7	8.6	>11.1	9.2	70	>11.1	9.0	8.9	>11.1	>11.1
15	>11.1	8.7	8.5	>11.1	9.2	75	>11.1	8.6	9.3	>11.1	>11.1
20	>11.1	8.7	8.5	>11.1	9.2	80	>11.1	8.7	9.2	>11.1	10.6
25	>11.1	8.9	8.6	>11.1	9.6	85	>11.1	8.7	9.3	>11.1	10.2
30	>11.1	8.7	8.6	>11.1	10.7	90	>11.1	8.4	8.5	>11.1	10.0
35	>11.1	9.1	8.8	>11.1	>11.1	95	>11.1	8.9	8.5	>11.1	10.3
40	>11.1	8.9	8.8	>11.1	>11.1	100	>11.1	8.5	8.4	>11.1	10.1
45	>11.1	9.1	8.8	>11.1	>11.1	105	>11.1	8.6	8.6	>11.1	10.7
50	>11.1	9.2	8.8	>11.1	>11.1	110	>11.1	9.6	8.4	>11.1	10.0
55	>11.1	9.5	9.0	>11.1	>11.1	115	>11.1	9.3	8.9	>11.1	9.8
60	>11.1	9.3	8.4	>11.1	>11.1	120	>11.1	8.8	8.8	>11.1	10.5
65	>11.1	9.0	8.7	>11.1	>11.1	125	>11.1	8.7	8.8	>11.1	10.1

*Channel 5 was designated as the one below the identification tab in the top end fitting. The other channels are referenced from channel 5.

Table VII

WATER-CHANNEL DIMENSIONS ON EBWR FUEL ELEMENT ET-43
BEFORE 100-Mw OPERATION (in mm)

Dist. from Top (cm)	Channel*					Dist. from Top (cm)	Channel*				
	1	2	3	4	5		1	2	3	4	5
10	9.2	9.6	9.2	9.8	9.5	70	9.2	9.8	9.1	10.0	9.0
15	9.2	9.4	9.3	9.4	9.3	75	9.0	>11.1	9.6	10.2	9.5
20	9.1	9.4	9.3	9.3	9.2	80	9.2	>11.1	9.7	10.2	9.0
25	9.2	9.6	9.3	9.4	9.4	85	8.9	>11.1	9.6	10.3	8.9
30	9.3	9.6	9.7	9.5	9.3	90	8.9	9.5	9.7	10.3	8.9
35	9.3	10.2	9.4	9.6	9.4	95	9.4	10.1	9.6	10.5	9.4
40	9.4	10.3	9.3	9.5	9.4	100	9.3	10.2	9.7	10.3	9.5
45	9.4	>11.1	9.3	9.6	9.4	105	9.2	>11.1	9.6	10.2	9.1
50	9.7	>11.1	9.3	9.7	9.7	110	9.2	>11.1	9.5	10.2	9.0
55	10.2	>11.1	9.6	9.8	10.3	115	9.8	>11.1	9.5	9.8	9.1
60	>11.1	11.0	9.6	9.8	9.4	120	10.2	>11.1	9.4	9.7	9.8
65	9.4	9.7	9.7	9.9	9.1	125	9.8	>11.1	9.4	9.8	10.2

*Channel 5 was designated as the one below the identification tab in the top end fitting. The other channels are referenced from channel 5.

CONCLUSIONS

1. Water-channel gaps on fuel elements, measured before 100-Mw operation of the EBWR, ranged from 8.4 mm (0.330 in.) to greater than the reference value of 11.1 mm (0.438 in.).

2. After 100-Mw operation, the minimum water channel on re-measured fuel elements was found to be 10.2 mm (0.400 in.).

3. Swelling (if any occurred) was negligible and was masked by a loss of oxide scale from the fuel-plate surfaces.

4. The eddy-current technique, as applied to the measurement of water-channel gaps, was demonstrated to be simple and capable of meeting the design requirements.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of V. M. Kolba in the development of the fuel-element holding fixture, and of W. A. Ahrens and W. C. Kettman in equipment setup, checkout, and measurement.

REFERENCES

1. The EBWR Experimental Boiling Water Reactor, ANL-5607 (1957).

2. C. F. Reinke and R. Carlander, Examination of Irradiated EBWR Core-I Fuel Elements, ANL-6091 (1960).

3. C. R. Breden, I. Charak, and R. H. Leyse, Water Chemistry and Fuel Element Scale in EBWR, ANL-6136 (1960).

4. E. A. Wimunc, M. Petrick, W. C. Lipinski, and H. Iskenderian, Performance Characteristics of the EBWR from 0-100 Mwt, ANL-6775 (1963).