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HTGR FUEL ELEMENT PERFORMANCE IN PEACH BOTTOM REACTOR

by

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ABSTRACT

The Peach Bottom reactor utilizes fuel elements which each consist of pyrocarbon-coated particles of mixed uranium-thorium carbides dispersed in a graphite matrix contained in a low permeability graphite tube; the tube functions as the main structural member. The reactor core contains 804 fuel elements of this type, each 3-1/2 in. in diameter and 12 ft long positioned vertically in a close-packed array. Cooling is accomplished by helium gas at 350 psi flowing through the interstices among the elements. The outlet gas temperature is 1340°F.

Operation of the Peach Bottom reactor at high power began in January 1967, and the reactor has accumulated several hundred megawatt hours since that time. The thermal performance of the fuel has been gratifying and has easily met the design objective of 8.3 kw/liter at an average fuel temperature of approximately 1800°F. The good thermal performance of this fuel has confirmed the objective of high coolant temperature necessary to generate modern steam at 1000°F and 1450 psi.

Retention of fission products by the fuel has been very good; the total circulating gaseous fission-product radioactivity in the helium coolant inventory has been approximately 200 millicuries at full power. Deposition of solid fission-product plateout on components of the primary loop has been so low as to allow easy access to primary loop components.

INTRODUCTION

The development of the HTGR concept has been pursued with the following system features as important objectives:

1. The generation of steam at modern conditions of temperature and pressure of 1000°F and 1400 psi, or higher.
2. The achievement of high neutron economy by avoiding the use of core structural materials that have strong neutron absorbing characteristics.
3. The development of graphite and ceramic fuel elements that are capable of operating for very long periods of time while limiting the release of fission products to the main coolant.
4. The achievement of negative coefficients of reactivity, both prompt and over-all, which assure ease of control throughout core life.

The Peach Bottom atomic power station is the prototype HTGR in the United States and is successfully demonstrating the achievement of these system objectives (Ref. 1).

The Peach Bottom reactor first operated at high power in January 1967 and began full power commercial operation on June 1, 1967.

CORE DESIGN FEATURES

The reactor core employs enriched U^{235} as the initial fissile material and Th^{232} as the fertile material. The core is made up of 804 individual fuel elements which form a cylindrical core array with an effective diameter of 9 ft and an active height of 7.5 ft. End reflectors are integral parts of the fuel elements, and are approximately 2 ft long at the top and 2.5 ft at the bottom. Some of the significant core parameters are given in Table 1. A photograph of a portion of the core during initial loading is shown in Fig. 1.

Table 1
CORE PARAMETERS

Thermal power	115.5 Mw
Net plant electrical power	40 Mw
Average power density	8.3 kw/l
Core loading:	
U^{235}	220 kg
Th^{232}	1450 kg
Carbon	20,500 kg
Average burnup	60,000 Mwd/tonne

Fig. 1--View of core during loading

Each Single fuel element is a complete assembly which is handled and located individually within the reactor. The fuel element, shown in Fig. 2, consists of an upper reflector section, a fuel-bearing middle section, and a bottom reflector section. A 115-in. long graphite sleeve having a low permeability to helium extends from the upper reflector section to the bottom connector of the fuel element and contains the fuel compacts, a lower reflector piece, and an internal fission-product trap. In this graphite-clad fuel element the approach is not to attempt hermetic containment of fission products within the fuel elements, but rather to control the escape of these fission products and retain them in traps in such a way that the activity in the primary circuit is maintained at a satisfactorily low level.

All 804 fuel elements are of the same external geometry. Outwardly each fuel element has the appearance of a solid graphite cylinder 3.50 in. in diameter and 144 in. long, with a grappling knob at the top for handling.

The main coolant in the core passes upward through tricuspid-shaped passageways formed by the triangular packing of the cylindrical fuel elements. Spacer rings machined onto the outside surface of the fuel elements at three axial locations serve to maintain the pitch and prevent line contact along the length of the elements.

The primary components making up the fuel element are a bottom connector, a sleeve, a screen, an internal fission-product trap assembly, a lower reflector piece, fuel compacts, spines, burnable poison compacts (in selected elements), a fuel cap, and an upper reflector assembly.

The bottom connector and the sleeve are joined by a silicon braze, and together they form the main barrier against fission-product leakage from the fuel element. These components are made of graphite which has a helium permeability* of 3×10^{-3} cm²/sec or less, and an effective permeability to gaseous fission products of approximately 10^{-5} cm²/sec at reactor conditions.

The screen, internal trap assembly, lower reflector piece, fuel compacts with spines, and the fuel cap are stacked in that order within the sleeve.

The upper reflector assembly is a graphite piece that is threaded and cemented into the sleeve of the fuel element. The upper end of this reflector piece is machined to become engaged with the fuel handling machines. A 1/4-in. diameter hole down from the centerline of the reflector serves as an inlet channel for purge gas. A porous plug cemented and retained within the upper reflector provides a controlled pressure drop for inflowing purge gas.

The uranium and thorium within the fuel compacts are in the form of carbides uniformly dispersed as particles in the graphite matrix.

*Measured at room temperature and one-half atmosphere mean pressure. These are conditions accepted within the graphite industry as standard for comparing permeability.

Fig. 2--Fuel element

The fuel particles consist of uranium-thorium carbide substrates coated with pyrolytic carbon. The uranium is fully enriched, i.e., 93.15%. The coated particles are between 210 and 595 microns in diameter. The coating thickness is 55 ± 10 microns. The size distribution of the particles is selected so that the volume fraction of coated particles in the finished compacts does not exceed 30% of the total compact volume.

The purge flow that sweeps fission products from the core of the reactor is provided by drawing 900 lb/hr of main coolant helium through the 804 fuel elements. This purge flow rate amounts to 1.1 lb/hr per element. In addition to the purge streams passing through the fuel elements, an inleakage of helium around the stand-off connectors could contribute a maximum of 100 lb/hr to the total purge flow rate. Therefore, the total maximum helium flow rate in the purge line leading to the external traps is 1000 lb/hr.

The purge gas enters each fuel element through the hole at the top of each upper-reflector piece. The gas is filtered and drops 4 psi in pressure as it passes through the porous plug in the reflector. This pressure drop to the inside of the fuel element serves to decrease the permeability of the sleeve to fission products and to provide equal flow into the individual elements. The gas then flows downward around the fuel compacts, sweeping fission products out of the space between the fuel compacts and the graphite sleeve. Grooves molded in the outer surface of the fuel bodies provide additional flow area for the purge gas. After sweeping fission products from the active core zone, the purge gas flows through the internal trap where some of the fission products are adsorbed by the charcoal reagent. At the bottom end of the internal trap, the gas stream is filtered through a porous graphite cylinder. Volatile fission products leaving each internal trap enter the stand-off pin and are drawn through a purge line leading to the external fission-product traps.

THERMAL DESIGN FEATURES

The core thermal performance has been monitored during full power reactor operation. The primary coolant flow rate, the core pressure drop, and the core inlet and exit coolant temperatures are among the coolant system parameters measured. Significant thermal design parameters are shown in Table 2.

From measured coolant flow and temperature values the thermal power of the total core is calculated. More specific information on internal temperatures within the fuel elements is obtained from 36 instrumented fuel elements distributed throughout the core. These elements contain 59 thermocouples within the active core region and 13 within the internal traps and the lower reflectors. Approximately 50 of the 59 in-core thermocouples have continued to operate reliably. The mean design lifetime for these in-core thermocouples was 1000 hr at full power, and it appears that most will outlive this design value.

The temperature data indicate very gratifying thermal performance. The design objective of 8.3 kw/liter power density is easily met and fuel temperatures are well within expected values.

Table 2
THERMAL DESIGN PARAMETERS

Coolant pressure	350 psia
Coolant circuit pressure drop	2.7 psi
Coolant temperature at core inlet	650°F
Coolant temperature at core exit	1340°F
Coolant flow rate	4.5×10^5 lb/hr
Maximum fuel temperature	2430°F
Power peaking factors:	
Radial peak/avg.	1.3
Over-all peak/avg.	1.6

Observed temperature profiles in fuel elements across the core and in peak local spots have been compared with predicted values (Ref. 2). In Fig. 3 are shown radial temperature profiles observed and predicted in the fuel bodies at the hottest axial plane, 6 ft up from the core bottom (Ref. 3). The agreement between predicted and observed values is very close. The local power density changes somewhat as control rod patterns change, and this accounts for the difference in profile. For the measured case shown, nine control rods were fully inserted and three were 1/3 inserted, all within the inner 30 in. of core radius. A comparison between predicted and measured fuel element internal temperatures is shown in Fig. 4. Measurements are made with thermocouples located in the space between the spine and fuel body and in the space between fuel body and sleeve. The data show good agreement between predicted and measured values.

FISSION-PRODUCT RETENTION

The fission-product activity released from the fuel elements to the reactor coolant is very low. A comparison of observed activity in the main coolant versus the "expected" and "design" values (Ref. 4) are shown in Table 3. The design value is the basis for a Technical Specification limit under provisions of the operating license for the plant.

Table 3
REACTOR COOLANT ACTIVITY

<u>Case</u>	<u>Activity Inventory (curies)</u>
Expected at beginning of life	108
Design	4225
Observed at 5000 Mwd	0.2

Fig. 3--Maximum fuel temperature across core radius

Fig. 4--Fuel temperature at hot spot height, measured versus predicted

Other fission-gas release parameters that have been evaluated at full power operation are the release fractions for krypton and xenon out of the fuel bodies and the release fraction for noble gases through the graphite sleeve of the element. The release/born ratio (R/B) versus half life of noble-gas fission products is shown in Fig. 5. The release, as predicted, is dependent upon the square root of half life, and the release of xenon is lower than that of krypton. This behavior correlates with that observed in the General Atomic in-pile loop, where a full-diameter section of a Peach Bottom fuel element (GAIL III-B) was irradiated for two years (Ref. 5).

In Fig. 6 the release of Xe^{135} during Peach Bottom operation is shown plotted on a curve of release versus burnup for the GAIL III-B element. At comparable burnups, the release is low for both cases.

The release fraction for krypton and xenon passing through the graphite sleeve has been observed to be in the range of 1 to 2 parts in 10^4 . This is a more effective retention than had been predicted from design studies and from observations in GAIL III-B. A comparison of these factors is shown in Table 4.

Table 4
FUEL ELEMENT SLEEVE RELEASE FRACTION

<u>Case</u>	<u>Release fraction through sleeves</u>
GAIL III-B	6×10^{-3}
Peach Bottom Design	2×10^{-4}
Peach Bottom Observed	$<1 \times 10^{-4}$

SUMMARY

The Peach Bottom fuel elements are operating completely favorably during full power operation. Fuel temperatures are observed to be essentially as predicted from earlier design studies. The release of fission products to the reactor coolant is very comfortably below the expected beginning-of-life values.

Fig. 5--Noble gas release from fuel bodies

Fig. 6--Release of Xe^{135} from fuel bodies as a function of burnup

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