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INFORMAL AEC RESEARCH
AND DEVELOPMENT REPORT

GAMD-9911

POSTIRRADIATION EXAMINATION OF
PEACH BOTTOM REFLECTOR ELEMENT B16-01
AFTER EXPOSURE TO 300 EFFECTIVE FULL POWER DAYS
by
H. R. W. Cobb

This document, which was prepared primarily for internal use at Gulf General Atomic, may contain preliminary or incomplete data. It is informal and is subject to revision or correction; it does not, therefore, represent a final report.

Gulf General Atomic Project 390
U.S. Atomic Energy Commission
Contract AT(04-3)-314

February 1, 1970

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CONTENTS

1. SUMMARY	1
2. INTRODUCTION	2
3. DESCRIPTION	3
3.1. Reflector Material	3
3.2. Reflector Arrangement	3
3.3. Reflector Element Service Conditions	6
4. HOT CELL EXAMINATION	9
4.1. Activity Levels	9
4.2. Surface Appearance	9
4.3. Thermocouple Inspection	13
4.4. Dimensional Inspection	21
4.4.1. Dimensional Inspection Methods	21
4.4.2. Dimensional Inspection Results	21
5. DISCUSSION	26
6. CONCLUSIONS	30
ACKNOWLEDGMENT	32
REFERENCES	33

FIGURES

1. Peach Bottom hexagonal reflector element showing test specimen location and disposition of datum holes	5
2. Reflector element B16-01 hot cell gamma count of outer surface over 144-in. length of double containment	10
3. Reflector element B16-01 hot cell gamma count outer surface over 144-in. length of double containment at 180 deg circumferential displacement to Fig. 2	11
4. Reflector element B16-01 gamma count of surface away from steel containment area	12
5. Hot cell view of reflector element showing (a) base and lower end and (b) with soot-like deposit at base and on hexagonal face showing symmetry in depth of deposit about center line	14

FIGURES (Continued)

6. Hot cell view of (a) central length and (b) upper central length showing intermittent areas of soot-like deposit. Note datum hole on face left of center in (a) and at left of picture (b)	15
7. Hot cell view of upper portion of reflector element showing heavier soot-like deposit: (a) upper end and (b) tip.	16
8. Hot cell view of reflector surface showing soot-like deposit in crevices of original machining and identity markings	17
9. Hot cell view of surface of reflector at contact point with stand-off band of adjacent fuel element (see Fig. 6(b)). Note flow contours of deposit	18
10. Hot cell view of cone shaped top end of reflector, with carbon deposit possibly reflecting coolant flow contours	19
11. Peach Bottom reflector No. B16-01 thermocouple continuity values . .	20
12. Peach Bottom reflector No. B16-01 postirradiation examination graphs	23
13. Effects of differential temperature and flux gradient across midlength section of Peach Bottom reflector element B16-01	28

TABLES

1. Typical properties of agot graphite	4
2. Measured values for neutron fluxes at base of reflector element B16-01 after 300 EFPD	8

1. SUMMARY

The results of hot cell examination of a graphite side-reflector element after 300 effective full power days (EFPD) in a high-flux and high-temperature position in the Peach Bottom reactor are reported. No significant distortion was detected in this examination, which indicated that similarly positioned reflector elements at Peach Bottom could be used to fast fluences well beyond their intended life of 1350 EFPD. The reasons for the limited amount of axial distortion as well as the causes of the discrete areas of carbonaceous deposit observed on the surfaces of the element are discussed.

2. INTRODUCTION

The Technical Specification of License DPF-12, Docket 50-171, issued to the Philadelphia Electric Company for the Peach Bottom Atomic Power Station, requires under the Operational Surveillance Section that the reactor core components be examined regularly. The surveillance schedule calls for a visual in-reactor examination of two reflectors after every 150 EFPD and for the removal of one reflector for postirradiation hot cell examination after 300 EFPD. The visual inspection of the reflector elements in the reactor vessel showed no significant changes in superficial appearance or shape, and the choice of an element for further examination at the Gulf General Atomic Incorporated Hot Cell was made from those located in the peak fluence and temperature environments of the core. Reflector element B16-01 was selected since it (1) operated in a peak reflector temperature position adjacent to an outer row fuel element, (2) was in a maximum fast flux position, (3) was easy and convenient to remove, and (4) was one of 20 elements containing steel surveillance specimens located in its base. Because the element had undergone no apparent changes in service, priority was given in scheduling the postirradiation examination to the removal and testing of the steel surveillance specimens. The results of the Charpy tests on the steel specimens have been reported separately by Roberts (Ref. 1). This reference covers the metrological and visual examination of reflector element B16-01, which was delivered to the Gulf General Atomic Hot Cell on September 26, 1969, after 300 EFPD in the Peach Bottom 40 MW(e) prototype High-Temperature Gas-Cooled Reactor (HTGR).

3. DESCRIPTION

3.1. REFLECTOR MATERIAL

The graphite used in the manufacture of Peach Bottom reflector elements is National Carbon Company's (Union Carbide Corporation, UCC) AGOT grade with the following typical properties (Table 1).

This grade of material is a gas-baked, pitch-impregnated extrusion of coke filler, up to 30-mil maximum size, mixed with flour and pitch that is finally graphitized at $\sim 5000^{\circ}\text{F}$ to produce a well crystallized high-purity nuclear graphite. Production inspection tests (Ref. 3) showed the flexural and tensile strength of the material ranged to a minimum of 37 and 57 percent respectively below the catalogued values, which is typically within the range for this grade of material.

3.2. REFLECTOR ARRANGEMENT

The general arrangement (Fig. 1) of the standard reflector elements is similar in outline to that of the fuel elements. The reflector elements are machined from solid extrusions of graphite to form a hexagonally shaped cross section. The element is 3.55 in. across the flats and 144 in. long, with an upper reflector grappling knob and bottom connector fitting for handling and positioning within the reactor. In the elements containing steel surveillance specimens, the test pieces were located 9-3/4 in. from the base and were sealed into the center of the section by a graphite plug. Through the end of the element extending from the steel test specimens were located two metal-sheathed thermocouples connecting to friction contact points. To measure possible length changes due to fast neutron irradiation, a series of datum holes were drilled on two opposite faces of the element. The holes, 1/8 in. diameter and 3/16 in. deep, were located by a master gauge at four consecutively pitched distances of 30 in.

TABLE 1
TYPICAL PROPERTIES OF AGOT GRAPHITE^(a)

Density (gm/cc)	Flexural Strength (lb/in. ²)		Tensile Strength (lb/in. ²)		Compressive Strength (lb/in. ²)		Young's Modulus x10 ⁶ lb/in. ²		C.T.E. (d) 10 ⁻⁶ C ⁻¹	
	WG(b)	AG(c)	WG	AG	WG	AG	WG	AG	AG	WG
1.70	2400	1970	1440	1260	5990	5960	1.49	1.11	4.0	1.9

(a) From Ref. 2.

(b) WG = with grain

(c) AG = Against grain

(d) C.T.E. = Coefficient of thermal expansion mean

Fig. 1. Peach Bottom hexagonal reflector element showing test specimen location and disposition of datum holes

3.3. REFLECTOR ELEMENT SERVICE CONDITIONS

Power operation of the Peach Bottom Atomic Power Station began in January 1967, full power was reached on May 26, 1967, and commercial operations began on June 1st. The reactor underwent a scheduled inspection in January, 1968, after 168 EFPD and again in October after about 300 EFPD of operation. The plant record of availability was high for the two extended periods between inspections.

In the reactor core, the reflector element base was located by using a standoff pin, with the axis of the element aligned vertically. The honeycomb packing of three rows of reflector elements surrounding the core fuel elements gave an arrangement that located one hexagonal face of element B16-01 adjacent to a fuel element. When initially loaded within the core, this face was arranged to be one of two diametrically opposing faces bearing the datum holes so that the maximum flux and temperature variations were experienced on the faces of the element containing datum markings.

The hexagonal reflector elements and the fuel elements are restricted from moving within the core by action of their weight, by the restraint of the standoff pins, and by clamping action of tilting side reflectors. Lateral movement of these elements is restricted at the lower end of the core by the standoff pins. At the upper end of the core, each element is restrained by lateral contact forces from adjacent elements. The plane of contact is at the spacer rings located 137.9 in. above the bottom of the fuel element. Contact forces on the outer ring of elements are applied by the tilting side reflectors which pivot at the lower end and are forced against the elements at the upper end. The radial compressive forces acting on the elements by the side reflectors is equivalent to 475 lb per outermost reflector element and results from the helium coolant pressure differential across the tilting side reflectors (Ref. 4).

No temperature measurements were made on the reflector element or its neighboring fuel element in service; however, estimates of the temperature along the length of fuel elements in similar flux profile positions provide a guide to an assessment of the service temperature of element B16-01.

Fuel element E15-01 is calculated to have a maximum temperature of 985 F at the base and 1815 F at the peak neutron flux position at a point 63 percent along its length (Ref. 5). The recorded temperature range of the steel surveillance specimens in the base of the B1601 reflector element is given as 690 to 696 F (Ref. 6); thus, if this temperature resulted from similar axial thermal gradients to the above, the maximum temperature at the peak flux position is estimated to be ~ 1200 F. These temperatures are less than the original design estimates (Ref. 7) of 1100 F at the midlength and ~ 1500 F at the upper end, which, on the evidence of the measured values, appear to be high.

Postirradiation evaluation of flux dosimeter wires in the cavity at the base of the element gave the flux readings shown in Table 2 (Ref. 8). Calculations by Lane (Ref. 9) of the fast neutron fluences in the reflector element at energies above 0.18 MeV for reactor fuel power conditions give a maximum fluence at 300 EFPD of 0.65×10^{21} n/cm² ($E > 0.18$ MeV), resulting from a combined longitudinal and radial peaking factor of 1.9 at the upper midlength inner face position. The flux gradient through the element reduces the peak fluence on the face furthest from the reactor core to 0.34×10^{21} n/cm² at 300 EFPD.

TABLE 2
MEASURED VALUES FOR NEUTRON FLUXES AT BASE OF REFLECTOR
ELEMENT B16-01 AFTER 300 EFPD(a)

Dosimeter Wire	Reaction	Cross Section	Flux (n/cm ² /sec) (E > 0.18 MeV)	Fluence (n/cm ²)
Al 0.9% Co	Co-59(n γ)Co-60	21.0 b	6.63×10^{11}	1.953×10^{19}
Fe	Fe-54(np)Mn-54	106.4 mb	3.26×10^{10}	9.60×10^{17}
Fe	Fe-54(np)Mn-54	106.4 mb	3.31×10^{10}	9.74×10^{17}

(a) Accuracy $\pm 15\%$.

4. HOT CELL EXAMINATION

4.1. ACTIVITY LEVELS

Reflector element Bl6-01, sealed within a metal canister, was delivered to the hot cell at Gulf General Atomic's San Diego facility on September 26, 1969. The assembly was mounted upon a 14-ft machining carriage within the hot cell, and this carriage was used for all subsequent dimensional inspection. The canister assembly was traversed past a fixed, collimated gamma probe mounted in the head stock of the machining carriage. The full length of the assembly was gamma scanned through a 50 mil slit covering a 2-in. sodium iodide phosphor at speeds of 1-1/2 to 10-1/2-in. linear displacement per minute. Buzzelli (Ref. 10) reports that, with an energy plateau of 100 keV, a number of scans along the length of the canister at different positions on the circumference gave count rates a factor of two greater than the general hot cell background levels (Figs. 2 and 3). A maximum count rate of 19.5×10^3 cpm over the bottom quarter length of the element indicated the location of the steel surveillance samples. Energy scans at this position revealed the cesium-137, manganese-54, and cobalt-58 and -60 peaks of the instrumented test section. The measured count rate of the element through the canister along the remainder of its length was 7.2 to 16×10^3 cpm; in the unclad state, the count rate was 13 to 16.5×10^3 cpm (Fig. 4). Charts of gamma scans along the element within the canister at two positions at 180° orientation of the circumference are given in Figs. 2 and 3. The gamma activity levels of the section of unclad graphite away from the steel test section was a mean value of 14×10^3 cmp (see Fig. 4).

4.2. SURFACE APPEARANCE

The metal canister enclosing the reflector element was removed with an abrasive wheel by cutting off the ends and making diametrically opposed cuts along the length. The inner and outer surface of the canister was sound, indicating no major damage during transit.

Z0298

Fig. 2. Reflector element B16-01 hot cell gamma count of outer surface over 144-in. length of double containment

Fig. 3. Reflector element B16-01 hot cell gamma count outer surface over 144-in. length of double containment at 180 deg circumferential displacement to Fig. 2

Z0299

Fig. 4. Reflector element B16-01 gamma count of surface away from steel containment area

Visual examination of the surfaces of the element showed discrete areas of a soot-like deposit, which, on analysis, was reported by Busch (Ref. 11) to be principally carbon and iron oxide. The hexagonal face of the element bearing the largest deposit was that closest to the adjacent fuel element, and, therefore, the face that (1) was nearest the core, (2) had the highest temperature and flux profile, and (3) was nearest the largest coolant flow passage. The density of the deposit varied along the length and appeared to have the greatest concentration at approximately midlength and at the upper elevation (Figs. 5 through 7). Evidence that the surface effects were the results of deposition rather than some form of attack is shown in Fig. 8, where the original machining and identification markings remain clearly evident, with the deposit retained in all the surface depressions. At the position coincident with a standoff band of the adjacent fuel element, the reflector shows a rubbing mark, giving evidence of the contact produced by the radial compressive force (Fig. 9). There is also some evidence of the constancy of this force since the deposit from the coolant is contoured and streaked to reflect the flow pattern. Further evidence of the fallout of the carbonaceous deposit from the coolant is given in views of the top cone-shaped end (Fig. 10) where it is thought that the patterns in the deposit again reflect the coolant flow path and velocity changes.

4.3. THERMOCOUPLE INSPECTION

Prior to further handling, the final room temperature electrical resistance values of the thermocouple assembly attached to the steel surveillance samples were recorded. The instrument used was a Monarch volt/ohm meter Model MT 220-A, and the results are shown in Fig. 11. In the absence of any recorded assembly data these results are interpreted solely to show evidence of continued electrical insulation of the hot joint and satisfactory and uniform conductivity of the two pairs of sheathed wires at the end of service life.

K308-6

(a)

HC308-5

(b)

Fig. 5. Hot cell view of reflector element showing (a) base and lower end and (b) with soot-like deposit at base and on hexagonal face showing symmetry in depth of deposit about center line

HC308-4

(a)

HC308-3

(b)

Fig. 6. Hot cell view of (a) central length and (b) upper central length showing intermittent areas of soot-like deposit. Note datum hole on face left of center in (a) and at left of picture (b)

HC308-2

(a)

HC308-1

(b)

Fig. 7. Hot cell view of upper portion of reflector element showing heavier soot-like deposit: (a) upper end and (b) tip

Z0297

(10x)

Fig. 8. Hot cell view of reflector surface showing soot-like deposit in crevices of original machining and identity markings

K308-4

(10x)

Fig. 9. Hot cell view of surface of reflector at contact point with standoff band of adjacent fuel element (see Fig. 6(b)). Note flow contours of deposit

K308-5

(10x)

Fig. 10. Hot cell view of cone shaped top end of reflector, with carbon deposit possibly reflecting coolant flow contours

Fig. 11. Peach Bottom reflector No. B16-01 thermocouple continuity values

4.4. DIMENSIONAL INSPECTION

During manufacture, the reflector faces, which in the reactor were located nearest to and furthest from the reactor center core position, were marked with a series of datum holes. The method by which the holes were located in the two opposite faces of the element was by an identical procedure, as directed by Hopkins et al. (Ref. 12), which ensured a constancy of pitch between each pair of consecutive holes through the use of a drill jig spanning the full length of the element. The drill jig is no longer available, but manufacturing inspection records imply that the items were acceptable on nominal dimension. Therefore, assessment of the dimensional changes in the graphite reflector is attempted on the premise that the discrepancy in linear displacement between consecutively spaced datum holes would, due to the machining procedure, have been essentially the same as at the time of manufacture.

4.4.1. Dimensional Inspection Methods

The displacement between the datum holes was measured with a rigid test bar having one fixed and one adjustable locating pin at the ends. The pins were 120 mils diameter and projected at right angles to the test bar length. Thus, the pins, when located in consecutive datum holes along the element, spanned the chord length. This distance was then measured in a clock gauge fixture calibrated to 0.1 mil.

4.4.2. Dimensional Inspection Results

Measurement of the overall length of reflector element B16-01 gave readings of $144\frac{1}{2}$ and $144\frac{7}{16}$ in. along opposing sides of the element. This dimension included a nominal $\frac{1}{2}$ -in. protrusion of the sheath protecting the thermocouple contacts at the base of the element. The accuracy in measuring this dimension is estimated to be $\pm\frac{1}{32}$ in.

The lower full-size diagram of Fig. 12 indicates the final dimensions of the chord distances between the original datum holes. Due to the

Fig. 12. Peach Bottom reflector No. B16-01 postirradiation examination graphs

1

2

3

slenderness of the assembly and problems of monitoring the element during hot-cell measurement, these dimensions are thought to be the most relevant indications of the degree of permanent bow.

5. DISCUSSION

The appearance and positions of the soot-like deposits on the surfaces of the element suggest that it is both coolant flow and temperature dependent. The predominant factor is reported to be temperature. Hirst and Palmer (Ref. 13) show that a carbon suboxide (C_3O_2) in a helium carrier gas has a ten fold increase in deposition rate constant for a ten percent increase in temperature. There is some evidence to suggest that the deposition process is due to chemical condensation, possibly from hydrocarbon as well as the suboxide, although Johnson and Anderson (Ref. 14) suggest the first solid reaction product from pyrolysis of hydrocarbons is observed at 1300 F and thus would occur mostly at the top end of the element. The equilibrium concentration in the carrier gas is temperature sensitive and reduces with reduction in pressure (Ref. 15). Thus, the face of the element nearest the largest coolant passages would have an atmosphere with greater aerosol carbon content. This possibly explains the larger amounts of deposit towards the edges of the reflector face nearest the cylindrically shaped fuel element.

From the original design tolerances, the dimensional shrinkage in the AGOT grade graphite reflector element is between 0.032 and 0.054 percent in the length (i.e., parallel to extrusion) and a maximum of 0.07 percent in the transverse direction. These values approximate the predicted values for the longitudinal and transverse orientations.

The amount of bow along the length of the element is extremely small, and, even with a conservative allowance of 100 percent measurement inaccuracies, the net bow is a factor of two lower than could be expected, for example, in the manufacture of tubes or extruded and machined assemblies. Since the elements are not expected to undergo large structural changes during their service life or to be subjected to excessive loads, a major

criterion of the service performance is the degree of distortion due to fast neutron irradiation that may hinder their removal from the core. From this standpoint, the dimensional measurements indicate that, with the insignificant dimensional changes or distortion occurring in the reflector at the end of 300 EFPD, it should perform satisfactorily in service for longer than its intended life of 1350 EFPD.

The small amount of distortion in the reflector element after 300 EFPD in Peach Bottom may be due to a uniformity of strain within the assembly. It is known that graphite contracts during the initial irradiation period and that the amount of contraction of similar materials increases with decreasing irradiation temperatures below 1450 F. Since for a given temperature the contraction increases with increases in flux level, it is possible that the two conflicting strains on opposite faces of the element reduce the resultant bow (see Fig. 13). The dimensional differences between datum holes on opposite faces of the element give a chord length difference of 0.04 percent. The resulting bow in the element is such that the free end moves away from the adjacent fuel element.

The slight distortion of the element (if due to service effect) indicates the configuration to be that of a beam supported at the base end and at a point 92 in. along the 144-in. length, where it contacts the restraining band of the adjacent fuel element. The coolant pressure differential puts a distributed load on the coldest face of the element, and the greater irradiation contraction of the graphite on this face produces a couple which adds to the curvature produced by the coolant pressures. Gross deflection at the upper end of the element is restricted by the side thrust of the adjacent fuel elements as well as the increases in coolant pressure; as a result, the deflection has a sinusoidal form. The central position of the maximum deflection indicated that the irradiation contraction was probably the predominant force throughout most of the irradiation life. The curvature at this point may be assessed from the differences in chord length between the datum points on each face of the element.

Fig. 13. Effects of differential temperature and flux gradient across mid-length section of Peach Bottom reflector element B16-01

If it is assumed that the displacement between holes was similar originally, the relative angular displacement θ of diametrically opposite holes is one-half the angle subtended by the arc of deflection of the beam:

$$\theta = \frac{6 \times 10^{-3} \text{ in.}}{3.55 \text{ in.}}$$

and

$$\text{radius} \equiv \frac{\text{chord length}}{2\theta} = \frac{30.006}{2 \times 6 \times 10^{-3} / 3.55} \equiv 740 \text{ ft.}$$

If a factor of two increase in the value of Young's Modulus due to irradiation is assumed, the fundamental beam formulae gives an equivalent permanent bending moment of 280 lb-ft at a maximum fiber stress of 598 lb/in.², which is 40 percent of the initial minimum flexural strength of the material.

6. CONCLUSIONS

The contraction in the AGOT grade graphite reflector element B16-01 after 300 EFPD operation in a peak flux and temperature position in Peach Bottom is approximately 0.07 percent in the transverse (across the width) direction and 0.032 to 0.054 percent in the longitudinal direction (along length), in good agreement with predicted changes. The distortion of the reflector element is well within the manufacturing tolerances for such an assembly and there is no evidence to indicate that the elements would not perform satisfactorily to well beyond their intended dose life. The maximum bow is at the midlength position of the 12-ft long element; the amount of twist along the length is found to be 0.1 degrees and thus well within the original machining tolerances.

The small degree of bow is thought to be due to the absence of any large strain differences across the section of the element, even in the largest temperature and flux gradients. Although for a given temperature the initial contraction in the graphite increases with increasing fast fluence, the contraction on the cold face is slightly greater even for a 50 percent lower dose level since at temperatures below 1450 F the graphite also undergoes increases in contraction for decreases in irradiation temperature. The distortion of the element in the peak flux region giving a radius of curvature of 740 ft equates to that produced by a bending moment of 280 lb-ft at a maximum fiber stress of 598 lb/in.² The flexural stress producing this bow in service is approximately 40 percent of the minimum measured value of the unirradiated material.

Carbonaceous deposits were observed on discrete areas of the surface of the element. The product is a deposit high in carbon with iron oxide. The deposition process is thought to be due to the production of aerosol particulate and condensates from the coolant that settles in protected places on the graphite surfaces. As the solubility of the carbon in the

coolant impurities varies with temperature and pressure, the areas within the system that are adjacent to increases in coolant passageways have preferred amounts of the deposit.

The visual and dimensional inspection of a Peach Bottom reflector element in the GGA Hot Cell after 300 EFPD of operation in a peak flux and temperature position indicates that the current service conditions put no loading on the component. The distortion is negligible and, except for discrete areas of a carbonaceous deposit on the surface of the element, there are no undue markings.

The inspection indicates the overall performance of the reflector elements in Peach Bottom is good, and there appear to be no restrictions on the use of these components to well beyond the intended life in the reactor of 1350 EFPD.

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