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June 1979

POST-IRRADIATION EXAMINATION OF OCONEE 1 FUEL
-- CYCLE 1 NONDESTRUCTIVE TEST PHASE --

Babcock & Wilcox

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— CYCLE 1 NONDESTRUCTIVE TEST PHASE —

B&W Contract No. CRD-1018
DOE Contract No. ET-78-C-02-4711

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Report BAW-1519

June 1979

Post-Irradiation Examination of Oconee 1 Fuel —
Cycle 1 Nondestructive Test Phase

Key Words: UO₂ Fuel, Zircaloy-4, Irradiation
Testing

ABSTRACT

Standard B&W pressurized water reactor fuel was examined after one cycle of irradiation in the Oconee 1 reactor. The examination was conducted in the Oconee Units 1 and 2 spent fuel storage pool using underwater test equipment. Data obtained included spring constants, rod and assembly dimensional changes, crud analysis, and fuel column axial gap and stack lengths. Parametric changes generally were well within the design envelope. The 36 assemblies that were visually examined were structurally sound and showed no evidence of cocked grids, fretting, or visually observable rod bowing. The only exception was two isolated cases of rod defects.

SUMMARY

The cycle 1 phase of the post-irradiation nondestructive examination of Ocone 1 fuel assemblies was completed in 1975. A total of 36 assemblies were visually examined; data were obtained in the following areas:

1. Visual appearance.
2. Holddown spring preload.
3. Rod and assembly length.
4. Rod and assembly bow.
5. Crud characteristics.
6. Fuel column axial gap and stack length.

The general appearance of the fuel assemblies was quite good, although two rod defects were seen among the 2,016 peripheral rods examined. Holddown spring relaxation was significantly less than expected, while length changes were well within the design envelope. Crud flake thickness averaged 1.03 mils on the assemblies that were sampled; crud composition was consistent with primary coolant circulation crud. Assemblies showed a tendency to bow outward from the center of the core with an average maximum bow of 0.108 inch. Rod bow was small in magnitude with a 2σ bow of about 0.014 inch. Fuel stack length data showed an average decrease that was somewhat less than expected from the densification model. Axial fuel column gap distributions were somewhat anomalous and were probably affected by fuel handling. This report summarizes the data obtained, along with pertinent core operating conditions.

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1. INTRODUCTION

The original B&W Mark-B fuel design was first used in the Oconee 1 reactor. The value of obtaining operating performance information on this fuel was recognized before plant startup. Therefore, a cooperative program with the owner/utility, Duke Power Company, was initiated to measure important fuel assembly parameters over the three-cycle life of the fuel in the Oconee 1 reactor.

The post-irradiation examination (PIE) program at Oconee 1 will cover the first three reactor cycles and include destructive and nondestructive testing on fuel assemblies and control components. Nondestructive testing (NDT) is performed at the Oconee site in the spent fuel storage pool. Destructive examination is performed at B&W's hot-cell laboratory at the Lynchburg Research Center. This report discusses the NDT results of cycle 1.

To accomplish the objectives of the NDT phase of the PIE program, an extensive array of underwater test equipment was designed, built, and installed in the Oconee 1 and 2 spent fuel storage pools. The following examinations and measurements were performed on 36 fuel assemblies at the end of cycle 1:

1. Television examination and videotaping of fuel assemblies and control components.
2. Periscope examination and 35-mm photography of fuel assemblies and control components.
3. Fuel assembly holddown spring force versus load deflection.
4. Rod and assembly length and spacer grid axial locations.
5. Fuel assembly and rod bow.
6. Rod-to-rod spacing (water channel).
7. Crud sampling.
8. Fuel column axial gamma scans.

The relevant fuel assembly design and core characteristics and the results of these poolside examinations are presented and discussed in the following sections of this report.

2. ASSEMBLY DESIGN AND CORE CHARACTERISTICS

A sketch of the Mark B fuel assembly is shown in Figure 1. For future reference, the six spacer grids are numbered sequentially from 1 to 6 from top to bottom. Figure 2 is a cross section of the assembly showing additional characteristics and identification conventions. The fuel is UO_2 in the form of dished, cylindrical pellets 0.7 inch in length. The cladding and guide tubes are of Zircaloy-4, while the holddown spring is made of Inconel X-750. The six spacer grids (Inconel-718) are not attached to the guide tubes but are free to move with the fuel rods as they grow.

Pertinent nominal assembly and core parameters are listed in Table 1. At the time of manufacture, several assemblies were selected for special characterization. These measurements included rod length and diameter, grid parameters, and fuel pellet characteristics which were utilized in analyzing the Oconee 1 end of cycle 1 data. Although the parameters in Table 1 are typical of all the assemblies in Oconee 1 (and other Mark B plants), slight differences exist between the batches. Where pertinent, any differences will be discussed along with the individual results. The 36 assemblies examined at the end of cycle 1 are listed in Table 2. The core loading configuration is displayed in Figure 3.

Table 1. Oconee 1 Fuel Parameters

Core power rating, MWt	2568
Average linear heat rate, kW/ft	5.66
Cycle 1 length, EFPD	310
EOC core average burnup, MWd/mtU	9600
No. of assemblies in core	177
No. of fuel rods per assembly	208
Cladding OD, in.	0.430
Cladding ID, in.	0.377
Cladding thickness, mils	26.5
Total fueled length, in.	144
Fuel pellet diameter, in.	0.370
Fuel density, % TD	93.5
Initial average enrichment, % ²³⁵ U	
Batch A	2.00
Batch B	2.10
Batch C	2.15

Table 2. Assemblies Examined at EOC 1

Assembly ID	Calculated assembly burnup, MWd/mtU	Visual	Holddown spring	Grid spring	Assembly length	Rod length	Assembly bow	Rod gap	Crud ^(a) analysis	Gamma ^(b) scan
1A06	10,725	x	--	--	--	--	x ^(c)	--	x(9)	x
1A10	12,098	x ^(d)	--	--	--	--	x	--	--	x
1A11	11,316	x	--	--	--	--	x ^(c)	--	--	x(2)
1A12	10,725	x	--	--	--	--	--	--	x	x
1A13	12,098	x	--	--	--	--	x ^(c)	--	--	x
1A16	10,530	x	x	x	x	x	x	x	--	x
1A17	12,031	x	--	--	--	--	x ^(c)	--	--	x
1A19	11,316	x ^(d)	x	--	--	--	x ^(c)	--	--	x
1A21	10,725	x	--	--	--	--	x ^(c)	--	x(7)	x
1A22	12,098	x	--	--	--	--	x ^(c)	--	--	x
1A23	10,808	x	--	--	--	--	--	--	x	x
1A25	11,569	x	--	--	--	--	--	--	x	x
1A26	10,725	x	--	--	--	--	--	--	x	x
1A30	12,098	x	--	--	--	--	x ^(c)	--	--	x
1A31	12,098	x	--	--	--	--	x ^(c)	--	--	x
1A32	10,808	x	--	--	--	--	x ^(c)	--	--	x(2)
1A33	12,098	x	--	--	--	--	x ^(c)	--	--	x
1A34	12,336	x	--	--	--	--	x ^(c)	--	--	x
1A35	12,098	x	x	--	--	--	x ^(c)	--	--	x
1A36	11,434	x	--	--	--	--	x ^(c)	--	x	--
1A39	11,316	x	--	--	--	--	x ^(c)	--	--	x(2)
1A40	12,031	x	--	--	--	--	--	--	--	x(1)
1B09	10,806	x	--	--	--	--	--	--	--	--
1B15	12,098	x	--	--	--	--	x ^(c)	--	--	--
1B22	12,270	x	--	--	--	--	x ^(c)	--	--	--
1B24	12,270	x	--	--	--	--	x ^(c)	--	--	--
1B41	12,270	x	--	--	x	x	x ^(c)	--	x	x
1B43	12,270	x	x	--	x	x	x	--	--	x
1B47	12,270	x	--	--	--	--	--	--	--	x(2)
1B52	12,270	x	--	--	--	--	--	--	--	x(2)
1C30	6,376	x	x	--	--	--	x	x	--	--
1C44	10,237	x	--	--	x	x	--	--	--	x
1C56	9,039	x	--	--	x	x	x	x	--	x
1C63	7,100	x	x	--	x	--	x	x	--	x
1C66	9,824	x	--	--	x	--	x	x	--	x
1C73	9,824	x	--	--	x	--	x	x	--	x

(a) One sample from each unless noted otherwise in parenthesis.

(b) Four corner rods scanned unless noted otherwise in parenthesis.

(c) Visual inspection only.

(d) Rod defect observed.

Figure 1. Mark B Fuel Assembly

Figure 2. Fuel Assembly Cross Section and
Numbering Conventions

Figure 3. Cycle 1 Core Loading - Oconee 1

Control Rod Configurations

Groups 1-5 100% withdrawn
 Group 6 ~85% withdrawn
 Group 7 ~20% withdrawn
 Group 8 Part-length APSRs, ~5% withdrawn

3. RESULTS AND DISCUSSION

The examination of the 36 assemblies comprising the NDT phase at the end of cycle 1 (EOC 1) was conducted in two parts. The first comprised an examination of six assemblies scheduled to be reinserted for cycle 2 and was performed during the refueling outage in November 1974. The second part covered the examination of an additional 30 assemblies discharged at EOC 1. This work was performed from March to June 1975. A summary of the examination scope is given in Table 3.

3.1. Visual Examinations

3.1.1. General Fuel Assembly Appearance

In all, 36 assemblies were visually examined. Most of this examination was performed with an optical periscope and recorded on 35-mm color slides. Several assemblies were also examined with the underwater television and videotape.

The overall appearance of the assemblies was quite good, indicating no significant rod bowing, cladding deformation, or cocked grids.

Fuel rod corrosion deposits were complex and showed marked axial variation. (Crud composition and thickness are discussed in section 3.8.) The patterns varied from areas of uniform color to very mottled, and displayed a variety of colors. Boundaries between colors were usually sharp, giving an appearance of flaked-off deposits. The smoother, more gradual boundaries varied from horizontal rings to diagonal and jagged (flame-like) lines. In general, the axial variation was consistent among the different assemblies. All showed a very dark, uniform brown deposit above the lower skirt. Above this area the deposits changed through a couple of shades of lighter brown, still uniform. Further up the assembly, the pattern became more mottled, with orange and tan predominating. The transition points between these three to five regions occurred at different axial locations in different assemblies and on different

faces of the same assembly. The transitions seemed to be higher up on the assemblies with lower burnup.

Superimposed on this general pattern were perturbations caused by flow variations just above the grids. Most of these areas were light-colored and reflective, giving the appearance of relatively clean cladding. The height of the light areas above the grids varied considerably (even across an assembly face), producing a "pipe-organ" appearance. The region between the top spacer grid and the upper skirt showed the most varied deposit patterns. In about half the cases, there were sharp, horizontal dividing lines separating two different colors near the top of the fuel column. In some cases, oblique lines occurred in this area.

Crud deposits on the grids also showed a wide variation. Some grids appeared quite clean although not as reflective as new grids, while others were quite mottled, usually showing a mixture of orange and black colorations. The lower skirt and end fitting crud deposits were generally uniform and dark. The deposits on the upper skirt and end fitting showed more variation and did not appear to be as dark.

3.1.2. Rod Defects

Of the 2016 peripheral rods examined during the NDT phase, two contained defects. The defective rods occurred in two different batch A assemblies scheduled for discharge at the end of cycle 1.

3.1.2.1. Defect in Assembly 1A10

Rod C14 had two defects which were located between spacer grids 4 and 5. The crud pattern on the adjacent rod confirmed that the failure occurred before EOC-1 shutdown.

Neither the defective rod nor the other rods showed gross outward bow in the area of the defect. Nothing unusual was seen during the visual inspection of the remainder of the assembly except that the typical complex crud patterns were not seen on the failed rod above the immediate vicinity of the defect area. This section was quite uniformly colored. The adjacent corner rod (C15) also looked uniform in some areas above the defect and somewhat shiny. Subsequent examination of the adjacent assembly (1A17, face A) revealed a similar pattern.

Nothing unusual was seen in the line-scan bow and diameter traces on rods C13, C14, and C15 (although the grid 4-grid 5 segment of rod C14 was not scanned). Inspection of the assembly adjacent to face C of assembly 1A10 during cycle 1 showed no indication of failure propagation. Except for the variations in crud patterns caused by the defect perturbation on coolant flow, nothing unusual was noted.

The gamma-scan of the corner rod adjacent to rod C-14 showed nothing unusual. A gamma-scan of the defective rod indicated a gap of slightly more than four pellets centered about the defect area.

A review of operating conditions for cycle 1 showed nothing unusual. The instrumentation tube of 1A10 contained a neutron detector string which indicated that the assembly operated most of the cycle at a relative assembly radial power density of about 1.2 and a maximum segment linear heat rate of 10.8 kW/ft. These values correspond to the design conditions for this particular fuel assembly.

3.1.2.2. Defect in Assembly 1A19

The defect in rod D14 of assembly 1A19 was located a few inches above grid 3. The influence of the defect on crud patterns above grid 3 was very strong, extending up to the skirt and upper end fitting on faces A and D. Except for slight changes in crud patterns, nothing unusual was seen on the assembly adjacent to the defect during cycle 1. Since the 1A19 defect is in almost the same symmetric position as the defect in 1A10, the same remarks concerning normal operating conditions apply.

3.1.2.3. Discussion

Nothing in the manufacturing records indicates any significant difference between these two assemblies and the other 175. Thus, it has been concluded that the defects were probably related to cladding hydriding, resulting either from internal moisture or from water entering an early-in-life fuel rod defect.

The theory of early defects is supported strongly by the Oconee 1 primary coolant radiochemistry data. A fission-product concentration indicative of about 20 defective rods became apparent early in life (about 10 EFPD). From that time until the end of cycle 1, the activity remained relatively constant, showing that no new defects were being formed.

3.2. Holddown Springs

Holddown spring loading and unloading curves were obtained on six assemblies, two of which were returned to the core for cycle 2. The spring preload and force constant were calculated from the loading portion of the curves. The results are given in Table 4, along with burnup and neutron fluence information. The average preload is 4% below the mean of the nominal beginning-of-life (BOL) range. Although this indicates some relaxation, the 2σ band on the PIE data includes the as-built nominal mean of 422.5 lb.

All the PIE data fall within the expected range of values for the unirradiated case, although the averages show slight decreases from the BOL mean. There is a slight correlation with neutron fluence that predicts a 10 to 15% loss of preload after three cycles of operation ($\sim 30,000$ MWd/mtU).

3.3. Length Measurements

Length change and spacer grid location data were obtained on eight fuel assemblies and are presented in Table 5. The length designations used in the table are explained in Figure 4; lengths N and K represent fuel assembly growth. Preirradiation measurements where available were used as the reference lengths; otherwise, nominal drawing lengths were used to calculate the irradiation growth ($\Delta L/L$). Figure 5 displays the fuel assembly growth data, along with the original guide tube growth design curve.

Actual length measurements were obtained on 33 fuel rods selected from five fuel assemblies. The results are shown in Table 6. These data and the spacer grid location data of Table 5, which are also representative of fuel rod growth, are plotted in Figure 6. Only the data from spacer grid lengths J and H are included in Figure 6.

As shown in Figure 6, the fuel rod growth data are scattered about the original guide tube growth design curve which is based on free irradiation growth in cold-worked Zircaloy-4. Since the original fuel rod growth design curve was derived assuming fuel-cladding interaction producing ratcheting of the cladding during power escalations, it is concluded (based on the data in Figure 6) that pellet-cladding interaction did not occur to a significant extent.

3.4. Assembly Bow

Fuel assembly bow data were obtained on 29 fuel assemblies. Quantitative measurements on eight fuel assemblies were obtained using the line-scan tester. Bow on the remaining 21 assemblies was estimated from visual observations.

The maximum fuel assembly bow observed with the line-scan tester was 0.347 inch. A smooth curve drawn through the bow measurements taken on the assembly of greatest bow indicates a maximum fuel assembly bow of about 0.375 inch. The average maximum bow of 23 faces on the eight fuel assemblies was 0.108 ± 0.080 inch and occurred between spacer grids three and five. The majority of the fuel assemblies were bowed outward toward the core periphery.

3.5. Rod Bow

Quantitative data on rod bow (deviation from straightness over a span length between spacer grids) were obtained by water channel spacing (rod gap) measurements. Line-scan bow measurements were used as a check on this data and as an indication of bow shape. From six fuel assemblies a total of 7164 midspan water channel spacings were measured with an estimated accuracy (2σ) of within 0.006 inch. Average fuel assembly burnup ranged from 6,376 to 10,530 MWd/mtU.

In addition to these quantitative bow determinations, qualitative bow data were obtained from visual examinations of 36 fuel assemblies, which correspond to 14,112 peripheral rod segment pairs. It was estimated that rod gap closure in excess of 0.050 inch would be easily detectable in the visual examinations. No closure of this magnitude was seen in any of the observations, which confirms the small bow magnitude determined in the measurements discussed below.

3.5.1. Water Channel (Rod Gap) Measurements

The water channel gage measures the distance between adjacent-rod ODs, including fuel rods, guide tubes, and the instrument tube. All peripheral and interior rod pairs were measured in two perpendicular directions. Measurements were taken at the seven midplanes, i.e., the axial midpoint between adjacent spacer grids. Rod gaps involving guide tubes and the instrument tube were not included in the analysis since their bow mechanism is different from that of the fuel rods and the data would thus be incorrectly biased.

For five of the six assemblies measured, as-built rod gap data were available. Figure 7 shows the EOC 1 data as a change from the actual as-built gap. (As-built 2σ rod bow or gap spacing is about 0.006 inch and slightly higher for

planes involving the end grids.) The smaller variation in this set of data indicates a possible relationship between as-built and post-irradiation bow. A slight correlation was also noted between the as-built and irradiated bow directions; i.e., small gaps tended to become smaller, while large gaps became larger.

The effect of fuel burnup on rod spacing (or bow) is shown in Figure 8. The total gap frequency distributions for two assemblies with a nearly complete set of spacing data differ slightly, with the assembly of higher burnup showing more average bow. Although the difference in deviation is only 0.0009 inch, the statistics indicate that the effect is real.

With respect to the effects of axial location on rod gap spacing, an increased tendency to bow occurred in the lower portion of the fuel assemblies, except for the bottom midplane. This increase in bow was probably due to the stackup of the restraining forces of the spacer grids. The reduced bow in the bottom midplane may be an effect of either lower burnup or the double end grid.

The axial effect also differed between peripheral and interior rod gaps. For all mid-span elevations, peripheral rods experienced more bow, presumably because of the stronger spring forces at the outside grip strip. This is further illustrated in Figure 9, showing overall frequency distributions for interior and peripheral rod gaps.

The results discussed above are summarized in Table 7.

3.5.2. Line-Scan Bow Measurements

Line-scan bow measurements were taken at 81 different scan locations on eight assemblies; some were scans on corner rods from both directions. Maximum segment bow was calculated from the traces, and bow shape was analyzed.

A standard deviation of 0.0106 inch was calculated for the bow value for all of the fuel rod segments for which a bow value could be determined. This compared with 0.0071 inch for the water channel (rod gap) measurements. The most significant factor contributing to this discrepancy is the lower precision (about ± 0.010 inch) for the line-scan data. Another factor is that the line-scan data are taken on peripheral rods only, for which a slightly higher σ is expected.

The bow results were analyzed for the effects seen in the rod gap measurements. An obvious increase in bow was noted toward the bottom of the assemblies, as

in the case of the rod gap measurements. A summary of the results of the line-scan bow measurements is presented in Table 8.

3.6. Crud Sampling

Cladding crud samples were taken using a steel-tipped scraper and vacuum pump apparatus. As the scraper was moved up and down on the fuel rod, the removed particles and pool water were drawn up through plastic tubing into a collection flask. The water sample was then passed through a 0.45-micron filter. For several of the samples, crud flakes were collected separately on filters for flake thickness measurements. The sample area of the fuel rod was estimated from photographs and ranged from 3 to 170 cm² with a mean area of approximately 23 cm².

A total of eight fuel assemblies were sampled for crud. Six of the assemblies were sampled only once, at the center between spacer grids 3 and 4. Several samples of the other two assemblies (1A06 and 1A21) were taken at various locations to determine any axial trends or patterns. Of the 31 samples collected, nine were taken from the spent fuel pool water to serve as background samples. At least one background sample was obtained each day that the fuel assemblies were sampled for crud.

3.6.1. Chemical Analysis

The chemical composition of the fuel assembly crud was determined quantitatively by x-ray fluorescence with an estimated standard error of $\pm 5\%$. A complete scan of the detectable elements (with an atomic number greater than 11) was completed for several of the heavier samples.

The average crud sample composition consisted primarily of Ni (57%, or approximately 6.8 mg) and Fe (40%). Small amounts of Cr (3%) were also present, and trace amounts of Zr (<0.9%) were detected in four samples. All of the spent fuel pool background samples contained less than 0.1 mg of Fe, Ni, and Cr, showing that the fuel crud samples were not significantly contaminated with the suspended spent fuel pool crud. Also, two of the fuel assembly crud samples were not distinguishable from the background samples.

For assemblies 1A06 and 1A21, the axial distributions of the relative Fe, Ni, and Cr content were determined. Little variation was found in the Ni and Fe distributions; however, the Cr content increased notably at both ends of the fuel assemblies.

3.6.2. Chemical Compound and Crystal Structure Composition

X-ray diffraction was used to identify the compounds present in three fuel crud samples. Each sample was taken from a separate fuel assembly between spacer grids 3 and 4.

Two major compounds and their crystalline structure were identified: NiO (NaCl structure) and NiFe_2O_4 (spinel). Trace amounts of Fe_3O_4 (spinel) were also found in two of the three samples. From the amounts of Fe and Ni determined in the chemical analysis and from these x-ray results, it is estimated that the crud is composed of 40% NiO and 60% NiFe_2O_4 by weight.

3.6.3. Radionuclide Composition

Gamma isotopic analysis was accomplished using a Ge(Li) detector and multi-channel analyzer with an estimated standard error of 10%. The isotopes detected were ^{51}Cr , ^{54}Mn , ^{57}Co , ^{58}Co , ^{59}Fe , ^{60}Co , ^{95}Zr , and ^{95}Nb (^{95}Nb is the beta decay daughter of ^{95}Zr).

The isotope ^{51}Cr was detectable in only two samples, both of which were taken below spacer grid 6 on two separate fuel assemblies. No ^{51}Cr was identified in the other samples since at least eight half-lives for ^{51}Cr elapsed between the time of reactor shutdown and the time the samples were analyzed.

The radionuclide activities of the spent fuel pool background samples were a factor of about 100 less than the radionuclide activities in all except two of the fuel crud samples. Also, the flake samples (of which there were 16) were typically 20% or less of the regular sample (22) activities.

The most abundant isotope detected in all of the samples was ^{58}Co . The average fuel crud sample composition of this radionuclide was $1.24 \times 10^3 \mu\text{Ci}$; for the spent fuel pool samples, the average was $14.4 \mu\text{Ci}$, indicating that the fuel crud samples were not significantly contaminated with suspended spent fuel pool crud. The average relative fuel crud radionuclide compositions normalized to ^{58}Co were: $^{58}\text{Co} = 1.00$, $^{51}\text{Cr} = 0.29$, $^{60}\text{Co} = 0.15$, $^{95}\text{Zr} = 0.084$, $^{54}\text{Mn} = 0.067$, $^{59}\text{Fe} = 0.039$, and $^{57}\text{Co} = 0.00095$.

3.6.4. Specific Activities

The specific activities were calculated for ^{51}Cr , ^{54}Mn , ^{58}Co , and ^{59}Fe . The average specific activities are $3.4 \times 10^7 \text{ dps } ^{51}\text{Cr}/\text{mg Cr}$, $9.8 \times 10^5 \text{ dps } ^{54}\text{Mn}/\text{mg Fe}$, $9.8 \times 10^6 \text{ dps } ^{58}\text{Co}/\text{mg Ni}$, and $0.58 \times 10^5 \text{ dps } ^{59}\text{Fe}/\text{mg Fe}$. The

axial distribution of the specific activities for fuel assemblies 1A06 and 1A21 were also determined. As expected, the specific activities peak in the middle of the assemblies.

3.6.5. Crud Thickness Measurements

The thickness of the crud layer was estimated by two methods. The first was a direct microscope measurement on the crud flakes separated from some of the samples. The second was a calculation based on sample weight, scraped area, and an assumed value for crud density of 1.0 g/cm^3 .

3.6.5.1. Flake Thickness

Crud flakes with an area of up to 2 mm^2 were isolated on filters and appeared to be an amalgamation of much smaller particles in microscope observations. Flakes that were lying reasonably flat on the filter surface were mounted on the microscope stage for thickness measurements. The microscope was focused first on the lower edge of the flake and then on the upper surface. The thickness of the flake was then determined directly from the difference in the fine adjustment readings of the microscope.

Of a total of 16 crud flake samples collected, 12 samples were analyzed by this microscope technique. About 20 thickness measurements were taken on at least six flakes from each sample. The average thickness of the crud flake samples ranged from 0.73 ± 0.04 to 1.35 ± 0.05 mils, with an overall average thickness of 1.03 ± 0.06 mils. Note that the actual thickness of the crud deposits on the fuel at shutdown could be greater than this.

Four flake samples each from assemblies 1A06 and 1A21 were also analyzed as above. For assembly 1A06, the crud thickness was found to be greatest near the bottom of the fuel assembly; for assembly 1A21, the crud thickness was greatest near the center.

The approximate fuel burnup values at the crud sample locations were compared to the corresponding fuel crud thicknesses. However, a linear least squares fit to the data indicates only a very weak correlation between increasing fuel assembly crud thickness and increased burnup.

3.6.5.2. Thickness Measurement by Weight

The fuel crud thickness was also determined using another approach. The total sample weight of Fe, Ni, and Cr was determined by chemical analysis. As

mentioned previously, most of the fuel crud is composed of NiFe_2O_4 and NiO . Therefore, it is possible to calculate the total oxide weight of the sample (the chromium oxide was assumed to be Cr_2O_3). Knowing the weight of each sample, the "specific" thickness (in terms of mg/cm^2) of the fuel crud can be estimated by dividing the weight by the area. This will result in a lower limit since (for the purpose of these calculations) it is assumed that all the crud is removed from the rod and collected by the sampling apparatus. If the crud density is known, the thickness in mils can also be calculated.

Using this method and assuming a crud density of $1.0 \text{ g}/\text{cm}^3$, the average calculated thickness of the fuel crud is 0.4 mil. This is smaller than the average value obtained from the flake measurements, possibly because of the collection efficiency or the density assumption.

Seven thickness determinations were obtained for each of assemblies 1A06 and 1A21. For assembly 1A06, the thicknesses obtained from three samples appear to be significantly lower than the other four samples, probably due to the lower collection efficiency for these samples. For assembly 1A21, all of the thickness measurements fall on a reasonable curve with the fuel crud being thickest in the center of the assembly. The microscope measurements of flake thickness also indicate this trend for 1A21.

3.6.6. Trace Element Analysis

Eleven of the crud samples, obtained from five fuel assemblies, were analyzed by emission spectroscopy to quantify the trace elements present. The results are listed in Table 9.

3.6.7. Summary of Crud Sampling Results

1. The average elemental composition of fuel crud is 40% Fe, 57% Ni, 3.5% Cr, and less than 0.9% Zr.
2. Fuel crud is composed primarily of 40% NiO and 60% NiFe_2O_4 by weight.
3. The average relative fuel crud radionuclide compositions are $^{58}\text{Co} = 1.00$, $^{51}\text{Cr} = 0.29$, $^{60}\text{Co} = 0.15$, $^{95}\text{Zr} = 0.084$, $^{54}\text{Mn} = 0.067$, $^{59}\text{Fe} = 0.039$, and $^{57}\text{Co} = 0.00095$.
4. The average specific activities are: $3.4 \times 10^7 \text{ dps } ^{51}\text{Cr}/\text{mg Cr}$, $9.8 \times 10^5 \text{ dps } ^{54}\text{Mn}/\text{mg Fe}$, $9.8 \times 10^6 \text{ dps } ^{58}\text{Co}/\text{mg Ni}$, and $5.8 \times 10^5 \text{ dps } ^{59}\text{Fe}/\text{mg Fe}$.
5. The average thickness of flake samples is 1.03 mils.

6. The average calculated thickness based on weight, area, and an assumed density value of 1.0 g/cm^3 is 0.4 mil.

7. Only a weak correlation exists between fuel burnup and fuel crud thickness.

3.7. Gamma Scans

Full-length, axial gamma-scan profiles were obtained on 107 corner rods. Each profile is a continuous plot of gamma count rate (energies $> 0.3 \text{ MeV}$) as a function of axial position along the rod. In most cases, two scans of approximately 4 in./min. were obtained on each rod.

Resolution was sufficient to allow the measurement of axial gaps and fuel column lengths. A portion of a typical trace is shown in Figure 10, which shows one end of the fuel column and a small gap due to a cracked pellet. The resolution of the scanner is illustrated by the fact that individual pellet interfaces can be seen in the traces.

3.7.1. Fuel Column Gap Measurements

Fuel column gap distributions (gap size and location in the fuel column) were obtained on all 107 rods. The limiting gap size considered was about 0.1 inch for most scans since smaller gaps could not be accurately measured (the slit width of the scanner was approximately 0.1 inch). In addition, faster scans on the last 32 rods prevented measurement of gaps less than about 0.2 inch.

3.7.1.1. Data

For most purposes, only gaps greater than 0.25 inch are of interest. A total of 73 such gaps were found in the 107 rods scanned, with the following distribution:

- 57 rods with no gaps > 0.25 inch
- 32 rods with one gap > 0.25 inch
- 13 rods with two gaps > 0.25 inch
- 5 rods with three gaps > 0.25 inch

A plot of gap size versus location for each of the 73 gaps is shown in Figure 11; Figure 12 shows frequency distributions for size and location. For the rods in which accurate data on small gaps (< 0.25 inch) were obtained, such gaps outnumbered large gaps by three to one. For 92 rods, the total gap length was calculated; the distribution is shown in Figure 13.

3.7.1.2. Discussion

The in-core gap-forming mechanisms of pellet hangup followed by fuel shrinkage due to either cooldown or densification are quite similar in their end result. Both result in a gap size distribution that is approximately linear along the fuel column length with essentially no gaps possible at the bottom and with a certain maximum size possible at the top. For average irradiation conditions, the maximum gap size that could possibly form due to differential thermal expansion is about 0.5 inch. For densification shrinkage, the maximum possible gap size varies with several parameters, but could be as high as 2.5 inches. Thus, a total cold gap of 3 inches could occur at the top due to fuel shrinkage.

It is obvious from Figure 11 that the mechanism cannot explain all the gaps seen. There are about a dozen gaps at the bottom that are simply too large. It appears that the only remaining cause is fuel handling after cycle 1. The most likely source is the fuel assembly transfer device between the reactor building and the spent fuel storage pool. This transfer is done with the assembly horizontal, moving head first into the pool building. It is possible that the deceleration from 1 in./s to rest could shift the fuel column and wedge some pellet chips between the fuel and cladding at any location. The ability of the fuel column to move has been observed in gamma scans on fuel assemblies in the subsequent destructive examination; some gaps disappeared after shipping and handling. To aid in reducing gap formation, the collapsible corrugated spacers used in the original Mk-B fuel rod design have subsequently been replaced by restraining springs.

3.7.2. Pellet Stack Length Measurements

Of the 107 rods scanned, stack lengths were obtained on 92 of the rods. This length was obtained by measuring the chart paper length from the top to the bottom of the fuel column and then subtracting the total gap length. A built-in calibration was available to ensure reasonably good accuracy on the top-to-bottom measurement.

Stack length data for the individual rods were compiled along with pertinent gap information and operating characteristics. Figure 14 is a plot of stack length versus rod average heat rate during cycle 1. The broken lines on the figure represent the spread in as-built tolerance on the stack length which accounts for much of the data variation.

A linear least-square fit to the data in Figure 14 results in a negative slope of only 0.081 in. per kW/ft. The correlation coefficient is almost zero. Attempts to correlate the stack length with other operational parameters (such as maximum heat rate during any 100-day operating period) were also unsuccessful. Analysis of the data for the 72 rods at high heat rate (average > 6.5 kW/ft) showed little difference from the full set of 92 rods.

The most probable explanation for the wide variation in the data and apparent lack of correlation is the fuel itself. Ocone 1 core 1 contained 65 different fuel lots, each with its own particular tendency to densify. Lack of resinter data on the individual pellet lots made it impossible to analyze each rod individually.

3.7.3. Fuel Rod Corrugated Spacer Length

In some of the gamma scans, it was possible to determine the distance from the bottom of the fuel column down to the top of the lower skirt. A decrease in this dimension below the as-built value of 0.125 inch would indicate compression of the lower corrugated spacer. However, measurements on 20 rods from five assemblies indicated little or no compression of the spacer.

Table 3. Data Obtained on Oconee 1, EOC 1 Fuel

	<u>Refueling phase</u>	<u>Post- refueling</u>
Fuel assemblies examined	6	30
Assembly lengths measured	5	3
Rod lengths measured	24	24
Rods gamma-scanned	20	87
Holddown springs measured	2	4
Rods line-scanned	43	30
Channel spacings measured	4700	2400
Crud samples taken	--	22
Control rod assembly examined	1	--
Orifice rod assemblies examined	--	2

Table 4. Holddown Spring Results

<u>Fuel assembly</u>	<u>Assembly burnup, MWd/mtU</u>	<u>Fluence at spring, n/cm² > 1 MeV</u>	<u>EOC 1 preload, lb</u>	<u>EOC 1 spring rate, lb/in.</u>
1C30	6,376	5.0×10^{19}	427	193
1C63	7,624	5.5×10^{19}	400	177
1A16	10,530	7.5×10^{19}	400	169
1A19	11,316	8.0×10^{19}	395	175
1A35	12,098	8.0×10^{19}	400	170
1B43	12,270	8.5×10^{19}	412	172

Note: BOL preload tolerance = 350 to 495 lb.

Table 5. Fuel Assembly Growth and Grid Location Data

Location (Fig. 16)	Growth	1C73	1C56	1C66	1C44	1C63	1A16	1B43	1B41
	Fluence								
N	$\Delta L/L$	0.00139	0.00148	0.00126	0.00145	0.00152	0.00233	0.00129	0.00188
	$nvt \times 10^{-21}$	1.631	1.525	1.631	1.755	1.246	1.753	2.063	2.063
K	$\Delta L/L$	0.00198	0.00197	0.00168	0.00187	0.00181	0.00226	0.00206	0.00206
	$nvt \times 10^{-21}$	1.631	1.525	1.631	1.755	1.246	1.753	2.063	2.063
J	$\Delta L/L$	0.00185	0.000881	0.00105	0.00196	0.00151	0.00234	0.00222	0.00204
	$nvt \times 10^{-21}$	1.740	1.626	1.740	1.882	1.335	1.887	2.191	2.191
H	$\Delta L/L$	0.00174	0.00153	0.00134	0.00190	0.00224	0.00203	0.00161	0.00153
	$nvt \times 10^{-21}$	1.741	1.626	1.741	1.895	1.346	1.922	2.180	2.180
G	$\Delta L/L$	0.000607	0.00116	0.00188	0.00172	0.00232	0.00229	0.00057	0.001085
	$nvt \times 10^{-21}$	1.702	1.588	1.702	1.866	1.330	1.930	2.115	2.115
F	$\Delta L/L$	0.000417	0.000561	0.00202	0.00174	0.00230	0.00269	0.00645	0.00112
	$nvt \times 10^{-21}$	1.624	1.510	1.624	1.796	1.295	1.928	1.992	1.992
E	$\Delta L/L$	0.00083	0.000867	0.00289	0.00258	0.00207	0.00344	0.00227	0.00152
	$nvt \times 10^{-21}$	1.624	1.510	1.624	1.796	1.295	1.883	1.765	1.765
D	$\Delta L/L$	-0.00216	0.00132	0.00235	0.00317	0.00187	0.00367	-0.00093	0.00425
	$nvt \times 10^{-21}$	1.123	1.013	1.123	1.235	0.945	1.552	1.351	1.351

Table 6. Fuel Rod Growth Data

<u>FA No.</u>	<u>Fuel rod</u>	<u>$\Delta L/L$</u>	<u>Fluence > 1 MeV, $n/cm^2 \times 10^{-21}$</u>
1A16	B5	0.0025	1.992
	C5	0.0023	1.992
	D5	0.0024	1.992
	B11	0.0023	1.992
	D11	0.0022	1.992
1B43	A5	0.0021	2.062
	B5	0.0022	2.172
	C5	0.0025	2.138
	D5	0.0021	1.953
	A11	0.0017	2.133
	B11	0.0019	2.168
	C11	0.0018	2.082
	D11	0.0019	1.944
1B41	A5	0.0023	1.944
	B5	0.0020	2.082
	C5	0.0023	2.168
	D5	0.0023	2.133
1C56	A11	0.00219	1.794
	A5	0.00254	1.683
	B11	0.0021	1.540
	B5	0.00256	1.751
	C11	0.0019	1.096
	C5	0.00206	1.275
	D11	0.00191	1.459
	D5	0.00198	1.177
1C44	A11	0.00174	2.024
	A5	0.00202	2.024
	B11	0.00190	1.716
	B5	0.00225	1.913
	C11	0.00161	1.556
	C5	0.00156	1.556
	D11	0.00117	1.913
	D5	0.00120	1.716

Table 7. Rod Gap Data Summary

Magnitude: 95% (2σ) of gaps show 0.014 inch or less change from as-built.

Only four gaps out of 7164 showed closure in excess of 0.030 inch.

Precision: ± 0.006 -inch based on repeat runs on the same water channels.

Trends: Increase in rod bow toward bottom of assembly.

Larger bow associated with outer rods (higher grid spring force).

Slight increase in bow with increased burnup. Average fuel assembly burnup ranged from 6376 to 10,530 MWd/mtU.

Slight but consistent correlation with as-built gaps.

Table 8. Line Scan Rod Bow Results

Data base: 81 scans from eight assemblies, including 11 rods with traces in two directions. Rod burnup range from 3800 to 13,000 MWd/mtU.

Magnitude: 95% (2σ) of gaps show 0.0212 inch or less change from as-built.

Precision: ± 0.010 -inch based on repeat runs on same rods and traces on reference rod.

Trends: No apparent effects of flux gradient.

No pronounced burnup effects.

No major differences between corner and other peripheral rods.

General increase in bow magnitude toward bottom of bundle.

Primarily single loop per span, 85%. (No double loop with magnitude in excess of 0.010 inch.)

Primarily sinusoidal (changes direction in adjacent spans).

Table 9. Emission Spectroscopic Analysis of Crud Samples

Assembly No.	Content, wt %											
	Al	Cr	Mo	Zr	Ca	Cu	Co	Mg	Mn	Sn	Ti	W
1A06	5	3	3	6	0.3	0.7	0.3	<0.07	0.3	<0.07	<0.07	<0.07
	0.7	2	2	2	0.3	0.3	0.1	0.05	0.1	0.1	0.3	0.3
	0.8	<1	0.1	>1	0.1	0.01	0.05	0.08	0.08	0.1	0.3	0.09
	5	5	2	>5	0.5	0.4	0.2	0.3	0.3	0.4	2	<0.05
1A21	0.08	0.7	0.08	>0.8	0.008	0.08	0.07	<0.008	<0.008	0.08	0.2	0.08
	1	1	1	0.9	0.1	0.08	0.08	0.04	0.1	0.1	0.1	0.1
	1	1	0.1	>1	0.1	0.1	0.1	<0.01	<0.01	0.1	0.5	0.1
	2	1	1	>4	0.04	<0.04	<0.04	<0.04	<0.04	<0.04	0.2	0.04
1A25	3	1	0.2	3	0.03	0.3	<0.03	<0.03	0.07	0.03	0.3	<0.03
1A23	0.8	2	2	2	0.02	0.2	<0.02	<0.02	<0.02	0.02	0.2	0.2
1A26	0.4	1	0.8	>4	0.3	0.4	<0.04	<0.04	0.3	0.02	<0.04	<0.04
Average	1.8	1.8	1.1	2.8	0.16	0.26	0.13	0.12	0.18	0.11	0.46	0.13

Figure 4. Length Measurement Nomenclature

Figure 5. Fuel Assembly Growth Data

Figure 6. Fuel Rod Growth Data

Figure 7. Distribution of Rod Gap Changes
(EOC 1 Gap Minus As-Built Gap)

Figure 8. Effect of Burnup on Rod Gap Distribution (Seven Mid Plane Elevations)

Figure 9. Rod Gap Distributions for Internal and Peripheral Rods

Figure 10. Portion of Gamma Scan Trace

$E_\gamma > 0.3 \text{ MeV}$

Figure 11. Axial Distribution of Fuel Column Gaps — Gamma Scans of
107 Rods — 73 Gaps > 0.25 Inch

Figure 12. Fuel Column Gap Frequency Distributions

Data Set: 73 Gaps > 0.25 in. (107 Rods Scanned)

Figure 13. Total Gap Length Frequency Distribution

Figure 14. Fuel Column Length Vs Rod Average Heat Rate (92 Rods Scanned)

4. CONCLUSION

Summarized below are pertinent comments on the results of measurements on each major parameter along with conclusions and potential problem areas uncovered.

1. Visual examinations revealed that the structural integrity of the fuel rods and assemblies was sound except for two isolated rod defects.
2. Holddown spring relaxation was quite small, indicating no problems with lift margin.
3. Assembly and rod axial growth was about as expected from Zircaloy-4 irradiation studies. No evidence of pellet-cladding interaction was noted.
4. The average of the maximum assembly bow was 0.108 inch and tended to be outward from the core center.
5. Row bow was quite small.
6. Crud composition was about as expected, consisting primarily of NiO and NiFe_2O_4 . The appearance of the assemblies suggests that crud deposition is quite variable. Also, it is not known how closely the sampled crud resembles that on the rods during operating conditions. The crud thickness measurements were not direct and involved only a portion of the crud layer removed during the sampling operation. Consequently, conclusions on thickness must be made with care.
7. Fuel stack length changes were somewhat less than expected from the densification model, but the lack of precise as-built data resulted in a large amount of scatter.
8. Fuel column gaps were noted and explained for the most part by normal operating conditions of thermal expansion and densification. However, a few cases of larger gaps in the bottom areas of the rod suggest that some gaps are formed from handling operations. Subsequent replacement of the corrugated spacers with restraining springs should provide a restraining force to minimize fuel column gap formation in future fuel rods.

9. Corrugated spacers showed no indication of being compressed below the as-built values.

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