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GULF GENERAL ATOMIC

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EXAMINATION OF PEACH BOTTOM HTGR CONTROL ROD, CONTROL ROD GUIDE TUBE,
AND THERMALLY RELEASED SHUTDOWN ROD C08-01 AFTER 300
EFFECTIVE FULL POWER DAYS OF OPERATION

by

O. M. Stansfield

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December 1970

GULF GENERAL ATOMIC COMPANY, P.O. BOX 608, SAN DIEGO, CALIFORNIA 92112

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Gulf General Atomic Project 390

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ABSTRACT

The control rod and control rod guide tube from position C08-01 of the Peach Bottom High-Temperature Gas-Cooled Reactor were examined after 300 effective full power days of operation. The general condition of the control rod was essentially unchanged from the manufactured condition except for a discoloration of metallic parts, some embrittlement of Haynes 25 alloy disk springs, and an axial shrinkage of the boronated graphite neutron absorbers. The maximum absorber shrinkage observed was about 0.28% in an absorber that had been positioned at the middle of the core and had received a fast neutron exposure of about $1.2 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$). The irradiation-induced axial shrinkage as a function of fast neutron exposure was in agreement with irradiation data from similar material at higher exposure. Changes in diametral dimensions were not great enough to exceed manufactured tolerances. On the basis of an analytical model of the absorber, the stresses and strains in the absorber walls were calculated. Satisfactory performance was predicted to full lifetime exposure.

The guide tube showed few effects of the reactor exposure. Spots were observed at the point of contact with fuel elements, but no wear was observed there. The major deviations from the manufactured condition were a cracked thermally released shutdown absorber support and an axial bow of about 0.122 in. in the guide tube. The direction of guide tube bow suggested an accelerated shrinkage on the surface facing the core outside diameter, which is consistent with the higher fast neutron exposure expected on that side. Restraint in the core, creep in the graphite, and a more constant rate of irradiation-induced dimensional change beyond 300 EFPD will tend to minimize stress and additional bow so that significant additional guide tube bow is not expected. The release temperature of the thermally released shutdown rod was measured and found to be $1740 \pm 5^\circ\text{F}$ and apparently unchanged by the reactor exposure.

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84
85
86
87
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89
90
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92
93
94
95
96
97
98
99
100

CONTENTS

ABSTRACT.	iii
INTRODUCTION.	1
CORE POSITION, DESCRIPTION, AND HISTORY OF C08-01	2
EXAMINATION OF CONTROL ROD C08-01, TEST KM-4	4
Initial Observations.	4
Control Rod Disassembly	7
Examination of Control Rod Components	8
Stainless Steel Weldment.	8
Rider Rings	8
Washers	13
Disk Springs.	13
Support Rings	17
Boronated Graphite Absorbers.	17
EXAMINATION OF CONTROL ROD GUIDE TUBE C08-01, TEST KM-3	44
Initial Observations.	44
Control Rod Guide Tube Dimensions	44
Guide Tube Disassembly.	49
Thermally Released Shutdown Rod	54
APPENDIX: MEASUREMENT OF STRENGTH OF UNIRRADIATED PEACH BOTTOM HTGR BORONATED GRAPHITE CONTROL MATERIAL.	71
REFERENCES.	73

FIGURES

1. Fuel element and control rod positions in the Peach Bottom HTGR.	3
2. Peach Bottom HTGR control rod assembly showing components referenced in the disassembly procedure	5
3. Control rod C08-01 after 300 EFPD (a collage of nine photo- graphs)	6

FIGURES (continued)

4. Top end fitting, rider ring, disk springs, and a portion of absorber 6 of control rod C08-01.	9
5. View into bottom connector of control rod support weldment showing electrical connections of continuity wire	10
6. Typical graphite rider ring between two boronated graphite absorbers with disk springs	11
7. Washer, rider ring, support ring, and disk spring from bottom of absorber 4	14
8. Disk springs from control rod after 300 EFPD bent under similar conditions with remote manipulators	16
9. Copper plated stainless steel support rings	18
10. Typical boronated graphite neutron absorber from control rod C08-01 after 300 EFPD	21
11. Microstructure of boronated graphite absorbers (B ₄ C granules dispersed in graphite matrix)	22
12. Location of powder samples taken from boronated graphite absorbers for lithium, boron, and B-10 - B-11 isotopic analysis .	24
13. B-10 isotope burnup gradient across the wall of neutron absorbers after 300 EFPD in Peach Bottom HTGR core position C08-01.	26
14. Lithium distribution across wall of neutron absorbers after 300 EFPD in position C08-01	27
15. Total boron content across wall of neutron absorber 1 after 300 EFPD in position C08-01	28
16. Dial indicator measuring device	29
17. Neutron absorber material operating temperature and neutron exposure profile after 300 EFPD in Peach Bottom HTGR core position C08-01	33
18. Irradiation-induced length change in Peach Bottom HTGR control rod absorbers	34
19. Predicted irradiation-induced dimensional change of inner and outer diameter of boronated graphite absorbers.	41
20. Control rod guide tube C08-01 after 300 EFPD (collage of six photographs).	45
21. Upper tube cap of control rod guide tube after 300 EFPD showing black deposit at point of contact with adjacent fuel element. . .	47

FIGURES (Continued)

22. Bow measurement in control rod guide tube C08-01 after 300 EFPD.	48
23. Control rod guide tube and adjacent fuel elements showing location of radial cuts made in the guide tube.	50
24. Sections 1 and 2 (see Fig. 23) cut from bottom portion of control rod guide tube C08-01	51
25. Inner surface of lower guide tube showing bottom of grooves cut in inner surface to guide thermally released shutdown rod and control its final position in core.	52
26. Top portion of guide tube (left) with thermally released shutdown rod removed (right).	52
27. Inner surface of guide tube showing joint between upper and lower guide tube.	53
28. Cross section of threaded joint between upper and lower guide tube.	53
29. Thermally released shutdown rod showing the absorber support and related components.	55
30. Absorber support resting on the guide tube groove ledge (metal supporting parts assumed to have melted and run out of the core).	56
31. Lower portion of thermally released shutdown rod showing radial crack observed in HLM-85 graphite absorber support	57
32. Fusible link in thermally released shutdown rod of guide tube.	58
33. Furnace apparatus used to determine release temperature of thermally released shutdown rod	59
34. Apparatus used to determine release temperature of thermally released shutdown rod of control rod guide tube C08-01 after 300 EFPD.	60
35. Thermally released shutdown rod after release temperature experiment.	62
36. Partially melted fusible link from thermally released shutdown rod C08-01 after the release temperature experiment. . .	63
37. Microstructure of outside surface of boronated graphite absorber of thermally released shutdown rod in C08-01 after 300 EFPD.	67
38. High magnification photographs of B ₄ C granules and matrix shown in Fig. 37.	68

TABLES

1. Dimensions of selected graphite rider rings of control rod C08-01 after 300 EFPD	12
2. Results of bending tests on selected disk springs of control rod C08-01 after 300 EFPD	15
3. Chemical composition of boronated graphite absorbers	20
4. Dimensions of boronated graphite absorbers of control rod C08-01 after 300 EFPD	31
5. Mean coefficient of thermal expansion of unirradiated cylindrical boronated graphite absorbers in three principal directions between 22° and 1000°C	35
6. Nomenclature for mathematical model	37
7. Boronated graphite dimensions, properties, and operating conditions	40
8. Results of flexure tests of unirradiated boronated graphite absorber material (30 wt % boron)	43
9. Results of compression tests of unirradiated boronated graphite absorber (30 wt % boron)	43
10. Comparison of maximum stress in boronated graphite control rod absorbers at end-of-life exposure (4.2×10^{21} n/cm ² ; E > 0.18 MeV) and measured strength of material	43
11. Dimensions of thermally released shutdown rod components from guide tube C08-01 after 300 EFPD	64

INTRODUCTION

The Peach Bottom High-Temperature Gas-Cooled Reactor (HTGR) started power operation in January 1967. Full power production was achieved and commercial operation began on May 26, 1967. On October 23, 1968, the reactor reached 300 effective full power days (EFPD) of operation.

As part of the postconstruction research and development program, inspection of control systems components in the core was conducted at the end of 300 EFPD. In accordance with this program, in-core examination of all control rod guide tubes (Test JM-3) was conducted on November 21, 1968 (Ref. 1). No broken or displaced guide tubes were detected. Another observation during the examination was that the tops of the guide tubes appeared darker than the adjacent fuel elements.

Out-of-pile examination of a control rod guide tube (Test KM-3) and a control rod (Test KM-4) from core position C08-01 was also conducted after 300 EFPD. The detailed examination of these two components in the Gulf General Atomic hot cell is the subject of this report.

CORE POSITION, DESCRIPTION, AND HISTORY OF C08-01

Core position C08-01 was in a high-temperature region of the core in control rod ring 2, as shown in Fig. 1. The control rod guide tube was a hollow tube of HLM-85 graphite and contained a thermally released shutdown rod in its upper section. The guide tube lower section contained the control rod. The control rod was fully inserted in the guide tube during the 300 EFPD. The guide tube and control rod were Type 4A, a designation which indicated that the boron content of the absorbers was 30 wt %, the position of the thermally released absorber after release was at the bottom of the core, and the control rod was on the same duty cycle as two other rods (A08-01, E08-01).

During normal operation about 200 lb/hr of helium from the coolant stream was made to pass up the center of the guide tube around the control rod and out a vent at the top. About 0.8% of the helium flowing through the guide tube came directly from the purification system.

On December 30, 1968, the control rod guide tube was removed from the core and canned for shipment. It was shipped to Gulf General Atomic on October 29, 1969.

The control rod was removed from the core on January 2, 1969, and shipped to Gulf General Atomic, arriving on May 22, 1969.

Examination of the control rod at GGA started August 21, 1969. Examination of the guide tube started January 15, 1970.

- 804 FUEL ELEMENTS
- 36 CONTROL RODS
- ⊗ 19 EMERGENCY CONTROL RODS

REGION 1	REGION 2	REGION 3
• 54 HEAVY RHODIUM ELEMENTS	• 588 LIGHT RHODIUM ELEMENTS ⊙ 60 LIGHT RHODIUM ELEMENTS WITH POISONED SPINES	• 102 LIGHT URANIUM HEAVY THORIUM ELEMENTS

LC22754

Fig. 1. Fuel element and control rod positions in the Peach Bottom HTGR. The position of control rod C08-01 is circled for identification.

EXAMINATION OF CONTROL ROD C08-01, TEST KM-4

INITIAL OBSERVATIONS

As received in the GGA hot cell, the aluminum shipping canister containing control rod C08-01 was dented in several places but no penetrations were observed. Before the shipping canister was opened an attempt was made to measure the gamma radioactivity along the length of the control rod (gamma scan). The weight of the canister and contents exceeded the capacity of the scanning facility, and the desired constant speed translation of the assembly past the gamma scanning device was not possible. Attempts to gamma scan were then abandoned (the facility has since been upgraded to handle similar loads).

The ends were cut from the aluminum canister and it was slit longitudinally at two 180° positions. A solid steel billet about 4 in. in diam and 2 ft long, filling the space between the canister end and control rod bottom connector, was removed from the canister. The two halves of the canister and a rod and rib centering device were removed from around the control rod. (Note for future operations: the removal operation would be facilitated if the axial parting line of the control rod centering device were marked on the outside of the canister. Axial cuts in the canister could be made to coincide with the parting line.)

A schematic drawing of an assembled control rod is shown in Fig. 2, and a collage of photographs of the rod is shown in Fig. 3. Comparison with detailed design drawings and the observations of personnel who assembled the Peach Bottom HTGR control rods at GGA indicated that the overall appearance of control rod C08-01 was unchanged after 300 EFPD except for a thin black deposit on all metallic components. The dust film was easily removed by rubbing with a paper tissue, but the metal substrate retained a dark brown-black color. No signs of wear or deposits other than those previously mentioned were visible.

Fig. 2. Peach Bottom HTGR control rod assembly showing components referenced in dissassembly procedure

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Fig. 3. Control rod C08-01 after 300 EFPD (a collage of nine photographs). The variation in shades of color were an artifact of the photography; the absorbers were uniformly black. White chalk lines were drawn along the length of the rod to maintain orientation.

The rider rings (see Fig. 2) showed no signs of wear or damage. In fact, the circumferential machine tool marks were still visible. The rings were loose fitting on the stainless steel weldment and could be easily rotated.

With one exception the disk springs were undistorted, with about equal compression at each end of the absorbers. The lower disk springs normally carrying the weight of absorber 6 (Fig. 2) were compressed, but the upper springs had expanded and kept the absorber in compression and centered on the rod. The disk springs of the top absorber (6) were fully compressed in the hot cell several times during disassembly without damage.

The boronated graphite neutron absorbers had the same texture and color as unirradiated absorbers. There was no indication of cracks, swelling, or other distortion in the absorbers.

CONTROL ROD DISASSEMBLY

Disassembly was first attempted by driving a wedge between the stainless steel washer and spacer at the top of absorber 6 (Fig. 2) and cutting the exposed stainless steel spider with a circular cutoff saw. It was possible to compress the springs sufficiently to allow the saw to pass between the spacer and the washer, but difficulty was experienced in keeping the wedges in place during the cutting operation. During repeated attempts to hold the disk springs in compression with wedges, a portion (about one-half the circumference, 1 in. long) of the wall of absorber 6 was broken away at the top of the absorber. This procedure was therefore abandoned.

The first complete cut through the control rod was made through the graphite rider ring, stainless steel spacer, and spider, adjacent to the washer at the top of absorber 6 (Fig. 2). This procedure removed a portion of the graphite rider ring equal in width to the saw cut. After the first cut through the rod, the remnant of the spacer adjacent to the washer was easily removed and the washers, disk springs, absorber 6, and rider ring 6

were slid off the control rod weldment. A saw cut was then made through the spacer and spider (the graphite rider ring 6 had been removed) adjacent to the upper washer of absorber 5. The procedure outlined above was repeated until all absorbers, disk springs, rider rings, and spacers were removed.

EXAMINATION OF CONTROL ROD COMPONENTS

Stainless Steel Weldment

The 304 stainless steel weldment consisted of the bottom connector, spine, continuity wire, spiders, and spacers. The surfaces of these components were dark brown or black, with original machine and tooling marks plainly visible. There were no signs of wear or deposits other than a thin layer of dust on some surfaces. The gas exit ports at the top of the rod, as shown in Fig. 4, were specifically examined for deposits of foreign material. The electrical connectors of the continuity wire in the latch end of the rod were examined and they appeared to be clean and undamaged, as shown in Fig. 5. The continuity wire was a single strand of 0.0319-in.-diam nickel wire with MgO insulation in a 1/8-in.-o.d. 304 stainless steel sheath. It was welded along the length of the weldment so that a disruption of the weldment would cause the wire to break, with consequent loss of electrical continuity. In this manner the continuity wire monitored the physical condition of the rod.

Rider Rings

The seven rider rings were made of HLM-85 graphite and were positioned at the ends of and between the six neutron absorbers. They had the largest o.d. of the control rod components and, with a nominal diametral clearance of 0.055 in. between the spring and guide tube inner wall, they served to keep the control rod centered in the guide tube. No distortion or wear was observed in the rider rings. In fact, the original circumferential machine tool marks were visible on the outer surface, as shown in Fig. 6. Measurements were made of several of the rider rings; the dimensions (shown in Table 1) were within original design tolerances.

K286-53

Fig. 4. Top end fitting, rider ring, disk springs, and a portion of absorber 6 of control rod C08-01. White marks are chalk reference marks. Note that gas exit ports in top end fitting are clean.

K286-78

Fig. 5. View into bottom connector of control rod support weldment showing electrical connections of continuity wire. Connections were clean and undamaged.

K286-48

Fig. 6. Typical graphite rider ring between two boronated graphite absorbers with disk springs. No signs of wear were visible after 300 EFPD. Note circumferential machine marks visible on rider ring o.d. White mark on absorber is chalk identification mark.

TABLE 1
 DIMENSIONS OF SELECTED GRAPHITE RIDER RINGS OF CONTROL
 ROD C08-01 AFTER 300 EFPD^(a)

Position	Outside Diam (in. $\pm$ 0.001)	Wall Thickness (in. $\pm$ 0.001)	Length (in. $\pm$ 0.001)
Bottom of absorber 1	2.445	0.213	0.621
Between absorbers 1 and 2	2.445	0.215	0.619
Between absorbers 2 and 3	2.445	0.215	0.617
Between absorbers 4 and 5	2.445	0.214	Not determined
Between absorbers 5 and 6	2.445	0.215	Not determined

(a) Manufactured dimensions and tolerances:

o.d. = 2.445 ± 0.002 in.

i.d. = 2.015 ± 0.005 in.

Length = 0.620 ± 0.005 in.

Washers

The stainless steel washers slid over the spider and were positioned on either side of the stainless steel spacers between each absorber. They served to hold the graphite rider ring on the spacer. The washers had a dark ring of discoloration or deposit on surfaces adjacent to the interface between the rider ring and spacer. An example of this effect is shown in Fig. 7.

Disk Springs

The disk springs were located at the top and bottom of each absorber. They serve to keep the absorber positioned between the spacers but allow the absorber to change axial dimensions relative to the weldment during thermal cycles and irradiation without excessive compressive loads on the absorber. Each disk spring was made up of 7 disks shaped to form a spring when assembled, as shown in the cross section in Fig. 2. The disks were made of Haynes Alloy 25, which contains about 55% cobalt. The radioactivity of the disk springs was relatively high. Single disks from the center of the rod (number 6), the top of the rod (number 12), and the bottom of the rod had gamma activities of 200 R at 24 in., 200 R at 18 in., and 250 R at 6 in., respectively.

During disassembly the disk springs at the top of absorber 6 cracked radially in a nonductile fashion when a wedge was driven between the disks and rotated to facilitate removal. This indicated some mechanical degradation of the disk springs.

A qualitative indication of the effect of 300 EFPD exposure on the mechanical properties of the disk springs was obtained by holding the individual disks with a manipulator and bending about 90°. The results of that work, summarized in Table 2, showed that the disks that operated at the top of the rod in the high-temperature high neutron exposure region showed the greatest degradation in properties. At the bottom of the rod the disks did not crack and could be bent only 45° under the force available with the remote manipulators. Some of the bent and broken disks are shown in Fig. 8. The embrittlement of the disk springs is not expected to impair their function of positioning the absorbers and accommodating relative axial dimensional changes between the absorber and weldment throughout the service lifetime of the control rod.

K286-65

Fig. 7. Washer (bottom), rider ring (left), support ring (top), and disk spring (right) from bottom of absorber 4. Dark ring on washer near outer radius coincides with i.d. of rider ring that was adjacent during service.

TABLE 2
RESULTS OF BENDING TESTS ON SELECTED DISK SPRINGS OF CONTROL
ROD C08-01 AFTER 300 EFPD^(a)

Position of Disk Spring	Remarks
Bottom of absorber 1	Could be bent only ~45° with available manipulator force. No break or cracking observed.
Top of absorber 3	Could be bent only ~60° with available manipulator force. Crack at bend on tensile surface.
Bottom of absorber 4	~90° bend; crack on tensile surface at bend.
Top of absorber 4	Brittle fracture one side; ~90° bend with crack on tensile surface on other side.
Top of absorber 6	Broke in brittle fashion with no permanent deformation.

(a) Individual disks were clamped and held across the diameter and a 90° bend at the diameter was attempted with remote manipulators.

K286-61

(a)

K286-68

(b)

Fig. 8. Disk springs from control rod after 300 EFPD bent under similar conditions with remote manipulators: (a) disk spring from top of absorber 4 (1300°F, 1.1×10^{21} n/cm², $E > 0.18$ MeV); (b) disk spring from top of absorber 3 (1250°F, 1.2×10^{21} n/cm², $E > 0.18$ MeV)

Support Rings

The support rings were made of 304 stainless steel and concave shaped to accept the ends of the boronated graphite neutron absorber. The support rings fit closely on the spider and held the absorber centered axially on the control rod. The support rings were covered with a 0.0005-in.-thick copper plate to prevent carbonization of the steel in contact with the boronated graphite.

The copper plate was visible on the surfaces in contact with absorber 1, which had operated at inlet temperature. There were also radial fan-shaped regions of dark discoloration on the inner surface of this ring at positions corresponding with the grooves in the spider containing the continuity wires. An example of this effect is shown in Fig. 9. The support rings of the other absorbers were black, but there was no evidence of spalling or flaking of deposits. Examples are shown in Fig. 9.

When the rings from the top and bottom of the rod were compressed in a remote manipulator across the diameter under an estimated force of 150 to 200 lb, some elastic deformation was noted. No permanent deformation or cracking was observed.

The gamma radioactivities of single support rings from the bottom, middle, and top of the control rod were 2 R, 70 R, and 25 R, respectively, at a distance of 2 in.

Boronated Graphite Absorbers

Fabrication. The boronated graphite neutron absorbers were extruded as tubes from a mixture of graphite flour, coal tar pitch, and B_4C granules (100% < 100 mesh, 5% < 325 mesh). The extrusions were baked in nitrogen at a maximum temperature of 2200°C for 30 min. After baking, about 0.050 in. of material was machined from the inner and outer surfaces with diamond-tipped tools to the final dimensions of 2.310 in. o.d. x 1.310 in. i.d. x 16.879 in. long. No coolant was used during the machining operation.

K286-73

(a)

K286-54

(b)

Fig. 9. Copper plated stainless steel support rings: (a) from absorber 1, showing black deposits on inside surface adjacent to continuity wire penetration, copper color elsewhere on inside surface; (b) from absorber 6, showing overall black appearance, no copper color

The chemical composition of the absorbers as fabricated is given in Table 3. The rather high nitrogen content (3 wt %) probably resulted from conversion of some B_4C to BN during the 2200°C bake under a protective nitrogen purge gas.

Appearance after Irradiation. The irradiated absorbers were black and had the texture and appearance of as-manufactured absorbers. No damage or changes due to irradiation were detected. A photograph of a typical absorber after 300 EFPD is shown in Fig. 10.

Microstructure. The microstructures of an unirradiated specimen taken from storage and an irradiated boronated graphite specimen removed from the middle of absorber 4 are shown in Fig. 11. The most significant difference between the two microstructures is the fracture pattern exhibited within a single B_4C granule on the outer surface of the irradiated absorber. Similar crack patterns have been observed in B_4C granules after high B-10 burnup in boronated graphite irradiation experiments (Ref. 2). The intergranular crack pattern is probably an indication of high B-10 burnup. The B-10 burnup causes anisotropic dimensional changes (Refs. 3, 4) and helium and lithium generation within the B_4C granule from the $B-10(n,\alpha)Li-7$ reaction. The B_4C granules on the inner surface and in the middle of the absorber tube wall did not exhibit the crack pattern.

B-10 Burnup Profile. A gradient in B-10 depletion was developed in the absorber wall during irradiation because most of the thermal neutrons were absorbed by B-10 within 0.1 in. of the surface. The profile of B-10 isotope depletion was determined by B-10 and B-11 isotopic analysis of powder samples abraded from selected radial positions in sections taken from the middle of absorbers 1, 4, 5, and 6. The location of samples in the wall section is shown in Fig. 12.

It was noted that during the filing of powder samples from the wall segments with steel files the material in absorbers 4 and 5 was much harder than that in absorbers 1 and 6. This observation is probably

TABLE 3
CHEMICAL COMPOSITION OF BORONATED GRAPHITE ABSORBERS

Boron, wt %	30 ± 4 ^(a)
Nitrogen, wt %	3
Iron, ppm	>1000
Barium, ppm	10
Manganese, ppm	80
Vanadium, ppm	100
Copper, ppm	20
Magnesium, ppm	10
Chromium, ppm	20
Titanium, ppm	400
Calcium, ppm	1000
Zirconium, ppm	200
Silicon, ppm	1000
Tungsten, ppm	1000
Nickel, ppm	200
Niobium, ppm.	100
Molybdenum, ppm	20
Cobalt, ppm	>1000

(a) Approximately 0.3 wt % boron was present as B₂O₃.

K286-84

Fig. 10. Typical boronated graphite neutron absorber from control rod C08-01 after 300 EFPD. Note: Absorber was uniformly black; uneven shading in photograph was due to in-cell lighting effects.

M23756-01

(a)

(100x)

M286-1

(b)

(100x)

Fig. 11. Microstructure of boronated graphite absorbers (B_4C granules dispersed in graphite matrix): (a) unirradiated (extrusion direction horizontal), (b) irradiated 300 EFPD in position C08-01, absorber 4 ($1300^\circ F$, $1.2 \times 10^{21} \text{ n/cm}^2$, $E > 0.18 \text{ MeV}$). Outer edge shown; B_{10} burnup $\sim 30\%$ (extrusion direction perpendicular to page)

M286-4

(c)

(500x)

M286-3

(d)

(500x)

Fig. 11. Microstructure of boronated graphite absorbers (B_4C granules dispersed in graphite matrix) after 300 EFPD in position C08-01, absorber 4: (c) porous microstructure such as shown here is common even in unirradiated B_4C ; (d) the transgranular cracks shown here are observed in B_4C at high B-10 burnup

Fig. 12. Location of powder samples taken from boronated graphite absorbers for lithium, boron, and B-10 - B-11 isotopic analysis

associated with the reported increase in strength, hardness, and elastic modulus of graphite with fast neutron exposure (Refs. 5, 6).

The B-10 - B-11 isotopic analysis of aliquots of each powder sample was performed at AVCO Laboratories in Tulsa, Oklahoma. Results of that work are shown in Fig. 13 as profiles of B-10 burnup and the absorber wall thickness.

Aliquots of the isotopic analysis samples were also analyzed for lithium content at GGA. The lithium content followed the same relative profile as the B-10 burnup gradients, as shown in Fig. 14. The amount of lithium detected indicated that essentially all of the lithium generated by B-10 fission remained in the vicinity of the original B-10 atom.

The total boron profile was also determined from aliquots of the isotopic samples for absorber 1. Those results are shown in Fig. 15. No consistent trend is indicated, probably because the total boron depletion was relatively low. There has been no evidence of significant boron transport in boronated graphite under similar service conditions (Ref. 2).

Dimensional Change. The inside and outside diameters and the length of the boronated graphite absorbers were measured remotely in the hot cell with the dial indicator devices shown in Fig. 16. The o.d. was measured at 120° intervals around the circumference at both ends and the middle of each absorber. The i.d. was measured at 120° intervals only at the two ends. The length was measured at 120° intervals around the circumference. The accuracy of the measurements was ± 0.001 in. The original unirradiated absorber elements were 2.310 in. o.d. x 1.310 in. i.d. x 16.879 in. long. The o.d. and length were machined to a ± 0.005 -in. tolerance; the i.d. of the extrusion had a much greater tolerance, i.e., -0.005, +0.025 in.

The o.d. and i.d. of the irradiated absorbers taken from control rod C08-01 were within the stated tolerances, but the lengths were 0.010 to 0.048 in. less than the nominal manufactured dimension. The average for each dimension measured is shown in Table 4.

Fig. 13. B-10 isotope burnup gradient across the wall of neutron absorbers after 300 EFPD in Peach Bottom HTGR core position C08-01

Fig. 14. Lithium distribution across wall of neutron absorbers after 300 EFPD in position C08-01. The lithium was generated by $B-10(n,\alpha)Li-7$ reaction, and concentrations measured indicate no significant lithium migration after creation.

Fig. 15. Total boron content across wall of neutron absorber 1 after 300 EFPD in position C08-01. No consistent trend was indicated. Measured values are within normal scatter from sample to sample of this material.

HC286-6

(a)

HC286-9

(b)

Fig. 16. Dial indicator measuring device for measuring inside diameter of absorber: (a) without absorber in place, and (b) with absorber in place

HC286-15

(c)

Fig. 16. (c) Dial indicator measuring devices for measuring length and outside diameter of neutron absorbers

TABLE 4

DIMENSIONS OF BORONATED GRAPHITE ABSORBERS OF CONTROL ROD C08-01 AFTER 300 EFPD

Absorber Number	Outside Diam ^(a)	Inside Diam ^(b)	Length		Average Fast Neutron Fluence at Absorber Midplane (E > 0.18 MeV) (n/cm ²)
			Measured Length ^(c) (in.)	Change from Nominal Length (16.879 in.) (%)	
1	2.314 ± 0.002	1.317 ± 0.002	16.881 ± 0.001	(d)	0.05 x 10 ²¹
2	2.313 ± 0.002	1.320 ± 0.011	16.862 ± 0.002	-0.10	0.70 x 10 ²¹
3	2.309 ± 0.003	1.318 ± 0.002	16.845 ± 0.002	-0.20	1.20 x 10 ²¹
4	2.307 ± 0.003	1.325 ± 0.004	16.831 ± 0.001	-0.28	1.20 x 10 ²¹
5	2.306 + 0.005 - 0.003	1.320 ± 0.003	16.849 ± 0.004	-0.18	1.00 x 10 ²¹
6	2.312 ± 0.002	1.332 ± 0.008	16.869 ± 0.001	-0.06	0.60 x 10 ²¹

(a) Within manufactured dimension and tolerance of 2.310 ± 0.005 in.; average and range of values measured at top, middle, and bottom of absorber at 90° intervals on the circumference.

(b) Average and range of values measured at top and bottom of absorber at 90° intervals on the circumference. Manufactured dimension and tolerance 1.310 (+0.025, -0.005) in.

(c) Average and range of values measured at 120° intervals around the circumference.

(d) Within manufactured dimension and tolerance of 16.879 ± 0.005 in.

The reduction in absorber length was ascribed to irradiation-induced shrinkage in the extrusion direction. The maximum shrinkage corresponded with the core center and a fast neutron exposure of about $1.2 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$). The calculated temperature and fast neutron exposure profile along the control rod axis is shown in Fig. 17. The maximum thermal neutron exposure was $3.1 \times 10^{19} \text{ n/cm}^2$ ($E < 2.38 \text{ eV}$) near the center of the core with an average of $2.6 \times 10^{19} \text{ n/cm}^2$ ($E < 2.38 \text{ eV}$) for the entire control rod.

Irradiation of small (0.2 in. x 0.4 in. x 0.6 in.) samples of this material in earlier work to neutron exposures of 2.0 to $2.5 \times 10^{21} \text{ n/cm}^2$ ($E > 0.18 \text{ MeV}$) at about 1100°F resulted in length shrinkage up to 0.52% (Ref. 2). Such dimensional change is consistent with the changes observed in full-sized absorbers assuming dimensional change is approximately linear with neutron dose at these exposures. The length changes parallel to the extrusion direction for full-sized absorbers and the smaller specimens reported in the literature are shown in Fig. 18. A straight line representing a least squares fit of the data was drawn through the data points. The fact that the data from the full-sized absorber could be correlated on the basis of fast neutron exposure with data from small specimens with much higher B-10 burnup (40 to 90%) is consistent with the previous work (Ref. 2). Apparently B-10 burnup does not strongly influence dimensional change in this material.

Since the diametral dimensions were within the original machined tolerances, no conclusion regarding dimensional change could be made for the diameter. However, data reported in Ref. 2 suggested that the irradiation-induced dimensional change of the boronated graphite was anisotropic. During irradiation the material tends to expand perpendicular to the extrusion direction (radial) and contract in the parallel direction (axial). Furthermore, the coefficient of thermal expansion measured on unirradiated material cut with axes parallel to the three primary directions indicated that the thermal expansion, and hence the irradiation-induced dimensional change rate in the tangential direction, was intermediate between that in the perpendicular and parallel directions. The coefficient of thermal expansion data are shown in Table 5. Such anisotropic properties might give rise to significant stress and strain in the absorber wall as irradiation progressed.

Fig. 17. Neutron absorber material operating temperature and neutron exposure profile after 300 EFPD in Peach Bottom HTGR core position C08-01

Fig. 18. Irradiation-induced length change in Peach Bottom HTGR control rod absorbers

TABLE 5
 MEAN COEFFICIENT OF THERMAL EXPANSION
 OF UNIRRADIATED CYLINDRICAL BORONATED GRAPHITE ABSORBERS
 IN THREE PRINCIPAL DIRECTIONS BETWEEN 22° AND 1000°C^(a)

Direction	Coefficient of Thermal Expansion (b) (°C) ⁻¹
Tangential	5.46×10^{-6}
Radial	6.25×10^{-6}
Longitudinal	5.10×10^{-6}

(a) Specimen size: 0.5 in. diam x 0.5 in. long. Expansion measured in a helium-purged quartz dilatometer.

(b) Average of two specimens, one run each.

To predict the magnitude of the stress and strain that might develop during irradiation, a mathematical model of the absorber cylinder was created and an analysis of the model was conducted (Ref. 7). In the interest of completeness, a summary of the analysis has been taken nearly verbatim from the original report and is presented in the following section.

The Mathematical Model (Ref. 7). The analysis accounts for stresses arising from anisotropic thermal expansion and anisotropic, irradiation-induced dimensional changes and for stress relaxation from irradiation-induced creep. The thick-walled cylinder was assumed to be homogeneous (i.e., the mechanical effects of B_4C inclusions are ignored) and orthotropic (i.e., the property axes of symmetry were orthogonal and, in this case, coincident with the principal axes of the cylinder and the axes of cylindrical coordinates). A uniform temperature distribution was assumed. The ends were free and it was assumed that the center was sufficiently far away from the ends (~ 3.7 outside diameters) so that stresses near the center were not influenced by end effects (this is the condition of generalized plane-strain). It was assumed that Hooke's law, a linear creep law, and the condition of static equilibrium applied. It was also assumed that the elastic properties were isotropic. These conditions and assumptions, combined with the condition of strain compatibility, yield total integro-differential equations between stress and both r (radial position) and γ (fast-neutron fluence) when displacements in the cylinder are small compared to its dimensions. The equations were set up and solutions derived. The results were as follows (see Table 6 for nomenclature).

In the tangential direction,

$$\sigma_{\theta} = \frac{1}{2} h_1(x) \left(1 + \ln \frac{r}{a} - \frac{1 + a^2/r^2}{1 - a^2/b^2} \ln \frac{b}{a} \right),$$

in the radial direction,

$$\sigma_r = -\frac{1}{2} h_1(x) \left(\frac{1 - a^2/r^2}{1 - a^2/b^2} \ln \frac{r}{a} \right),$$

TABLE 6
NOMENCLATURE FOR MATHEMATICAL MODEL

a	= inner radius
b	= outer radius
E	= Young's modulus
K	= creep constant
r, θ, z	= cylindrical coordinates
T	= operating temperature
T_f	= temperature at which cylinder is formed (i.e., is stress-free)
α	= coefficient of linear thermal expansion
γ	= fast-neutron fluence (energy > 0.18 MeV)
η	= fractional irradiation-induced dimensional change
ν	= Poisson's ratio
ν_c	= "Poisson's ratio in creep" (Ref. 8)
σ	= stress

and in the longitudinal direction,

$$\sigma_z = \frac{1}{2} h_2(x) \left(1 + 2 \ln \frac{r}{a} - \frac{2 \ln (b/a)}{1 - a^2/b^2} \right),$$

where

$$h_1(x) = f(x) + \frac{m_1}{2} (1 + \nu) e^{m_1 x} \int_0^x f(x) e^{-m_1 x} dx$$

$$+ \frac{m_2}{2} (1 - \nu) e^{m_2 x} \int_0^x f(x) e^{-m_2 x} dx ,$$

$$h_2(x) = \nu f(x) + \frac{m_1}{2} (1 + \nu) e^{m_1 x} \int_0^x f(x) e^{-m_1 x} dx$$

$$- \frac{m_2}{2} (1 - \nu) e^{m_2 x} \int_0^x f(x) e^{-m_2 x} dx ,$$

$$m_1 = - \frac{1 - \nu_c}{1 - \nu} , \quad m_2 = - \frac{1 + \nu_c}{1 + \nu} ,$$

$$f(x) = \frac{E}{1 - \nu^2} [(\alpha_r - \alpha_\theta)(T - T_f) + \eta_r - \eta_\theta] ,$$

and $x = KE\gamma$.

The analysis for stress in terms of r was similar to a large group of analyses of stresses due to the imposition of distorting, inelastic strains such as thermal strains (c.f. Chapter 14 of Ref. 9). Similar problems have been analyzed for the case where creep occurs. The solution for stress

in terms of time typically involves approximate calculation methods such as finite-element methods (Refs. 10, 11) relaxation and effective modulus methods (Ref. 12), and trial-and-error methods (Ref. 13). However, the assumption of a linear creep law allows the explicit solution to be made.

A computer code was written for the purpose of performing calculations of stress and strain without the above requirement for small displacements. The code employed a trial-and-error calculation method whereby stresses and total strains were allowed to accumulate in small increments. During each increment in time, an iterative scheme was employed in which the geometry of the cylinder was continually updated in accordance with calculated strain until strain converged.

Results of Analysis. The dimensions and materials properties shown in Table 7 were used as input data for the computer program, and the stresses and strains were computed as a function of fast neutron exposure. The predicted dimensional changes of both the o.d. and i.d. of the absorbers beyond the end of life exposure (4.2×10^{21} n/cm²; $E > 0.18$ MeV) are shown in Fig. 19. These displacement results were independent of the value of elastic modulus or creep constant but directly proportional to the difference between radial and tangential irradiation-induced dimensional change rate. The outer diameter does not change dimensions significantly but the inner diameter tends to shrink and narrow the gap between the absorber and the stainless steel spider. The predicted shrinkage of the i.d. was about 0.75% at 4.2×10^{21} n/cm² ($E > 0.18$ MeV) or about 0.010 in. The minimum design diametral gap was 0.033 in. so that the predicted shrinkage does not present an interference problem.

The calculated stresses in the absorber wall in the as-fabricated condition at operating temperature showed a maximum tensile stress at the inner surface and a maximum compressive stress at the outer surface. These stresses resulted from the effects of anisotropic thermal expansion coefficients in the three principal directions during cooldown from the original baking temperature (2200°C). The effects of irradiation tended to cancel the

TABLE 7
BORONATED GRAPHITE DIMENSIONS,
PROPERTIES, AND OPERATING CONDITIONS

Dimensions and Properties

Inner radius	0.655 in.
Outer radius	1.155 in.
Length	17 in.
Poisson's ratio	0.2
Poisson's ratio in creep	0.4
Young's modulus	0.7×10^6 psi
Modulus of rupture	3800 psi
Compressive strength	5460 psi
Creep constant	0.9×10^{-27} (psi n/cm ²) ⁻¹
Irradiation-induced fractional- dimensional-change rate	
Tangential direction	-0.00068 (10 ²¹ n/cm ²) ⁻¹
Radial direction	+0.00288 (10 ²¹ n/cm ²) ⁻¹
Longitudinal direction	-0.00230 (10 ²¹ n/cm ²) ⁻¹
Coefficient of thermal expansion	
Tangential direction	5.46×10^{-6} (°C) ⁻¹
Radial direction	6.25×10^{-6} (°C) ⁻¹
Longitudinal direction	5.10×10^{-6} (°C) ⁻¹

Operating Conditions

Temperature of formation	2200°C
Temperature of operation	600°C
Fast-neutron fluence	6×10^{21} n/cm ²

Fig. 19. Predicted irradiation-induced dimensional change of inner and outer diameter of boronated graphite absorbers

thermal effects so that as fast neutron exposure increased, the sign of the stresses at the inner and outer surfaces was reversed.

By means of a parametric study of the effect of variations in elastic modulus and creep constant, it was shown that the maximum stresses are relatively insensitive to the value of elastic modulus when a realistic creep constant was assumed [0.7×10^{-27} to 0.9×10^{-27} (psi n/cm²)⁻¹]. When a creep constant of zero was assumed, the stresses were directly proportional to elastic modulus.

Some mechanical property data for the boronated graphite existed in the literature⁽²⁾ but additional data were desirable to improve confidence in predicted performance. Therefore, crush strength and flexible strength (modulus of rupture) were determined on samples cut from an unirradiated absorber, and the results are shown in Tables 8 and 9. The elastic moduli determined from the modulus of rupture determinations were about a factor of 2 greater than used in the parametric study discussed above, but the bending (modulus of rupture) and compressive strength were similar to the values assumed in Table 7. Details of the mechanical property measurements are discussed in the Appendix.

The mechanical properties reported in Tables 8 and 9 were used in conjunction with the analytical model, and the maximum stresses at the inner and outer surfaces of a control rod absorber were calculated for end-of-life conditions, as shown in Table 10. The predicted stresses are well below the maximum measured stress, and no mechanical damage is expected during the design lifetime of the absorber.

TABLE 8

RESULTS OF FLEXURE TESTS OF UNIRRADIATED BORONATED
GRAPHITE ABSORBER MATERIAL (30 WT % BORON)

Specimen Total Length of Span (in.) ^(a)	Average ^(b) and Range of Modulus of Rupture (psi)	Average ^(b) and Range of Elastic Modulus (psi x 10 ⁶)
5.7	3845 +235 -292	1.49 +0.33 -0.10
2.6	3820 +124 -303	1.09 +0.09 -0.04

(a) Diameter 0.43 in.

(b) Six determinations.

TABLE 9

RESULTS OF COMPRESSION TESTS OF UNIRRADIATED BORONATED
GRAPHITE ABSORBER (30 WT % BORON)^(a)

Direction in Extruded Cylinder	Average ^(b) and Range of Crush Strength (psi)
Tangential	5500 ± 190
Radial	5440 ± 64
Longitudinal	5715 ± 7

(a) Specimen size: 0.5 in. diam, 0.5 in. long.

(b) Two determinations.

TABLE 10

COMPARISON OF MAXIMUM STRESS IN BORONATED GRAPHITE CONTROL
ROD ABSORBERS AT END-OF-LIFE EXPOSURE (4.2×10^{21} n/cm²;
E > 0.18 MeV) AND MEASURED STRENGTH OF MATERIAL

Surface	Predicted Stress (psi)	Percent of Measured Strength
Outer	1083 tensile	28 ^(a)
Inner	1584 compressive	29 ^(b)

(a) Tensile strength assumed equal to modulus of rupture (3800 psi).
Elastic modulus 1.4×10^6 psi.(b) Tangential compressive strength (5500 psi) assumed. Elastic modulus
 1.4×10^6 psi.

EXAMINATION OF CONTROL ROD GUIDE TUBE C08-01, TEST KM-3

INITIAL OBSERVATIONS

The guide tube was received in an aluminum shipping container. A gamma scan of the sealed container in the hot cell showed only background activity except for a few inches along the length about 3 ft from one end. The activity in this area was more than 100 times background and was later found to correspond with the position of the Hastelloy-X (1.5% Co) snubber of the thermally released shutdown rod.

The ends were cut off the can and the sides were slit longitudinally at 180° intervals on the circumference. A steel spacer, with what appeared to be asbestos padding, and the aluminum can were removed from around the guide tube.

The exterior of the guide tube showed no effects from the reactor exposure except for spots on the outer surface which had been worn smooth by contact between the guide tube and the standoff rings on adjacent fuel elements. Around the points of contact there was a thin deposit of black powder. A collage of photographs of the guide tube is shown in Fig. 20.

CONTROL ROD GUIDE TUBE DIMENSIONS

The o.d. of the upper and lower guide tube measured at 12-in. intervals was within the design dimension and tolerance of 3.545 ± 0.002 in. The upper tube end was also within manufactured dimension and tolerance of 3.558 ± 0.002 in. The overall length was $147\frac{1}{16}$ in., which was within the manufactured tolerance of $147 \pm \frac{7}{64}$ in. Six contact spots equally spaced around the o.d. were visible on the surface of the guide tube at $57\frac{5}{8}$ in., $95\frac{7}{16}$ in., and $142\frac{11}{16}$ in. above the bottom end of the tube where the fuel elements made

K82892

Fig. 20. Control rod guide tube C08-01 after 300 EFPD (collage of six photographs). Inset section shows contact spots at axial position on tube which was covered by support during collage photography

contact with the guide tube. Wear at the contact spots was undetectable by micrometer and was estimated as less than 0.001 in. surface recession. A photograph of a typical contact spot is shown in Fig. 21. The dark, soot-like deposit around each wear spot was very adherent and appeared to outline regions where the axial coolant flow was disrupted by the contact between fuel elements and the guide tube.

The axial bow in the guide tube was determined by first supporting the tube on vee roller supports at positions 28 to 31 in. in from each end, as shown in Fig. 22. A dial indicator micrometer with a 3/4-in.-diam flat foot was then passed along the side of the tube 90° around the circumference from a vertical line across the tube diameter. The effect of gravity on the bow of the tube was minimized by this technique. The track along which the micrometer traveled was parallel with a straight line through the vee supports to within ± 0.001 in. as determined by transit. Measurements were repeatable within ± 0.002 in.

Bow was measured along the side of the tube in line with the locking lug and also 90° clockwise (bottom view) from that position. The results of the measurements are shown in Fig. 22.

The maximum axial bow in the guide tube assembly was determined to be 0.122 in. about 6 ft from the bottom end. The bow in the lower guide tube was 0.075 in. At 90° around the circumference the maximum axial bow in the lower guide tube was 0.032 in. 8 ft from the bottom of the tube. There was no specified maximum bow for the guide tube assembly but the maximum design tolerance for bow in the lower guide tube was 0.060 in., so it is possible that some permanent bow of the guide tube took place in the reactor. With the assumption that the tube was initially straight, the amount of bow observed could have been caused by a diametral fast neutron flux gradient of about 1.5% (Ref. 14). It is conceivable that gradients of at least that magnitude existed in the reactor with the flux increasing across the tube diameter toward the outside diameter of the core (Ref. 15). The locking lug was located on the side of the tube facing the outside of the core but rotated 30° away from the core radius passing through the tube.

K303-4

Fig. 21. Upper tube cap of control rod guide tube after 300 EFPD showing black deposit at point of contact with adjacent fuel element. Six similar areas were equally spaced around circumference of rod at $57\text{-}5/8$ in., $95\text{-}7/16$ in., and $142\text{-}11/16$ in. above bottom end.

Fig. 22. Bow measurement in control rod guide tube C08-01 after 300 EFPD. Measurements are given relative to position of guide tube shown in schematic drawing at top.

The center of curvature of the bow in the tube was toward the outside of the core. The observed bow direction was consistent with a predicted higher fast neutron exposure and consequent accelerated contraction in the tube wall facing the core o.d. Restraint in the core, creep in the graphite, and a more constant rate of irradiation-induced dimensional change beyond 300 EFPD will tend to minimize stress and additional bow so that significant additional guide tube bow is not expected.

Guide Tube Disassembly

The guide tube was cut into six sections, as shown in Fig. 23, for further examination. The bottom two sections are shown in Fig. 24. The section containing the latching lugs showed no sign of wear or indication of malfunction. The other section in Fig. 24 was used in fission product release analysis, which was reported elsewhere (Ref. 16).

The central section (3 in Fig. 23) of the guide tube was slit longitudinally on opposing sides and the inside surface was examined. No wear or material deposits were observed on the inside surface. Figure 25 shows a typical example of the condition of the inner surface at the termination of the grooves machined into the inner guide tube walls to control the position of the thermally released shutdown rod in the core after activation.

The upper section of the guide tube contained the thermally released shutdown rod, which was disconnected by cutting through the stainless steel rod at the retaining nut in the tip of the guide tube. The thermally released shutdown rod was then removed by sliding it out the bottom of the tube. A photograph of the upper guide tube and the boronated graphite thermally released shutdown rod is shown in Fig. 26.

A 4-in.-long section was cut from the guide tube (5 in Fig. 23) and used for fission product analysis reported in Ref. 16. The remaining portion of the rod was slit longitudinally and examined. The inner surface showed no signs of wear or material deposits. A photograph of the opened upper guide tube and the tip of the guide tube is shown in Fig. 27. The threaded joint between the upper and lower guide tube visible in Fig. 27 showed no effects of irradiation. A high-magnification photograph of the joint cross section is shown in Fig. 28.

Fig. 23. Control rod guide tube and adjacent fuel elements showing location of radial cuts made in the guide tube

K303-24

Fig. 24. Sections 1 and 2 (see Fig. 23) cut from bottom portion of control rod guide tube C08-01. No damage or wear was detected in outer portion of guide tube

K303-33

Fig. 25. Inner surface of lower guide tube showing bottom of grooves cut in inner surface to guide thermally released shutdown rod and control its final position in core. No evidence of wear or damage was detected on inner surface of guide tube.

M32669-4

Fig. 26. Top portion of guide tube (left) with thermally released shutdown rod removed (right). Metallic components of shutdown rod were covered with thin, black deposit. No damage or unusual features were observed in boronated graphite absorber; however, graphite absorber support had radial crack (see Fig. 31).

M32669-1

Fig. 27. Inner surface of guide tube showing joint between upper and lower guide tube. Thermally released shutdown rod was held in smooth walled section. No damage or wear was detected.

K303-39

Fig. 28. Cross section of threaded joint between upper and lower guide tube. Locking pin and carbonaceous cement can be seen in joint. No irradiation effects were detected.

THERMALLY RELEASED SHUTDOWN ROD

The thermally released shutdown rod consisted of a boronated graphite absorber containing 30 wt % boron in the form of B_4C and held in the guide tube as shown in Fig. 29. An over-temperature condition would cause the absorber to be dropped into the core by gravity. The absorber would fall to a position in the core determined by the height of ledges on the inside surface of the guide tube which were contacted by the snubber. In the event that extreme temperature should cause the metal components to melt and drop out of the core, a graphite absorber support, positioned between the snubber and the absorber, would remain in the core and provide axial support for the absorber, as shown in Fig. 30.

The metal components of the thermally released shutdown rod assembly were covered with a thin, black adherent coating but otherwise appeared unchanged from the manufactured condition. The boronated graphite absorber also appeared unchanged, but the graphite (HLM-85) absorber support had a single radial crack, as shown in Fig. 31.

The fusible link (an alloy of 85% silver and 15% manganese) had a relatively thick, dark scale on the surface which could be easily scraped off. Otherwise, the link was unchanged from the manufactured condition. Photographs of the fusible link in place in the stainless steel weldment are shown in Fig. 32.

The release temperature for the thermally released shutdown rod was determined experimentally in the hot cell in a furnace apparatus shown in Figs. 33 and 34. The apparatus held the shutdown rod vertically in a helium-purged tube furnace while the fusible link and surrounding components were heated. Temperature was monitored by a millivolt potentiometer and a chromel-alumel thermocouple which was touching the stainless steel weldment within about 1/4 in. of the fusible link. The shutdown rod assembly could be heated slowly to the release temperature while the temperature of the link was continually measured. Upon release, there was an audible sound as the rod struck the bottom of the apparatus and the cooler portion of the rod

Fig. 29. Thermally released shutdown rod showing the absorber support and related components

LC83995

Fig. 30. Absorber support resting on the guide tube groove ledge (metal supporting parts assumed to have melted and run out of the core)

K303-29

Before test

K303-46

After test

Fig. 31. Lower portion of thermally released shutdown rod showing radial crack observed in HLM-85 graphite absorber support. The crack probably developed during reactor operation as a result of thermal expansion mismatch and inadequate gap between support and stainless steel weldment. No increase in damage took place during release test.

K303-23

(a)

K303-25

(b)

M32493-1

(c)

(4x)

Fig. 32. Fusible link in thermally released shutdown rod of guide tube: (a) overall view of link and lower portion of rod; (b) close view of link showing scratches in scale formed on link; (c) an unused link as cast from braze alloy (85% Ag-15% Mn).

M32669-2

Fig. 33. Furnace apparatus used to determine release temperature of thermally released shutdown rod. Unirradiated shutdown rod is at right with holding bracket attached. Unirradiated absorber was made of two sections having total length equal to that of rod in C08-01.

Fig. 34. Apparatus used to determine release temperature of thermally released shutdown rod of control rod guide tube C08-01 after 300 EFPD

fell into position around the thermocouple, causing the indicated temperature to drop rapidly. The maximum temperature prior to these events was taken as the release temperature.

Prior to heating the shutdown rod from C08-01, a complete, unirradiated, thermally released shutdown assembly weighing 5.9 lb was heated in the apparatus to 1743°F in 2-3/4 hr when release took place. The graphite absorber support cracked during the first heating in a manner similar to that illustrated in Fig. 31. A new fusible link was installed and the assembly was heated a second time. Release was achieved in 2-1/4 hr when the indicated temperature reached 1740°F. The results of these two experiments were in good agreement with the reported melting point of the fusible link, which was $1745^{\circ} \pm 3^{\circ}\text{F}$ (Ref. 17). From the results of the experiments and consideration of the experimental procedure, the accuracy of the temperature measurements was estimated at $\pm 5^{\circ}\text{F}$.

The irradiated thermally released shutdown rod from C08-01 was loaded into the apparatus and heated until, at the end of 2 hr, the indicated temperature reached 1740°F and the rod was released. The release temperature was therefore set at $1740 \pm 5^{\circ}\text{F}$.

The rod was undamaged by the experiment. A photograph of the rod after the experiment is shown in Fig. 35. The remains of the fusible link are shown in Fig. 36. Partial melting of the outer surface of the link took place before the threaded inner surface yielded under the load of the rod. Some of the black scale was noted on the bottom surface of the link, as can be seen in Fig. 36, where it floated on the molten link material.

After the thermal release experiments, the boronated absorber was removed from the stainless steel weldment and the components were measured. The results of this work and the deviation from design values, if any, are shown in Table 11. Determination of the outside dimensions of the snubber, tube weldment, and absorber support was of primary importance to ensure that no interference existed between the shutdown assembly and the guide tube.

M32669-3

Fig. 35. Thermally released shutdown rod after release temperature experiment

K303-48

Fig. 36. Partially melted fusible link from thermally released shutdown rod C08-01 after release temperature experiment. Apparently entire fuse had not reached melting temperature ($1745 \pm 3^{\circ}\text{F}$) when release was experienced at $1740 \pm 5^{\circ}\text{F}$.

TABLE 11
 DIMENSIONS OF THERMALLY RELEASED SHUTDOWN ROD
 COMPONENTS FROM GUIDE TUBE CO8-01 AFTER 300 EFPD

Component	Position in Component	Diameter								Length	
		Outside Diameter				Inside Diameter					
		Minimum		Maximum		Minimum		Maximum			
		Inches (±0.001)	% Deviation from Design Limits	Inches (±0.001)	% Deviation from Design Limits	Inches (±0.001)	% Deviation from Design Limits	Inches (±0.001)	% Deviation from Design Limits	Inches (±0.001)	% Deviation from Design Limits
Absorber (boronated graphite, 30 wt % B)	Top	2.234	-0.3	2.238	-0.1	1.198	--	1.200	--	19.151	0
	Middle	2.238	-0.1	2.238	-0.1	(a)	--	(a)	--	--	--
	Bottom	2.237	-0.1	2.240	0	(a)	--	(a)	--	--	--
Absorber support ^(b) (HLM-85 graphite)	Across lobes	2.688	0	2.693	+0.2	(a)	--	(a)	--	(a)	--
	Across flats	2.318	0 ^(c)	2.328	+0.3 ^(c)	(a)	--	(a)	--	--	--
Tube weldment (at snubber) (stainless steel)	Across lobes	2.684	0	2.687	0	(a)	--	(a)	--	(a)	--
	Across flats	2.315	0 ^(c)	2.316	0 ^(c)	(a)	--	(a)	--	--	--
Snubber	Across lobes	2.683	0	2.684	0	(a)	--	(a)	--	(a)	--
	Across flats	2.324	+0.1 ^(c)	2.325	+0.1 ^(c)	(a)	--	(a)	--	(a)	--

(a) Not determined

(b) The absorber support had a single radial crack through the wall. The maximum diameter was measured at 90° around the circumference from the crack.

(c) Assumes ± 0.005 tolerance distance from center

The absorber support diameter showed the greatest deviation from design, probably as a result of a crack through the wall, which was mentioned previously. The crack in the absorber support resulted from inadequate design clearance and a thermal expansion mismatch between the graphite absorber support (i.d. as-manufactured: $1.377 +0.002, -0.000$) and the stainless steel weldment (o.d. as-manufactured: $1.375 +0.000, -0.002$), which passes through the absorber support and the boronated graphite absorber. At 900°F (the temperature of the thermally released absorber assembly in the top of the guide tube during normal operation) the minimum i.d. of the absorber support would be about 0.007 in. less than the maximum o.d. of the stainless steel weldment (if free expansion of the components were possible). The resulting tensile strain in the absorber support ($\sim 0.5\%$) is sufficient to cause failure. The circumferential thermal stresses that could be induced in the absorber support as a result of heatup from room temperature to 900°F , assuming no graphite failure, exceed the ultimate tensile strength for HLM-85 graphite, even if the largest initial gap (within the manufacturing tolerances) is assumed.

A complete engineering and safety analysis provided the following conclusions:

1. Most, if not all, of the absorber supports installed in the guide tubes remaining within the reactor have a single characteristic radial crack, which occurred on initial heatup of the reactor.
2. The irradiation-induced graphite contraction does not affect the integrity of the absorber support.
3. Adequate clearance still exists between the absorber support and the guide tube to permit the thermally released absorbers to drop onto the guide tube groove ledge in the core upon melting of the fusible links.
4. The absorber support will support the absorber within the core in the event that melting of the metal components does occur.

No irradiation-induced dimensional change was expected in the thermally released shutdown absorber because the fast neutron exposure was not significant. The fast neutron fluence and the operating temperature of the thermally released shutdown rod are shown in Fig. 17.

The microstructure of the boronated graphite in the thermally released shutdown rod was determined from metallography on a wall section cut from the middle of the tube length. There was no difference in the condition of B_4C grains between the exposed outer surface and the inner surface which was shielded from thermal neutrons. Comparison of the microstructure of a piece from an unirradiated absorber showed virtually the same features; this similarity was expected in view of the relatively low thermal and fast neutron exposure. Typical microstructures of the irradiated material are shown in Figs. 37 and 38.

M303-10

Bright field

(75x)

M303-6

Polarized light

(75x)

Fig. 37. Microstructure of outside surface of boronated graphite absorber of thermally released shutdown rod in C08-01 after 300 EFPD. B_4C granules can be seen dispersed in graphite matrix. Wide range of porosity in B_4C is typical of as-manufactured material and is probably not caused by irradiation effects

M303-11

Bright field

(450x)

M303-12

Polarized light

(450x)

Fig. 38. High magnification photographs of B₄C granules and matrix shown in Fig. 37

SUMMARY

During the examination of the control rod and guide tube from position C08-01 after 300 EFPD the following observations were made:

CONTROL ROD

1. The stainless steel components appeared unchanged by the exposure except for a darkened color.
2. The rider rings made of HLM-85 graphite were unchanged by service conditions.
3. The disk springs were undamaged by service conditions and kept the absorbers positioned between the spacers even though they showed evidence of reduced ductility at high temperature and high neutron exposure. It is expected that the disk springs will continue to fulfill their design requirement of positioning the absorbers throughout the service lifetime of the control rods.
4. The boronated graphite neutron absorbers were unchanged in appearance by the exposure but an axial shrinkage of up to 0.28% was measured in the absorber with maximum fast neutron exposure (1.2×10^{21} n/cm²; $E > 0.18$ MeV). A stress-strain analysis of the absorber indicated that at end-of-life exposure the radial dimensional change and stress within the absorbers will not cause disruption of the absorber.
5. The microstructure of the boronated graphite revealed some intragranular cracking of B₄C, which was considered normal for the exposure conditions.

GUIDE TUBE

1. The guide tube dimensions were within manufactured tolerances except for an overall axial bow of about 0.122 in. and a bow of 0.075 in.

in the lower guide tube, which was considered in excess of the manufactured tolerance. The middle of the guide tube was bowed toward the center of the core. From consideration of in-core restraint and irradiation properties of graphite, significant additional bow is not expected for the remainder of the service life.

2. The boronated graphite thermally released shutdown rod was not visibly affected by the exposure.

3. The graphite absorber support was cracked radially because of a thermal expansion mismatch between the graphite and a stainless steel support. An analysis showed that cracks such as this would not impair the proper operation of the system.

4. The release temperature of the thermally released shutdown rod was determined to be $1740 \pm 5^{\circ}\text{F}$. The release temperature was unaffected by the reactor exposure.

5. The microstructure of the boronated graphite showed no effects of irradiation.

APPENDIX

MEASUREMENT OF STRENGTH OF UNIRRADIATED PEACH BOTTOM HTGR BORONATED GRAPHITE CONTROL MATERIAL

An unirradiated Type 2 (30 wt % boron) control rod absorber that was part of the original shipment from the vendor was obtained. Both crush and flexure specimens were cut from the absorber. All specimens were cut from the absorber wall as cylinders. The flexure specimen and two crush specimens were cut with axes parallel to the extrusion direction while two each crush specimens had axes parallel and perpendicular to the radius of the extruded absorber tube.

Strength measurements were made at room temperature in an Instron Model TTCM-1 testing machine at a cross-head speed of 0.005 in./min. A four-point loading technique with equal spanning of contact points was used to determine flexure strength. The midpoint deflection of the specimen was measured during the test. The modulus of rupture was calculated using the expression

$$MR = \frac{2 Pa}{\pi r^3}$$

where P = total load (lb)

a = distance between contact points [1/3 span length (in.)]

r = radius of sample (in.)

The elastic modulus of the material was calculated from the flexure measurements using the expression

$$E = - \frac{P}{d} \frac{23 a^3}{12 \pi r^4}$$

where P = total load (lb)

d = maximum deflection between outside supports (in.)

a = distance between contact points [$1/3$ span length (in.)]

r = radius of sample (in.)

The specimen dimension and results of the flexure tests are shown in Table 8.

Crush strength was measured by loading the cylinders to failure axially at a cross-head speed of 0.005 in./min. The specimen dimension and results of the crush tests are shown in Table 9. Some anisotropy of crush strength was indicated but it was not significant to the stress-strain analysis discussed in this report.

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