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MASTER

THE EVALUATION AND DEMONSTRATION OF METHODS FOR IMPROVED FUEL UTILIZATION

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END-OF-CYCLES 4 AND 5 POOLSIDE INSPECTION PROGRAMS

Prepared for
The United States
Department
of Energy

Omaha Public Power District

GE POWER
SYSTEMS

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EVALUATION AND DEMONSTRATION
OF METHODS FOR IMPROVED
FUEL UTILIZATION

FORT CALHOUN POOLSIDE INSPECTION PROGRAMS
END-OF-CYCLES 4 AND 5

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ABSTRACT

The purpose of this program is to demonstrate two techniques for improving fuel utilization in current Pressurized Water Reactors (PWR): (1) more efficient fuel management, and (2) high burnup. These improvements are being demonstrated in the Fort Calhoun reactor, a 1420 Mwt PWR. A more efficient fuel management scheme called SAVFUEL (Shimmed And Very Flexible Uranium Element Loading), will be demonstrated which reduces neutron leakage and is expected to reduce uranium requirements. Another part of the demonstration program will increase the fuel burnup of the current 14 x 14 fuel design to further reduce uranium requirements. The program is a joint Department of Energy (DOE), Omaha Public Power District (OPPD) and Combustion Engineering (C-E) endeavor and is part of a national effort to improve uranium utilization in light water reactors.

The current Phase I of the program will be accomplished in two parts. Phase IA will demonstrate the SAVFUEL management scheme and Phase IB will demonstrate increased burnup capability of standard design fuel. SAVFUEL management causes some fuel rods to experience a different power history as compared to the present conventional management scheme. Therefore, Phase IA will demonstrate that this duty cycle does not have a deleterious effect on fuel performance. Phase IB will include poolside examinations of fuel rods and fuel assemblies and hot cell examination of selected fuel rods which will be irradiated for three, four and five cycles and are expected to achieve a peak rod average burnup of greater than 45 GWD/MTU.

This report covers the poolside inspection after the first cycle of irradiation of the SAVFUEL demonstration assemblies (Cycle 5) and the third and fourth cycles of the high burnup demonstration assemblies (Cycles 4 and 5). The inspections consisted of visual and dimensional examinations to assure that the SAVFUEL and the high burnup demonstration fuel assemblies were in good condition and could be reinserted in the core for the next reactor cycle.

Summary

The general objective of the program is to demonstrate two techniques for improving uranium resource utilization in current Pressurized Water Reactors. These two techniques are: (1) to develop and demonstrate a low leakage fuel management scheme and (2) to extend discharge burnup for the current 14X14 fuel design. These demonstrations are being performed in the Fort Calhoun Reactor located near Omaha, Nebraska. Phase I, the current program, consists of lead bundle demonstrations of the uranium utilization improvements. These lead bundle demonstrations will be followed by a core-wide implementation in a future Phase II demonstration program.

Part A of Phase I will be a demonstration, in Cycles 5, 6, and 7 that the different power history of the SAVFUEL (1,2,3) (Shimmed And Very Flexible Uranium Element Loading) fuel management scheme does not cause detrimental effects on fuel performance. The four assemblies which will experience the modified power duty cycle are part of Batch G inserted in Fort Calhoun in December, 1978.

Part B of Phase I includes poolside and hot cell examinations of fuel rods which will have been irradiated for three, four, and five cycles and will have achieved an anticipated peak rod average burnup of greater than 45 GWD/MTU. Most of the rods to be examined are from Batch D, which was inserted in the core at the beginning of Cycle 2 in May, 1975. This report presents the results of the poolside examinations after Reactor Cycle 4 and Cycle 5.

The fresh "G" fuel assemblies were loaded on the periphery of the core for Cycle 5 and have accumulated approximately 7.1 GWD/MTU at the end of Cycle 5. For Cycle 6, these assemblies were returned to the periphery of the core, but rotated such that some of the rods in the assembly simulate the SAVFUEL power cycle. For the final cycle, the fuel assemblies will be moved to interior core locations.

Seventeen "D" assemblies have accumulated 4 Cycles of exposure at end-of-cycle 5 (approximately 33.4 GWD/MTU assembly average burnup) and one fuel assembly from this group (D005) was returned to the core for a fifth cycle.

A brief visual exam was performed at end-of-cycle 4 and a poolside inspection after end-of-cycle 5 was carried out in February 1980. All four "G" and 17 "D" fuel assemblies were visually inspected by remote television techniques and were found to be in excellent condition. Shoulder gap measurements were taken on 5 fuel assemblies (4 "G" and 1 "D"). These measurements indicate sufficient clearances to permit further irradiation of the assemblies.

In the case of assembly D005, sufficient clearance between the fuel rods and upper end fitting (UEF) was found to be present to conservatively allow 5 cycles of operation. The maximum shoulder gap closure for the "D" fuel assembly was 62%.

Measurements of fuel rod bow were taken by examining the video tapes and recording the channel widths on selected assemblies. Channel widths between peripheral fuel rods were measured for 3 fuel assemblies (2 "G"'s and one "D") and were found to be consistent with C-E's past experience⁽⁴⁾. The maximum channel closures were 36% for the "G" fuel assemblies and 34% for the "D" fuel assembly. The worst channel closure at the 95th percentile of probability for the worst span in the fuel assembly (the second span from the bottom) was 13% for the "G" fuel assemblies and 24% for the "D" fuel assembly.

Fuel assembly growth was measured for one "D" fuel assembly after 4 operating cycles and found to be approximately 0.12% which agrees well with previously reported data⁽⁵⁾ for annealed Zircaloy after an exposure of approximately 7.5×10^{21} nvt (fast neutron fluence with neutron energy greater than .821 MeV).

TABLE OF CONTENTS

<u>SECTION</u>	<u>PAGE NO.</u>
ACKNOWLEDGEMENTS	i
ABSTRACT	ii
SUMMARY	iii
1.0 Introduction	1
2.0 Background	
2.1 Fort Calhoun Operating History	2
2.2 Fuel Assembly and Rod Design	2
2.3 Demonstration Assemblies Irradiation History	10
2.4 Inspection Program	20
3.0 Discussion of Results	
3.1 Introduction	23
3.2 Visual Inspection Results	23
3.3 Shoulder Gap Measurements	24
3.4 Fuel Assembly Growth	29
3.5 Fuel Rod Channel Widths	36
4.0 References	
Appendix A - Characterization Measurements for Batch "G" SAVFUEL Demonstration Assemblies G-037, -038, -040, and -041	
Appendix B - Characterization Measurements for High Burnup Demonstration Assembly D005	
Appendix C - Description of Portable Fuel Inspection Stand - "Mini-Stand"	
Appendix D - Explanation and Measurement Techniques	

TABLES

<u>TABLE</u>	<u>TITLES</u>	<u>PAGE NO.</u>
2.1-1	Fort Calhoun Operating History	2
2.2-1	Fuel Rod Design Parameters	7
2.2-2	Batch "D" Pre-Irradiation Characterization	8
2.2-3	Batch "G" Pre-Irradiation Characterization	9
2.3-1	End-of-Cycle 5 Burnup Summary for Four Cycle Irradiated Batch D High Burnup Demonstration Assemblies	19
3.3-1	End-of-Cycle 5 Fuel Rod Shoulder Gap Measurements	30
3.4-1	Fuel Assembly Length Increases	38
3.5-1	Summary of End-of-Cycle 5 Channel Width Measure- ments for Fuel Assemblies G040 and G041	39
3.5-2	Summary of End-of-Cycle 5 Channel Width Measure- ments for Fuel Assembly D005	40

ILLUSTRATIONS

<u>FIGURE</u>	<u>TITLE</u>	<u>PAGE</u>
2.1-1	Fort Calhoun Reactor Operating History	3
2.2-1	Schematic of "D" Assembly and Fuel Rod	5
2.2-2	Schematic of "G" Assembly and Fuel Rod	6
2.3-1	Core Map Showing the Location of Fuel Assemblies G-037, -038, -040, and -041 for Cycles 5 and 6	11
2.3-2	Core Map Showing the Location of Fuel Assembly D005 for Cycles 2 through 6	12
2.3-3	Core Map Showing the Locations of the "D" Fuel Assemblies in Their 4th Exposure Cycles (5th Reactor Cycle)	13
2.3-4	Assembly Average Power from Assembly D005 for Reactor Cycles 2 through 5	14
2.3-5	Normalized Axial Power Shape in Assembly D005 for Reactor Cycles 2 through 5	15
2.3-6	SAVFUEL Assembly Peak Rod Power History	16
2.3-7	EOC-5 Pin-by-Pin Axially Averaged Burnup for D005 Assembly	17
2.3-8	EOC-5 Pin-by-Pin Axially Averaged Fluence for D005 Assembly	18
2.3-9	EOC-5 Pin-by-Pin Axially Averaged Burnup for "G" Demonstration Assemblies	21
2.3-10	EOC-5 Pin-by-Pin Axially Averaged Fluence for "G" Demonstration Assemblies.	22
3.2-1	Assembly D005, Upper End Fitting	25
3.2-2	Assembly D005, Between Grids 4 and 5	25
3.2-3	Assembly D005, Grid 4	26
3.2-4	Assembly D005, Inconel Grid/Lower End Fitting	26
3.2-5	Assembly G038, Upper End Fitting	27
3.2-6	Assembly G038, Between Grids 4 and 5	27

ILLUSTRATIONS (cont'd)

<u>FIGURE</u>	<u>TITLE</u>	<u>PAGE</u>
3.2-7	Assembly G038, Grid 4	28
3.2-8	Assembly G038, Inconel Grid	28
3.3-1	Peripheral Fuel Rod Shoulder Gaps as a Function of Axially Averaged Rod Burnup	34
3.3-2	Histogram of Fuel Assembly D005 Shoulder Gap Closure	35
3.4-1	Fort Calhoun Fuel Assembly D005, Growth Data Compared with Previously Reported Data	37
3.5-1	Histogram of Fuel Assembly D005 Channel Closure	41
3.5-2	Histogram of Fuel Assembly G040 and G041 Channel Closure	42
3.5-3	Worst Span Channel Closure at the 95th Percentile	44
A-1	Location of Characterized Rods in Batch "G" SAVFUEL Demonstration Assemblies	A-7
C-1	Portable Fuel Inspection Stand - "Mini-Stand"	C-3
D-1	Assembly D005, Upper End Fitting High Magnification View Typical of What was Used to Measure Shoulder Gaps	D-2

1.0 Introduction

In 1977, a major change in United States nuclear energy policy was announced which was to defer the plutonium fuel breeder as well as commercial reprocessing and recycling of plutonium in conventional light water reactors. At the same time, United States energy policy called for a reduction of the nation's reliance on oil and natural gas through an increased and more efficient use of current generation light water reactors. In recognition of this requirement, the United States Department of Energy has initiated a uranium utilization improvement program for light water reactors. This program seeks to develop and demonstrate a number of fuel design and operation procedure modifications which result in improved uranium utilization.

The current program being performed by Combustion Engineering and Omaha Public Power District has the objective of demonstrating two improvements. The first is a low leakage fuel management concept called SAVFUEL (Shimmed and Very Flexible Uranium Element Loading) which is expected to reduce uranium requirements by two to four percent (2% to 4%). The second improvement is to be achieved by demonstrating increased burnup capability of the current (14X14) fuel design to a peak rod average burnup of 45 GWD/MTU (batch average burnup 37 GWD/MTU) which will further reduce uranium requirements by five to fifteen percent (5% to 15%) depending on the means chosen to exploit the additional burnup capability of the fuel. A detailed description of the current program is presented in the first semi-annual report ⁽²⁾.

Section 2.0 of this report presents background information; the Fort Calhoun operating history, the irradiation history of the fuel assemblies, the fuel assembly and fuel rod designs and a brief description of the poolside inspection plan at end-of-Cycle 5. Section 3.0 presents the results of the inspections. Additional details on the pre-irradiation characterization data, the inspection equipment, and the examination and measurement techniques are presented in the Appendices.

2.0 Background

2.1 Fort Calhoun Operating History

Fort Calhoun is a Combustion Engineering-built PWR which is owned and operated by the Omaha Public Power District. The reactor achieved initial criticality on August 5, 1973 and began commercial operation September 25, 1973. The reactor operating history relative to this program is shown below in Table 2.1-1.

TABLE 2.1-1

FORT CALHOUN OPERATING HISTORY

Cycle	Start	End	Core Average linear heat generation rate(kw/ft) at 100% power	Core Average Burnup (GWD/MTU)
2	5-75	10-76	5.8	10.9
3	12-76	9-77	5.73	7.7
4	11-77	10-78	5.69	8.1
5	12-78	1-80	5.69	10.5

The thermal power rating of the core is 1420 Mwt.* Except for refueling outages, the core has operated at essentially 90 - 100% of rated power during the irradiation history of fuel assemblies in this program as shown in Figure 2.1-1.

2.2 Fuel Assembly and Rod Design

The fuel assemblies in the program are standard batch "D" and batch "G" assemblies which were inserted at the beginning of Reactor Cycles 2 and 5, respectively. All these assemblies are reconstitutable, that is, the upper end fitting is remotely removable allowing access to all fuel rods

* A submittal is before the NRC to increase the power rating to 1500 Mwt.

Figure 2.1-1
FORT CALHOUN REACTOR OPERATING HISTORY

REACTOR OPERATING PARAMETERS

100% POWER	1420 MWT
SYSTEM PRESSURE	2100 PSI
REACTOR INLET TEMPERATURE	535 °F
REACTOR OUTLET TEMPERATURE	587 °F
COOLANT FLOW @ 100% POWER	2.10×10^6 LBS/HR·FT ²
AVERAGE CORE LINEAR HEAT RATE	5.80 KW/FT

for removal and replacement. Each fuel assembly contains 176 fuel rods in a 14 X 14 array. The structural material employed in the fuel assembly is Zircaloy-4 to reduce parasitic neutron absorption except for the upper and lower stainless steel end fittings and an Inconel spacer grid at the bottom which are away from the high neutron flux region of the core.

There are slight design differences in the "D" and "G" batch assemblies as shown in Figures 2.2-1 and 2.2-2 and Table 2.2-1. The main difference in the fuel assembly design is that the "G" assemblies have a flow skirt between the bottom grid and the lower end fitting to reduce coolant cross flow and the bottom grids for the "D" assemblies are attached by means of straps.

In addition to the standard quality control inspections, the demonstration assemblies associated with this program were characterized before insertion into the reactor. The scope of these specific measurements is shown in Tables 2.2-2 and 2.2-3. Summaries of the characterization measurements are presented in Appendices A and B. Selected data from the characterization will be reported in detail to the Nuclear Fuels Performance Data Base coordinated and maintained by Science Applications Inc. under Electric Power Research Institute contract.

The specific pre-irradiation characterization differs between batches "D" and "G". Batch "D" was characterized in 1975 to provide measurements for following the general performance of Fort Calhoun fuel. The four batch "G" fuel assemblies were characterized in 1978 for the specific purpose of the SAVFUEL program.

Figure 2.2-1
SCHEMATIC OF "D" ASSEMBLY AND FUEL ROD

Figure 2.2-2

SCHEMATIC OF "G" ASSEMBLY AND FUEL ROD

* ALL DIMENSIONS IN INCHES

TABLE 2.2-1
FUEL ROD DESIGN PARAMETERS

<u>FUEL</u>	<u>TYPE D</u>	<u>TYPE G</u>
active length, inches	128	128
pellet OD, inches	0.3805	0.3765
pellet length, inches	0.450	0.450
pellet L/OD	1.2	1.2
enrichment, % U ₂₃₅	2.97	3.03
 <u>CLADDING</u>		
material	Zircaloy-4	Zircaloy-4
OD, inches	0.440	0.440
ID, inches	0.388	0.384
wall thickness, inches	0.026 nominal	0.028 nominal
wall thickness/OD	0.059	0.064
condition	stress relief annealed	stress relief annealed
 <u>ROD</u>		
overall length, inches	136.7	136.7
initial helium fill pressure, psig	400	360
nominal pellet/clad diametral gap, mils	7.5	7.5

TABLE 2.2-2

BATCH "D" PRE-IRRADIATION CHARACTERIZATION

<u>CHARACTERIZATION</u>	<u>BATCH "D" FUEL ASSEMBLIES (D005)</u>
<u>Fuel Pellets</u>	
Lot Number	4 rods/assembly
Chemical and Physical Properties	4 rods/assembly
<u>Fuel Rods</u>	
Overall length	4 rods/assembly
Radiographs of Plenum	4 rods/assembly
Profilometry	4 rods/assembly
Fuel Cladding Certification Data	2 assemblies
Cladding Wall Thickness	4 rods/assembly
Fuel Stack Weight	2 assemblies
<u>Fuel Assembly</u>	
Rod Location and Serial No.	2 assemblies
Shoulder Gaps	2 assemblies, 8 corner rods
Guide Tube Length	2 assemblies
Overall Length	2 assemblies
Spacer Grid Width	2 assemblies, all grids

TABLE 2.2-3

BATCH "G" PRE-IRRADIATION CHARACTERIZATIONCharacterizationBatch "G" Fuel Assemblies
(G037, 038, 040, and 041)Fuel Pellets

Lot Number	4 assemblies
Chemical and Physical Properties	4 assemblies

Fuel Rods

Overall Length	12 rods/assembly
Radiography of Plenum	12 rods/assembly
Profilometry	12 rods/assembly
Archive Rods	2 rods
Fuel Stack Weight	4 assemblies

Fuel Assembly

Rod Location and Serial No.	4 assemblies
Shoulder Gaps	4 assemblies/all peripheral and characterized rods
Guide Tube OD	2 assemblies
Guide Tube Length	4 assemblies
Spacer Grid Width	1 assembly, all grids
Peripheral Fuel Rod Channel Widths	2 assemblies, selected spans

2.3 Demonstration Assemblies Irradiation History

As previously described in Section 2.1, the Ft. Calhoun reactor was operated at essentially full power since the start of Cycle 2. The average linear heat generation rate for the core at 100% core power is 5.69 kw/ft for a core without burnable poison rods.

The core locations of the demonstration fuel assemblies during their exposure cycles are shown in Figures 2.3-1, and 2.3-2, and 2.3-3.

The axially averaged assembly power for each of the four reactor cycles (i.e., cycles 2-5) for fuel assembly D005 is shown in Figure 2.3-4, which presents the changes in power which occurred with increasing burnup and as the fuel assembly was shifted in the core. The maximum power reached was 6.6 kw/ft during Reactor Cycle 3 and diminished to 4.0 kw/ft during the last part of Reactor Cycle 5.

The cycle averaged axial power distribution for each cycle of D005's history (Figure 2.3-5) shows that the cycle averaged axial peaking factors were between 1.10 and 1.12 throughout its irradiation history.

The peak rod power versus the peak rod burnup for the four (4) batch "G" SAVFUEL demonstration assemblies has been plotted in Figure 2.3-6. Peak rod power is plotted against peak rod burnup because it is the rods with peak power in the first power cycle that will more directly represent the duty cycle associated with SAVFUEL. The peak rod power reached 7.6 kw/ft at the beginning of Cycle 5 and tapered off to 6.1 kw/ft at the end of that cycle.

Figures 2.3-7 and -8 present the pin-by-pin axially averaged burnups and fluences, respectively, for Assembly D005. The assembly average burnup after four cycles was 37.2 GWD/MTU, while rod average burnups ranged from 34.7 to 40.0 GWD/MTU. The assembly average and peak rod average burnups for all "D" fuel assemblies in the High Burnup Program are shown in Table 2.3-1. Since D005 has occupied the central position in the core during Reactor Cycle 5, it has achieved the highest burnup.

Figure 2.3-1
CORE MAP SHOWING THE LOCATION OF FUEL ASSEMBLIES G-037, 038, 040
AND 041 FOR CYCLES 5 AND 6

Figure 2.3-2
CORE MAP SHOWING THE LOCATION OF FUEL ASSEMBLY D005
FOR CYCLES 2 THROUGH 6

Figure 2.3-3
CORE MAP SHOWING THE LOCATIONS OF THE BATCH "D" HIGH BURNUP
DEMONSTRATION ASSEMBLIES IN THEIR 4TH EXPOSURE CYCLE
(5TH REACTOR CYCLE)

Figure 2.3-4

ASSEMBLY AVERAGE POWER FROM ASSEMBLY D005 FOR REACTOR CYCLES 2 THROUGH 5

Figure 2.3-5
NORMALIZED AXIAL POWER SHAPE IN ASSEMBLY D005
FOR REACTOR CYCLES 2 THROUGH 5

Figure 2.3-6
SAVFUEL ASSEMBLY PEAK ROD POWER HISTORY
CYCLE 5

Figure 2.3-7

EOC-5 PIN-BY-PIN AXIAL AVERAGE BURNUPS ^(a) FOR ASSEMBLY D005

SOUTH FACE	38.15	38.15	38.35	38.16	37.53	36.88	36.53	35.03	35.36	35.98	36.59	36.77	36.58	36.58
	38.10													36.53
	38.30													36.72
	38.12													36.55
	37.48													35.94
	36.81													35.29
	36.43													34.93
	37.04													35.31
	37.42													35.68
	38.10													36.33
	38.75													36.94
	38.93													37.12
	38.73													36.92
	38.78	38.78	38.99	38.79	38.15	37.49	37.14	35.41	35.74	36.37	36.98	37.17	36.97	36.97

(a) BURNUPS IN GWD/MTU

Figure 2.3-8
EOC-5 PIN-BY-PIN AXIAL AVERAGE FLUENCES (a) FOR ASSEMBLY D005

SOUTH FACE	7.51	7.51	7.51	7.52	7.56	7.60	7.62	7.31	7.29	7.26	7.22	7.20	7.20	7.20
	7.63													7.22
	7.54													7.23
	7.56													7.25
	7.61													7.30
	7.66													7.34
	7.68													7.36
	7.81													7.44
	7.78													7.42
	7.74													7.38
	7.69													7.33
	7.67													7.31
	7.66													7.30
	7.63	7.64	7.63	7.65	7.69	7.73	7.75	7.39	7.37	7.33	7.29	7.28	7.28	7.28

(a) VALUES INDICATED ARE $\times 10^{21}$ ($E > 0.821$ MeV)

Table 2.3-1

END-OF-CYCLE 5 BURNUP SUMMARY FOR FOUR CYCLESIRRADIATED BATCH D HIGH BURNUP DEMONSTRATION ASSEMBLIES

<u>ASSEMBLY SERIAL #</u>	<u>CYCLE 5 CORE LOCATION</u>	<u>ASSEMBLY AXIAL AVG. B/U (GWD/MTU)</u>	<u>PEAK ROD AXIAL AVG. B/U (GWD/MTU)</u>
D005	J9	37.2	40.0
D038	G2	33.7	38.4
D034	L2	33.7	38.4
D032	G16	33.7	38.4
D029	L16	33.7	38.4
D040	D3	33.1	38.3
D028	P3	33.1	38.3
D036	D15	33.1	38.3
D033	P15	33.1	38.3
D044	C4	33.1	38.2
D035	R4	33.1	38.2
D042	C14	33.1	38.2
D039	R14	33.1	38.2
D037	B7	33.7	37.8
D031	B11	33.7	37.8
D030	S11	33.7	37.8
D027	S7	33.7	37.8

Figures 2.3-9 and -10 present the pin-by-pin axially averaged burnups and fluences, respectively, for the SAVFUEL demonstration assemblies. The individual rod histories for each of the SAVFUEL assemblies are essentially identical to each other due to residence in symmetric core locations in Cycle 5 as was shown in Figure 2.3-1. The axially averaged burnup for the "G" fuel assemblies after their first cycle was 7.1 GWD/MTU with a peak burnup of 11.7 GWD/MTU for the lead rod.

2.4 Inspection Program

As each cycle is completed in Phase I, poolside inspections of the fuel assemblies will be performed. Through these inspections, the condition of the assemblies is determined allowing the assessment of performance to be made and decisions to be made as to the further irradiation capability of the fuel. Poolside inspections are scheduled after the first*, second and third irradiation cycles of the SAVFUEL assemblies and after the third*, fourth*, and fifth irradiation cycles of the high burnup assemblies.

The end of Reactor Cycle 5 inspection which is the inspection after the first SAVFUEL cycle and the fourth high burnup cycle was performed with an inspection stand that attaches to a spent fuel rack location. A description of the stand, called the Mini-Stand⁽⁶⁾, is presented in Appendix C. The inspection was carried out by remote television viewing and consisted of the following examinations:

INSPECTION	"D" FUEL ASSEMBLIES	"G" FUEL ASSEMBLIES
Visual	17	4
Shoulder Gaps	1	4
Fuel Assembly Length	1	None
Fuel Rod Channel Width	1	2

The procedures and accuracies for performing these inspections are described in Appendix D, Examination and Measurement Techniques.

*These inspections have already been completed and are the subject of this report.

Figure 2.3-9

(a)
EOC-5 PIN-BY-PIN AXIAL AVERAGE BURNUPS FOR "G" SAVFUEL
DEMONSTRATION ASSEMBLIES

G041 SOUTH FACE

	2.65	2.89	3.18	3.41	3.58	3.73	3.92	4.13	4.39	4.69	4.98	5.16	5.25	5.39	
	2.98	3.34											5.97	6.00	
	3.36													6.67	
	3.72													7.21	
	4.01													7.69	
	4.32													7.95	
	4.67													8.38	
	5.09													8.88	
	5.56													9.45	
	6.08													10.11	
	6.57													10.73	
	6.91													11.12	
	7.13	7.97											11.40	11.32	
	7.57	8.26	8.86	9.23	9.38	9.50	9.69	9.96	10.35	10.81	11.25	11.47	11.49	11.61	

G038 SOUTH FACE

G037 SOUTH FACE

G040 SOUTH FACE

(a) BURNUPS IN GWD/MTU

Figure 2.3-10
EOC-5 PIN-BY-PIN AXIAL AVERAGE FLUENCES ^(a) FOR "G" SAVFUEL
DEMONSTRATION ASSEMBLIES

G041 SOUTH FACE													
0.34	0.40	0.45	0.50	0.54	0.59	0.62	0.66	0.69	0.72	0.75	0.77	0.79	0.81
0.41	0.48											0.93	0.96
0.47													1.09
0.53													1.21
0.59													1.33
0.66													1.44
0.72													1.54
0.79													1.64
0.86													1.72
0.93													1.79
1.00													1.85
1.08													1.90
1.18	1.29											1.93	1.95
1.28	1.39	1.49	1.57	1.66	1.73	1.80	1.85	1.89	1.92	1.95	1.97	1.98	1.99
G038 SOUTH FACE													

(a) VALUES INDICATED ARE $\times 10^{21}$ ($E > 0.821$ MeV)

3.0 Discussion of Results

3.1 Introduction

A total of 21 fuel assemblies were examined after Reactor Cycle 5. All 21 fuel assemblies were visually examined and dimensional measurements taken on 5 of the assemblies. Measurements were taken on Assembly D005 before returning it to the core for its fifth cycle. The four precharacterized "G" assemblies (G037, G038, G040 and G041) were visually inspected and dimensional measurements obtained during the fuel shuffling operations prior to reinsertion for their second cycle.

Inspection results derived from the information obtained during the current examination are presented in this section, as well as the results of a visual exam conducted by personnel from The Omaha Public Power District (OPPD) at the end of Reactor Cycle 4 on five of the 17 batch D assemblies which are part of this program.

3.2 Visual Inspection Results

End-of-Cycle 4 Results

After Reactor Cycle 4, five Batch "D" fuel assemblies (D005, D038, D044, D034 and D033) were inspected by TV in the spent fuel pool. The purpose of that examination was to characterize the visual appearance and to confirm satisfactory performance after three cycles of operation. The inspection showed no anomalous features or unusual conditions. The crud patterns were typical of fuel assemblies with three cycles of burnup, i.e., light to medium crud uniformly distributed over the most active region of the fuel (Grids 2 to 7*) and light crud above and below this region.

The quality of the TV images precluded dimensional analyses of shoulder gaps or channel widths. The TV camera was subsequently modified providing better images for the examinations after Cycle 5.

*Numbering of the grids begins with "0" for the Inconel grid at the bottom and "1" thru "8" for the Zircaloy grids from bottom to top.

End of Cycle 5 Results

The visual examination after the fifth reactor cycle included all seventeen of the assemblies from the high-burnup portion of the program and all four of the assemblies in the SAVFUEL portion. The examination was completed as planned and no anomalous features were observed.

The characteristics of the crud deposits on the batch "D" assemblies were similar to those after the previous cycle, and are described in the previous section.

The specific assembly selected for extended irradiation (D005) was found to be suitable from both the visual appearance and dimensional considerations. The data on shoulder gaps and fuel rod bowing are presented for this assembly along with the others in the sections which follow.

The batch "G" assemblies were found to have a lighter and more uniform crud than the batch "D"'s, as would be expected from only one cycle of irradiation.

Photographs of the TV monitor image from typical areas of assemblies D005 and G038 are shown in Figures 3.2-1 through 3.2-8. The following areas are shown: spacer grid 8 and the tops of fuel rods; span 5 (between grids 4 and 5); grid 4 and the bottom Inconel-625 grid. A comparison of Figures 3.2-1 and 3.2-5 clearly show more shoulder gap closure with D005 than with G038 as will be further discussed in the next section (3.3). In addition, the same figures show that the crud buildup on D005 appears thicker and less uniform than on G038. This effect is typical of longer operation.

3.3 Shoulder Gap Measurements

The distance between the top of the fuel rod end cap and the bottom of the upper end fitting (UEF) flow plate is referred to as the shoulder gap. This distance changes with burnup since fuel rod axial elongation occurs at a more rapid rate than does guide tube growth. The result is a decreasing shoulder gap with increasing irradiation exposure.

FIGURE 3.2-1 ASSEMBLY D005, SPACER GRID 8 AND TOPS
OF FUEL RODS, WEST FACE

FIGURE 3.2-2 ASSEMBLY D005, BETWEEN GRIDS 4 AND 5,
WEST FACE

FIGURE 3.2-3 ASSEMBLY D005, GRID 4, WEST FACE

FIGURE 3.2-4 ASSEMBLY D005, INCONEL GRID/LOWER END FITTING,
WEST FACE

FIGURE 3.2-5 ASSEMBLY G038, SPACER GRID 8 AND
TOPS OF FUEL RODS, EAST FACE

FIGURE 3.2-6 ASSEMBLY G038, BETWEEN GRIDS 4 AND 5,
EAST FACE

FIGURE 3.2-7 ASSEMBLY G038, GRID 4, EAST FACE

FIGURE 3.2-8 ASSEMBLY G038, INCONEL GRID, EAST FACE

After Reactor Cycle 5, a total of 260 peripheral rod to upper end fitting gap measurements were made on the four "G" assemblies (G037, G038, G040 and G041) and one "D" assembly. The data are presented in Table 3.3-1, giving the shoulder gap, percent gap closure and rod average burnup values.

Figure 3.3-1 shows the shoulder gap closure as a function of rod average burnup. The large variation of rod burnup within the "G" fuel assemblies (see Figures 2.3-9 in Section 2.3, Demonstration Assemblies Irradiation History) contributes to a wide variation of shoulder gap closures (0.5 to 16.5%). The trend established by these data is clearly similar to that found in Calvert Cliffs I data⁽⁴⁾ also plotted in Figure 3.3-1.

The shoulder gaps for fuel assembly D005 have been plotted as a histogram (Figure 3.3-2). Since the burnup gradient across the fuel assembly is relatively flat, the statistical distribution shown is a good measure of the variation to be found in a given design with components of a common source. The data show a mean shoulder gap closure of 55.2% with a standard deviation of 3.65% for a burnup of 37 GWD/MTU.

The data on shoulder gaps presented in Figures 3.3-1 support the continued irradiation of Assembly D005 for a fifth cycle.

3.4 Fuel Assembly Growth

The overall fuel assembly growth was measured on D005 as the increase in distance between the upper flow plate and the supporting pin shoulders at the bottom of the lower end fitting. The growth of the batch "G" assemblies could not be measured by the TV system as the pre-irradiation data were not provided by the precharacterization method used for these assemblies. However, these fuel assemblies, as well as D005, will be measured after Cycle 6 using the C-E Comprehensive Fuel Inspection Stand.

TABLE 3.3-1
END-OF-CYCLE 5 FUEL ROD SHOULDER GAP MEASUREMENTS

FUEL ASSEMBLY	FACE	(a) *	RODS LEFT TO RIGHT													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
G037	North	1	1.025	1.058	1.038	1.045	1.025	1.033	1.025	1.041	1.036	1.072	1.075	1.085	1.089	1.085
		2	13.1	11.2	12.1	11.4	12.0	12.4	13.1	11.8	11.8	9.7	10.2	9.4	9.2	9.6
		3	11.6	11.3	11.1	10.7	10.1	9.5	8.9	8.4	8.0	7.7	7.2	6.7	6.0	5.4
	East	1	1.091	1.061	1.068	1.048	1.048	1.051	1.045	1.015	1.025	1.025	1.027	1.061	1.028	0.992
		2	8.6	10.1	10.9	12.6	11.9	11.7	11.5	15.1	13.9	14.0	13.2	10.3	13.0	15.9
		3	7.6	8.3	8.9	9.2	9.4	9.5	9.7	10.0	10.3	10.8	11.2	11.5	11.5	11.6
	South	1	1.145	1.117	1.126	1.117	1.104	1.097	1.067	1.067	1.083	1.083	1.080	1.083	1.055	1.039
		2	3.4	5.6	5.0	5.0	6.9	7.4	8.7	8.8	8.2	7.8	8.1	8.2	10.8	12.9
		3	2.6	3.0	3.4	3.7	4.0	4.3	4.7	5.1	5.6	6.1	6.6	6.9	7.1	7.6
	West	1	----	1.121	1.117	1.117	1.106	1.095	1.098	1.078	1.091	1.102	1.117	1.124	1.124	1.101
		2	----	6.6	6.6	6.8	7.7	7.8	7.7	8.9	8.2	7.1	5.5	4.2	4.2	7.1
		3	5.4	5.3	5.2	5.0	4.7	4.4	4.1	3.9	3.7	3.6	3.4	3.2	2.9	2.6
G038	North	1	1.103	1.106	1.116	1.109	1.087	1.080	1.070	1.077	1.100	1.083	1.109	1.090	1.080	1.083
		2	12.5	12.2	11.2	11.6	12.9	13.2	12.7	11.9	10.6	11.4	9.3	10.3	10.1	9.3
		3	5.4	5.3	5.2	5.0	4.7	4.4	4.1	3.9	3.7	3.6	3.4	3.2	2.9	2.6

- * 1 = shoulder gap (inches)
 2 = gap closure (%)
 3 = rod average burnup (GWD/MTU)

(a) The south face is defined as that face having the assembly serial number on the upper end fitting.

TABLE 3.3-1 (Continued)
END-OF-CYCLE 5 FUEL ROD SHOULDER GAP MEASUREMENT

			RODS LEFT TO RIGHT													
FUEL ASSEMBLY	(a) FACE *		1	2	3	4	5	6	7	8	9	10	11	12	13	14
G038	East	1	1.058	1.064	1.058	1.049	1.067	1.072	1.068	1.087	1.095	1.116	1.138	1.138	1.158	1.172
		2	12.0	11.0	11.3	12.3	11.7	11.1	13.0	11.3	11.3	9.1	8.1	8.3	7.1	7.0
		3	11.6	11.3	11.1	10.7	10.1	9.5	8.9	8.4	8.0	7.7	7.2	6.7	6.0	5.4
	South	1	1.101	1.072	1.069	1.046	1.066	1.035	1.032	1.020	1.038	0.997	1.043	1.049	1.040	1.020
		2	6.8	9.1	10.3	12.4	11.1	13.6	13.9	15.0	13.3	16.5	12.6	11.9	12.6	15.1
		3	7.6	8.3	8.9	9.2	9.4	9.5	9.7	10.0	10.3	10.8	11.2	11.5	11.5	11.6
	West	1	1.169	1.152	1.159	1.135	1.125	1.115	----	1.139	1.118	1.104	1.084	1.097	1.067	1.077
		2	2.1	3.1	2.2	3.2	4.3	4.8	----	4.0	4.8	6.0	7.2	5.8	9.0	8.9
		3	2.6	3.0	3.4	3.7	4.0	4.3	4.7	5.1	5.6	6.1	6.6	6.9	7.1	7.6
G040	North	1	1.190	1.174	1.174	1.168	1.119	1.107	1.088	1.088	1.074	1.082	1.125	1.105	1.103	1.105
		2	0.5	2.0	2.3	2.7	5.4	6.8	7.8	6.4	9.6	8.5	5.0	7.5	8.8	7.4
		3	2.6	3.0	3.4	3.7	4.0	4.3	4.7	5.1	5.6	6.1	6.6	6.9	7.1	7.6
	East	1	1.162	1.152	1.164	1.150	1.140	1.131	1.140	1.133	1.138	1.147	1.150	1.164	1.140	1.123
		2	2.4	3.1	1.8	3.0	4.7	5.0	4.7	5.0	4.6	3.9	4.4	2.2	4.3	6.1
		3	5.4	5.3	5.2	5.0	4.7	4.4	4.1	3.9	3.7	3.6	3.4	3.2	2.9	2.6
	South	1	----	1.067	1.089	1.070	1.056	1.035	1.040	1.040	1.056	1.089	1.072	1.089	1.089	1.102
		2	----	12.8	10.7	12.3	13.2	14.6	13.7	13.0	12.1	9.2	10.4	8.9	9.0	7.4
		3	11.6	11.3	11.1	10.7	10.1	9.4	8.9	8.4	8.0	7.7	7.2	6.7	6.0	5.4

- * 1 = shoulder gap (inches)
2 = gap closure (%)
3 = rod average burnup (GWD/MTU)

(a) The south face is defined as that face having the assembly serial number on the upper end fitting.

TABLE 3.3-1 (Continued)
END-OF-CYCLE 5 FUEL ROD SHOULDER GAP MEASUREMENTS

FUEL ASSEMBLY	FACE	(a) *	RODS LEFT TO RIGHT													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
G040	West	1	1.147	1.132	1.123	1.097	1.105	1.155	1.138	1.105	1.103	1.126	1.111	1.067	1.070	1.064
		2	3.9	6.5	7.6	9.2	8.7	4.1	6.6	8.3	9.1	7.9	9.2	12.9	12.5	14.1
		3	7.6	8.3	8.9	9.2	9.4	9.5	9.7	10.0	10.3	10.8	11.2	11.5	11.5	11.6
G041	North	1	1.208	1.200	1.181	1.166	1.155	1.143	1.138	1.128	1.105	1.109	1.110	1.109	1.094	1.090
		2	5.3	5.0	5.4	5.7	7.0	7.8	7.1	8.3	9.5	8.6	9.0	9.5	10.2	9.5
		3	7.6	8.3	8.9	9.2	9.4	9.5	9.7	10.0	10.3	10.8	11.2	11.5	11.5	11.6
32	East	1	1.119	1.129	1.122	1.094	1.091	1.081	1.067	1.088	1.081	1.081	1.088	1.085	1.078	1.066
		2	6.8	6.8	7.3	9.6	6.7	10.8	12.2	11.8	13.2	13.2	13.1	13.6	14.8	16.5
		3	2.6	3.0	3.4	3.7	4.0	4.3	4.7	5.1	5.6	6.1	6.6	6.9	7.1	7.6
	South	1	----	1.073	1.105	1.100	1.102	1.090	1.062	1.059	1.059	1.080	1.102	1.108	1.102	1.108
		2	----	7.9	11.1	5.8	6.2	7.1	10.1	10.0	10.3	8.2	6.6	7.3	8.2	7.7
		3	5.4	5.3	5.2	5.0	4.7	4.4	4.1	3.9	3.7	3.6	3.4	3.2	2.9	2.6
	West	1	1.088	1.099	1.095	1.074	1.049	1.049	1.045	1.056	1.077	1.088	1.088	1.099	1.106	1.113
		2	9.6	9.0	9.4	9.1	11.0	10.7	10.9	9.7	7.7	7.0	6.5	6.1	4.7	5.5
		3	11.6	11.3	11.1	10.7	10.1	9.4	8.9	8.4	8.0	7.7	7.2	6.7	6.0	5.4

*

1 = shoulder gap (inches)

2 = gap closure (%)

3 = rod average burnup (GWD/MTU)

(a) The south face is defined as that face having the assembly serial number on the upper end fitting.

TABLE 3.3-1 (Continued)

END-OF-CYCLE 5 FUEL ROD SHOULDER GAP MEASUREMENTS

FUEL ASSEMBLY	FACE	(a) *	RODS LEFT TO RIGHT													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
D005 **	North	1	.555	.478	.502	.632	.522	.583	.537	.579	.438	.599	.581	.577	.562	.636
		2	54.5	60.8	58.8	48.2	57.2	52.2	56.0	52.5	60.4	50.9	52.3	52.7	53.9	47.8
		3	37.0	36.9	37.1	36.9	36.3	35.7	35.3	34.9	35.2	35.9	36.6	36.7	36.5	36.6
	South	1	----	.526	.499	.608	.483	.516	.578	.485	.485	.459	.562	.497	.564	.550
		2	----	56.8	59.1	50.1	60.3	57.7	52.6	60.2	60.2	62.4	53.9	59.2	53.7	54.9
		3	38.2	38.1	38.3	38.1	37.5	36.8	36.4	37.0	37.4	38.1	38.8	38.9	38.7	38.8
	West	1	----	.558	.535	.531	.518	.589	.541	.581	.539	.552	.525	.633	.550	.539
		2	----	54.2	56.1	56.4	57.5	51.7	55.6	52.3	55.8	54.7	56.9	48.1	54.9	55.8
		3	36.6	36.6	36.8	36.6	36.0	35.4	35.0	36.5	36.9	37.5	38.2	38.4	38.2	38.2

- *
 1 = shoulder gap (inches)
 2 = gap closure (%)
 3 = rod average burnup (GWD/MTU)

(a) The south face is defined as that face having the assembly serial number on the upper end fitting.

** Only three faces of this assembly were measured due to critical time consideration.

Figure 3.3-1

PERIPHERAL FUEL ROD SHOULDER GAPS AS A FUNCTION OF AXIALLY AVERAGED ROD BURNUP

Figure 3.3-2
HISTOGRAM OF SHOULDER GAP CLOSURE FOR ASSEMBLY D005
DISTRIBUTION ROD AVERAGE BURNUP 37 GWD/MTU

Growth of the assemblies is a result of anisotropic growth of the guide tubes and therefore, these two parameters are treated synonymously. Growth of the guide tubes from D005, at each corner of the fuel assembly, are shown in Figure 3.4-1 and in Table 3.4-1. The guide tube growths range from 0.107 to 0.125% $\Delta L/L$. These results compare favorably with previously reported data of annealed Zircaloy, including the Calvert Cliffs I, three-cycle data⁽⁴⁾, and the analytical correlation developed from growth data for annealed Zircaloy metallurgical specimens, also presented in Figure 3.4-1. As in the case of shoulder gaps, the allowances for additional growth of the assembly is sufficient to permit further irradiation of D005.

3.5 Fuel Rod Channel Widths

Fuel rod bow between spacer grids results in measurable closure of the channels between rods. Peripheral fuel rod channel spacings were measured at the eight mid-span locations on each face of 2 "G" fuel assemblies (G040 and G041) and three faces of D005.

A total of 1082 mid-span channels were measured from the three assemblies and Tables 3.5-1 and 3.5-2 summarize the data. The measurement results are presented in the form of percent channel closure. This relationship was made by comparing the mid span channel widths to channel widths just above each adjacent spacer grid where the spacing would not be affected by fuel rod bow.

The data indicate that the worst span for channel closure for the "D" and "G" fuel assemblies was span 2, between spacer grids 1 and 2. The worst span is defined here as having the largest standard deviation of the measured channel widths. The maximum single closure for the "G" fuel assemblies was 36.3% (span 2) and for the "D" fuel assembly 34.0% (span 3).

Figures 3.5-1 and 3.5-2 show histograms of all channel widths for the "D" and "G" fuel assemblies over spans 2 through 8. Span 1 is eliminated from this comparison because of the shorter span length, 14-5/16 in. vs. the nominal 16-13/16 in. for spans 2 through 8. The resultant curves show a normal distribution centered about a wider channel by 0.8% for D005 and 0.4% for the "G" fuel assemblies. This corresponds to average channel

Figure 3.4-1
FT. CALHOUN FUEL ASSEMBLY D-005 GROWTH DATA
COMPARED WITH PREVIOUSLY REPORTED DATA

Table 3.4-1

FUEL ASSEMBLY LENGTH* INCREASES

<u>VIEWING DIRECTION</u>	<u>ASSEMBLY CORNER</u>			
	<u>NE</u>	<u>NW</u>	<u>SW</u>	<u>SE</u>
(a)**	.125%	.111%	.103%	.118%
(b)**	<u>N A</u>	<u>.103%</u>	<u>.133%</u>	<u>N A</u>
average $\Delta L/L$	.125%	.107%	.118%	.118%
average fluence	7.3	7.2	7.5	7.6
($\times 10^{-21}$ nvt)				
($E > 0.821$ MeV)				

NA not available

* length is measured between the bottom of the upper end fitting to the supporting shoulder of the lower alignment pins

** the arrows indicate the direction from which the measurements were taken

TABLE 3.5-1
SUMMARY OF END-OF-CYCLE 5 CHANNEL WIDTH MEASUREMENTS
FUEL ASSEMBLIES G-040 AND G-041

	SPAN NO.	TOTAL NO. OF FUEL ROD CHANNELS MEASURED	MAXIMUM CHANNEL CLOSURE, %	AVERAGE MID-SPAN CHANNEL COMPARED TO CHANNELS ADJACENT TO GRIDS	σ , %
<p>16 3/16"</p> <p>16 13/16" (6 SPANS)</p> <p>14 7/16"</p>	NO. 8	104	19.6	1.8% smaller	5.8
	NO. 7	104	15.8	1.8% smaller	6.5
	NO. 6	104	13.6	0.3% larger	6.1
	NO. 5	104	9.3	1.6% larger	5.6
	NO. 4	104	12.8	0.8% larger	6.3
	NO. 3	104	14.4	0.5% larger	6.0
	NO. 2	104	36.3	2.9% larger	8.1 (worst span)
	NO. 1 ASSEMBLY AVERAGE	90 728 ^(a)	17.3	2.4% larger 0.4% larger ^(a)	6.4 6.6 ^(a)

As-fabricated channel width = 0.140 inch

(a) does not include span No. 1

TABLE 3.5-2

SUMMARY OF END-OF-CYCLE 5 CHANNEL WIDTH MEASUREMENTS FOR
FUEL ASSEMBLY D005 (3 FACES)

SPAN NO.	TOTAL NO. OF FUEL ROD CHANNELS MEASURED	MAXIMUM CHANNEL CLOSURE %	AVERAGE MID-SPAN CHANNEL COMPARED TO CHANNELS ADJACENT TO GRIDS	σ , %
NO. 8	31	9.6	1.0% smaller	5.4
NO. 7	30	15.3	0.3% smaller	8.4
NO. 6	29	19.7	1.3% larger	11.2
NO. 5	34	16.8	2.4% larger	13.1
NO. 4	36	11.7	2.8% larger	11.0
NO. 3	35	34.0	0.2% larger	13.4
NO. 2	35	24.9	0.1% larger	14.4 (worst span)
NO. 1	34	24.5	0.2% smaller	8.4
ASSEMBLY AVERAGE	230 ^(a)		0.8% larger ^(a)	11.4 ^(a)

As-fabricated channel width = 0.140 inch

(a) does not include span No. 1

Figure 3.5.1
HISTOGRAM OF FUEL ASSEMBLY D005 CHANNEL CLOSURE
(SPANS 2 - 8)

Figure 3.5.2
HISTOGRAM OF FUEL ASSEMBLIES G040 AND G041 CHANNEL CLOSURE
(SPANS 2 - 8)

widths at mid-span which are within 1.1 and 0.6 mils, respectively, of the average channel widths just above adjacent spacer grids. These values are well within the accuracy of measurement by the techniques described in Appendix D, "Examination and Measurement Techniques".

The statistical distribution of channel closures is important to the fuel design as it affects the thermal-hydraulics of the system. For this reason, the parameter chosen for comparison among spans and among plants is the 95th percentile of the channel closures. The channel closure of the worst span at the 95th percentile has been determined by multiplying the standard deviation for the worst span by 1.65. Accordingly, this level of the distribution represents 13.4% closure for the "G" assemblies and 23.8% closure for D005. The data closely follow the best estimate curve, shown in Figure 3.5-3, which is based upon the following equation:

$$FCC = 1.65 \frac{(a + b\sqrt{bu})}{c}^{(4)}$$

where:

- FCC = fractional channel closure at the 95th percentile.
- a = pre-irradiation value of $1\sigma = 0.005$ inches.
- b = constant = 6.96×10^{-5} (in/(MWD/MTU)^{1/2})
- c = nominal channel width (inches).
- bu = assembly burnup (MWD/MTU)

The Fort Calhoun "D" and "G" data compare favorably with other C-E fuel including data from Calvert Cliffs I, Maine Yankee, Palisades and Fort Calhoun "B" batch⁽⁴⁾.

Figure 3.5-3

WORST SPAN CHANNEL CLOSURE AT THE 95TH PERCENTILE

4.0 References

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APPENDIX A

Pre-Irradiation Characterization Measurements
for Batch "G" SAVFUEL Demonstration Assemblies

APPENDIX A

<u>SECTION</u>	<u>TITLE</u>	<u>PAGE</u>
A-1	Batch "G" Pre-Irradiation Fuel Rod Profilometry	A-1

<u>TABLE</u>	<u>TITLE</u>	<u>PAGE</u>
A-1	Batch "G" Pre-Irradiation Peripheral Fuel Rod Shoulder Gap Measurement Summary	A-2
A-2	Batch "G" Pre-Irradiation Fuel Rod Length Measurements	A-3
A-3	Batch "G" Pre-Irradiation Fuel Assembly Guide Tube Length Measurements	A-4
A-4	Pre-Irradiation Grid Width Characterization for Assembly G041	A-5
A-5	Batch "G" Pre-Irradiation Fuel Rod Channel Width Measurement Summary	A-6

<u>FIGURE</u>	<u>TITLE</u>	<u>PAGE</u>
A-1	Location of Characterized Rods in Batch "G" SAVFUEL Demonstration Assemblies	A-7

A-1. Batch "G" Pre-Irradiation Fuel Rod Profilometry

Each of 48 characterized fuel rods from the Batch "G" assemblies were profiled over the entire length to obtain local cladding diameters and ovalities. The profilometer used in the characterization consists of two linear variable differential transducers (LVDT's) positioned 180° apart that tranverse axially along the fuel rod as the rod is rotated. The spring loaded LVDT probes, which remain in continuous contact with the surface of the rod, respond to fuel rod diameter changes as they traverse along the rod. Fluctuations in fuel rod diameter are electronically converted and the data output on a strip chart recorder. The profilometer system is accurately calibrated with a standard having precisely machined, varying diameters. The accuracy and reproducibility of the profilometer system was determined to be within 0.0002 inches.

The data obtained on each of the 48 characterized Batch "G" fuel rods are in the form of strip chart traces and therefore, are not included in this report. Examination of the traces indicates nominal fuel rod ovalities from 0.2 to 0.5 mils, with a maximum pre-irradiation ovality for the 48 rods of 0.9 mils. The average diameters of the characterized fuel rods ranged from 0.4410 to 0.4396 inches with a mean diameter and standard deviation of 0.4402 inches and 0.0003 inches, respectively. These traces will be used in a direct comparison to traces obtained at the end of Cycle 6 using the C-E Comprehensive Inspection Stand profilometer.

TABLE A-1

BATCH "G" PRE-IRRADIATION PERIPHERAL FUEL ROD
SHOULDER GAP MEASUREMENT SUMMARY

Assembly	Mean Shoulder Gap ^(a) (inches)	Std. Dev. (inches)	N	Shoulder Gap Range (inches)	
				Max.	Min.
G037	1.185	0.009	52	1.200	1.164
G038	1.206	0.026	52	1.260	1.164
G040	1.202	0.014	52	1.238	1.180
G041	1.205	0.031	52	1.276	1.161

(a) measurements accurate to ± 0.002 inches

Table A-2

BATCH "G" PRE-IRRADIATION FUEL ROD LENGTH MEASUREMENTS

Assembly	Rod Serial Number	Rod Length ⁽¹⁾ (inches)	Assembly	Rod Serial Number	Rod Length ⁽¹⁾ (inches)
G037	HSK 148	136.662	G040	HSK 161	136.662
	HSK 149	136.669		HSK 162	136.668
	HSK 151	136.668		HSK 163	136.668
	HSK 152	136.679		HSK 164	136.665
	HSK 153	136.663		HSK 165	136.662
	HSK 154	136.667		HSK 166	136.666
	HSK 155	136.672		HSK 167	136.672
	HSK 156	136.662		HSK 168	136.666
	HSK 157	136.669		HSK 169	136.665
	HSK 158	136.666		HSK 170	136.679
	HSK 159	136.671		HSK 171	136.665
	HSK 160	136.660		HSK 172	136.659
G038	HSK 132	136.674	G041	HSK 173	136.662
	HSK 133	136.667		HSK 174	136.662
	HSK 134	136.664		HSK 175	136.662
	HSK 135	136.679		HSK 176	136.659
	HSK 136	136.669		HSK 177	136.660
	HSK 137	136.665		HSK 178	136.660
	HSK 138	136.667		HSK 179	136.659
	HSK 139	136.667		HSK 180	136.661
	HSK 140	136.665		HSK 181	136.663
	HSK 141	136.672		HSK 182	136.661
	HSK 146	136.659		HSK 183	136.663
	HSK 147	136.671		HSK 184	136.669

Archive Rods: HSL 038 and HSL 132

(1) Length measurements accurate to ± 0.001 inches

TABLE A-3

BATCH "G" PRE-IRRADIATION FUEL ASSEMBLY GUIDE TUBE LENGTH MEASUREMENTS^(a)

<u>FUEL ASSEMBLY</u>	<u>CORNER (b)</u>	<u>LENGTH, INCHES^(c)</u>
G037	NE	138 1/4
	NW	138 1/4
	SE	138 5/16
	SW	138 5/16
G038	NE	138 9/32
	NW	138 11/32
	SE	138 7/16
	SW	138 13/32
G040	NE	138 11/32
	NW	138 3/8
	SE	138 3/8
	SW	138 11/32
G041	NE	138 11/32
	NW	138 5/16
	SE	138 11/32
	SW	138 5/16

- (a) The fuel assembly length is measured from the lower bevel on the upper end fitting to the lower bevel on the lower end fitting.
- (b) The south face is defined as having the fuel assembly serial number on the upper end fitting.
- (c) Measurements accurate to $\pm 1/64$ inch.

TABLE A-4

PRE-IRRADIATION GRID WIDTH⁽¹⁾ CHARACTERIZATION
FOR ASSEMBLY G041

<u>Grid #</u> ⁽²⁾	<u>0°</u> ⁽³⁾	<u>90°</u> ⁽³⁾
0	8.093	8.099
1	8.091	8.095
2	8.093	8.096
3	8.095	8.098
4	8.098	8.099
5	8.098	8.093
6	8.098	8.099
7	8.094	8.095
8	8.093	8.096

- (1) Data presented are average grid widths determined from measurements at the 13 weld locations along the centerline of each perimeter strip. Measurements accurate to ± 0.001 ".
- (2) Grids numbered 0 to 8, bottom to top. Lower inconel grid = Grid #0
- (3) 0° - Grid envelope on North/South faces
 90° - Grid envelope on East/West faces
 0° on South face of assembly upper end fitting

TABLE A-5

BATCH "G" PRE-IRRADIATION PERIPHERAL FUEL ROD CHANNEL WIDTH MEASUREMENT (a) SUMMARY (b)

SPACER GRID ^(c) SPAN	MEAN CHANNEL ^(d) WIDTH (inches)	STD. DEV.	N	CHANNEL WIDTH RANGE (INCHES) ^(d)	
				MAX.	MIN.
8	0.139	.006	104	.152	.128
7	----	not measured		----	----
6	0.140	.006	104	.156	.128
5	----	not measured		----	----
4	0.139	.004	103	.149	.131
3	0.138	.005	104	.149	.125
2	0.140	.005	104	.153	.129
1	0.136	.007	104	.151	.114

(a) measurements accurate to ± 0.001 inches

(b) summary includes measurements from characterized assemblies G040 and G041

(c) spacer grid spans numbered 1 to 8, bottom to top (e.g., span 1 from Inconel Grid to 1st Zircaloy spacer grid from the bottom of the assembly)

(d) measurements taken at mid-span location

Figure A-1
 LOCATION OF CHARACTERIZED RODS IN BATCH "G" SAVFUEL
 DEMONSTRATION ASSEMBLIES

Appendix B

Pre-Irradiation Characterization Measurements
for Batch "D" High Burnup Demonstration Assemblies

APPENDIX B

<u>TABLE</u>	<u>TITLE</u>	<u>PAGE</u>
B-1	Batch "D" Pre-Irradiation Fuel Rod Profilometry Summary	B-1
B-2	Batch "D" Pre-Irradiation Corner Shoulder Gap and Overall Rod Length Measurements	B-2
B-3	Batch "D" Pre-Irradiation Fuel Assembly Guide Tube Length Measurements	B-3
B-4	Batch "D" Pre-Irradiation Grid Width Measurements	B-4

TABLE B-1

Batch D Pre-Irradiation Fuel Rod
Profilometry Summary

<u>Rod No.</u>	<u>Average Diameter (inches)</u>	<u>Nominal Ovality (mils)</u>	<u>Maximum Ovality (mils)</u>
KJE 104	0.4407	0.4 - 0.6	0.95
KJE 093	0.4410	0.3 - 0.4	0.70
KJN 064	0.4404	0.3 - 0.4	0.65
KJN 058	0.4396	0.4 - 0.5	1.0
KJN 063	0.4398	0.3 - 0.5	0.95
KJE 097	0.4405	0.3 - 0.5	0.65
KJN 052	0.4395	0.3 - 0.5	0.95
KJE 109	0.4407	NA	NA

Each of the eight (8) characterized fuel rods for assemblies D005 and D013 was profiled over the entire length to obtain cladding diameters and ovalities using the same technique and equipment as discussed in Section A-1 of Appendix A. The recorded data are in the form of strip charts and, therefore, are not included in this report. The traces will be used in a direct comparison to traces obtained when the assembly is disassembled using the C-E Comprehensive Fuel Inspection Stand.

NA - Not Available

TABLE B-2

Batch "D" Pre-Irradiation Corner Shoulder Gap
Measurements, Inches

<u>Fuel Assembly</u>	<u>Pre-characterized Rod Serial Number</u>	<u>Corner</u> ^(c)	<u>Shoulder Gap</u> ^(b)	<u>Overall Rod Length</u> ^(b)
D005 ^(a)	KJE 093	NE	1 7/32	148 7/8
	KJE 109	NW	1 7/32	148 7/8
	KJE 104	SE	1 7/32	148 7/8
	KJE 097	SW	1 7/32	148 7/8
D013 ^(a)	KJN 063	NE	1 13/64	148 7/8
	KJN 058	NW	1 13/64	148 7/8
	KJN 052	SE	1 15/64	148 7/8
	KJN 064	SW	1 15/64	148 7/8

(a) Only the corner rod shoulder gaps were measured, all other shoulder gaps were assumed to be 1 7/32 inches.

(b) Measurements accurate to $\pm 1/64$.

(c) The south face is defined as having the fuel assembly serial number on the upper end fitting.

TABLE B-3

BATCH "D" PRE-IRRADIATION FUEL ASSEMBLY GUIDE TUBE LENGTH MEASUREMENTS (c)

<u>FUEL ASSEMBLY</u>	<u>FACE (a)</u>	<u>LEFT SIDE (inches) (b)</u>	<u>RIGHT SIDE (inches) (b)</u>
D005	N	137 7/8	137 7/8
	E	137 7/8	137 7/8
	S	137 7/8	137 7/8
	W	137 7/8	137 7/8
D013	N	137 27/32	137 57/64
	E	137 27/32	137 27/32
	S	137 57/64	137 27/32
	W	137 57/64	137 57/64

- (a) The south face is defined as having the fuel assembly serial number on the upper end fitting.
- (b) Measurements accurate to $\pm 1/64$
- (c) The length is measured from the lower surface of the upper end fitting to the top surface of the lower end fitting.

TABLE B-4
BATCH "D" PRE-IRRADIATION GRID WIDTH MEASUREMENTS
(Inches)⁽³⁾

Grid ⁽²⁾	<u>D005</u>				<u>D013</u>			
	A ⁽¹⁾		B ⁽¹⁾		A ⁽¹⁾		B ⁽¹⁾	
	<u>Max.</u>	<u>Min.</u>	<u>Max.</u>	<u>Min.</u>	<u>Max.</u>	<u>Min.</u>	<u>Max.</u>	<u>Min.</u>
8	8.100	8.083	8.098	8.083	8.096	8.088	8.092	8.082
7	8.101	8.090	8.096	8.087	8.105	8.092	8.104	8.091
6	8.101	8.082	8.097	8.087	8.104	8.087	8.096	8.083
5	8.093	8.080	8.097	8.081	8.100	8.092	8.091	8.083
4	8.097	8.079	8.099	8.086	8.105	8.093	8.102	8.088
3	8.098	8.089	8.095	8.081	8.099	8.092	8.100	8.089
2	8.096	8.083	8.097	8.087	8.092	8.078	8.086	8.078
1	8.102	8.090	8.099	8.089	8.104	8.089	8.095	8.083
0	8.099	8.078	8.095	8.077	8.105	8.085	8.095	8.076

- (1) Assembly serial number located on south face. "A" measurement taken on EAST-WEST grids, "B" measurements taken on NORTH-SOUTH grids.
- (2) Grids numbered 0 to 8, bottom to top. (e.g. Grid 0 - Inconel Grid).
- (3) Measurements accurate to ± 0.001 inches

APPENDIX C

PORTABLE FUEL INSPECTION STAND (6) - "MINI-STAND"

Reference - V. G. Scotti, "A Compact, Portable Irradiated Fuel Inspection Stand", 1978 Annual Meeting of the American Nuclear Society, San Diego, CA., June 18-23, 1978.

Description of the Mini-Stand

The design of the Mini-Stand (Figure C-1) was developed by Combustion Engineering at the request of OPPD to provide an inexpensive portable compact fuel inspection stand suitable for a state-of-the-art inspection of discharged assemblies.

The basic elements of an inspection stand are: (1) a means of viewing the fuel assembly by an underwater television camera, (2) a means of vertical and lateral movement of the fuel assembly relative to the TV camera, (3) a means of viewing all four faces of the fuel assembly. The Mini-Stand makes use of the spent fuel handling machine to provide the vertical motion; the lateral motion is provided by movement of the television camera mounted on a gear drive. The spent fuel storage rack serves as a base upon which to mount the stand and an assembly storage position serves as a guide into which the assembly is lowered for inspection.

The basic parts of the stand are the mounting base, the roller bearing support plate, the gear drive plate, TV carriage and the gear drive mechanism. All materials used are of stainless steel. Attached to the mounting base as illustrated in Figure C-1 are three ten-inch long pins that fit snugly into the mounting holes of the spent fuel rack. Leveling pads are provided with each of these pins for orientation of the subject fuel assembly. Attached to the mounting base by means of rectangular bar stock are two one-half inch thick picture frame plates. The inner dimensions of the plates are nine inches by nine inches to allow for a one-half inch clearance on all sides of the assembly as it is lowered into the stand. The lower picture frame plate provides on its outer surface a bearing surface for the lower rollers of the television carriage. The upper one provides a bearing surface on the inner surface for the upper rollers of the television carriage. Welded to the outer surface of the upper picture frame is a stainless steel roller chain. The roller chain engages a sprocket which is driven by the gear train mounted on the underside of the horizontal carriage plate. The gear train may be driven

by a hydraulic motor or manually operated by means of a 20-foot shaft. Thus, by driving the wheel sprocket through the gear mechanism, the television camera can be traversed from side to side enabling an examiner to view the entire face of the assembly.

The closed circuit television system has a minimum focal length of 28 inches and has a zoom capability with approximate magnifications from 1X to 10X.

Visual Examination of an Assembly

A fuel assembly can be visually examined as it is being lowered by means of the spent fuel machine through the stand into the storage cell. The rate of lowering the assembly and the television field of view are adjusted to meet the inspection requirements. The assembly is viewed on the television monitor which can be provided with a tape recorder. After a face of the assembly has been examined, the assembly is raised by means of the spent fuel machine and the next face is examined.

Dimensional Measurements

The calibration standard was fabricated to conform to the geometry of the outer envelope of a standard fuel assembly. Just below the upper end fitting is contained a plate upon which are mounted rows of simulated fuel pin ends. Subsequent to fabrication, the standard was dimensionally characterized to ± 0.1 mil in the standards laboratory to establish the following dimensions:

1. Overall assembly length - the assembly length measurement was stamped at each of the four edges measured.
2. The gap between the top of the simulated fuel pins to the bottom surface of the upper end fitting - this measurement is used to calibrate the system for fuel pin growth measurements. A variety of gap sizes provides several calibration points.

Figure C-1

PORTABLE FUEL INSPECTION STAND - "MINI-STAND"

Appendix D

Examination and Measurement Techniques

Examination and Measurement Techniques

Shoulder Gap Measurements

As discussed in Section 3.0, the shoulder gaps were measured for five fuel assemblies including four, one-cycle "G" assemblies and one, four-cycle "D" fuel assembly. A total of 247 shoulder gaps were determined by measurements taken from a TV monitor screen. A typical TV image is shown in Figure D-1. The magnification factor needed to adjust the measurements to actual values was determined by measurements of a simulated fuel assembly having known gaps between simulated fuel rods and upper end fitting.

Magnification factors for the actual fuel assembly measurements were determined by the relationship of a scale on the simulated assembly and a scale permanently attached to the Mini-Stand⁽⁶⁾. Thereafter, once that relationship was established, a measurement of the scale on the Mini-Stand was converted to a magnification factor for measurements on the subject fuel assemblies. Multiple measurements of the known gaps, using a steel scale with 20 mil divisions, indicate that this method of measurement has a precision of ± 42 mils (based on a 2σ standard deviation) and a bias, due to TV effects and the subjective nature of the method of $(-) 29$ mils.

Channel Width Measurements

The channel widths between peripheral rods were measured at each mid-span location of two, one-cycle "G" fuel assemblies (G040 and -041) and one, four-cycle "D" fuel assembly (D005). A total of approximately 2300 measurements (mid-span and above adjacent spacer grids) were taken by measuring directly on the screen of a TV monitor.

To calibrate the measured channel width closure data, channel widths above each spacer grid were measured and considered to be unaffected by rod bow because of the close proximity to the restraint of the spacer grid.

FIGURE D-1 ASSEMBLY D005, FUEL ROD SHOULDER GAPS, HIGH MAGNIFICATION
VIEW TYPICAL OF WHAT WAS USED TO MEASURE SHOULDER GAPS,
WEST FACE

The percentage closure at the mid-span was determined by:

$$\text{Percent closure} = \left(1 - \frac{G_m}{\frac{(G_u + G_l)}{2}} \right) \times 100$$

where: G_m = mid-span gap
 G_u = gap above upper grid
 G_l = gap above lower grid

The precision of the gap closure values, based on the 2σ deviation of gap measurement above each grid, is $\pm 10.6\%$ closure.

4.3 Fuel Assembly Length Measurements

The support of a fuel assembly during the inspection process requires a spacer between the assembly and the spent fuel storage rack. The distance from the top of the spacer to the steel scales attached to the Mini-Stand was calibrated by measurements of the simulated fuel assembly discussed in the section describing shoulder gap measurements. The calibration was adjusted for temperature by assuming pool water to be 90°F and the original measurements of the simulated assembly to be at 72°F.

Each corner of the fuel assembly was measured by aligning the lower surface of the upper flow plate with the adjacent steel scale. The readings were taken to the nearest 1/32 inch. Based upon the accuracy of multiple simulated assembly measurements, the accuracy of fuel assembly growth measurements is considered to be $\pm 1/32$ inch (± 0.031 inch).

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