27
12/5/77
2508-5 NTIS

TREE-NUREG-1088
for U.S. Nuclear Regulatory Commission

MASTER

**EXPERIMENT DATA REPORT
GAP CONDUCTANCE TEST SERIES
TEST GC 1-3
POSTIRRADIATION EXAMINATION**

BEVERLY A. MURDOCK

September 1977

EG&G Idaho, Inc.

IDAHO NATIONAL ENGINEERING LABORATORY

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

IDAHO OPERATIONS OFFICE UNDER CONTRACT EY-76-C-07-1570

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy \$9.00; Microfiche \$3.00

"The NRC will make available data tapes and operational computer codes on research programs dealing with postulated loss-of-coolant accidents in light water reactors. Persons requesting this information must reimburse the NRC contractors for their expenses in preparing copies of the data tapes and the operational computer codes. Requests should be submitted to the Research Applications Branch, Office of Nuclear Regulatory Research, Nuclear Regulatory Commission, Washington, D.C. 20555."

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Energy Research and Development Administration, nor the Nuclear Regulatory Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

TREE-NUREG-1088

EXPERIMENT DATA REPORT

GAP CONDUCTANCE TEST SERIES

TEST GC 1-3

POSTIRRADIATION EXAMINATION

Prepared by the

Fuels and Materials Division

For the

Thermal Fuels Behavior Program

Approved:

L. S. Richardson

L. S. Richardson, Manager
Fuels Engineering Branch

P. E. MacDonald / RKM

P. E. MacDonald, Manager
Experiment Specification and Analysis Branch

J. G. Crocker

J. G. Crocker, Manager
Thermal Fuels Behavior Division

L. J. Barrondo

L. J. Barrondo, Director
Water Reactor Research

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TREE-NUREG-1088

Distributed Under Category:
NRC-3
Water Reactor Safety Research
Fuel Behavior

EXPERIMENT DATA REPORT
GAP CONDUCTANCE TEST SERIES
TEST GC 1-3
POSTIRRADIATION EXAMINATION

by

Beverly A. Murdock

EG&G IDAHO, INC.

September 1977

PREPARED FOR THE
U.S. NUCLEAR REGULATORY COMMISSION
AND
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
IDAHO OPERATIONS OFFICE
UNDER CONTRACT NO. EY-76-C-07-1570

ABSTRACT

The results of the postirradiation examination of four boiling water reactor type, zircaloy-clad, UO_2 -fueled rods tested as part of the Thermal Fuels Behavior Program are discussed. These rods were employed in Gap Conductance Test GC 1-3 which was conducted to obtain experimental data from which test rod gap conductance values could be determined by both the steady state $\int k dT$ and the power oscillation methods. The postirradiation examination results provided in this document will aid in interpreting and understanding the experimental data obtained during Test GC 1-3 and in evaluating the effect of fuel behavior on the fuel rod thermal response and interpreted gap conductances. Fuel rod fill gas composition and pressure and rod power profiles are discussed. Evidence is presented showing that significant amounts of water had been present in two of the four fuel rods during testing. For the two fuel rods that remained intact during the test, measurements of fuel pellet-to-cladding gap, as well as the surface area of the fuel cracks at several axial locations are presented. A total effective radial gap is calculated and the fuel structure and porosity are analyzed.

SUMMARY

Four instrumented fuel rods were subjected to a postirradiation examination following the Gap Conductance Test GC 1-3, which was conducted as part of the EG&G Idaho, Inc., Thermal Fuels Behavior Program. The previously unirradiated, zircaloy-clad, UO_2 -fueled rods were tested in a boiling water reactor environment, simulated within the in-pile test loop of the Power Burst Facility to determine the fuel rod gap conductance by power oscillation and steady state $\int k dT$ methods.

The objectives of the postirradiation examination were:

- (1) To measure the fuel rod internal gas pressure and composition
- (2) To determine posttest fuel pellet-to-cladding gap sizes
- (3) To evaluate the fuel crack patterns
- (4) To provide fuel characterization data
- (5) To evaluate any changes in the fuel or cladding that would affect the parameters used in the gap conductance calculations.

These results will aid in interpreting the observed fuel rod thermal response during Test GC 1-3, and in evaluating changes in design parameters (for example, pellet-to-cladding gap size and fuel pellet crack patterns) that affect evaluation of gap conductance.

Evidence was found that significant amounts of water were present in fuel Rods GC-1-002 and GC-1-003 during testing. These rods were not analyzed completely because the presence of water in the rods altered the fuel rod composition to such a degree that reliable gap conductance evaluations could not be made.

Fuel rod internal gas compositions and pressure were evaluated; however, the data obtained could not be related to the condition of the fuel rods during testing. The measured fuel pellet-to-cladding gap sizes ranged from 30 to 64% of the original gap size for Rods GC-1-001 and GC-1-004. At selected cross sections, the area of the fuel cracks was measured and added to the area of the gap to obtain an effective posttest gap width ranging from 78 to 116% of the original radial gap. Significant changes in fuel crack patterns were observed to have occurred within a 2.0-mm axial distance from the original plane of each sample taken from the rods. The posttest fuel grain structures were observed to be equiaxed throughout, with a maximum grain diameter of 52 μm ; 2.4 times the original grain diameter.

CONTENTS

ABSTRACT	ii
SUMMARY	iii
I. INTRODUCTION	1
II. POSTTEST FUEL ROD CHARACTERIZATION	4
1. INTERNAL GAS PRESSURE AND COMPOSITION	4
2. FUEL PELLET-TO-CLADDING GAP SIZES	5
3. FUEL CRACK PATTERNS	10
4. FUEL CHARACTERIZATIONS	20
III. POSTTEST EVALUATION OF TEST CONDITIONS	29
1. SUMMARY OF TEST ROD INSTRUMENTATION POSTTEST CONDITION	29
2. FUEL ROD POWER PROFILES	32
2.1 Analytical Burnup Evaluation	32
2.2 Gross and Spectral Gamma Scans	33
2.3 Flux Wire Gamma Scan	33
IV. REFERENCES	37
APPENDIX A – PRETEST FUEL ROD CHARACTERIZATION	39
APPENDIX B – POSTTEST VISUAL AND PHOTOGRAPHIC EXAMINATION	63
APPENDIX C – POSTTEST DIAMETRAL CHARACTERIZATION	75
APPENDIX D – POSTTEST NEUTRON RADIOGRAPHY	87
APPENDIX E – GROSS AND SPECTRAL GAMMA SCANS	93
APPENDIX F – FLUX WIRE GAMMA SCAN	99

APPENDIX G – METALLOGRAPHIC EXAMINATION, X-RAY DIFFRACTION, AND CLADDING MICROHARDNESS MEASUREMENTS OF FUEL ROD GC-1-002	107
APPENDIX H – METALLOGRAPHIC EXAMINATION OF FUEL ROD GC-1-003	125
APPENDIX I – METALLURGICAL SAMPLE PREPARATION	139
APPENDIX J – INSTRUMENTATION POSTTEST CONDITION	145

FIGURES

1. Several axial locations from fuel Rod GC-1-001 showing pellet-to-cladding gap sizes	6
2. Sample located 475.8 mm from bottom of fuel Rod GC-1-004 showing pellet-to-cladding gap sizes	7
3. Radial fuel pellet-to-cladding gap width at 475.0, 471.4, 431.8, and 248.0 mm from the bottom of fuel Rod GC-1-001	8
4. Radial fuel pellet-to-cladding gap width at 476.0 mm from the bottom of fuel Rod GC-1-004	9
5. Transverse sections of fuel Rod GC-1-001 showing crack patterns at the 246.7- and 248.0-mm elevations	11
6. Transverse section of fuel Rod GC-1-001 showing crack patterns at 431.8-mm elevation	12
7. Transverse sections of fuel Rod GC-1-001 showing crack patterns at 465.3-, 471.4-, and 475.0-mm elevations	13
8. Transverse sections of fuel Rod GC-1-004 showing crack patterns at the 244.0- and 246.3-mm elevations	15
9. Transverse sections of fuel Rod GC-1-004 showing crack patterns at the 463.6-, 474.0-, and 476.0-mm elevations	16
10. Grain structures of the cladding and fuel from transverse sample located 471.7 mm from the bottom of fuel Rod GC-1-001	22

11.	Grain structures of the cladding and fuel from transverse sample located 246.7 mm from the bottom of fuel Rod GC-1-001	23
12.	Cladding and fuel grain structures from transverse sample located 244.0 mm from the bottom of fuel Rod GC-1-004	24
13.	Sample M7 at 474.0 mm from the bottom of the fuel Rod GC-1-004	25
14.	Fuel porosity versus pellet radius for fuel Rod GC-1-001, at the 246.7- and 471.7-mm elevations	26
15.	Fuel porosity versus pellet radius for fuel Rod GC-1-004, at the 244.0- and 474.0-mm elevations	27
16.	Fuel pellet outer surface and cladding inner surface from scanning electron microscope (sample from fuel Rod GC-1-004)	28
17.	Gross gamma scans of Gap Conductance Test GC 1-3 fuel rods	34
18.	Neutron fluence from the flux wire versus burnup for fuel Rod GC-1-004	35
19.	Normalized gamma activity determined from the gross gamma scan of fuel Rod GC-1-004 and the test flux wire	36
B-1.	Fuel Rod GC-1-001 at 0 degrees	66
B-2.	Fuel Rod GC-1-001 at 180 degrees	67
B-3.	Fuel Rod GC-1-002 at 0 degrees	68
B-4.	Fuel Rod GC-1-002 at 180 degrees	68
B-5.	Fuel Rod GC-1-003 at 0 degrees	69
B-6.	Fuel Rod GC-1-003 at 180 degrees	70
B-7.	Fuel Rod GC-1-004 at 0 degrees	71
B-8.	Fuel Rod GC-1-004 at 180 degrees	72
B-9.	Cladding thermocouple junctions at 0.48 m from the bottom of fuel Rod GC-1-001	73
C-1.	Postirradiation diameter of fuel Rod GC-1-001	78

C-2.	Postirradiation diameter of fuel Rod GC-1-002	79
C-3.	Postirradiation diameter of fuel Rod GC-1-003	80
C-4.	Postirradiation diameter of fuel Rod GC-1-004	81
D-1.	Neutron radiographs of fuel Rods GC-1-001 and GC-1-002 at 0- and 90-degree orientations	90
E-1.	Normalized gamma activity determined from the gross gamma scan of fuel Rod GC-1-004	98
F-1.	Normalized gamma activity determined from the gamma scanning of the flux wire from fuel Rod GC-1-004	105
G-1.	Sectioning diagram for fuel Rod GC-1-002	110
G-2.	Transverse sample from fuel Rod GC-1-002 at several axial locations, showing cladding and internal thermocouple junctions	111
G-3.	Composite across the fuel and cladding, sample located 463.3 mm from the bottom of fuel Rod GC-1-002	113
G-4.	Composite across the fuel and cladding, sample located 475.7 mm from the bottom of fuel Rod GC-1-002	116
G-5.	Internal thermocouple sheaths located at 475.7 mm from the bottom of fuel Rod GC-1-002	117
G-6.	The 0-, 120-, and 240-degree cladding thermocouple junction welds located at 475.7 mm from the bottom of fuel Rod GC-1-002	118
G-7.	Transverse sample from fuel Rod GC-1-002 at several axial locations, showing cladding thermocouple junctions	119
G-8.	Cladding and fuel grain structure from transverse sample located 246.5 mm from the bottom of fuel Rod GC-1-002	120
G-9.	The 90- and 270-degree cladding thermocouple junction welds at 246.5 mm from the bottom of fuel Rod GC-1-002	121
G-10.	Cladding from sample of fuel Rod GC-1-002 showing cracking on inner diameters	122

G-11.	Cladding from sample of fuel Rod GC-1-002 showing cracking on inner diameters	123
H-1.	Sectioning diagram for fuel Rod GC-1-003	128
H-2.	Transverse sample from fuel Rod GC-1-003 at several axial locations, showing cladding thermocouple junctions and the condition of the junction welds	129
H-3.	The 0-, 120-, and 240-degree cladding thermocouple welds of sample located at 478.3 mm from the bottom of fuel Rod GC-1-003	131
H-4.	Internal thermocouples and ultrasonic thermometer sheaths of sample located at 478.3 mm from the bottom of fuel Rod GC-1-003	132
H-5.	Composite across fuel and cladding of sample located 465.0 mm from the bottom of fuel Rod GC-1-003	133
H-6.	Transverse sample from fuel Rod GC-1-003 at several axial locations, showing cladding thermocouple junctions and the condition of the junction welds	135
H-7.	The 90-, and 270-degree cladding thermocouple junction welds from sample of fuel Rod GC-1-003	136
H-8.	Grain structures of the cladding and fuel from transverse sample located 248.0 mm from the bottom of fuel Rod GC-1-003	137
J-1.	Diagram of relative angular and axial locations of thermocouples and orientation of test fuel rods in 4x hardware for Gap Conductance Test GC 1-3	148
J-2.	Transverse sample from fuel Rod GC-1-001 at several axial location, showing internal and cladding thermocouple junctions and the condition of the junction welds	150
J-3.	Centerline thermocouple sheath and zero-degree, off-center internal thermocouple sheath of sample located 465.3 mm from the bottom of fuel Rod GC-1-001	152
J-4.	The 0-, 120-, and 240-degree cladding thermocouple junction welds of sample located 471.7 mm from the bottom of fuel Rod GC-1-004	153

J-5.	Transverse sample from fuel Rod GC-1-001 at several axial locations, showing cladding thermocouple junctions and the condition of the junction welds	154
J-6.	The 90- and 270-degree cladding thermocouple junction welds of sample located 246.7 mm from the bottom of fuel Rod GC-1-001	155
J-7.	Transverse sample from fuel Rod GC-1-004 at several axial locations, showing internal and cladding thermocouple junctions and the condition of the junction welds	157
J-8.	The 0-, 120-, and 240-degree cladding thermocouple junction welds from sample of fuel Rod GC-1-004	159
J-9.	Transverse sample from fuel Rod GC-1-004 at several axial locations, showing cladding thermocouple junctions and the condition of the junction welds	160
J-10.	The 90- and 270-degree cladding thermocouple junction welds from sample located 244.0 mm from the bottom of fuel Rod GC-1-004 . . .	161
J-11.	Parameters used for pellet hole diameter measurements	163

TABLES

I.	Average Effective Gap Widths	18
II.	Crack Patterns of Fuel from Fuel Rod GC-1-001	19
III.	Summary of Posttest Instrument Conditions for Rods GC-1-001 and GC-1-004	30
IV.	Gap Conductance Test GC 1-3 Radiochemical Analysis Results	32
A-I.	Gap Conductance Test GC 1-3 Fuel Rod Component Characterization Data	41
A-II.	Test GC 1-3 Fuel Pellet Characterization Data for Test Rod GC-1-001	42
A-III.	Test GC 1-3 Fuel Pellet Characterization Data for Test Rod GC-1-002	46

A-IV.	Test GC 1-3 Fuel Pellet Characterization Data for Test Rod GC-1-003	50
A-V.	Test GC 1-3 Fuel Pellet Characterization Data for Test Rod GC-1-004	54
A-VI.	Test GC 1-3 Fuel Rod Cladding Diameter Data for Test Rod GC-1-001	58
A-VII.	Test GC 1-3 Fuel Rod Cladding Diameter Data for Test Rod GC-1-002	59
A-VIII.	Test GC 1-3 Fuel Rod Cladding Diameter Data for Test Rod GC-1-003	60
A-IX.	Test GC 1-3 Fuel Rod Cladding Diameter Data for Test Rod GC-1-004	61
C-I.	Gap Conductance Test GC 1-3 Postirradiation Examination Diametral Measurements from Rod GC-1-001	82
C-II.	Gap Conductance Test GC 1-3 Postirradiation Examination Diametral Measurements from Rod GC-1-002	83
C-III.	Gap Conductance Test GC 1-3 Postirradiation Examination Diametral Measurements from Rod GC-1-003	84
C-IV.	Gap Conductance Test GC 1-3 Postirradiation Examination Diametral Measurements from Rod GC-1-004	85
E-I.	Gamma Scan Data for Fuel Rod GC-1-004, 0 Degrees	96
F-I.	Flux Wire Gamma Scan Data from Gap Conductance Test GC 1-3	102
G-I.	Location of Instrumentation for Fuel Rod GC-1-002	112
G-II.	Thermodynamic Data for UO_2 , Ta_2O_5 , WO_3 , and H_2O	115
G-III.	Cladding Microhardness Test	124
H-I.	Location of Instrumentation for Fuel Rod GC-1-003	130
I-I.	Sectioning Schedule for Gap Conductance Test GC 1-3	142

J-I.	Fuel Rod Instrumentation	149
J-II.	Axial Location of Instrumentation for Fuel Rod GC-1-001	151
J-III.	Axial Location of Instrumentation for Fuel Rod GC-1-004	158
J-IV.	Pre- and Posttest Measurements of the Drilled Instrumentation Holes for Fuel Rods GC-1-001 and GC-1-004	162

EXPERIMENT DATA REPORT
GAP CONDUCTANCE TEST SERIES

TEST GC 1-3

POSTIRRADIATION EXAMINATION

I. INTRODUCTION

Fuel rod behavior studies are being conducted in the Thermal Fuels Behavior Program (TFBP) as part of the Nuclear Regulatory Commission's Water Reactor Safety Research Fuel Behavior Program^[1]. The TFBP is conducted by EG&G Idaho, Inc., under contract to the Energy Research and Development Administration. The program is being performed in the Power Burst Facility (PBF) at the Idaho National Engineering Laboratory. Experimental data are being obtained from in-pile tests in the PBF reactor to characterize and evaluate fuel rod performance, and to verify analytical models developed to predict the behavior of light water nuclear reactor fuel rods under normal and postulated accident conditions. Gap Conductance Test GC 1-3 was one of a number of tests designed to assist in providing these experimental data. Test GC 1-3 was performed with four nominal design (except for length), boiling water reactor (BWR) test rods symmetrically positioned in the PBF in-pile tube (IPT).

The primary objectives of Test GC 1-3 were to:

- (1) Obtain experimental data for estimating gap conductance values by both the steady state $fkdT$ and the power oscillation experimental methods, and to determine the feasibility of using the power oscillation method for estimating gap conductance values
- (2) Obtain data for evaluating the effects of oscillation amplitude and frequency on the estimated gap conductance values for boiling water reactor test fuel rods
- (3) Obtain data to evaluate the capability for internal off-center thermocouples to provide more accurate fuel pellet surface temperature information than can be obtained by fuel centerline temperature measurements and associated calculations.

Additional objectives of the test were to:

- (1) Obtain data on four, identically designed test fuel rods to provide replication from a single test rather than from repeated tests
- (2) Evaluate reproducibility of the test results by repeating some of the test conditions and comparing thermal response data.

This report describes the results of the postirradiation examination (PIE) of the four Gap Conductance Test GC 1-3 fuel rods. The objective of the postirradiation examination was to provide specific experimental data on the fuel rod gas pressure and composition, posttest condition of the fuel-cladding gap, fuel crack patterns, and fuel structure and to evaluate any changes in the fuel or cladding that would affect the parameters used in the gap conductance calculations.

Test GC 1-3 was performed with four, nominal design, BWR-6 fuel rods, each contained in a flow shroud (19.3-mm ID) and located within the PBF in-pile tube. Test fuel rod designations were Rods GC-1-001, GC-1-002, GC-1-003, and GC-1-004.

The test fuel rods were composed of 0.91-m-long fuel stacks of 95% theoretical density, 10% enriched UO_2 ceramic fuel pellets, each nominally 10.6 mm in diameter and 10.7 mm long. The pellets were contained in zircaloy-2 alloy cladding tubes of nominal 12.5-mm outside diameter and 0.84-mm wall thickness. The nominal fuel pellet-cladding diametral gap was 250 μm . The bottom of the fuel stack was located 35.10 mm from the bottom of the rod. The fuel rod internal void volume was 12.26 cm^3 for Rod GC-1-001, 12.50 cm^3 for Rod GC-1-002, 12.13 cm^3 for Rod GC-1-003, and 12.08 cm^3 for Rod GC-1-004. The assembled fuel rods were pressurized to 0.103 MPa with helium gas at ambient temperature. The specific pretest characterization data of the unirradiated fuel rods are presented in Appendix A.

The test assembly was instrumented for measurement of fuel centerline temperatures, fuel temperatures close to the fuel pellet surface, cladding surface temperatures, fuel rod coolant flow rates, coolant pressure, coolant temperature rise for each rod, and instantaneous and integrated relative thermal neutron flux in the test space.

Test GC 1-3 consisted of three parts: (a) steady state operation (power calibration) over a range of PBF core power levels to determine power densities for each of the four test fuel rods, (b) a preconditioning period to evaluate fuel pellet cracking and rearrangement effects on thermal response and gap conductance values, and (c) a power oscillation period to determine gap conductance values for a variety of oscillation magnitudes and periods at four different power levels.

Section II of this report presents the measured posttest fuel rod internal gas pressures, fuel pellet-to-cladding gap sizes, fuel crack patterns, and fuel characterizations. Section III

discusses the posttest evaluation of the test conditions. The pretest fuel rod characterization data are presented in Appendix A. Posttest visual and photographic inspections, posttest diametral measurements, neutron radiography, gross gamma scans, and flux wire gamma scans are presented in Appendices B through F. The destructive examination information for two of the fuel rods which failed during the test is presented in Appendices G and H. Appendix I describes the metallographic sample preparation procedures. The posttest condition of the fuel rod instrumentation is presented in Appendix J.

II. POSTTEST FUEL ROD CHARACTERIZATION

The postirradiation examination of the four fuel rods from Test GC 1-3 included both nondestructive and destructive examinations. The posttest visual and photographic inspection, posttest diameter measurements, neutron radiography, and gross and flux wire gamma scan data are presented in Appendices B through F.

Fuel Rods GC-1-002 and GC-1-003 were found to contain water. The water reacted with the fuel and the internal instrumentation, changing the parameters for gap conductance calculations significantly. Because of the large uncertainty in the final fuel composition, gap conductance calculations were not performed for these two fuel rods. The fuel rod characterization data for Rods GC-1-002 and GC-1-003 are presented in Appendices G and H.

The following sections present the measured posttest gas pressures and compositions, fuel pellet-to-cladding gaps, fuel crack patterns, and general fuel structure for fuel Rods GC-1-001 and GC-1-004.

1. INTERNAL GAS PRESSURE AND COMPOSITION

The internal gas in the fuel rods was sampled by mechanically puncturing the fuel rod fill tube and removing the gas. After the internal gas was removed, the fuel rod void volume was determined. Use of the mechanical puncturing fixture requires a fill tube length of 34.9 mm. Since the fill tube on Rod GC-1-001 was only 17.5 mm long, gas sampling and void volume measurements could not be made on this rod. Fuel rod fill tube lengths will be changed for future tests in order to avoid this problem.

When the fill tube on Rod GC-1-002 was punctured, it was discovered that a break in the cladding had admitted air to the fuel rod, thus precluding fill gas sampling and void volume measurements. (A vacuum of 10^{-4} torr within the fuel rod must be achieved to perform void volume measurements.)

A large amount of water was removed from fuel Rod GC-1-003 in the form of vapor which condensed on the inside of the gas collection glassware. Even with the use of heat lamps, all of the water could not be removed from the rod. A gas sample was not taken and void volume measurements were not made on this fuel rod.

The gas from fuel Rod GC-1-004 was sampled and the evaluated composition in mole percent was 0.01% H_2 with the standard deviation (σ) = 0.00017% assuming a normal distribution, 0.48% He with σ = 0.008%, 80.7% N_2 with σ = 0.1345%, 17.6% O_2 with σ = 0.0293%, 1.2% Ar with σ = 0.020%, and 0.1% CO_2 with σ = 0.0017%. Although this rod, as well as the other three rods, was helium filled during fabrication. This composition

indicates the rod was air filled at the time of examination. The void volume of fuel Rod GC-1-004 was $11.82 \pm 0.2 \text{ cm}^3$ (a decrease of 0.3 cm^3 from the original void volume), and the internal pressure was 0.077 MPa with a standard deviation of 0.00052 MPa, using second-order error propagation techniques (a decrease of 0.026 MPa from the original internal pressure).

Because of the difficulties encountered in obtaining void volume measurements and gas sample evaluations, the fuel rod fabrication and pre- and posttest handling procedures used were reevaluated. The internal instrumentation leads were found to provide possible posttest leak paths for the internal gas from the fuel rods. Following the test, these leads were cut to permit removal of the fuel rods from the reactor. If the sheaths of the leads had split inside a fuel rod, internal gas could slowly leak through the open leads. The conclusion reached was that the presence of air in fuel Rod GC-1-004 may have been due to gas replacement by air during the storage period following the test and preceding the examination.

2. FUEL PELLET-TO-CLADDING GAP SIZES

The fuel pellet-to-cladding gap was measured at four axial locations in fuel Rod GC-1-001 (475.0, 471.4, 431.8, and 248.0 mm) and at the 476.0-mm axial location in fuel Rod GC-1-004. A discussion of the uncertainty in the axial location is presented in Appendix I. Measurements were taken from 100x photographs at intervals of at least every 30 degrees around the edge of the pellet, with the sample in the as-polished condition. The location and values of the measured gap widths are shown in Figures 1 and 2. Assuming a normal distribution, the standard deviation of the gap width measurements is $1.7 \text{ }\mu\text{m}$.

The measured average radial gap was $47 \text{ }\mu\text{m}$ (31% of the original radial gap) at the 485.0-mm location, $38 \text{ }\mu\text{m}$ (30% of the original radial gap) at the 471.4-mm location, $59 \text{ }\mu\text{m}$ (47% of the original radial gap) at the 431.8-mm location, and $70 \text{ }\mu\text{m}$ (56% of the original radial gap) at the 248.0-mm location on Rod GC-1-001. The average radial gap was $80 \text{ }\mu\text{m}$ (64% of the original radial gap) at the 476.0-mm location on Rod GC-1-004. The radial gaps at each of four axial locations are plotted in Figure 3 for Rod GC-1-001, and at one axial location on Rod GC-1-004 in Figure 4.

Fig. 1 Several axial locations from fuel Rod GC-1-001 showing pellet-to-cladding gap sizes.

Fig. 2 Sample located 475.8 mm from bottom of fuel Rod GC-1-004 showing pellet-to-cladding gap sizes.

INEL-A-4977

Fig. 3 Radial fuel pellet-to-cladding gap width at 475.0, 471.4, 431.8, and 248.0 mm from the bottom of fuel Rod GC-1-001.

Fig. 4 Radial fuel pellet-to-cladding gap width at 476.0 mm from the bottom of fuel Rod GC-1-004.

3. FUEL CRACK PATTERNS

The crack patterns in the fuel of Rods GC-1-001 and GC-1-004 were examined in an attempt to obtain data for evaluating the effects of cracks on the change in pellet-to-cladding gap width and for correlating crack patterns with an effective pellet-to-cladding gap width to be used in gap conductance determinations.

Figures 5, 6, and 7 show cross sections at six axial locations of fuel Rod GC-1-001. Measurements were made of crack areas at the four axial locations of 248.0, 431.8, 471.4, and 475.0 mm and the crack patterns are shown on the appropriate figures. A discussion of the uncertainty in the axial locations is presented in Appendix I. Figures 8 and 9 show cross sections at five axial locations of fuel Rod GC-1-004. Measurements were made of the crack area at the 476.0-mm elevation, and the crack pattern is shown in Figure 9. The widths of the cracks were measured on 100x photographs taken along the length of the cracks. Assuming a normal distribution, the standard deviation of the crack width measurements is 0.0017 mm. The lengths of the cracks were determined from an approximately 15x photograph of the cross section of the fuel rod. Assuming a normal distribution, the standard deviation of the crack length measurements is 0.011 mm. The width of the cracks that separate the internal instrumentation are marked on the figures. These individual cracks are important in evaluating the heat transfer in the fuel between thermocouples.

The relation between the area of the fuel cracks and the gap width is derived from the following equation :

$$\pi(r_{ID})^2 - \pi(r_p)^2 = A$$

where

r_{ID} = radius to the cladding inner diameter minus the average radial gap

r_p = radius of fuel pellet if all of the fuel cracks were removed

A = total area of fuel cracks (measured).

The standard deviation of the total crack area is 0.89 mm^2 using first-order error propagation techniques.

Therefore,

$$r_{ID}^2 - r_p^2 = \frac{A}{\pi}$$

and r_p is the quantity solved for. The added gap due to the area of the cracks is given by $r_{ID} - r_p$. Table I shows the calculated average effective gap widths.

(a) 246.7-mm elevation

(b) 248.0-mm elevation

Fig. 5 Transverse sections of fuel Rod GC-1-001 showing crack patterns at the 246.7- and 248.0-mm elevations.

Fig. 6 Transverse section of fuel Rod GC-1-001 showing crack patterns at the 431.8-mm elevation.

(a) 465.3-mm elevation

(b) 471.4-mm elevation

Fig. 7 Transverse sections of fuel Rod GC-1-001 showing crack patterns at 465.3-, 471.4-, and 475.0-mm elevations.

(c) 475.0-mm elevation

Fig. 7 (continued).

(a) 244.0-mm elevation

(b) 246.3-mm elevation

Fig. 8 Transverse sections of fuel Rod GC-1-004 showing crack patterns at the 244.0- and 246.3-mm elevations.

(a) 463.6-mm elevation

(b) 474.0-mm elevation

Fig. 9 Transverse sections of fuel Rod GC-1-004 showing crack patterns at the 463.6-, 474.0-, and 476.0-mm elevations.

(c) 476.0-mm elevation

Fig. 9 (continued).

TABLE I
AVERAGE EFFECTIVE GAP WIDTHS

Sample Location (mm from bottom of rod)	Average Gap Width (μm)	Area of Cracks (mm^2)	Gap Added Width from Cracks (μm)	Total Effective Gap (μm)
<u>Rod GC-1-001</u>				
475.0	47	1.708	51	98
471.7	38	2.174	65	103
431.8	59	2.054	61	120
248.0	70	2.515	75	145
<u>Rod GC-1-004</u>				
476.0	80	1.850	55	135

Figures 5(a) and 5(b) show two surfaces located about one-fourth the distance up from the bottom of fuel Rod GC-1-001. The crack pattern at the two locations, 1.3 mm apart, is essentially the same. One large radial crack, varying from 65 to 250 μm in width, splits the pellet into two approximately equal pieces. The cracks are primarily radial, with nine cracks intersecting the pellet surface. The laser attachment welds of the cladding thermocouples at this elevation did not affect the cracking pattern of the fuel.

Figure 6 shows the fuel at the 431.8-mm elevation of Rod GC-1-001, about 35 mm below the location of the internal thermocouples. The cracks were more numerous and of smaller width at this location than at the lower elevation shown in Figure 5. The majority of the cracks were radial, with 21 of them intersecting the pellet surface. The fuel pellet had shattered at the surface in an area between 210 and 245 degrees. The laser attachment welds of the cladding thermocouples at this elevation did not affect the fuel crack pattern.

Figure 7 shows transverse sections of fuel Rod GC-1-001 between 465.3 and 475.0 mm. The crack pattern shown changes between 465.3 mm [Figure 7(a)] and 471.4 mm [Figure 7(b)], a 6.1-mm change in elevation. The crack pattern also changes between 471.4 mm [Figure 7(b)] and 475.0 mm [Figure 7(c)], a 3.6-mm change in elevation.

The internal fuel rod instrumentation affected the fuel cracking pattern. At all three elevations in Figure 7 the crack pattern is primarily radial, with one large crack running from the centerline-drilled hole to each of the off-center-drilled holes. A crack also extends radially from the off-center-drilled holes to the edge of the fuel pellet at all of the elevations shown. No circumferential cracks separated the off-center-drilled holes from the edge of the pellet. Table II shows statistics for the cracking pattern at each of the three elevations. The

TABLE II
CRACK PATTERNS OF FUEL FROM FUEL ROD GC-1-001

Elevation (mm from bottom of rod)	Number of Radial Cracks Intersecting Pellet Surface	Number of Cracks Separating Off-Center and Centerline Thermocouples		
		0 degrees	120 degrees	240 degrees
465.3	14, plus shattered fuel between 290 and 310 degrees	Two circumferential cracks	Three circumferential, plus one radial crack	Three circumferential, plus one radial crack
471.4	15	Two circumferential, plus one radial crack	One circumferential, plus one radial crack	Two circumferential, plus one radial crack
475.0	13	Two radial cracks	Two radial cracks	One circumferential, plus one radial crack

number of circumferential cracks indicated is the maximum number of cracks separating any given path between the centerline and off-center thermocouples. The widths of these cracks are marked on the figures.

Figures 8(a) and 8(b) show two surfaces located about one-fourth the distance up from the bottom of fuel Rod GC-1-004 (244.0 and 246.3 mm). One large crack through the center of the pellet occurred at both locations; however, the rest of the crack pattern had changed in the 2.3 mm that separated the two locations. Both radial and circumferential cracks were present, with nine radial cracks intersecting the pellet surface at the 244.0-mm elevation, and fourteen radial cracks intersecting the surface at the 246.3-mm elevation. The cracking pattern of the fuel was not influenced by the laser welding of the thermocouple to the cladding.

Figures 9(a), 9(b), and 9(c) show three transverse sections of Rod GC-1-004 between the 463.6- and 476.0-mm elevations. The crack pattern at the 463.6-mm elevation [Figure 9(a)] is not evident at the 474.0-mm elevation [Figure 9(b)], 10.4 mm above, nor is the crack pattern at the 474.0-mm elevation [Figure 9(b)] recognizable at the 476.0-mm elevation [Figure 9(c)], 2.0 mm above. At all three elevations the cracks were primarily radial, with one large crack running from the centerline-drilled hole to the one off-center-drilled hole.

At the 463.6-mm location [Figure 9(a)], 17 radial cracks intersected the pellet surface. No circumferential cracks occurred between the one off-center-drilled hole and the edge of the fuel pellet. Two circumferential cracks occurred between the off-center-drilled hole and the centerline-drilled hole. The fine cracks visible in the photograph are generally less than 20 μm in width.

At the 474.0-mm location [Figure 9(b)], 17 radial cracks intersected the pellet surface. The large, dark area in the photograph indicates missing fuel. Apparently, a crack ran along each edge of the area of missing fuel. No circumferential cracks occurred between the off-center-drilled hole and the edge of the fuel pellet.

At the 476.0-mm elevation [Figure 9(c)], 14 radial cracks intersected the pellet surface. No circumferential cracks occurred between the off-center-drilled hole and the edge of the fuel pellet. Two circumferential cracks occurred between the off-center-drilled hole and the centerline-drilled hole.

4. FUEL CHARACTERIZATIONS

The fuel in fuel Rods GC-1-001 and GC-1-004 was examined following the test to characterize the fuel structure and porosity and to estimate the maximum centerline fuel temperature during the test. The outside surface of a fuel pellet and the inside surface of the cladding were examined for determination of surface roughness. The grain structure of the cladding was also examined.

Figure 10 shows the fuel and cladding grain structure at the 471.7-mm elevation of Rod GC-1-001. The cladding exhibited as-received, recrystallized α -phase zircaloy grain structure throughout, with a grain diameter of $5.8 \pm 0.4 \mu\text{m}$. The fuel showed equiaxed grains, with the grain diameter increasing from $22 \pm 1.8 \mu\text{m}$ near the outside edge of the pellet to $52 \pm 8.9 \mu\text{m}$ at the center of the pellet. Figure 11 shows the cladding and fuel grain structure at the 246.7-mm elevation of Rod GC-1-001. The cladding exhibited as-received, recrystallized α -phase zircaloy grain structure throughout, with a grain diameter of $5.9 \pm 0.4 \mu\text{m}$. The fuel showed equiaxed grains, with the grain diameter varying from $16 \pm 0.9 \mu\text{m}$ near the outside edge of the pellet to $25 \pm 2.3 \mu\text{m}$ at the center.

Figure 12 shows the grain structure of the fuel and cladding at the 244.0-mm elevation of Rod GC-1-004. The cladding grain diameter was $6.3 \pm 0.4 \mu\text{m}$ and the fuel grain diameter varied from $17 \pm 1.1 \mu\text{m}$ at the outside edge to $24 \pm 2.1 \mu\text{m}$ at the center of the fuel. The cladding structure was as-received, recrystallized α -phase zircaloy. Figure 13 shows a composite across the fuel and cladding at the 474.0-mm elevation of Rod GC-1-004. The fuel grain diameter changed from $16 \pm 0.9 \mu\text{m}$ at the outside edge of the pellet to $23 \pm 2.0 \mu\text{m}$ near the center. The cladding grain diameter was $6.4 \pm 0.4 \mu\text{m}$. The cladding structure was recrystallized α -phase zircaloy.

An unirradiated fuel pellet was examined to determine an original fuel grain diameter for the gap conductance test fuel. In the unirradiated pellet the grain diameter was found to be $22 \pm 1.8 \mu\text{m}$ uniformly throughout the pellet. However, fuel with a grain diameter of $16 \mu\text{m}$ was found in both Rods GC-1-001 and GC-1-004. Apparently, the original fuel grain size varied from pellet to pellet between 16 and $22 \mu\text{m}$.

The posttest porosity of the fuel was evaluated at two elevations each, for fuel Rods GC-1-001 and GC-1-004. The number of pores in a 14.5-cm^2 area were counted on 200x photographs for each of the areas evaluated. An average pore diameter was estimated. The pore diameter measurements were accurate to within $\pm 28\%$, resulting in large errors in the final percent porosity calculated from the measured values. Figure 14 shows the percent porosity plotted against fractional pellet radius for the 246.7- and 471.7-mm elevations of Rod GC-1-001. Because of the large error, no definite trend can be distinguished. The average porosity for both elevations across the pellet was 6.8%. Figure 15 presents the percent porosity plotted against the pellet radius for the 474.0- and 244.0-mm elevations of Rod GC-1-004. The average porosity for these axial locations was 9.4%.

The maximum fuel centerline temperature was calculated from grain growth kinetics. The following equation from the materials properties computer code MATPRO^[2] was used:

$$D^4 - D_0^4 = 6.18 \times 10^{13} \exp (-92\,400/RT)t$$

Etched, Polarized Light

(a) Typical Cladding, As-Received,
Recrystallized α -Phase Zircaloy
Grain Diameter $5.8\ \mu\text{m}$

20 μm

Etched, Bright Field

(b) Fuel near Outer Edge of Pellet
Grain Diameter $22\ \mu\text{m}$, Unrestructured Fuel

50 μm

Etched, Bright Field

(c) Fuel at Mid-Radius of Pellet
Grain Diameter $26\ \mu\text{m}$, Equiaxed Grain Growth

50 μm

Etched, Bright Field

(d) Fuel at Center of Pellet
Grain Diameter $52\ \mu\text{m}$, Equiaxed Grain Growth

50 μm

Metallic
Inclusion

Fig. 10 Grain structures of the cladding and fuel from transverse sample located 471.7 mm from the bottom of fuel Rod GC-1-001.

Etched, Polarized Light

(a) Typical Cladding, As-Received
Recrystallized α -Phase Zircaloy
Grain Diameter $5.9\ \mu\text{m}$

20 μm

Etched, Bright Field

(b) Unrestructured Fuel Near
Outer Edge of Pellet
Grain Diameter $16\ \mu\text{m}$

50 μm

Etched, Bright Field

(c) Fuel at Center of Pellet
Equiaxed Grain Growth
Grain Diameter $26\ \mu\text{m}$

50 μm

Fig. 11 Grain structures of the cladding and fuel from transverse sample located 246.7 mm from the bottom of fuel Rod GC-1-001.

Etched, Polarized Light

(a) Typical Cladding, As-Received,
Recrystallized α -Phase Zircaloy
Grain Diameter $6.3 \mu\text{m}$,

20 μm

Etched, Bright Field

(b) Unaffected Fuel Near Outer Edge of Pellet
Grain Diameter $17 \mu\text{m}$

50 μm

Etched, Bright Field

(c) Fuel at Mid-Radius, Equiaxed Grain Growth
Grain Diameter $20 \mu\text{m}$

50 μm

Etched, Bright Field

(d) Fuel at Center, Equiaxed Grain Growth
Grain Diameter $24 \mu\text{m}$

50 μm

Fig. 13 Sample M7 at 474.0 mm from the bottom of the fuel Rod GC-1-004.

Fig. 14 Fuel porosity versus pellet radius for fuel Rod GC-1-001, at the 246.7- and 471.7-mm elevations.

where

- D = grain diameter (μm)
- D_0 = original grain diameter – 16 μm for the 246.7-mm elevation and 22 μm for the 471.7-mm elevation
- R = 1.98 cal/K-mol
- T = temperature (K)
- t = time.

INEL-A-4978

Fig. 15 Fuel porosity versus pellet radius for fuel Rod GC-1-004, at the 244.0- and 474.0-mm elevations.

The time used was the time the fuel rod operated above the 500-W/cm power level. The maximum centerline temperature was calculated to be 2656 ± 120 K at the 471.7-mm elevation and 2280 ± 70 K at the 246.7-mm elevation of Rod GC-1-001, and 2215 ± 55 K at the 474.0-mm elevation and 2238 ± 60 K at the 244.0-mm elevation of Rod GC-1-004. The uncertainties reported here only account for the uncertainty in the grain diameter measurements. The equation used has an estimated standard deviation of $4.8 \mu\text{m}$.

The fuel was removed from the cladding of Sample R1, located 0.20 to 0.22 mm from the bottom of fuel Rod GC-1-004. (A discussion of sample preparation procedures is contained in Appendix I.) The outside surface of the fuel pellet and the inside surface of the cladding were replicated. Positive casts were made from the replicas and were examined with the scanning electron microscope. Figure 16 shows both surfaces, each at three different magnifications. Some fuel adhered to the cladding surface. Future work will attempt to quantify surface roughness by calibration against conventional stylus measurements.

(a) Fuel Outer Surface

200 μm

(b) Fuel Outer Surface

50 μm

(c) Fuel Outer Surface

5 μm

(d) Cladding Inner Surface

50 μm

(e) Cladding Inner Surface

50 μm

(f) Cladding Inner Surface

50 μm

Fig. 16 Fuel pellet outer surface and cladding inner surface from scanning electron microscope (sample from fuel Rod GC-1-004).

III. POSTTEST EVALUATION OF TEST CONDITIONS

The instrumentation on the test fuel rods was examined to better understand the validity of the data obtained from these instruments. A summary of this examination is presented in Section 1.

The fuel rod axial power profile was determined in a number of ways following the test to confirm the reactor test conditions. These results are presented in Section 2. The information provided in these two sections was obtained for subsequent use in identifying the test conditions and for providing a better understanding of the test results.

1. SUMMARY OF TEST ROD INSTRUMENTATION POSTTEST CONDITION

During the performance of Test GC 1-3, on-line measurement transducer signals indicated that all of the rod internal instruments in Rod GC-1-001 worked well throughout the test, but that many of the internal transducers failed in Rods GC-1-002, GC-1-003, and GC-1-004 at various times during the test. Posttest examinations of the instruments revealed many physical characteristics that will aid in evaluating instrument performance and interpreting fuel rod thermal response. Specific details of instrument performance and posttest examination results are provided in Appendix J. Table III summarizes pertinent physical characteristics of the important measurement transducers that were identified during the posttest examinations. Interpretation of the fuel rod thermal responses may be highly influenced by identified peculiarities in the physical condition of the measurement transducers.

TABLE III

SUMMARY OF POSTTEST INSTRUMENT CONDITIONS FOR RODS GC-1-001 AND GC-1-004

Rod	Centerline Thermocouple or Ultrasonic Thermometer	Off-Center Thermocouples (0, 120, and 240 degrees)	Instrument Condition				
			Cladding Surface Thermocouples				
			474.5-mm Elevation			244.6-mm Elevation	
			0 degrees	180 degrees	240 degrees	90 degrees	270 degrees
GC-1-001	Unidentified chemical reaction on surface of sheath. (Operated satisfactorily throughout test.)	Holes decreased slightly in diameter and moved slightly toward pellet surface. All thermocouple junctions appeared intact and no thermocouple sheath reactions were observed. (All off-center thermocouples responded satisfactorily throughout the test.) ^[a]	Weld penetrated two-thirds of cladding wall.	No unusual geometry changes.	No unusual geometry changes.	Weld penetrated cladding. Weld material found in pellet-to-cladding gap. Weld contained large voids extending nearly to the inside of the cladding.	No unusual geometry changes.

TABLE III (continued)

Rod	Centerline Thermocouple or Ultrasonic Thermometer	Off-Center Thermocouples (0, 120, and 240 degrees)	Instrument Condition				
			Cladding Surface Thermocouples				
			474.5-mm Elevation			244.6-mm Elevation	
			0 degrees	180 degrees	240 degrees	90 degrees	270 degrees
GC-1-002	Ultrasonic thermometer broke into at least two pieces (Thermometer failed during power calibration portion of test.)	Holes decreased slightly in diameter. (No apparent reason for 240-degree thermocouple failure during power calibration portion of test.)	No unusual geometry changes.	No unusual geometry changes.	Weld material on inside of cladding.	Sheath separated from cladding by 0.12 mm ± 0.01 mm.	Void, 0.24-mm ± 0.01 mm in diameter, directly beneath junction at base of weld penetration.

[a] From on-line data.

2. FUEL ROD POWER PROFILES

The objective of the power calibration portion of the test was to determine the fuel rod power generation for each of the four rods relative to the PBF core power, as indicated by the core neutron detection chambers. The power generation for each rod relative to the PBF core power was determined during the test by a thermal hydraulic energy balance and was verified by posttest fission product analysis of selected fuel samples.

The fuel rod axial power profile is directly related to the activity profiles obtained by (a) radiochemical analysis of fuel samples from the rods, (b) the gross and spectral gamma scans of the fuel rods, and (c) the cobalt flux wire activation, all of which are discussed in the following subsections.

2.1 Analytical Burnup Evaluation

The results of radiochemical analysis of one sample each from Rods GC-1-001, GC-1-002, and GC-1-003, and of three samples from Rod GC-1-004 are presented in Table IV, where fissions per kilogram of total uranium are related to burnup in fissions per cubic

TABLE IV

GAP CONDUCTANCE TEST GC 1-3 RADIOCHEMICAL ANALYSIS RESULTS

Sample Location (m from bottom of fuel rod)	Fissions per kg of T_u	Fissions per m^3 UO_2 fuel	Burnup (MWd/tU)
<u>Rod GC-1-001</u>			
0.22 to 0.23	$1.18 \times 10^{20} / \pm 1.7 \times 10^{18}$	10.97×10^{23}	39.94
<u>Rod GC-1-002</u>			
0.22 to 0.23	$1.23 \times 10^{20} / \pm 1.9 \times 10^{18}$	11.44×10^{23}	41.64
<u>Rod GC-1-003</u>			
0.22 to 0.23	$1.25 \times 10^{20} / \pm 1.7 \times 10^{18}$	11.62×10^{23}	42.31
<u>Rod GC-1-004</u>			
0.45 to 0.46	$1.66 \times 10^{20} / \pm 2.4 \times 10^{18}$	15.44×10^{23}	56.19
0.22 to 0.23	$1.19 \times 10^{20} / \pm 1.6 \times 10^{18}$	11.07×10^{23}	40.28
0.13 to 0.14	$0.68 \times 10^{20} / \pm 0.99 \times 10^{18}$	6.32×10^{23}	23.02

meter and megawatt days per metric ton of uranium (MWd/tU). These data are compared with the neutron flux axial profile in Subsection 2.3.

2.2 Gross and Spectral Gamma Scans

Figure 17 presents the results of the gross gamma scans of all four test fuel rods. The uncertainty in the gross gamma activity is $\pm 5\%$. An unusual shift upward in gamma activity starting at 0.40 to 0.45 m from the bottom of the fuel stack and continuing to the top of the rod is shown for fuel Rods GC-1-001, GC-1-002, and GC-1-003. Spectral gamma scanning, performed on fuel Rod GC-1-001 at the two areas indicated in Figure 17, indicated that the increase was due to tantalum activation. Fuel Rods GC-1-001 and GC-1-002 both contained four tantalum-sheathed internal thermocouples which ended at about 0.43 m from the bottom of the fuel stack. Apparently, these sheaths became activated. Fuel Rod GC-1-003 contained only three tantalum-sheathed internal thermocouples, which resulted in less increase in activity. Fuel Rod GC-1-004 contained only one tantalum-sheathed thermocouple and no apparent increase in activity was detected in this fuel rod. The gamma intensity profile of fuel Rod GC-1-004 appears to be generally consistent with the expected axial power distribution.

2.3 Flux Wire Gamma Scan

The relative axial neutron flux profile was measured for Test GC 1-3 from a 0.510% cobalt aluminum flux wire attached to the shroud of fuel Rod GC-1-004 to an estimated uncertainty of $\pm 6\%$. The flux wire was removed after the test and gamma scanned. The integrated thermal neutron flux is approximately proportional to the induced radioactivity of the flux wire. The results of this scan are presented in Appendix F, Table F-I, and plotted in Figure F-1.

The neutron flux axial profile is directly related to the fuel rod axial power profile. Figure 18 presents the burnup results from radiochemical analysis of selected fuel rod segments of Rod GC-1-004 plotted against the neutron fluence from the flux wire attached to the shroud of the rod. The resulting straight line indicates that the cobalt flux wire scan is consistent with the axial power profile from the radiochemical analysis.

The fuel rod axial power profile obtained from the gamma scan data is related to the neutron flux axial profile. Results of the relative fuel rod gamma activity along the scan, compared with the average activity (1.405 arbitrary units), are presented in Appendix E, Table E-I. The results of the relative flux wire activity are presented in Appendix F, Table F-II. The normalized data from Tables E-I and F-II are shown in Figure 19. The peak for the normalized fuel rod gamma scan activity was 1.402 and was located between 0.43 and 0.51 m from the bottom of the fuel stack. The peak for the normalized flux wire activity was 1.347 and was located 0.45 ± 0.01 m from the bottom of the fuel stack. These two measurements of rod axial power profile are in good agreement.

Fig. 17 Gross gamma scans of Gap Conductance Test GC 1-3 fuel rods.

INEL-A-4979

Fig. 18 Neutron fluence from the flux wire versus burnup for fuel Rod GC-1-004.

INEL-A-4973

Fig. 19 Normalized gamma activity determined from the gross gamma scan of fuel Rod GC-1-004 and the test flux wire.

IV. REFERENCES

1. United States Nuclear Regulatory Commission, Reactor Safety Research Program, *A Description of Current and Planned Reactor Safety Research Sponsored by the Nuclear Regulatory Commission's Division of Reactor Safety Research*, NUREG-75/058 (June 1975).
2. P. E. MacDonald et al, *MATPRO – A Handbook of Materials Properties for Use in the Analysis of Light Water Reactor Fuel Behavior*, ANCR-1263 (February 1976).

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX A
PRETEST FUEL ROD CHARACTERIZATION

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX A

PRETEST FUEL ROD CHARACTERIZATION

The design nominal physical characteristics of the fuel rod components needed for model evaluation and verification are presented in this appendix.

The Gap Conductance Test GC 1-3 fuel rod component characterization is presented in Table A-I.

The physical characteristics (diameter, length, weight, and density) of the boiling water reactor type pellets used in the Test GC 1-3 fuel rods are presented in Tables A-II through A-V. The fuel diameter and length measurements are accurate to within $\pm 5 \mu\text{m}$.

Individual fuel rod cladding diameter measurements for the Test GC 1-3 fuel rods are listed in Tables A-VI through A-IX. An air gauge was used to obtain the inner diametral measurements listed in these tables. All cladding measurements are accurate to within $\pm 3 \mu\text{m}$.

TABLE A-I

GAP CONDUCTANCE TEST GC 1-3 NOMINAL
FUEL ROD COMPONENT CHARACTERIZATION DATA

FUEL	
Ceramic grade, sintered uranium dioxide (UO_2) pellets	
Enrichment (wt% U-235 of total U)	10.01 ± 0.05
Density (kg/m^3)	10.406×10^3
Pellet diameter (mm)	10.58
Pellet length (mm)	10.7
CLADDING	
Inside diameter (mm)	10.83
Outside diameter (mm)	12.51
Wall thickness (mm)	0.84
Yield strength (0.2% offset, MPa)	138
Tensile strength (MPa)	262
Elongation (%)	48
Hardness (R_B)	85

TABLE A-II

TEST GC 1-3 FUEL PELLETT CHARACTERIZATION DATA FOR TEST ROD GC-1-001

Pellet ^[a]	Diameter (cm)				Length (cm)			Weight (g)	Geometric Density (g/cm ³)	Immersion Density (g/cm ³)	Centerline Hole Diameter (cm)	
	Top	Center	Bottom	Average	0°	90°	Average				Top	Bottom
1	1.0579	1.0579	1.0579	1.0579	0.5783	0.5679	0.5721	5.2358	10.4111	0.0000	0.0000	0.0000
2	1.0579	1.0579	1.0579	1.0579	1.0671	1.0622	1.0648	9.7198	10.3864	0.0000	0.0000	0.0000
3	1.0582	1.0587	1.0582	1.0583	1.0759	1.0709	1.0734	9.7995	10.3778	0.0000	0.0000	0.0000
4	1.0577	1.0577	1.0577	1.0577	1.0693	1.0617	1.0655	9.7278	10.3913	0.0000	0.0000	0.0000
5	1.0579	1.0579	1.0574	1.0577	1.1031	1.0978	1.1005	10.0632	10.4068	10.4887	0.0000	0.0000
6	1.0579	1.0579	1.0574	1.0577	1.1140	1.1107	1.1124	10.1583	10.3924	0.0000	0.0000	0.0000
7	1.0571	1.0574	1.0577	1.0574	1.0780	1.0719	1.0749	9.7953	10.3769	0.0000	0.0000	0.0000
8	1.0569	1.0574	1.0574	1.0572	1.0622	1.0571	1.0597	9.6801	10.4057	0.0000	0.0000	0.0000
9	1.0579	1.0577	1.0584	1.0580	1.0810	1.0772	1.0791	9.8535	10.3864	0.0000	0.0000	0.0000
10	1.0569	1.0574	1.0579	1.0574	1.0665	1.0625	1.0645	9.7186	10.3964	10.4853	0.0000	0.0000
11	1.0569	1.0569	1.0566	1.0568	1.0927	1.0894	1.0911	9.9658	10.4131	0.0000	0.0000	0.0000
12	1.0574	1.0577	1.0579	1.0577	1.0523	1.0480	1.0502	9.5767	10.3796	0.0000	0.0000	0.0000
13	1.0571	1.0579	1.0577	1.0576	1.0800	1.0757	1.0778	9.8420	10.3948	0.0000	0.0000	0.0000
14	1.0577	1.0577	1.0571	1.0575	1.0859	1.0780	1.0819	9.8861	10.4038	0.0000	0.0000	0.0000
15	1.0584	1.0584	1.0577	1.0582	1.0566	1.0508	1.0537	9.6031	10.3631	10.4080	0.0000	0.0000
16	1.0579	1.0574	1.0571	1.0575	1.0787	1.0762	1.0775	9.8357	10.3935	0.0000	0.0000	0.0000
17	1.0584	1.0579	1.0579	1.0581	1.0757	1.0719	1.0738	9.8042	10.3841	0.0000	0.0000	0.0000
18	1.0579	1.0577	1.0577	1.0577	1.0668	1.0386	1.0527	9.5048	10.2752	0.0000	0.0000	0.0000
19	1.0574	1.0574	1.0571	1.0573	1.0660	1.0594	1.0627	9.7123	10.4087	0.0000	0.0000	0.0000
20	1.0566	1.0571	1.0577	1.0571	1.0706	1.0620	1.0663	9.7353	10.4019	10.4739	0.0000	0.0000

TABLE A-II (continued)

Pellet ^[a]	Diameter (cm)				Length (cm)			Weight (g)	Geometric Density (g/cm ³)	Immersion Density (g/cm ³)	Centerline Hole Diameter (cm)	
	Top	Center	Bottom	Average	0°	90°	Average				Top	Bottom
21	1.0577	1.0577	1.0571	1.0575	1.0732	1.0681	1.0706	9.7871	10.4068	0.0000	0.0000	0.0000
22	1.0566	1.0577	1.0571	1.0571	1.0927	1.0879	1.0903	9.9723	10.4205	0.0000	0.0000	0.0000
23	1.0570	1.0584	1.0579	1.0581	1.0516	1.0465	1.0490	9.5855	10.3921	0.0000	0.0000	0.0000
24	1.0569	1.0574	1.0574	1.0572	1.0602	1.0551	1.0577	9.6471	10.3901	0.0000	0.0000	0.0000
25	1.0571	1.0574	1.0577	1.0574	1.0528	1.0503	1.0516	9.6160	10.4133	10.4799	0.0000	0.0000
26	1.0574	1.0571	1.0569	1.0571	1.0427	1.0381	1.0404	9.4981	10.4012	0.0000	0.0000	0.0000
27	1.0577	1.0574	1.0574	1.0575	1.0752	1.0719	1.0735	9.7979	10.3915	0.0000	0.0000	0.0000
28	1.0566	1.0571	1.0574	1.0571	1.0602	1.0571	1.0587	9.6485	10.3850	0.0000	0.0000	0.0000
29	1.0574	1.0579	1.0577	1.0577	1.0795	1.0744	1.0770	9.8342	10.3935	0.0000	0.0000	0.0000
30	1.0574	1.0574	1.0577	1.0575	1.0749	1.0719	1.0734	9.7930	10.3875	10.4806	0.0000	0.0000
31	1.0577	1.0579	1.0579	1.0578	1.0765	1.0711	1.0738	9.7824	10.3660	0.0000	0.0000	0.0000
32	1.0582	1.0577	1.0574	1.0577	1.0757	1.0693	1.0725	9.7959	10.3942	0.0000	0.0000	0.0000
33	1.0579	1.0579	1.0579	1.0579	1.0678	1.0643	1.0660	9.7360	10.3901	0.0000	0.0000	0.0000
34	1.0577	1.0569	1.0566	1.0571	1.0620	1.0556	1.0588	9.6645	10.4010	0.0000	0.0000	0.0000
35	1.0577	1.0584	1.0579	1.0580	1.0658	1.0607	1.0632	9.7117	10.3898	10.4769	0.0000	0.0000
36	1.0571	1.0571	1.0579	1.0574	1.0693	1.0658	1.0676	9.7411	10.3907	0.0000	0.0000	0.0000
37	1.0574	1.0571	1.0569	1.0571	1.0836	1.0780	1.0808	9.8553	10.3890	0.0000	0.0000	0.0000
38	1.0569	1.0574	1.0582	1.0575	1.0676	1.0612	1.0644	9.7151	10.3922	0.0000	0.0000	0.0000
39	1.0579	1.0577	1.0571	1.0576	1.0302	1.0505	1.0404	9.3824	10.2662	0.0000	0.0000	0.0000
40	1.0577	1.0584	1.0584	1.0582	1.0947	1.0897	1.0922	9.9610	10.3706	10.4631	0.0000	0.0000
41	1.0571	1.0569	1.0564	1.0568	1.0592	1.0528	1.0560	8.9423	10.3989	10.3301	0.1905	0.1905
42	1.0579	1.0582	1.0577	1.0579	1.0627	1.0556	1.0592	8.8815	10.2634	10.2968	0.1880	0.1880
43	1.0571	1.0571	1.0577	1.0573	1.0541	1.1008	1.0775	8.7098	9.9038	10.2734	0.1905	0.1880
44	1.0577	1.0577	1.0571	1.0575	1.0328	1.0282	1.0305	8.9119	10.6167	10.4437	0.1905	0.1905
45	1.0587	1.0584	1.0582	1.0584	1.0640	1.0571	1.0606	8.9293	10.3130	10.2699	0.1930	0.1930

TABLE A-II (continued)

Pellet ^[a]	Diameter (cm)				Length (cm)			Weight (g)	Geometric Density (g/cm ³)	Immersion Density (g/cm ³)	Centerline Hole Diameter (cm)	
	Top	Center	Bottom	Average	0°	90°	Average				Top	Bottom
46	1.0589	1.0589	1.0330	1.0503	1.0549	1.0498	1.0523	8.8795	10.5028	10.3608	0.1905	0.1905
47	1.0579	1.0587	1.0584	1.0583	1.0538	1.0488	1.0513	9.1181	10.6148	10.4629	0.1905	0.1880
48	1.0577	1.0574	1.0574	1.0575	1.0767	1.0709	1.0738	9.0672	10.3385	10.4601	0.1880	0.1880
49	1.0577	1.0579	1.0577	1.0577	1.0627	1.0554	1.0591	8.9452	10.3514	10.2837	0.1905	0.1905
50	1.0579	1.0584	1.0579	1.0581	1.0317	1.0239	1.0278	8.6281	10.2845	10.2742	0.1880	0.1880
51	1.0566	1.0571	1.0577	1.0571	1.0554	1.0503	1.0528	8.6496	10.0832	10.0107	0.1905	0.1905
52	1.0569	1.0569	1.0571	1.0570	1.0792	1.0754	1.0773	9.0723	10.3194	10.5747	0.1880	0.1880
53	1.0574	1.0574	1.0574	1.0574	1.0726	1.0681	1.0704	9.0564	10.3624	10.1450	0.1880	0.1880
54	1.0571	1.0571	1.0564	1.0569	1.0770	1.0691	1.0730	9.0436	10.3461	10.2749	0.1930	0.1905
55	1.0584	1.0584	1.0584	1.0584	1.0737	1.0691	1.0714	8.9491	10.2226	10.1180	0.1905	0.1930
56	1.0579	1.0577	1.0577	1.0577	1.0612	1.0564	1.0588	8.9614	10.3632	10.2456	0.1880	0.1880
57	1.0569	1.0574	1.0574	1.0572	1.0721	1.0663	1.0692	9.0007	10.3232	10.3201	0.1905	0.1905
58	1.0574	1.0577	1.0577	1.0576	1.0681	1.0605	1.0643	8.9354	10.2814	10.4347	0.1880	0.1880
59	1.0579	1.0579	1.0569	1.0576	1.0785	1.0698	1.0742	9.0068	10.2641	10.4593	0.1880	0.1880
60	1.0571	1.0579	1.0584	1.0578	1.0650	1.0607	1.0629	8.9553	10.3084	10.4567	0.1854	0.1880
61	1.0574	1.0574	1.0571	1.0573	1.0775	1.0734	1.0754	9.0373	10.3095	10.3292	0.1854	0.1880
62	1.0582	1.0587	1.0584	1.0584	1.0767	1.0734	1.0751	9.0732	10.3283	10.3780	0.1905	0.1905
63	1.0579	1.0577	1.0574	1.0577	1.0701	1.0658	1.0679	8.9998	10.3213	10.3274	0.1880	0.1905
64	1.0574	1.0577	1.0579	1.0575	1.0780	1.0709	1.0744	9.0915	10.3598	10.2511	0.1880	0.1880
65	1.0571	1.0574	1.0577	1.0574	1.0671	1.0635	1.0653	9.9934	11.4913	10.2657	0.1880	0.1880
66	1.0574	1.0579	1.0574	1.0576	1.0361	1.0310	1.0335	8.6965	10.3217	10.3767	0.1905	0.1880
67	1.0574	1.0574	1.0574	1.0574	1.0759	1.0714	1.0737	9.0511	10.3185	10.1837	0.1880	0.1854
68	1.0577	1.0577	1.0574	1.0576	1.0785	1.0767	1.0776	9.0796	10.3223	10.2516	0.1905	0.1905
69	1.0579	1.0574	1.0566	1.0573	1.0663	1.0605	1.0634	8.9712	10.3091	10.3542	0.1778	0.1829
70	1.0579	1.0582	1.0579	1.0580	1.0823	1.0693	1.0758	9.1264	10.3795	10.1835	0.1880	0.1905

TABLE A-II (continued)

Pellet ^[a]	Diameter (cm)				Length (cm)			Weight (g)	Geometric Density (g/cm ³)	Immersion Density (g/cm ³)	Centerline Hole Diameter (cm)	
	Top	Center	Bottom	Average	0°	90°	Average				Top	Bottom
71	1.0577	1.0579	1.0579	1.0578	1.0856	1.0516	1.0686	9.1039	10.4355	10.4722	0.1905	0.1905
72	1.0577	1.0577	1.0584	1.0579	1.0706	1.0747	1.0726	9.0283	10.2967	10.5113	0.1880	0.1880
73	1.0577	1.0582	1.0582	1.0580	1.0701	1.0528	1.0615	8.9879	10.3708	10.2478	0.1905	0.1905
74	1.0569	1.0571	1.0579	1.0573	1.1057	1.1034	1.1045	8.9958	9.9682	9.8874	0.1905	0.1880
75	1.0584	1.0584	1.0579	1.0582	1.0810	1.0693	1.0752	9.0235	10.2828	10.3749	0.1930	0.1956
76	1.0574	1.0577	1.0577	1.0576	1.0592	1.0516	1.0554	8.8614	10.2953	10.2822	0.1905	0.1905
77	1.0574	1.0577	1.0579	1.0577	1.0787	1.0747	1.0767	9.0620	10.3093	9.9569	0.1905	0.1905
78	1.0566	1.0571	1.0571	1.0570	1.0599	1.0528	1.0564	8.8560	10.2967	9.7063	0.1880	0.1880
79	1.0582	1.0582	1.0579	1.0581	1.0721	1.0660	1.0691	8.9739	10.2809	10.3922	0.1930	0.1905
80	1.0577	1.0579	1.0582	1.0579	1.0716	1.0693	1.0705	9.0225	10.3164	10.4593	0.1905	0.1880
81	1.0579	1.0579	1.0579	1.0579	1.1052	1.1016	1.1034	9.3150	10.3351	10.4641	0.1956	0.1905
82	1.0579	1.0579	1.0579	1.0579	1.0643	1.0638	1.0640	8.9006	10.2416	10.4726	0.1880	0.1905
83	1.0577	1.0577	1.0579	1.0577	1.0696	1.0648	1.0672	8.8374	10.1456	10.2758	0.1905	0.1905
84	1.0579	1.0577	1.0571	1.0576	1.0554	1.0485	1.0519	8.8366	10.2966	10.4503	0.1905	0.1880
85	1.0566	1.0574	1.0574	1.0571	1.0660	1.0620	1.0640	8.9131	10.2767	10.4332	0.1905	0.1905
86	1.0577	1.0579	1.0579	1.0578	1.0724	1.0671	1.0697	8.9364	10.2226	10.3236	0.1880	0.1880

[a] Pellets are numbered from the bottom of the fuel stack.

TABLE A-III

TEST GC 1-3 FUEL PELLET CHARACTERIZATION DATA FOR TEST ROD GC-1-002

Pellet ^[a]	Diameter (cm)				Length (cm)			Weight (g)	Geometric Density (g/cm ³)	Immersion Density (g/cm ³)	Centerline Hole Diameter (cm)	
	Top	Center	Bottom	Average	0°	90°	Average				Top	Bottom
1	1.0571	1.0571	1.0571	1.0571	0.5933	0.5878	0.5906	5.3779	10.3752	0.0000	0.0000	0.0000
2	1.0566	1.0569	1.0574	1.0570	1.0658	1.0615	1.0636	9.7133	10.4077	0.0000	0.0000	0.0000
3	1.0569	1.0574	1.0577	1.0573	1.0683	1.0632	1.0658	9.7413	10.4101	0.0000	0.0000	0.0000
4	1.0584	1.0584	1.0584	1.0584	1.0742	1.0691	1.0716	9.8037	10.3974	0.0000	0.0000	0.0000
5	1.0579	1.0582	1.0582	1.0581	1.0493	1.0437	1.0465	9.5487	10.3774	10.4628	0.0000	0.0000
6	1.0584	1.0587	1.0579	1.0583	1.0577	1.0533	1.0555	9.6396	10.3817	0.0000	0.0000	0.0000
7	1.0582	1.0579	1.0574	1.0578	1.0564	1.0513	1.0538	9.6273	10.3946	0.0000	0.0000	0.0000
8	1.0577	1.0577	1.0577	1.0577	1.0625	1.0582	1.0603	9.6890	10.4007	0.0000	0.0000	0.0000
9	1.0574	1.0577	1.0577	1.0576	1.0592	1.0536	1.0564	9.6434	10.3920	0.0000	0.0000	0.0000
10	1.0579	1.0584	1.0579	1.0581	1.0584	1.0523	1.0554	9.6271	10.3744	10.4637	0.0000	0.0000
11	1.0577	1.0579	1.0577	1.0577	1.0706	1.0673	1.0690	9.7555	10.3858	0.0000	0.0000	0.0000
12	1.0577	1.0577	1.0574	1.0576	1.0559	1.0513	1.0536	9.6195	10.3937	0.0000	0.0000	0.0000
13	1.0577	1.0582	1.0579	1.0579	1.0671	1.0638	1.0654	9.7227	10.3821	0.0000	0.0000	0.0000
14	1.0582	1.0582	1.0584	1.0582	1.0409	1.0368	1.0389	9.5052	10.4025	0.0000	0.0000	0.0000
15	1.0579	1.0577	1.0577	1.0577	1.0541	1.0503	1.0522	9.6199	10.4046	10.4616	0.0000	0.0000
16	1.0574	1.0577	1.0577	1.0576	1.0752	1.0709	1.0730	9.7941	10.3907	0.0000	0.0000	0.0000
17	1.0574	1.0577	1.0579	1.0577	1.0749	1.0706	1.0728	9.8107	10.4091	0.0000	0.0000	0.0000
18	1.0584	1.0587	1.0584	1.0585	1.0701	1.0643	1.0672	9.7586	10.3914	0.0000	0.0000	0.0000
19	1.0574	1.0574	1.0574	1.0574	1.0884	1.0636	1.0860	9.9341	10.4169	0.0000	0.0000	0.0000
20	1.0574	1.0579	1.0574	1.0576	1.0729	1.0686	1.0707	9.7671	10.3842	10.4632	0.0000	0.0000

TABLE A-III (continued)

Pellet ^[a]	Diameter (cm)				Length (cm)			Weight (g)	Geometric Density (g/cm ³)	Immersion Density (/cm ³)	Centerline Hole Diameter (cm)	
	Top	Center	Bottom	Average	0°	90°	Average				Top	Bottom
21	1.0577	1.0582	1.0579	1.0579	1.0790	1.0739	1.0765	9.8419	10.4015	0.0000	0.0000	0.0000
22	1.0566	1.0579	1.0577	1.0574	1.0688	1.0625	1.0657	9.7258	10.3929	0.0000	0.0000	0.0000
23	1.0577	1.0579	1.0577	1.0577	1.0605	1.0556	1.0580	9.6282	10.3561	0.0000	0.0000	0.0000
24	1.0387	1.0582	1.0577	1.0582	1.0767	1.0706	1.0737	9.8169	10.3971	0.0000	0.0000	0.0000
25	1.0577	1.0582	1.0577	1.0578	1.0663	1.0594	1.0629	9.6816	10.3646	10.4185	0.0000	0.0000
26	1.0579	1.0574	1.0559	1.0571	1.0544	1.0488	1.0516	9.6104	10.4139	0.0000	0.0000	0.0000
27	1.0569	1.0569	1.0577	1.0571	1.0709	1.0665	1.0687	9.7603	10.4050	0.0000	0.0000	0.0000
28	1.0584	1.0579	1.0571	1.0578	1.0531	1.0478	1.0504	9.5872	10.3851	0.0000	0.0000	0.0000
29	1.0533	1.0582	1.0577	1.0564	1.0833	1.0780	1.0806	9.8583	10.4084	0.0000	0.0000	0.0000
30	1.0577	1.0574	1.0569	1.0573	1.0704	1.0660	1.0682	9.7404	10.3854	10.4559	0.0000	0.0000
31	1.0579	1.0577	1.0566	1.0574	1.0704	1.0650	1.0677	9.7555	10.4048	0.0000	0.0000	0.0000
32	1.0569	1.0574	1.0579	1.0574	1.0932	1.0897	1.0914	9.9766	10.4091	0.0000	0.0000	0.0000
33	1.0571	1.0569	1.0566	1.0569	1.0516	1.0488	1.0502	9.5981	10.4178	0.0000	0.0000	0.0000
34	1.0577	1.0574	1.0569	1.0573	1.0551	1.0516	1.0533	9.6199	10.4016	0.0000	0.0000	0.0000
35	1.0577	1.0574	1.0574	1.0575	1.0737	1.0683	1.0710	9.7798	10.3969	10.4510	0.0000	0.0000
36	1.0571	1.0577	1.0577	1.0575	1.0645	1.0599	1.0622	9.6812	10.3770	0.0000	0.0000	0.0000
37	1.0582	1.0579	1.0574	1.0578	1.0843	1.0795	1.0819	9.8966	10.4082	0.0000	0.0000	0.0000
38	1.0579	1.0582	1.0582	1.0581	1.0848	1.0792	1.0820	9.9044	10.4102	0.0000	0.0000	0.0000
39	1.0556	1.0559	1.0571	1.0562	1.0577	1.0541	1.0559	9.6267	10.4056	0.0000	0.0000	0.0000
40	1.0574	1.0579	1.0579	1.0577	1.0876	1.0825	1.0851	9.9201	10.4041	10.4719	0.0000	0.0000
41	1.0579	1.0579	1.0582	1.0580	1.0315	1.0279	1.0297	8.6837	10.3470	10.3800	0.1930	0.1905
42	1.0582	1.0802	1.0579	1.0581	1.0635	1.0571	1.0603	8.9116	10.2926	10.4423	0.1905	0.1905
43	1.0584	1.0582	1.0574	1.0580	1.0749	1.0691	1.0720	9.0186	10.2997	10.4487	0.1905	0.1905
44	1.0592	1.0587	1.0582	1.0587	1.0665	1.0607	1.0636	8.9490	10.2899	10.4603	0.1905	0.1905
45	1.0579	1.0582	1.0579	1.0580	1.0704	1.0643	1.0673	8.9778	10.2906	10.4798	0.1880	0.1880

TABLE A-III (continued)

Pellet ^[a]	Diameter (cm)				Length (cm)			Weight (g)	Geometric Density (g/cm ³)	Immersion Density (g/cm ³)	Centerline Hole Diameter (cm)	
	Top	Center	Bottom	Average	0°	90°	Average				Top	Bottom
46	1.0579	1.0579	1.0571	1.0577	1.0671	1.0579	1.0625	8.9425	10.3153	10.4320	0.1905	0.1905
47	1.0579	1.0584	1.0579	1.0581	1.0765	1.0719	1.0742	9.0461	10.2982	10.4818	0.1880	0.1880
48	1.0579	1.0579	1.0584	1.0581	1.0762	1.0706	1.0734	9.0082	10.2817	10.4415	0.1930	0.1930
49	1.0582	1.0579	1.0569	1.0577	1.0729	1.0691	1.0710	9.0516	10.3452	10.4772	0.1880	0.1880
50	1.0579	1.0579	1.0582	1.0580	1.0795	1.0757	1.0776	8.9496	10.1657	10.4476	0.1905	0.1905
51	1.0584	1.0582	1.0577	1.0581	1.0747	1.0691	1.0719	9.0419	10.3258	10.4915	0.1905	0.1905
52	1.0587	1.0584	1.0582	1.0584	1.0818	1.0754	1.0786	9.1002	10.3082	10.4498	0.1880	0.1880
53	1.0582	1.0582	1.0582	1.0582	1.0759	1.0709	1.0734	9.0179	10.2814	10.4600	0.1905	0.1905
54	1.0577	1.0579	1.0579	1.0578	1.0780	1.0724	1.0752	9.0702	10.3208	10.4756	0.1880	0.1880
55	1.0582	1.0582	1.0577	1.0580	1.0645	1.0597	1.0621	9.0015	10.3705	10.4665	0.1880	0.1880
56	1.0579	1.0584	1.0584	1.0582	1.0767	1.0714	1.0740	9.0363	10.2848	10.4631	0.1880	0.1880
57	1.0571	1.0571	1.0574	1.0572	1.0719	1.0668	1.0693	9.0126	10.3261	10.4794	0.1880	0.1880
58	1.0587	1.0587	1.0587	1.0587	1.0721	1.0681	1.0701	9.0149	10.2909	10.4493	0.1880	0.1880
59	1.0582	1.0592	1.0584	1.0586	1.0653	1.0607	1.0630	8.9647	10.3067	10.4665	0.1880	0.1880
60	1.0584	1.0584	1.0584	1.0584	1.0767	1.0732	1.0749	9.0717	10.3126	10.3139	0.1880	0.1880
61	1.0582	1.0582	1.0579	1.0581	1.0676	1.0620	1.0648	8.9788	10.3156	10.2187	0.1880	0.1880
62	1.0579	1.0582	1.0582	1.0581	1.0650	1.0625	1.0638	9.0984	10.4634	10.2763	0.1880	0.1880
63	1.0582	1.0582	1.0579	1.0581	1.0792	1.0747	1.0770	8.9643	10.1775	10.4807	0.1880	0.1880
64	1.0571	1.0579	1.0579	1.0577	1.0605	1.0574	1.0589	8.9528	10.3633	10.4124	0.1905	0.1905
65	1.0574	1.0579	1.0579	1.0577	1.0744	1.0706	1.0725	9.0669	10.3551	10.4598	0.1905	0.1905
66	1.0574	1.0582	1.0582	1.0579	1.0716	1.0683	1.0700	9.0250	10.3196	10.4331	0.1880	0.1880
67	1.0574	1.0584	1.0584	1.0581	1.0594	1.0546	1.0570	8.8919	10.2937	10.4364	0.1880	0.1880
68	1.0577	1.0571	1.0559	1.0569	1.0825	1.0782	1.0804	9.1351	10.3621	10.4550	0.1880	0.1880
69	1.0579	1.0579	1.0579	1.0579	1.0691	1.0627	1.0659	8.9677	10.3044	10.4536	0.1905	0.1905
70	1.0574	1.0574	1.0574	1.0574	1.0762	1.0726	1.0744	8.6696	9.8808	10.4592	0.1880	0.1880

TABLE A-III (continued)

Pellet ^[a]	Diameter (cm)				Length (cm)			Weight (g)	Geometric Density (g/cm ³)	Immersion Density (g/cm ³)	Centerline Hole Diameter (cm)	
	Top	Center	Bottom	Average	0°	90°	Average				Top	Bottom
71	1.0582	1.0577	1.0574	1.0577	1.0716	1.0671	1.0693	8.9386	10.2307	10.4519	0.1880	0.1880
72	1.0571	1.0574	1.0577	1.0574	1.0602	1.0538	1.0570	8.9023	10.3200	10.4328	0.1880	0.1880
73	1.0579	1.0579	1.0582	1.0580	1.0716	1.0663	1.0690	9.0138	10.3153	10.4372	0.1880	0.1880
74	1.0571	1.0577	1.0579	1.0576	1.0648	1.0599	1.0624	8.9677	10.3474	10.4627	0.1905	0.1905
75	1.0579	1.0574	1.0571	1.0575	1.0287	1.0246	1.0267	8.6696	10.3681	10.4560	0.1905	0.1905
76	1.0579	1.0582	1.0577	1.0579	1.0724	1.0686	1.0705	9.0055	10.3018	10.4970	0.1905	0.1905
77	1.0577	1.0577	1.0566	1.0573	1.0655	1.0594	1.0625	8.9646	10.3383	10.4493	0.1880	0.1880
78	1.0584	1.0584	1.0574	1.0581	1.0739	1.0691	1.0715	8.9643	10.2222	10.1894	0.1854	0.1854
79	1.0582	1.0579	1.0569	1.0577	1.0566	1.0521	1.0544	8.7597	10.1762	10.1230	0.1880	0.1880
80	1.0584	1.0584	1.0577	1.0582	1.0744	1.0676	1.0710	8.9836	10.2475	10.4252	0.1854	0.1854
81	1.0577	1.0577	1.0577	1.0577	1.0737	1.0668	1.0702	9.0262	10.3333	10.4478	0.1905	0.1905
82	1.0584	1.0584	1.0579	1.0582	1.0683	1.0610	1.0646	8.9183	10.2533	10.4295	0.1905	0.1905
83	1.0571	1.0577	1.0577	1.0575	1.0663	1.0622	1.0643	8.9785	10.3328	10.2664	0.1880	0.1880
84	1.0579	1.0579	1.0579	1.0579	1.0704	1.0663	1.0683	8.9583	10.2693	10.4091	0.1905	0.1905
85	1.0566	1.0574	1.0574	1.0571	1.0818	1.0754	1.0786	9.0208	10.2542	10.4356	0.1905	0.1905
86	1.0579	1.0579	1.0571	1.0577	1.0640	1.0587	1.0613	8.9042	10.2826	9.9189	0.1905	0.1905

[a] Pellets are numbered from the bottom of the fuel stack.

TABLE A-IV

TEST GC 1-3 FUEL PELLET CHARACTERIZATION DATA FOR TEST ROD GC-1-003

Pellet ^[a]	Diameter (cm)				Length (cm)			Weight (g)	Geometric Density (g/cm ³)	Immersion Density (g/cm ³)	Centerline Hole Diameter (cm)	
	Top	Center	Bottom	Average	0°	90°	Average				Top	Bottom
1	1.0582	1.0582	1.0582	1.0582	0.5753	0.5702	0.5728	5.2340	10.3910	0.0000	0.0000	0.0000
2	1.0574	1.0577	1.0566	1.0572	1.0754	1.0714	1.0734	9.7992	10.3991	0.0000	0.0000	0.0000
3	1.0569	1.0579	1.0584	1.0577	1.0673	1.0620	1.0646	9.7194	10.3893	0.0000	0.0000	0.0000
4	1.0577	1.0579	1.0574	1.0577	1.0648	1.0610	1.0629	9.7053	10.3933	0.0000	0.0000	0.0000
5	1.0574	1.0579	1.0584	1.0579	1.0665	1.0635	1.0650	9.7101	10.3724	10.4600	0.0000	0.0000
6	1.0574	1.0579	1.0582	1.0578	1.0655	1.0617	1.0636	9.7184	10.3965	0.0000	0.0000	0.0000
7	1.0574	1.0577	1.0577	1.0576	1.0559	1.0495	1.0627	9.5831	10.3631	0.0000	0.0000	0.0000
8	1.0569	1.0582	1.0571	1.0574	1.0724	1.0663	1.0693	9.7615	10.3951	0.0000	0.0000	0.0000
9	1.0571	1.0577	1.0574	1.0574	1.1298	1.1245	1.1271	10.2794	10.3855	0.0000	0.0000	0.0000
10	1.0574	1.0579	1.0582	1.0578	1.0711	1.0671	1.0691	9.7745	10.4031	10.5386	0.0000	0.0000
11	1.0574	1.0571	1.0564	1.0570	1.1186	1.1151	1.1168	10.2185	10.4274	0.0000	0.0000	0.0000
12	1.0582	1.0584	1.0584	1.0583	1.0704	1.0678	1.0691	9.7541	10.3715	0.0000	0.0000	0.0000
13	1.0579	1.0587	1.0584	1.0583	1.0605	1.0556	1.0580	9.6547	10.3730	0.0000	0.0000	0.0000
14	1.0564	1.0566	1.0566	1.0566	1.0668	1.0602	1.0635	9.7133	10.4173	0.0000	0.0000	0.0000
15	1.0582	1.0579	1.0574	1.0578	1.0719	1.0683	1.0701	9.7732	10.3919	10.4873	0.0000	0.0000
16	1.0577	1.0577	1.0574	1.0576	1.0843	1.0785	1.0814	9.8795	10.4001	0.0000	0.0000	0.0000
17	1.0579	1.0571	1.0566	1.0572	1.0704	1.0643	1.0673	9.7459	10.4016	0.0000	0.0000	0.0000
18	1.0577	1.0577	1.0574	1.0576	1.0272	1.0234	1.0253	9.3464	10.3776	0.0000	0.0000	0.0000
19	1.0577	1.0582	1.0582	1.0580	1.0607	1.0554	1.0580	9.6651	10.3908	0.0000	0.0000	0.0000
20	1.0579	1.0579	1.0577	1.0578	1.0648	1.0592	1.0620	9.6979	10.3907	10.4763	0.0000	0.0000

TABLE A-IV (continued)

Pellet ^[a]	Diameter (cm)				Length (cm)			Weight (g)	Geometric Density (g/cm ³)	Immersion Density (g/cm ³)	Centerline Hole Diameter (cm)	
	Top	Center	Bottom	Average	0°	90°	Average				Top	Bottom
21	1.0574	1.0579	1.0577	1.0577	1.0775	1.0714	1.0744	9.8133	10.3959	0.0000	0.0000	0.0000
22	1.0582	1.0582	1.0579	1.0581	1.0541	1.0505	1.0523	9.6121	10.3883	0.0000	0.0000	0.0000
23	1.0587	1.0587	1.0584	1.0586	1.0650	1.0617	1.0634	9.7092	10.3742	0.0000	0.0000	0.0000
24	1.0574	1.0577	1.0574	1.0575	1.0838	1.0782	1.0810	9.8432	10.3672	0.0000	0.0000	0.0000
25	1.0582	1.0582	1.0582	1.0582	1.0632	1.0602	1.0617	9.6914	10.3796	10.4969	0.0000	0.0000
26	1.0571	1.0577	1.0584	1.0577	1.0795	1.0759	1.0777	9.8987	10.4526	0.0000	0.0000	0.0000
27	1.0569	1.0574	1.0577	1.0573	1.0780	1.0739	1.0759	9.8278	10.4032	0.0000	0.0000	0.0000
28	1.0579	1.0582	1.0574	1.0578	1.0599	1.0566	1.0583	9.6621	10.3884	0.0000	0.0000	0.0000
29	1.0582	1.0582	1.0584	1.0582	1.0843	1.0792	1.0818	9.8922	10.3965	0.0000	0.0000	0.0000
30	1.0579	1.0584	1.0584	1.0582	1.0869	1.0808	1.0838	9.8955	10.3804	10.4989	0.0000	0.0000
31	1.0582	1.0579	1.0574	1.0578	1.0752	1.0704	1.0728	9.7909	10.3848	0.0000	0.0000	0.0000
32	1.0577	1.0577	1.0577	1.0577	1.0904	1.0856	1.0880	9.9462	10.4051	0.0000	0.0000	0.0000
33	1.0584	1.0584	1.0577	1.0582	1.0546	1.0498	1.0522	9.6139	10.3898	0.0000	0.0000	0.0000
34	1.0577	1.0577	1.0571	1.0575	1.0800	1.0749	1.0775	9.8398	10.3978	0.0000	0.0000	0.0000
35	1.0564	1.0574	1.0574	1.0571	1.0775	1.0734	1.0754	9.8092	10.3934	10.4842	0.0000	0.0000
36	1.0574	1.0574	1.0571	1.0574	1.0800	1.0744	1.0772	9.8601	10.4234	0.0000	0.0000	0.0000
37	1.0569	1.0579	1.0577	1.0575	1.0653	1.0607	1.0630	9.6054	10.2884	0.0000	0.0000	0.0000
38	1.0577	1.0574	1.0566	1.0572	1.0795	1.0759	1.0777	9.0786	10.3174	10.4583	0.1880	0.1880
39	1.0574	1.0574	1.0569	1.0572	1.0820	1.0782	1.0801	9.0806	10.2863	10.4566	0.1854	0.1854
40	1.0582	1.0582	1.0579	1.0581	1.0582	1.0536	1.0559	8.8758	10.2773	10.4585	0.1854	0.1854
41	1.0564	1.0564	1.0569	1.0566	1.0665	1.0630	1.0648	8.9962	10.3677	10.4914	0.1880	0.1880
42	1.0566	1.0566	1.0566	1.0566	1.0754	1.0704	1.0729	9.0486	10.3488	10.4800	0.1905	0.1880
43	1.0574	1.0579	1.0577	1.0577	1.0744	1.0706	1.0725	9.0088	10.2905	10.4609	0.1905	0.1905
44	1.0579	1.0579	1.0577	1.0578	1.0742	1.0714	1.0728	9.0164	10.2931	10.4563	0.1905	0.1905
45	1.0579	1.0579	1.0579	1.0579	1.0643	1.0605	1.0624	8.8973	10.2591	10.4739	0.1905	0.1905

TABLE A-IV (continued)

Pellet ^[a]	Diameter (cm)				Length (cm)			Weight (g)	Geometric Density (g/cm ³)	Immersion Density (g/cm ³)	Centerline Hole Diameter (cm)	
	Top	Center	Bottom	Average	0°	90°	Average				Top	Bottom
46	1.0582	1.0532	1.0577	1.0580	1.0658	1.0617	1.0638	8.9203	10.2698	10.4861	0.1905	0.1905
47	1.0566	1.0566	1.0566	1.0566	1.0660	1.0577	1.0618	8.9554	10.3580	10.4965	0.1905	0.1905
48	1.0571	1.0577	1.0577	1.0575	1.0698	1.0643	1.0671	8.9677	10.3017	10.4728	0.1905	0.1905
49	1.0574	1.0574	1.0574	1.0574	1.0686	1.0635	1.0660	8.9562	10.3005	10.3337	0.1905	0.1905
50	1.0574	1.0579	1.0571	1.0575	1.0729	1.0678	1.0704	8.7763	10.0402	10.4722	0.1880	0.1880
51	1.0579	1.0574	1.0566	1.0573	1.0693	1.0653	1.0673	8.9678	10.3029	10.4613	0.1905	0.1905
52	1.0571	1.0574	1.0574	1.0573	1.0439	1.0391	1.0415	8.7786	10.3458	10.4542	0.1905	0.1905
53	1.0584	1.0584	1.0584	1.0584	1.0665	1.0635	1.0650	8.9775	10.3139	10.4712	0.1905	0.1905
54	1.0574	1.0579	1.0579	1.0577	1.0909	1.0864	1.0880	9.1541	10.2935	10.4776	0.1905	0.1905
55	1.0577	1.0579	1.0587	1.0581	1.0759	1.0719	1.0739	9.0596	10.3256	10.4751	0.1905	0.1905
56	1.0566	1.0566	1.0566	1.0566	1.0530	1.0579	1.0605	8.9518	10.3681	10.4779	0.1905	0.1905
57	1.0584	1.0579	1.0571	1.0578	1.0648	1.0602	1.0625	8.9682	10.3414	10.4799	0.1905	0.1905
58	1.0577	1.0577	1.0579	1.0577	1.0678	1.0602	1.0640	8.9648	10.3238	10.4649	0.1905	0.1905
59	1.0579	1.0577	1.0574	1.0577	1.0589	1.0541	1.0565	8.9206	10.3506	10.4807	0.1905	0.1905
60	1.0566	1.0574	1.0579	1.0573	1.0785	1.0734	1.0759	9.0665	10.3196	10.4372	0.1880	0.1880
61	1.0579	1.0577	1.0574	1.0577	1.0841	1.0813	1.0827	9.1403	10.3387	10.4690	0.1905	0.1905
62	1.0592	1.0587	1.0579	1.0586	1.0632	1.0571	1.0602	8.8881	10.2561	10.4499	0.1905	0.1905
63	1.0579	1.0579	1.0579	1.0579	1.0772	1.0724	1.0748	9.0813	10.3450	10.4784	0.1905	0.1905
64	1.0584	1.0584	1.0579	1.0582	1.0719	1.0693	1.0706	8.9199	10.1956	10.4861	0.1905	0.1905
65	1.0566	1.0574	1.0574	1.0571	1.0673	1.0630	1.0651	8.9114	10.2632	10.4853	0.1905	0.1905
66	1.0574	1.0579	1.0579	1.0577	1.0602	1.0571	1.0587	8.8402	10.2338	10.4743	0.1905	0.1905
67	1.0574	1.0574	1.0579	1.0576	1.0668	1.0625	1.0646	8.8656	10.2067	10.4883	0.1905	0.1905
68	1.0579	1.0584	1.0584	1.0582	1.0511	1.0480	1.0495	8.5858	10.0192	10.4826	0.1905	0.1905
69	1.0584	1.0579	1.0571	1.0578	1.0546	1.0511	1.0528	8.8657	10.3209	10.4797	0.1905	0.1905
70	1.0571	1.0571	1.0566	1.0570	1.0658	1.0620	1.0639	8.9338	10.3054	10.4776	0.1905	0.1905

TABLE A-IV (continued)

Pellet ^[a]	Diameter (cm)				Length (cm)			Weight (g)	Geometric Density (g/cm ³)	Immersion Density (g/cm ³)	Centerline Hole Diameter (cm)	
	Top	Center	Bottom	Average	0°	90°	Average				Top	Bottom
71	1.0587	1.0587	1.0582	1.0585	1.0683	1.0630	1.0657	8.9916	10.3124	10.4797	0.1880	0.1880
72	1.0569	1.0577	1.0577	1.0574	1.0742	1.0693	1.0718	9.0221	10.3091	10.5017	0.1880	0.1880
73	1.0564	1.0561	1.0566	1.0564	1.0683	1.0612	1.0648	8.9546	10.3233	10.4855	0.1880	0.1880
74	1.0571	1.0571	1.0566	1.0570	1.0772	1.0709	1.0740	9.0291	10.3031	10.4927	0.1880	0.1880
75	1.0577	1.0571	1.0564	1.0571	1.1102	1.1011	1.1057	9.2795	10.2721	10.4860	0.1880	0.1880
76	1.0571	1.0574	1.0571	1.0572	1.0693	1.0622	1.0658	8.9461	10.2950	10.4928	0.1905	0.1905
77	1.0579	1.0574	1.0569	1.0574	1.0698	1.0653	1.0676	8.7045	9.9962	10.3431	0.1905	0.1905
78	1.0571	1.0574	1.0574	1.0573	1.0820	1.0711	1.0766	9.0091	10.2575	10.4890	0.1905	0.1905
79	1.0571	1.0577	1.0579	1.0576	1.0770	1.0663	1.0716	8.9582	10.2433	10.4926	0.1905	0.1905
80	1.0579	1.0579	1.0579	1.0579	1.0516	1.0488	1.0502	8.8394	10.3157	10.4838	0.1905	0.1905
81	1.0571	1.0574	1.0571	1.0572	1.0668	1.0632	1.0650	8.9712	10.3220	10.4882	0.1880	0.1880
82	1.0569	1.0571	1.0571	1.0571	1.0711	1.0655	1.0683	8.9613	10.2810	10.4363	0.1880	0.1880
83	1.0577	1.0577	1.0577	1.0577	1.0843	1.0785	1.0814	9.0410	10.2295	10.4402	0.1880	0.1880
84	1.0577	1.0582	1.0582	1.0580	1.0770	1.0721	1.0745	8.9743	10.2239	10.4967	0.1905	0.1905
85	1.0577	1.0577	1.0577	1.0577	1.0627	1.0556	1.0592	8.8837	10.2808	10.4847	0.1905	0.1905
86	1.0571	1.0574	1.0574	1.0573	1.0653	1.0597	1.0625	8.9475	10.3186	10.4666	0.1880	0.1880

[a] Pellets are numbered from the bottom of the fuel stack.

TABLE A-V

TEST GC 1-3 FUEL PELLET CHARACTERIZATION DATA FOR TEST ROD GC-1-004

Pellet ^[a]	Diameter (cm)				Length (cm)			Weight (g)	Geometric Density (g/cm ³)	Immersion Density (g/cm ³)	Centerline Hole Diameter (cm)	
	Top	Center	Bottom	Average	0°	90°	Average				Top	Bottom
1	1.0571	1.0571	1.0571	1.0571	0.6017	0.5898	0.5958	5.4276	10.3795	0.0000	0.0000	0.0000
2	1.0577	1.0579	1.0584	1.0580	1.0721	1.0683	1.0702	9.7769	10.3912	0.0000	0.0000	0.0000
3	1.0574	1.0579	1.0582	1.0578	1.0698	1.0660	1.0679	9.7593	10.3981	0.0000	0.0000	0.0000
4	1.0577	1.0579	1.0574	1.0577	1.0752	1.0711	1.0737	9.8024	10.3917	0.0000	0.0000	0.0000
5	1.0579	1.0582	1.0584	1.0582	1.0533	1.0478	1.0505	9.5954	10.3861	10.4806	0.0000	0.0000
6	1.0582	1.0571	1.0569	1.0574	1.0714	1.0678	1.0696	9.7592	10.3902	0.0000	0.0000	0.0000
7	1.0582	1.0582	1.0582	1.0582	1.0622	1.0577	1.0599	9.6671	10.3709	0.0000	0.0000	0.0000
8	1.0574	1.0577	1.0584	1.0578	1.0678	1.0630	1.0654	9.7405	10.4028	0.0000	0.0000	0.0000
9	1.0587	1.0584	1.0584	1.0585	1.0636	1.0632	1.0659	9.7507	10.3954	0.0000	0.0000	0.0000
10	1.0579	1.0584	1.0587	1.0583	1.0798	1.0747	1.0772	9.8399	10.3837	10.4748	0.0000	0.0000
11	1.0587	1.0584	1.0582	1.0584	1.0834	1.0820	1.0852	9.9057	10.3744	0.0000	0.0000	0.0000
12	1.0574	1.0577	1.0579	1.0577	1.0899	1.0866	1.0883	9.9315	10.3873	0.0000	0.0000	0.0000
13	1.0587	1.0589	1.0589	1.0588	1.0825	1.0785	1.0805	9.8585	10.3616	0.0000	0.0000	0.0000
14	1.0579	1.0582	1.0577	1.0579	1.0579	1.0508	1.0544	9.6331	10.3942	0.0000	0.0000	0.0000
15	1.0582	1.0574	1.0569	1.0575	1.0495	1.0460	1.0478	9.5617	10.3905	10.4518	0.0000	0.0000
16	1.0574	1.0571	1.0574	1.0573	1.0704	1.0665	1.0685	9.7558	10.3994	0.0000	0.0000	0.0000
17	1.0577	1.0577	1.0579	1.0577	1.1039	1.1003	1.1021	10.0735	10.4018	0.0000	0.0000	0.0000
18	1.0574	1.0577	1.0579	1.0577	1.0841	1.0772	1.0806	9.8910	10.4179	0.0000	0.0000	0.0000
19	1.0582	1.0584	1.0584	1.0583	1.0729	1.0688	1.0709	9.8097	10.4133	0.0000	0.0000	0.0000
20	1.0582	1.0574	1.0566	1.0574	1.0566	1.0531	1.0549	9.6322	10.3982	10.4692	0.0000	0.0000

TABLE A-V (continued)

Pellet ^[a]	Diameter (cm)				Length (cm)			Weight (g)	Geometric Density (g/cm ³)	Immersion Density (g/cm ³)	Centerline Hole Diameter (cm)	
	Top	Center	Bottom	Average	0°	90°	Average				Top	Bottom
21	1.0579	1.0582	1.0582	1.0581	1.0848	1.0800	1.0824	9.8810	10.3819	0.0000	0.0000	0.0000
22	1.0577	1.0571	1.0569	1.0572	1.0825	1.0767	1.0796	9.8588	10.4021	0.0000	0.0000	0.0000
23	1.0564	1.0579	1.0582	1.0575	1.0922	1.0810	1.0866	9.8668	10.3386	0.0000	0.0000	0.0000
24	1.0582	1.0582	1.0579	1.0581	1.0673	1.0615	1.0644	9.7335	10.4002	0.0000	0.0000	0.0000
25	1.0577	1.0571	1.0569	1.0572	1.0803	1.0752	1.0777	9.8454	10.4063	10.4807	0.0000	0.0000
26	1.0569	1.0577	1.0569	1.0571	1.0815	1.0775	1.0795	9.8662	10.4128	0.0000	0.0000	0.0000
27	1.0566	1.0566	1.0566	1.0566	1.0579	1.0536	1.0558	9.6336	10.4060	0.0000	0.0000	0.0000
28	1.0584	1.0584	1.0584	1.0584	1.0635	1.0584	1.0610	9.6922	10.3829	0.0000	0.0000	0.0000
29	1.0577	1.0577	1.0577	1.0577	1.0605	1.0538	1.0571	9.6752	10.4171	0.0000	0.0000	0.0000
30	1.0571	1.0571	1.0579	1.0574	1.0709	1.0597	1.0653	9.6903	10.3587	10.4573	0.0000	0.0000
31	1.0571	1.0582	1.0584	1.0579	1.0709	1.0645	1.0677	9.7358	10.3738	0.0000	0.0000	0.0000
32	1.0571	1.0571	1.0571	1.0571	1.0881	1.0833	1.0857	9.9222	10.4118	0.0000	0.0000	0.0000
33	1.0566	1.0566	1.0569	1.0567	1.0747	1.0711	1.0729	9.7711	10.3842	0.0000	0.0000	0.0000
34	1.0571	1.0571	1.0571	1.0571	1.1044	1.1001	1.1022	10.0534	10.3915	0.0000	0.0000	0.0000
35	1.0574	1.0574	1.0559	1.0569	1.0592	1.0556	1.0574	9.6670	10.4207	10.4615	0.0000	0.0000
36	1.0551	1.0554	1.0556	1.0554	1.0907	1.0848	1.0878	9.9192	10.4243	0.0000	0.0000	0.0000
37	1.0579	1.0579	1.0579	1.0579	1.0739	1.0693	1.0716	9.7979	10.4017	0.0000	0.0000	0.0000
38	1.0582	1.0587	1.0582	1.0583	1.0798	1.0744	1.0771	9.3237	10.3009	10.4456	0.1880	0.1905
39	1.0582	1.0587	1.0574	1.0581	1.0775	1.0721	1.0748	9.3191	10.3232	10.4487	0.1905	0.1880
40	1.0582	1.0579	1.0577	1.0579	1.1064	1.1008	1.1036	9.5709	10.3204	10.4413	0.1880	0.1880
41	1.0569	1.0579	1.0584	1.0577	1.0671	1.0627	1.0649	9.2431	10.3425	10.4374	0.1880	0.1905
42	1.0571	1.0579	1.0571	1.0574	1.0658	1.0602	1.0630	9.2201	10.3424	10.4481	0.1880	0.1905
43	1.0587	1.0584	1.0569	1.0580	1.0577	1.0526	1.0551	9.1927	10.3729	10.4419	0.1880	0.1880
44	1.0577	1.0579	1.0571	1.0576	1.0698	1.0650	1.0674	9.2748	10.3518	10.4839	0.1880	0.1880
45	1.0564	1.0579	1.0559	1.0567	1.0635	1.0610	1.0622	9.2311	10.3762	10.4074	0.1905	0.1880

TABLE A-V (continued)

Pellet ^[a]	Diameter (cm)				Length (cm)			Weight (g)	Geometric Density (g/cm ³)	Immersion Density (g/cm ³)	Centerline Hole Diameter (cm)	
	Top	Center	Bottom	Average	0°	90°	Average				Top	Bottom
46	1.0582	1.0582	1.0556	1.0573	1.0785	1.0749	1.0767	9.3470	10.3512	10.4495	0.1905	0.1880
47	1.0579	1.0584	1.0579	1.0581	1.0653	1.0622	1.0638	9.2442	10.3434	10.3858	0.1880	0.1880
48	1.0574	1.0582	1.0582	1.0579	1.0744	1.0668	1.0706	9.3054	10.3524	10.3496	0.1905	0.1880
49	1.0584	1.0584	1.0574	1.0581	1.0625	1.0554	1.0589	9.1827	10.3314	10.4556	0.1930	0.1880
50	1.0571	1.0577	1.0577	1.0575	1.0899	1.0866	1.0883	9.4423	10.3454	10.4114	0.1905	0.1905
51	1.0579	1.0579	1.0579	1.0579	1.0716	1.0673	1.0695	9.2841	10.3446	10.3780	0.1905	0.1905
52	1.0569	1.0579	1.0579	1.0576	1.0777	1.0742	1.0759	9.3453	10.3609	9.8588	0.1905	0.1930
53	1.0577	1.0574	1.0584	1.0578	1.0851	1.0805	1.0828	9.3948	10.3297	10.4572	0.1880	0.1880
54	1.0574	1.0582	1.0579	1.0578	1.0594	1.0531	1.0563	9.1697	10.3483	10.4694	0.1905	0.1905
55	1.0577	1.0579	1.0582	1.0579	1.0683	1.0620	1.0651	9.2667	10.3583	10.4925	0.1880	0.1880
56	1.0582	1.0587	1.0589	1.0586	1.0518	1.0467	1.0493	9.0862	10.3077	10.4615	0.1905	0.1905
57	1.0584	1.0584	1.0579	1.0582	1.0602	1.0554	1.0578	9.1673	10.3172	10.3273	0.1905	0.1880
58	1.0584	1.0579	1.0574	1.0579	1.0605	1.0559	1.0582	9.4098	10.5886	10.4340	0.1880	0.1880
59	1.0582	1.0584	1.0579	1.0582	1.0574	1.0523	1.0549	9.1872	10.3657	10.5256	0.1880	0.1880
60	1.0579	1.0587	1.0587	1.0584	1.0869	1.0833	1.0851	9.4098	10.3120	10.4529	0.1880	0.1880
61	1.0587	1.0587	1.0587	1.0587	1.0635	1.0592	1.0613	9.1877	10.3011	10.4742	0.1905	0.1905
62	1.0587	1.0589	1.0589	1.0588	1.0752	1.0701	1.0726	9.2963	10.3034	10.3382	0.1905	0.1880
63	1.0587	1.0587	1.0579	1.0584	1.0130	1.0094	1.0112	8.7356	10.2828	10.2917	0.1880	0.1880
64	1.0582	1.0589	1.0584	1.0585	1.0838	1.0787	1.0813	9.3240	10.2620	10.4552	0.1905	0.1905
65	1.0584	1.0584	1.0584	1.0584	1.0785	1.0747	1.0766	9.3182	10.2934	10.4229	0.1880	0.1880
66	1.0589	1.0582	1.0579	1.0583	1.0704	1.0668	1.0686	9.2553	10.3033	10.5913	0.1880	0.1880
67	1.0582	1.0587	1.0587	1.0585	1.0671	1.0635	1.0653	9.2146	10.2867	10.4632	0.1880	0.1880
68	1.0584	1.0584	1.0452	1.0540	1.0876	1.0818	1.0847	9.2981	10.2919	10.4639	0.1905	0.1905
69	1.0569	1.0579	1.0577	1.0575	1.0696	1.0648	1.0672	9.2418	10.3238	10.2559	0.1880	0.1905
70	1.0574	1.0571	1.0566	1.0571	1.0792	1.0732	1.0762	9.2093	10.2087	10.2164	0.1880	0.1905

TABLE A-V (continued)

Pellet ^[a]	Diameter (cm)				Length (cm)			Weight (g)	Geometric Density (g/cm ³)	Immersion Density (g/cm ³)	Centerline Hole Diameter (cm)	
	Top	Center	Bottom	Average	0°	90°	Average				Top	Bottom
71	1.0582	1.0582	1.0582	1.0582	1.0897	1.0820	1.0859	9.4441	10.3383	10.2780	0.1880	0.1829
72	1.0589	1.0589	1.0579	1.0586	1.0902	1.0833	1.0867	9.3103	10.1839	10.3573	0.1905	0.1854
73	1.0579	1.0579	1.0579	1.0579	1.0605	1.0561	1.0583	9.2102	10.3581	10.4285	0.1880	0.1854
74	1.0565	1.0577	1.0577	1.0573	1.0617	1.0569	1.0593	9.2313	10.3794	10.3409	0.1880	0.1829
75	1.0579	1.0577	1.0577	1.0577	1.0450	1.0406	1.0428	9.0404	10.3057	10.4777	0.1854	0.1778
76	1.0579	1.0582	1.0582	1.0581	1.0818	1.0747	1.0782	9.3120	10.2684	10.4027	0.1880	0.1829
77	1.0574	1.0574	1.0571	1.0573	1.0752	1.0605	1.0678	9.3235	10.3672	10.4360	0.1676	0.1854
78	1.0582	1.0579	1.0571	1.0577	1.0892	1.0861	1.0876	9.4185	10.2667	10.4555	0.1854	0.1651
79	1.0571	1.0571	1.0561	1.0568	1.0655	1.0615	1.0635	9.2730	10.3905	10.2917	0.1854	0.1829
80	1.0569	1.0571	1.0577	1.0572	1.0795	1.0732	1.0763	9.3732	10.3450	10.4799	0.1854	0.1702
81	1.0582	1.0579	1.0579	1.0580	1.0442	1.0404	1.0423	9.0898	10.3575	10.4584	0.1880	0.1727
82	1.0577	1.0582	1.0579	1.0579	1.0800	1.0772	1.0786	9.3310	10.2713	10.4585	0.1880	0.1727
83	1.0462	1.0574	1.0571	1.0536	1.0371	1.0300	1.0335	8.7792	10.1692	10.4443	0.1854	0.1702
84	1.0571	1.0577	1.0579	1.0576	1.1064	1.0998	1.1031	9.6087	10.3592	10.3656	0.1854	0.1829
85	1.0574	1.0582	1.0579	1.0578	1.0874	1.0825	1.0850	9.4484	10.3585	10.4399	0.1880	0.1829
86	1.0582	1.0584	1.0577	1.0581	1.0729	1.0691	1.0710	9.2713	10.3027	10.4385	0.1930	0.1829

[a] Pellets are numbered from the bottom of the fuel stack.

TABLE A-VI

TEST GC 1-3 ROD CLADDING DIAMETER DATA FOR TEST ROD GC-1-001

Distance from Bottom of Cladding (cm)	Cladding Inside Diameter (cm)		Cladding Outside Diameter (cm)	
	0°	90°	0°	90°
0.00	1.0832	1.0836		
2.54	1.0830	1.0837	1.2506	1.2508
5.08	1.0828	1.0836		
7.62	1.0820	1.0837		
10.16	1.0828	1.0837		
12.70	1.0827	1.0838		
15.24	1.0830	1.0835		
17.78	1.0831	1.0836		
20.32	1.0830	1.0834		
22.86	1.0832	1.0834		
25.40	1.0831	1.0835		
27.94	1.0831	1.0835		
30.48	1.0830	1.0835	1.2507	1.2508
33.02	1.0829	1.0834		
35.56	1.0828	1.0836		
38.10	1.0828	1.0836		
40.64	1.0829	1.0833		
43.18	1.0831	1.0833		
45.72	1.0831	1.0833		
48.26	1.0833	1.0832		
50.80	1.0833	1.0829		
53.34	1.0834	1.0830		
55.88	1.0829	1.0834		
58.42	1.0826	1.0836		
60.96	1.0830	1.0833	1.2507	1.2509
63.50	1.0829	1.0834		
66.04	1.0829	1.0833		
68.58	1.0831	1.0833		
71.12	1.0830	1.0831		
73.66	1.0831	1.0832		
76.20	1.0829	1.0831		
78.74	1.0829	1.0832		
81.28	1.0826	1.0834		
83.82	1.0824	1.0836		
86.36	1.0824	1.0835		
88.90	1.0826	1.0835		
91.44	1.0827	1.0836	1.2506	1.2512
93.98	1.0832	1.0842		

TABLE A-VII

TEST GC 1-3 FUEL ROD CLADDING DIAMETER DATA FOR TEST ROD GC-1-002

Distance from Bottom of Cladding (cm)	Cladding Inside Diameter (cm)		Cladding Outside Diameter (cm)	
	0°	90°	0°	90°
0.00	1.0827	1.0830		
2.54	1.0827	1.0831	1.2516	1.2499
5.08	1.0830	1.0829		
7.62	1.0830	1.0831		
10.16	1.0831	1.0830		
12.70	1.0831	1.0831		
15.24	1.0829	1.0831		
17.78	1.0829	1.0832		
20.32	1.0827	1.0832		
22.86	1.0829	1.0830		
25.40	1.0828	1.0829		
27.94	1.0830	1.0829		
30.48	1.0829	1.0829	1.2516	1.2516
33.02	1.0830	1.0829		
35.56	1.0830	1.0831		
38.10	1.0830	1.0831		
40.64	1.0828	1.0832		
43.18	1.0842	1.0834		
45.72	1.0825	1.0834		
48.26	1.0827	1.0833		
50.80	1.0823	1.0834		
53.34	1.0825	1.0834		
55.88	1.0826	1.0833		
58.42	1.0829	1.0833		
60.96	1.0829	1.0832	1.2515	1.2513
63.50	1.0830	1.0833		
66.04	1.0829	1.0832		
68.58	1.0829	1.0833		
71.12	1.0827	1.0832		
73.66	1.0828	1.0831		
76.20	1.0831	1.0829		
78.74	1.0831	1.0830		
81.28	1.0831	1.0830		
83.82	1.0831	1.0832		
86.36	1.0829	1.0833		
88.90	1.0830	1.0833		
91.44	1.0830	1.0833	1.2516	1.2511
93.98	1.0834	1.0834		

TABLE A-VIII

TEST GC 1-3 FUEL ROD CLADDING DIAMETER DATA FOR TEST ROD GC-1-003

Distance from Bottom of Cladding (cm)	Cladding Inside Diameter (cm)		Cladding Outside Diameter (cm)	
	0°	90°	0°	90°
0.00	1.0828	1.0833		
2.54	1.0826	1.0834	1.2506	1.2513
5.08	1.0827	1.0835		
7.62	1.0825	1.0833		
10.16	1.0827	1.0832		
12.70	1.0829	1.0830		
15.24	1.0831	1.0830		
17.78	1.0830	1.0832		
20.32	1.0830	1.0833		
22.86	1.0830	1.0833		
25.40	1.0829	1.0833		
27.94	1.0829	1.0832		
30.48	1.0829	1.0834	1.2507	1.2513
33.02	1.0828	1.0831		
35.56	1.0828	1.0831		
38.10	1.0830	1.0829		
40.64	1.0832	1.0829		
43.18	1.0830	1.0832		
45.72	1.0831	1.0833		
48.26	1.0826	1.0833		
50.80	1.0829	1.0836		
53.34	1.0827	1.0831		
55.88	1.0822	1.0836		
58.42	1.0828	1.0832		
60.96	1.0830	1.0830	1.2507	1.2515
63.50	1.0832	1.0829		
66.04	1.0833	1.0829		
68.58	1.0833	1.0828		
71.12	1.0833	1.0830		
73.66	1.0832	1.0831		
76.20	1.0831	1.0832		
78.74	1.0830	1.0832		
81.28	1.0831	1.0831		
83.82	1.0830	1.0829		
86.36	1.0830	1.0829		
88.90	1.0832	1.0827		
91.44	1.0833	1.0828	1.2510	1.2516
93.98	1.0839	1.0831		

TABLE A-IX

TEST GC 1-3 FUEL ROD CLADDING DIAMETER DATA FOR TEST ROD GC-1-004

Distance from Bottom of Cladding (cm)	Cladding Inside Diameter (cm)		Cladding Outside Diameter (cm)	
	0°	90°	0°	90°
2.54	1.0831	1.0827	1.2517	1.2514
5.08	1.0832	1.0826		
7.62	1.0831	1.0826		
10.16	1.0831	1.0827		
12.70	1.0831	1.0828		
15.24	1.0828	1.0832		
17.78	1.0828	1.0831		
20.32	1.0828	1.0832		
22.86	1.0828	1.0830		
25.40	1.0828	1.0829		
27.94	1.0828	1.0829	1.2511	1.2515
30.48	1.0830	1.0829		
33.02	1.0829	1.0829		
35.56	1.0830	1.0828		
38.10	1.0829	1.0830		
40.64	1.0838	1.0832		
43.18	1.0824	1.0833		
45.72	1.0824	1.0834		
48.26	1.0826	1.0831		
50.80	1.0823	1.0832		
53.34	1.0826	1.0830	1.2506	1.2513
55.88	1.0823	1.0834		
58.42	1.0826	1.0831		
60.96	1.0828	1.0830		
63.50	1.0827	1.0831		
66.04	1.0824	1.0833		
68.58	1.0823	1.0833		
71.12	1.0822	1.0833		
73.66	1.0823	1.0833		
76.20	1.0824	1.0831		
78.74	1.0825	1.0829	1.2503	1.2511
81.28	1.0825	1.0829		
83.82	1.0827	1.0831		
86.36	1.0826	1.0829		
88.90	1.0827	1.0832		
91.44	1.0825	1.0833		
93.98	1.0829	1.0835		

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX B

POSTTEST VISUAL AND PHOTOGRAPHIC EXAMINATION

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX B

POSTTEST VISUAL AND PHOTOGRAPHIC EXAMINATION

Following testing, the Gap Conductance Test GC 1-3 fuel rods were removed from their individual shrouds and examined for any breach of the cladding or other unusual features. Photographs were taken of each fuel rod.

Figures B-1 through B-8 show all four test fuel rods at both 0- and 180-degree orientations. All of the fuel rods were shiny, with little or no black oxide. The tubing connected to the top end cap of the fuel rods, by which the rods were initially evacuated and backfilled, was examined. These fill tubes were in good condition on all of the rods, but were of varying lengths. The length of the fill tubes affected the mechanical puncturing of the rods to remove the fission gas. The fill tube on Rod GC-1-001 was 17.5 mm long from the end cap to the crimp sleeve, on Rod GC-1-003 it was 114.3 mm, and on Rod GC-1-004 it was 34.9 mm. The fill tube length of Rod GC-1-002 was not measured as it was obviously long enough for sampling.

The cladding thermocouple welds were examined. Although all of the welds appeared to be in good condition, cross sections taken through the junction welds revealed that the 90-degree thermocouple junction weld on Rod GC-1-001, the 270-degree thermocouple junction weld on Rod GC-1-002, the 90-degree thermocouple junction weld on Rod GC-1-003, and the 240-degree thermocouple junction weld on Rod GC-1-004 had all penetrated the cladding. The average length of the cladding thermocouple junction welds was 3.5 mm. Figure B-9 shows typical cladding thermocouple junction welds as they appeared following the test.

Bottom of Rod

77-2192

Fig. B-1 Fuel Rod GC-1-001 at 0 degree.

Fig. B-2 Fuel Rod GC-1-001 at 180 degrees.

Fig. B-4 Fuel Rod GC-1-002 at 180 degrees.

Fig. B-3 Fuel Rod GC-1-002 at 0 degrees.

Fig. B-6 Fuel Rod GC-1-003 at 180 degrees.

Bottom of Rod

Fig. B-7 Fuel Rod GC-1-004 at 0 degrees.

Fig. B-8 Fuel Rod GC-1-004 at 180 degrees.

Fig. B-9 Cladding thermocouple junctions at 0.48 m from the bottom of fuel Rod GC-1-001.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX C
POSTTEST DIAMETRAL CHARACTERIZATION

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX C

POSTTEST DIAMETRAL CHARACTERIZATION

Outer diameter measurements were made remotely on all four fuel rods with a micrometer. The measurements were made every 25.4 mm at the 45- and 135-degree orientations. Figures C-1 through C-4 show the diameter measurements for fuel Rods GC-1-001, GC-1-002, GC-1-003, and GC-1-004, respectively. The variation in measured diameters over the length of the rods is random, showing no significant trends such as collapse or swelling. Tables C-I through C-IV present the diameter measurements in tabular form.

INEL-A-4981

Fig. C-1 Postirradiation diameter of fuel Rod GC-1-001.

INEL-A-4982

Fig. C-2 Postirradiation diameter of fuel Rod GC-1-002.

INEL-A-4983

Fig. C-2 Postirradiation diameter of fuel Rod GC-1-003.

INEL-A-4984

Fig. C-4 Postirradiation diameter of fuel Rod GC-1-004.

TABLE C-1

GAP CONDUCTANCE TEST GC 1-3 POSTIRRADIATION EXAMINATION
DIAMETRAL MEASUREMENTS FROM ROD GC-1-001

Location (m from bottom of fuel stack) [a]	Fuel Rod Orientation Plane	
	45 degrees (mm)	135 degrees (mm)
0	12.51	12.50
0.051	12.50	12.53
0.102	12.49	12.51
0.152	12.49	12.51
0.203	12.49	12.50
0.254	12.50	12.53
0.305	12.49	12.50
0.356	12.53	12.51
0.406	12.49	12.50
0.457	12.48	12.49
0.508	12.48	12.49
0.559	12.49	12.51
0.610	12.51	12.53
0.660	12.53	12.50
0.711	12.48	12.53
0.762	12.51	12.53
0.813	12.51	12.51
0.864	12.51	12.50
0.914	12.50	12.51
0.965	12.53	12.53

[a] Measurements were made using a 0- to 25.4-mm micrometer with an estimated uncertainty of 0.03 mm.

TABLE C-II

GAP CONDUCTANCE TEST GC 1-3 POSTIRRADIATION EXAMINATION
DIAMETRAL MEASUREMENTS FROM ROD GC-1-002

Location (m from bottom of fuel stack) ^[a]	Fuel Rod Orientation Plane	
	45 degrees (mm)	135 degrees (mm)
0	12.52	12.51
0.51	12.61	12.53
0.102	12.53	12.53
0.152	12.56	12.51
0.203	12.61	12.58
0.254	12.61	---
0.279	12.57	12.54
0.305	12.54	12.51
0.356	12.56	12.51
0.406	12.52	12.53
0.457	12.50	12.53
0.508	12.53	12.51
0.559	12.57	12.52
0.610	12.54	12.53
0.660	12.52	12.51
0.711	12.54	12.52
0.762	12.54	12.51
0.813	12.51	12.53
0.864	12.51	12.51
0.914	12.49	12.51
0.965	12.49	12.50

[a] Measurements were made using a 0- to 25.4-mm micrometer with an estimated uncertainty of 0.03 mm.

TABLE C-III

GAP CONDUCTANCE TEST GC 1-3 POSTIRRADIATION EXAMINATION
DIAMETRAL MEASUREMENTS FROM ROD GC-1-003

Location (m from bottom of fuel stack) ^[a]	Fuel Rod Orientation Plane	
	45 degrees (mm)	135 degrees (mm)
0	12.52	12.49
0.051	12.52	12.50
0.102	12.52	12.50
0.152	12.53	12.53
0.203	12.49	12.52
0.254	12.53	12.50
0.305	12.52	12.49
0.356	12.49	12.52
0.406	12.53	12.52
0.457	12.50	12.52
0.508	12.52	12.50
0.559	12.54	12.53
0.610	12.54	12.54
0.660	12.54	12.53
0.711	12.54	12.52
0.762	12.54	12.52
0.813	12.52	12.54
0.864	12.52	12.53
0.914	12.53	12.52
0.965	---	12.50

[a] Measurements were made using a 0- to 25.4-mm micrometer with an estimated uncertainty of 0.03 mm.

TABLE C-IV

GAP CONDUCTANCE TEST GC 1-3 POSTIRRADIATION EXAMINATION
DIAMETRAL MEASUREMENTS FROM ROD GC-1-004

Location (m from bottom of fuel stack) ^[a]	Fuel Rod Orientation Plane	
	45 degrees (mm)	135 degrees (mm)
0	12.51	12.51
0.051	12.53	12.51
0.102	12.51	12.49
0.152	12.51	12.51
0.203	12.51	12.52
0.254	12.51	12.51
0.305	12.52	12.51
0.356	12.52	12.51
0.406	12.52	12.52
0.457	12.51	12.52
0.508	12.51	12.51
0.559	12.49	12.49
0.610	12.48	12.52
0.660	12.52	12.49
0.711	12.51	12.49
0.762	12.49	12.49
0.813	12.51	12.52
0.864	12.49	12.51
0.914	12.51	12.52
0.965	12.52	12.51

[a] Measurements were made using a 0- to 25.4-mm micrometer with an estimated uncertainty of 0.03 mm.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX D
POSTTEST NEUTRON RADIOGRAPHY

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX D

POSTTEST NEUTRON RADIOGRAPHY

Fuel Rods GC-1-001 and GC-1-002 were sent to the TREAT facility, operated by Argonne National Laboratory at the Idaho National Engineering Laboratory, for neutron radiography. The rods were neutrographed in the 0- and 90-degree orientations. The neutrographs are shown in Figure D-1.

The centerline void that was observed in the neutrograph of Rod GC-1-001 from 0.43 m to the top of the rod is due to the drilled holes in the fuel pellets for the internal thermocouples. The large gaps observed between pellets in the region from 0.87 to 0.92 m were probably exaggerated by the neutrograph. These areas were investigated during destructive examination. A section was cut from the rods, extending 19.0 mm on both sides of the gap for each large gap, so that the thermocouples could be removed. The thermocouples were found to be continuous through the gaps and were easily removed.

The centerline void observed in Rod GC-1-002 was too large to be accounted for by the internal instrumentation, although it was located above the 0.43-m location, which corresponds to the internal thermocouple location. Metallography showed the central void to be caused by melting of the fuel which had reacted with oxidized thermocouple components. This reaction is discussed in more detail in Appendix G. Dark spots were observed on the neutrograph at 0.18, 0.47, 0.61, and 0.72 m from the bottom of the fuel stack. Sections were taken at these locations to investigate areas of possible localized hydriding, indicating the presence of water in the fuel rod. Metallographic evidence of hydriding was found and is discussed in Appendix G. Sections were also cut from the rods to include the large pellet-to-pellet gaps.

Unlike fuel Rod GC-1-001, the internal thermocouples in Rod GC-1-002 were not easily removed from the pellets. The thermocouples were completely oxidized and disintegrated when touched. Whether the thermocouples extended through the large gaps in the pellet stack could not be determined.

Fig. D-1 Neutron radiographs of fuel Rods GC-1-001 and GC-1-002 at 0- and 90-degree orientations.

Fig. D-1 (continued).

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX E

GROSS AND SPECTRAL GAMMA SCANS

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX E

GROSS AND SPECTRAL GAMMA SCANS

The Gap Conductance Test GC 1-3 fuel rods were gamma scanned horizontally in the 0- and 90-degree orientations to document the relative level of gamma-ray activity as a function of distance along the fuel stack. The scans were accomplished using a NaI scintillation detector coupled to a multichannel pulse-height analyzer and strip chart recorder.

A Slo-Syn stepping motor provides the rod scanning drive and positioning mechanism, which allows setting the test interval to ± 0.03 mm. The fuel rod was situated in front of the NaI collimator slit (0.051×1.27 mm) and the output of the NaI detector was recorded on the strip chart recorder as the fuel rod was driven past the detector-collimator window at a slow, constant rate. The strip chart recording speed was matched to the positioning rate (8.46 mm/s) of the fuel rod past the collimator. A standard Cs-137 source was monitored prior to and following the gamma scan to determine whether any electronic drift in the initial and final data recording occurred during the scan. The bottom of the fuel stack was identified by step-scanning past the detector-collimator. The normalized gamma activity data (ratio of the local relative gamma activity to the average peak height for the scan) for fuel Rod GC-1-004 are given in Table E-I and are plotted in Figure E-1. Because of the irregular profiles due to the activated tantalum thermocouple sheaths, these ratios were not calculated for fuel Rods GC-1-001, GC-1-002, and GC-1-003.

Spectral gamma scans were made using a Ge (Li) detector attached to the NaI gamma scan collimator and rod drive mechanism at two positions on fuel Rod GC-1-002. The spectral scan confirmed that the increase in gamma activity in the top half of the rods was due to the activation of the tantalum sheaths of the internal thermocouples.

TABLE E-I.
GAMMA SCAN DATA FOR FUEL ROD
GC-1-004, 0 DEGREES

Distance from Bottom of the Fuel Stack (m)	Peak Height (relative activity, arbitrary units)	Normalized Activity Peak Activity/Average Activity ^[a]
0.	0	0
0.0254	0.600	0.421
0.0508	0.700	0.491
0.0762	0.800	0.561
0.1016	0.950	0.666
0.1270	1.100	0.771
0.1524	1.250	0.876
0.1778	1.300	0.911
0.2032	1.500	1.052
0.2286	1.650	1.157
0.2540	1.700	1.192
0.2794	1.750	1.227
0.3048	1.800	1.262
0.3302	1.850	1.297
0.3556	1.850	1.297
0.3810	1.900	1.332
0.4064	1.950	1.367
0.4318	2.000	1.402
0.4572	2.000	1.402
0.4826	2.000	1.402
0.5080	2.000	1.402
0.5334	1.900	1.332
0.5588	1.850	1.297
0.5842	1.800	1.262
0.6096	1.700	1.192
0.6350	1.650	1.157
0.6604	1.600	1.122
0.6858	1.500	1.052
0.7112	1.450	1.017

TABLE E-I (continued)

Distance from Bottom of the Fuel Stack (m)	Peak Height (relative activity, arbitrary units)	Normalized Activity Peak Activity/Average Activity ^[a]
0.7366	1.300	0.911
0.7620	1.200	0.841
0.7874	1.100	0.771
0.8128	1.000	0.701
0.8382	0.900	0.631
0.8636	0.750	0.526
0.8890	0.600	0.421
0.9144	0.400	0.280

[a] Average gamma activity is 1.426 deflection units. Integrated area is 0.03263425 m².

INEL-A-4974

Fig. E-1 Normalized gamma activity determined from the gross gamma scan of fuel Rod GC-1-004.

APPENDIX F
FLUX WIRE GAMMA SCAN

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX F

FLUX WIRE GAMMA SCAN

A 0.510% Co-Al flux wire was attached to the fuel Rod GC-1-004 assembly for in-pile monitoring of the relative axial irradiation flux profile. After the test, the flux wire was removed and the gamma intensity was measured in 7.6-mm increments at one-minute-per-measurement intervals along the length of the wire, beginning at the bottom. Table F-I lists the cobalt flux wire scan data and the normalized data. Figure F-1 presents the normalized data.

The thermal neutron flux is approximately proportional to the induced radioactivity of the cobalt flux wire. The time-integrated neutron flux (nvt) was determined at a point 0.429 m from the bottom of the wire and was used to establish a conversion factor K_n , for the scanned measurements. The (nvt) at 0.429 m was divided by the total counts per minute at that location to give $K_n = 4.717 \times 10^{13}$. The ratio of (nvt) at a point along the wire to the total counts per minute at that point was assumed to remain constant over the flux wire. The neutron fluence in neutrons/m² is obtained by multiplying K_n times the counts per minute.

TABLE F-I

FLUX WIRE GAMMA SCAN DATA FROM
GAP CONDUCTANCE TEST GC 1-3

Location (m from bottom of fuel stack)	10^4 Counts per Minute	Normalized Activity
0.025	1.905	1.457
0.033	1.981	0.477
0.041	2.080	0.501
0.048	2.196	0.527
0.056	2.242	0.539
0.064	2.334	0.561
0.071	2.512	0.604
0.079	2.593	0.623
0.086	2.649	0.635
0.094	2.817	0.678
0.102	2.876	0.692
0.109	3.003	0.723
0.117	3.083	0.742
0.124	3.205	0.771
0.132	3.283	0.790
0.140	3.337	0.803
0.147	3.452	0.831
0.155	3.510	0.845
0.163	3.599	0.866
0.170	3.688	0.888
0.178	3.828	0.921
0.185	3.930	0.946
0.193	4.027	0.969
0.201	4.104	0.988
0.208	4.186	1.007
0.216	4.258	1.025
0.224	4.435	1.067
0.231	4.393	1.057
0.239	4.441	1.069
0.246	4.536	1.092
0.254	4.566	1.099
0.262	4.697	1.130
0.269	4.771	1.148
0.277	0.828	1.162
0.284	4.892	1.177

TABLE F-I (continued)

<u>Location (m from bottom of fuel stack)</u>	<u>10⁴ Counts per Minute</u>	<u>Normalized Activity</u>
0.292	4.956	1.193
0.300	4.990	1.201
0.307	5.041	1.213
0.315	5.075	1.221
0.323	5.112	1.242
0.330	5.160	1.261
0.345	5.252	1.264
0.353	5.325	1.282
0.361	5.301	1.276
0.368	5.292	1.274
0.376	5.378	1.294
0.384	5.406	1.301
0.391	5.442	1.310
0.399	5.495	1.323
0.406	5.492	1.322
0.414	5.526	1.330
0.422	5.535	1.332
0.429	5.525	1.330
0.437	5.555	1.337
0.445	5.567	1.340
0.452	5.596	1.347
0.460	5.484	1.320
0.467	5.568	1.340
0.475	5.515	1.327
0.483	5.502	1.324
0.490	5.484	1.320
0.498	5.466	1.316
0.505	5.456	1.313
0.513	5.388	1.297
0.521	5.410	1.302
0.528	5.332	1.283
0.536	5.257	1.264
0.544	5.196	1.251
0.551	5.153	1.240
0.559	5.063	1.219
0.566	5.038	1.213
0.574	5.029	1.210
0.582	4.926	1.186
0.589	4.899	1.179
0.597	4.853	1.168

TABLE F-I (continued)

<u>Location (m from bottom of fuel stack)</u>	<u>10⁴ Counts per Minute</u>	<u>Normalized Activity</u>
0.605	4.816	1.159
0.612	4.787	1.152
0.620	4.669	1.124
0.627	4.660	1.122
0.635	4.636	1.116
0.650	4.500	1.083
0.658	4.421	1.064
0.665	4.383	1.055
0.673	4.306	1.036
0.681	4.241	1.021
0.688	4.262	1.026
0.696	4.162	1.002
0.704	4.704	0.981
0.711	4.003	0.963
0.719	3.930	0.946
0.726	3.917	0.943
0.734	3.844	0.925
0.742	3.745	0.901
0.749	3.647	0.878
0.757	3.588	0.864
0.765	3.485	0.839
0.772	3.397	0.818
0.780	3.302	0.795
0.787	3.200	0.770
0.795	3.881	0.934
0.803	3.007	0.724
0.810	2.880	0.693
0.818	2.847	0.685
0.826	2.756	0.663
0.833	2.654	0.639
0.841	2.593	0.624
0.848	2.465	0.593
0.856	2.391	0.575
0.864	2.277	0.548
0.871	2.147	0.517
0.879	2.060	0.496
0.886	1.976	0.476
0.894	1.816	0.440

INEL-A-4975

Fig. F-1 Normalized gamma activity determined from the gamma scanning of the flux wire from fuel Rod GC-1-004.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX G

METALLOGRAPHIC EXAMINATION, X-RAY DIFFRACTION, AND CLADDING MICROHARDNESS MEASUREMENTS OF FUEL ROD GC-1-002

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX G

METALLOGRAPHIC EXAMINATION, X-RAY DIFFRACTION, AND CLADDING MICROHARDNESS MEASUREMENTS OF FUEL ROD GC-1-002

Two transverse samples were sectioned from fuel Rod GC-1-002 to examine the fuel and cladding at the thermocouple junction locations. Four transverse samples were sectioned to investigate the possibility of massive hydriding in the areas indicated by neutron radiography. One sample was also removed for examination of the fuel by X-ray diffraction. Figure G-1 shows the sectioning diagram for fuel Rod GC-1-002.

Figure G-2 shows a sample at several axial locations as it was ground through to locate the thermocouple junctions. On preliminary examination, molten material was found to be present in the center of the sample, completely filling the drilled hole for the centerline thermocouple. Attempts to sample the internal gas showed the cladding had been breached. Fuel Rod GC-1-002 is suspected to have failed during or before the test and to have contained water.

The centerline thermocouple sheath and thermoelements did not appear throughout the sample. The junction of the zero-degree internal thermocouple was located at some point below the 463.6-mm location, the bottom of the sample. Table G-I lists the design and posttest locations of the thermocouple junctions.

Figure G-3 shows a composite across the fuel and cladding at the axial location shown in Figure G-2 (464.3 mm). Figure G-3 shows a region of molten material in the center of the pellet, followed by a region of radially elongated grain growth, a region of equiaxed grain growth, and finally, unaffected fuel near the pellet outer diameter. Figure G-3 shows that the region of radially elongated grain growth is wider at some orientations than at others, making the region of equiaxed grain growth correspondingly narrower. The composite in Figure G-3 is at a location exhibiting a small area of radially elongated grains and a large area of equiaxed grains. Figures G-3(d) and G-3(e) show the growth of elongated grains partially into the drilled holes in the fuel pellet. The grain diameter of the fuel varied from $22 \pm 1.8 \mu\text{m}$ at the outside edge to $44 \pm 7.2 \mu\text{m}$ in the region of equiaxed grain growth.

A composite across the fuel and cladding at the axial location shown in Figure G-2, 475.7 mm, is shown in Figure G-4. This region contains a large area of radially elongated grains and essentially no equiaxed grain growth. The cladding grain diameter was $6.1 \pm 0.4 \mu\text{m}$ and the structure was as-received, recrystallized α -phase zircaloy. No oxide was present on either the inner or outer surface of the cladding.

The maximum fuel rod power during the test (461 W/cm) was not sufficient to cause fuel melting or substantial radially elongated grain growth in the UO_2 fuel. Thermodynamic data for the formation of oxides of uranium, tantalum, and tungsten are presented in Table G-II. These data indicate that tantalum and tungsten will not reduce UO_2 . However, in the

Fig. G-1 Sectioning diagram for fuel Rod GC-1-002.

Fig. G-2 Transverse sample from fuel Rod GC-1-002 at several axial locations, showing cladding and internal thermocouple junctions.

TABLE G-1
LOCATION OF INSTRUMENTATION FOR FUEL ROD GC-1-002^[a]

Instrument Orientation	Posttest Location of Junction (mm from bottom of fuel rod)	Design Location of Junction (mm from bottom of fuel rod)
0-degree internal thermocouple	<463.6	474.5
120-degree internal thermocouple	471.5	474.5
240-degree internal thermocouple	468.6	474.5
Centerline thermocouple	not present	474.5
0-degree cladding thermocouple	476.5	474.5
120-degree cladding thermocouple	between 475.9 and 476.5	474.5
240-degree cladding thermocouple	475.7	474.5
90-degree cladding thermocouple	246.4	244.6
270-degree cladding thermocouple	between 246.2 and 246.5	244.6

[a] A discussion of the uncertainty of the axial locations is presented in Appendix I.

presence of water, both tantalum and tungsten can oxidize. In the case of tantalum, the reaction with water to form Ta_2O_5 is highly favorable over the temperature range of the thermodynamic table (298 to 1700K). For tungsten, the formation of WO_3 by reaction with water is thermodynamically favorable over the range 298 to 1100K. Water contained in the rod, which entered prior to or during the test, probably reacted with the tantalum sheaths of the centerline and off-center internal thermocouples forming a tantalum oxide. The tantalum oxide then reacted with the UO_2 fuel. A 50-50 mixture of Ta_2O_5 and UO_2 melts easily at 2123K [G-1]. The melting point of the UO_2 is 3000K, of the tantalum it is 3269K, and of the tungsten thermoelements it is 3650K [G-2]. The highest centerline temperature measurement on any of the four fuel rods during the test was about 2500K.

Fig. G-3 Composite across the fuel and cladding, sample located 463.3 mm from the bottom of fuel Rod GC-1-002.

Fig. G-4 Composite across the fuel and cladding, sample located 475.7 mm from the bottom of fuel Rod GC-1-002.

TABLE G-II[G-2]

THERMODYNAMIC DATA FOR UO_2 , Ta_2O_5 , WO_3 , AND H_2O

$\text{U} + \text{O}_2 = \text{UO}_2$					$2\text{Ta} + 5/2\text{O}_2 = \text{Ta}_2\text{O}_5$					$\text{W} + 3/2\text{O}_2 = \text{WO}_3$				$\text{H}_2 + 1/2\text{O}_2 = \text{H}_2\text{O}$				
T, K_1	$H_T - H_{298}$	S_T	ΔH°_T	ΔF°_T	T, K_1	$H_T - H_{298}$	S_T	ΔH°_T	ΔF°_T	T, K_1	$H_T - H_{298}$	ΔH°_T	ΔF°_T	T, K_1	$H_T - H_{298}$	S_T	ΔH°_T	ΔF°_T
298		18.63	-259 200	-246 550	298		34.2	-488 800	-456 500	298		-200 850	-182 450	298		16.75	-68 320	-56 720
400	1680	23.47	-158 900	-242 300	400	3430	44.07	-488 350	-445 650	400	(3000)	(-197 850)	(-176 250)	400	11 345	47.01	-58 050	-53 350
500	3470	27.46	-258 100	-238 100	500	7070	52.18	-487 000	-435 000	500	(4050)	(-170 200)	(-170 200)	500	12 174	48.86	-58 300	-52 150
600	5340	30.86	-258 800	-234 100	600	1950	59.25	-487 050	-424 400	600	(6150)	(-194 700)	(-164 200)	600	13 026	50.41	-58 500	-50 900
700	7280	33.85	-258 000	-230 100	700	14 990	66.08	-486 250	-414 250	700	(8750)	(-192 100)	(-158 300)	700	13 910	51.77	-58 700	-49 600
800	9250	36.48	-257 800	-226 100	800	19 130	71.01	-485 400	-404 150	800	(10 450)	(-190 400)	(-152 450)	800	14 821	52 99	-58 900	-48 800
900	11 250	38.86	-257 600	-222 100	900	23 340	75.96	-484 500	-393 800	900	(12 800)	(-188 050)	(-146 650)	900	15 762	54.10	-59 100	-46 800
1000	13 230	40.97	-258 200	-218 100	1000	27 630	80.49	-483 600	-383 700	1000	(15 200)	(-185 650)	(-140 000)	1000	16 735	55.12	-59 250	-45 800
1100	15 340	42.94	-259 000	-214 000	1100	31 990	84.64	-482 600	-373 550	1100	(17 500)	(-183 350)	(-135 200)	1100	17 735	56.07	-59 350	-44 800
1200	17 420	44.75	-258 700	-210 000	1200	36 410	88.49	-481 600	-363 850	1200	(20 000)	(-180 850)	(-120 550)	1200	18 768	56.97	-59 500	-42 900
1300	19 510	46.42	-258 300	-205 900	1300	40 880	92.06	-490 600	-354 200	1300	(22 500)	(-178 350)	(-123 900)	1300	19 830	57.82	-59 600	-41 400
1400	21 620	47.98			1400	45 390	95.40	-479 550	-344 550	1400	(25 050)	(-175 800)	(-118 350)	1400	20 917	58.63	-59 700	-40 000
1500	23 750	49.45	(- 26 800)	(-19 700)	1500	49 970	98.56	-335 350	-335 350	1500	(27 850)	(-173 000)	(-112 850)	1500	22 031	59.40	-59 800	-38 650
					1600	54 030	101.57	-477 350	-325 850	1600	(30 400)	(-170 450)	(-107 400)	1600	23 040	60.06	-60 050	-37 350
					1700	59 880	104.45	-476 300	-316 300	1700	(33 200)	(-167 650)	(-101 950)	1700	24 180	60.71	-60 200	-35 950
										1800	(48 100)	(-152 750)	(- 97 050)	1800	25 335	61.42	-60 050	-34 400
										1900	(53 300)	(-147 550)	(- 92 500)	1900	26 510	62.02	-60 200	-33 050
										2000	(56 700)	(-144 150)	(- 88 050)	2000	27 915	62.78	-60 250	-31 650
														2500	34 205	65.59	-60 300	-24 400

H_T = Heat content, calories per gram-atom.
 S_T = Entropy, calories per gram-mole per K.
 ΔH°_T = Standard heat of formation, calories per gram-atom.
 ΔF°_t = Standard free-energy change, calories per gram-atom.

X-ray diffraction samples were taken at the positions indicated in Figure G-4. The sample at the center was found to be $\text{Ta}_3\text{UO}_{10.2}$ and UO_2 with a significant amount of tungsten present. The sample at midradius contained Ta_2O_5 with a significant amount of tungsten. Apparently, the tungsten thermoelement in the centerline thermocouple diffused through the pellet. The addition of tantalum oxide and tungsten to the UO_2 caused structural changes in the fuel (melting and grain growth) to occur at lower temperatures.

The tantalum sheaths of the off-center internal thermocouples are shown in Figure G-5. The sheaths oxidized and expanded to fill the drilled hole. The 120-degree sheath expanded into an adjoining crack.

Figure G-6 shows the cladding thermocouple junction welds at 475.7 mm. The 0- and 240-degree junction welds penetrated two-thirds of the cladding wall. The fuel pellet-to-cladding gap was $20\text{ }\mu\text{m}$ at zero degrees, $40\text{ }\mu\text{m}$ at 120 degrees, and $50\text{ }\mu\text{m}$ at 240 degrees.

Figure G-7 shows a sample at several axial locations where it was ground through to locate the 90- and 270-degree thermocouple junctions. Figure G-7(b) shows weld material on the inside of the cladding, indicating this was the most likely location for the ingress of water.

The sample in Figure G-7 was final polished at 246.5 mm to examine the fuel and cladding. Figure G-8 shows the fuel and cladding grain structure at this location. The cladding was as-received, recrystallized α -phase zircaloy grain structure with a grain diameter of $5.2 \pm 0.4\text{ }\mu\text{m}$. The fuel grain diameter varied from $25 \pm 2.3\text{ }\mu\text{m}$ in the unrestructured fuel near the outer edge, to $38 \pm 5.0\text{ }\mu\text{m}$ at the center in a region of equiaxed grain. Figure G-9 shows the cladding thermocouple junction welds at 246.5 mm. The 270-degree weld contains large voids and the weld had penetrated two-thirds of the cladding wall.

Four samples were sectioned from fuel Rod GC-1-002 for investigation of possible hydriding at 0.20, 0.48, 0.63, and 0.73 m. The samples were examined every 2.5 mm as they were ground through. No unusual cladding structures were observed in the samples at 0.20 and 0.48 m.

Figures G-10 and G-11 show the cladding structures found in the samples at 0.63 and 0.73 m. Large cracks were visible at all orientations on the inner surface of the cladding of both samples. The cladding grain structure changed from as-received at the outer edge to a restructured zone at the inner third of the cladding. Microhardness tests were performed at the two regions for the sample at 0.63 m. The standard deviation of these measurements, assuming a normal distribution, is 2.17 Vickers Diamond Pyramid Hardness (DPH). The microhardness averaged 231 DPH in the outer zone and 435 DPH in the inner zone, as shown in Table G-III. The microhardness was 210 DPH in the outer zone and 1141 DPH at the inner edge of the cladding of the 0.73-m sample. The microhardness of the unaffected cladding of the 0.20-m sample averaged 215 DPH. Although platlets were not distinguishable in either the as-polished or etched condition, the increase in hardness is suspected to be due to hydriding. A sample of the cladding from the 0.73-m sample was analyzed for hydrogen content. The sample was found to contain $3200 \pm 320\text{ ppm H}_2$ by weight, confirming that the increase in hardness was due to hydrogen.

Fig. G-5 Internal thermocouple sheaths located at 475.7 mm from the bottom of fuel Rod GC-1-002.

Fig. G-6 The 0-, 120-, and 240-degree cladding thermocouple junction welds located at 475.7 mm from the bottom of fuel Rod GC-1-002.

(a) 235.0 mm from Bottom of Fuel Rod

(b) 246.2 mm from Bottom of Fuel Rod

(c) 246.5 mm from Bottom of Fuel Rod

(d) 246.9 mm from Bottom of Fuel Rod

Fig. G-7 Transverse sample from fuel Rod GC-1-002 at several axial locations, showing cladding thermocouple junctions.

Etched, Polarized Light

(a) Typical Cladding, As-Received
Recrystallized α -Phase Zircaloy
Grain Diameter $5.2\ \mu\text{m}$

20 μm

Etched, Bright Field

(b) Fuel Near Outer Edge of Pellet
Grain Diameter $25.4\ \mu\text{m}$
Equiaxed Grain Growth

50 μm

Etched, Bright Field

(c) Fuel at Center of Pellet
Grain Diameter $37.5\ \mu\text{m}$
Equiaxed Grain Growth

50 μm

Fig. G-8 Cladding and fuel grain structure from transverse sample located 246.5 mm from the bottom of fuel Rod GC-1-002.

Fig. G-9 The 90- and 270-degree cladding thermocouple junction welds at 246.5 mm from the bottom of fuel Rod GC-1-002.

Fig. G-10 Cladding from sample of fuel Rod GC-1-002 showing cracking on inner diameters.

Fig. G-11 Cladding from sample of fuel Rod GC-1-002 showing cracking on inner diameters.

TABLE G-III
CLADDING MICROHARDNESS TEST

<u>Location</u>	<u>Vickers Diamond Pyramid Hardness (DPH)</u>
<u>0.20 m</u>	
Inside diameter	211, 205, 211
Midradius	223, 230, 223
Outside diameter	201, 211, 223
<u>0.63 m</u>	
Inside diameter	428, 428, 428, 461, 428
Midradius	223, 223, 223
Outside diameter	235, 235, 223
<u>0.73 m</u>	
Inside diameter	1549, 991, 1195, 991, 1549, 1505, 728, 853, 911
Midradius	205, 223, 205, 223, 215, 223
Outside diameter	205, 223, 201, 211

REFERENCES

- G-1. J. Belle, *Uranium Dioxide: Properties and Nuclear Applications*, Naval Reactors Division of Reactor Development, U.S. Government Printing Office (1961).
- G-2. C. E. Wicks and F. E. Block, *Thermodynamic Properties of 65 Elements — Their Oxides, Halides, Carbides, and Nitrides*, Bulletin 605, Bureau of Mines (1963).

APPENDIX H

METALLOGRAPHIC EXAMINATION OF FUEL ROD GC-1-003

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX H

METALLOGRAPHIC EXAMINATION OF FUEL ROD GC-1-003

Two transverse samples were sectioned from fuel Rod GC-1-003. The first was sectioned at the 463.6-mm location to examine the fuel and cladding at the junctions of the 0-, 120-, and 240-degree cladding thermocouples and the 0-, 120-, and 240-degree internal off-center thermocouples. The centerline ultrasonic thermometer was also present at this axial location. The second sample was located at the junctions of the 90- and 270-degree cladding thermocouples, 235.0 mm. In addition to the fuel and cladding, the cladding thermocouple junction welds were also examined in these sections. The sectioning diagram for fuel Rod GC-1-003 is shown in Figure H-1.

Figure H-2 shows the first sample at various axial locations as it was ground through to locate the thermocouple junctions. Grinding did not expose the ultrasonic thermometer thermoelement, although the sheath was present throughout the sample. The locations of the off-center thermocouple junctions were difficult to determine because the sheaths had totally oxidized. The sample was ground through until the cladding thermocouples appeared. The posttest and design thermocouple junction locations are presented in tabular form in Table H-I.

The first sample was final polished at 478.3 mm to examine the fuel and cladding. Figure H-3 shows the cladding thermocouple welds in the final polished condition. The cladding thermocouples on this rod were titanium sheathed, platinum-platinum 10% rhodium. Large voids were observed in the weld material directly beneath all three of the cladding thermocouple junctions. Figure H-3 shows voids approximately 240 μm in diameter, almost two times the pretest fuel pellet-to-cladding gap width, at the 120-degree thermocouple junction weld, and a void 300 μm in diameter, almost two and one half times the pretest fuel pellet-to-cladding gap width, at the 240-degree thermocouple junction weld. The posttest fuel pellet-to-cladding gap widths, as measured from Figure H-3, were 40 μm at zero degrees, 45 μm at 120 degrees, and 30 μm at 240 degrees. The 240-degree thermocouple junction weld penetrated about 70% of the cladding wall.

Figure H-4 shows the internal thermocouple and ultrasonic thermometer sheaths at the 478.3-mm axial location. Because of the water contained in the fuel rod during the test, all of the tantalum off-center thermocouple sheaths had completely oxidized. The 240-degree sheath, Figure H-4(a), had oxidized and expanded until it completely filled the drilled hole in the pellet. The sheath had also expanded partly into a radial crack that intersected the drilled thermocouple hole. The 120- and 0-degree sheaths, Figures H-4(b) and H-4(d), had also expanded until they completely filled the drilled holes.

The sheath of the centerline ultrasonic thermometer, Figure H-4(c), was tungsten-22% rhenium. The tungsten oxidized, although not as rapidly as the tantalum in fuel Rod GC-1-002. A mixture of UO_2 and the oxidized tungsten, probably WO_3 , can melt at

Burnup Samples: B4, B5, B6

Metallographic Samples: M7, M8

Sample for Replication for Scanning Electron Microscope: R1

INEL-A-297

Fig. H-1 Sectioning diagram for fuel Rod GC-1-003.

(a) 463.6 mm from Bottom of Fuel Rod

(b) 465.0 mm from Bottom of Fuel Rod

(c) 476.6 mm from Bottom of Fuel Rod

(d) 477.0 mm from Bottom of Fuel Rod

(e) 478.3 mm from Bottom of Fuel Rod

(f) 479.0 mm from Bottom of Fuel Rod

Fig. H-2 Transverse sample from fuel Rod GC-1-003 at several axial locations, showing cladding thermocouple junctions and the condition of the junction welds.

TABLE H-1
LOCATION OF INSTRUMENTATION FOR FUEL ROD GC-1-003^[a]

Instrument Orientation	Posttest Location of Junction (mm from bottom of rod)	Design Location of Junction (mm from bottom of rod)
0-degree internal thermocouple	not determined	474.5
120-degree internal thermocouple	not determined	474.5
240-degree internal thermocouple	not determined	474.5
Centerline thermocouple	not determined	474.5
0-degree cladding thermocouple	478.3	474.5
120-degree cladding thermocouple	478.3	474.5
240-degree cladding thermocouple	between 477.0 and 478.3	474.5
90-degree cladding thermocouple	between 248.0 and 248.7	244.6
270-degree cladding thermocouple	249.0	244.6

[a] A discussion of the uncertainty of the axial location is presented in Appendix I.

temperatures as low as 1370K [H-1]. A region that resembled molten material adhered to the outside surface of the ultrasonic thermometer sheath [Figure H-4(c)].

A composite across the fuel and cladding at the 465.0-mm axial location is shown in Figure H-5. The thermoelement in the centerline ultrasonic thermometer was not present and the tungsten sheath was oxidized both on the inside and the outside. Areas of molten material, probably a mixture of WO_3 and UO_2 , adhered to the outside of the tungsten sheath. An annulus of fuel around the centerline ultrasonic thermometer was missing. The fuel in this area may have combined with tungsten trioxide, melted, and slumped to a lower region of the fuel rod. Radially elongated grain growth appeared in the inner third of the radius of the fuel pellet. This radially elongated grain growth was surrounded by a region of equiaxed grain growth. Unaffected fuel with a grain diameter of 20 μm was observed at the pellet outer diameter. A circumferential crack existed at about two-thirds of the pellet

(a) 0° Thermocouple

(b) 120° Thermocouple

(c) 240° Thermocouple

(c) 240° Thermocouple

Fig. H-3 The 0-, 120-, and 240-degree cladding thermocouple welds of sample located at 478.3 mm from the bottom of fuel Rod GC-1-003.

Fig. H-4 Internal thermocouples and ultrasonic thermometer sheaths of sample located at 478.3 mm from the bottom of fuel Rod GC-1-003.

Fig. H-5 Composite across fuel and cladding of sample located 465.0 mm from the bottom of fuel Rod GC-1-003.

radius. The crack width was 90 μm at the location of the composite shown in Figure H-5, compared with a fuel pellet-to-cladding gap of 70 μm at this location. Fuel melting or radially elongated grain growth was not expected at the maximum rod power (424 W/cm) of this test. These fuel structures were probably due to the interaction of the oxidized tungsten sheath with the UO_2 , producing a relatively low melting mixture of oxides. The cladding exhibited as-received, recrystallized α -phase zircaloy grain structure throughout, with a grain diameter of 5.0 μm . No oxide was present on either the inside or outside surface of the cladding.

Photographs of the second sample at several axial locations are presented in Figure H-6. Figures H-6(b), H-6(c), and H-6(d) show that the weld material of the 90-degree cladding thermocouple junction weld had penetrated the cladding and solidified in the fuel pellet-to-cladding gap. Photomicrographs of the 90-degree junction weld at the 247.8- and 248.0-mm locations are shown in Figure H-7. The material in the fuel pellet-to-cladding gap prevented the gap from closing at temperature. A large radial crack occurred in the fuel pellet adjacent to the weld. The posttest pellet-to-cladding gap at the location of the 270-degree thermocouple weld was 50 μm .

Figure H-8 shows the fuel and cladding grain structure at the 248.0-mm location. Equiaxed grain growth occurred toward the center of the fuel, with the grain diameter increasing from 17 μm at the pellet outside diameter to 34 μm at the center. The cladding exhibited as-received, recrystallized α -phase zircaloy grain structure throughout, with a grain diameter of 5.8 μm .

Fig. H-6 Transverse sample from fuel Rod GC-1-003 at several axial locations, showing cladding thermocouple junctions and the condition of the junction welds.

Unetched, Bright Field

(a) 90° Thermocouple at 247.8 mm
Total Penetration of Cladding by Weld

200 μ m

Etched, Bright Field

(b) 90° Thermocouple at 248.0 mm
Total Penetration of Cladding by Weld

200 μ m

Etched, Bright Field

(c) 270° Thermocouple at 248.0 mm

200 μ m

Fig. H-7 The 90-, and 270-degree cladding thermocouple junction welds from sample of fuel Rod GC-1-003.

Etched, Polarized Light

(a) Typical Cladding, As-Received
Recrystallized α -Phase Zircaloy
Grain Diameter $5.8 \mu\text{m}$

20 μm

Etched, Bright Field

(b) Unaffected Fuel Near Outer Edge of Pellet
Grain Diameter $17 \mu\text{m}$

50 μm

Etched, Bright Field

(c) Fuel at Center of Pellet
Equiaxed Grain Growth
Grain Diameter $34 \mu\text{m}$

50 μm

Fig. H-8 Grain structures of the cladding and fuel from transverse sample located 248.0 mm from the bottom of fuel Rod GC-1-003.

REFERENCE

- H-1. J. Belle, *Uranium Dioxide: Properties and Nuclear Applications*, Naval Reactors Division of Reactor Development, U.S. Government Printing Office (1961).

APPENDIX I

METALLURGICAL SAMPLE PREPARATION

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX I

METALLURGICAL SAMPLE PREPARATION

The fuel rods were readied for metallurgical examination by epoxy encapsulation, sectioning, and metallographic mount preparation.

Epoxy encapsulation was accomplished by positioning the fuel rod inside a 19.1-mm (ID) diameter, stainless steel secondary tube. The stainless steel tube was pre-scribed with a longitudinal orientation line, a spotwelded wire, and circumferential marks locating the metallographic sections. The longitudinal line on the outside diameter was machined and vibra-etched to correspond to a 90-degree orientation, and the spot-welded wire corresponded to zero degrees. Angular orientations of the fuel rod were maintained by aligning the zero-degree surface thermocouple with the zero-degree orientation wire of the secondary tube during epoxying. Viewed from the top of the fuel rod, 90 degrees is located clockwise from the zero-degree orientation.

The void between the fuel rod and encapsulation tube was filled with dye-impregnated Armstrong C-7 resin^[a]. The epoxy was allowed to set at ambient temperature for 24 hours and then the fuel rod upper end cap was removed, by sectioning the rod at the plenum region, to allow epoxying of the fuel.

A vent was cut through the encasing tube and into the fuel rod near the lower end plug. Spurr resin epoxy was then injected under pressure at the top end of the fuel rod until it emerged from the vent. The epoxy was then allowed to set overnight at 343K prior to sectioning into metallurgical samples.

The fuel rod was sectioned using a "Cono" saw with a diamond impregnated blade, regulated by a Variac to control the cutting speed. The diamond impregnated blade was lubricated during cutting with kerosene, gravity fed onto the rotating wheel.

The sectioning schedule is presented in Table I-I. Sections of the fuel rods identified for analytical burnup analysis and X-ray diffraction were set apart for fuel removal, to be transferred later to the Idaho Chemical Processing Plant, a facility operated by Allied Chemical Company and located at the Idaho National Engineering Laboratory, for analysis. The metallography specimens (previously identified by Vibra-tool marking) were additionally marked with black ink on the surface to be examined and transferred to the metallography hot cell for mounting, polishing, and examination. Transverse sections were examined on the bottom surface, viewed looking toward the top end of the fuel rod.

The uncertainty in the axial location of the samples as they were sectioned was ± 1.59 mm. However, as the samples were ground through, the uncertainty of the location within the mounted sample was ± 0.025 mm.

[a] Armstrong Products Co., Warsaw, Indiana, 46500.

TABLE I-I

SECTIONING SCHEDULE FOR GAP CONDUCTANCE TEST GC 1-3

Fuel Rod Sample Identification	Sectioning Geometry	Cutting Location (m from bottom of fuel rod)	Comments
<u>GC-1-001</u>			
M1	Transverse	0.46	Location of four internal and three cladding thermocouples
M2	Transverse	0.23	Location of two cladding thermocouples
M9	Transverse	0.43	Crack pattern
B1	Transverse	0.22 to 0.23	Burnup
<u>GC-1-002</u>			
M3	Transverse	0.46	Location of four internal and three cladding thermocouples
M4	Transverse	0.23	Location of two cladding thermocouples
B2	Transverse	0.22 to 0.23	Burnup
H1	Transverse	0.20	Hydriding
H2	Transverse	0.48	Hydriding
H3	Transverse	0.63	Hydriding
H4	Transverse	0.73	Hydriding
D1	Transverse	0.45	X-ray diffraction
<u>GC-1-003</u>			
M5	Transverse	0.46	Location of three internal, and three cladding thermocouples, and a centerline ultrasonic thermometer
M6	Transverse	0.23	Location of two cladding thermocouples
B3	Transverse	0.22 to 0.23	Burnup

TABLE I-I (continued)

<u>Fuel Rod Sample Identification</u>	<u>Sectioning Geometry</u>	<u>Cutting Location (m from bottom of fuel rod)</u>	<u>Comments</u>
<u>GC-1-004</u>			
M7	Transverse	0.46	Location of one internal and three cladding thermocouples and a centerline ultrasonic thermometer
M8	Transverse	0.23	Location of two cladding thermocouples
B4	Transverse	0.45 to 0.46	Burnup
B5	Transverse	0.22 to 0.23	Burnup
B6	Transverse	0.13 to 0.14	Burnup
R1	Longitudinal	0.20 to 0.22	Replication of pellet outside diameter and cladding inside diameter for scanning electron microscope

The metallographic samples were mounted in Bakelite at 422 K and 29 MPa. The samples containing thermocouple junctions were ground and examined in the periscope until the junctions were located. They were then polished in the Automet. All samples were photographed initially at about 7x magnification.

Preparation included polishing the samples down to Linde A grade powder on the Syntron vibrapolisher. An etchant consisting of 10% sulfuric acid and 90% hydrogen peroxide was applied by swabbing for 1 to 1.5 minutes to reveal the UO_2 grain structure. An etchant of 56% lactic acid, 19% nitric acid, 2% hydrofluoric acid, and 18% water was applied to reveal the cladding grain structure. The fuel and cladding were examined and photomicrographs were made of both using bright field illuminations at magnifications ranging from 50x to 500x and also of the cladding using polarized light at 500x.

Grain sizes in the UO_2 fuel structure were determined from photomicrographs of selected samples by the intercept method. The grain boundaries intercepting a 50-mm line were counted. The average distance between intercepts was then calculated and used as an approximation for the average grain diameter. The average from six observations was used for each grain diameter calculation.

Photomicrographs at 100x were made of the fuel-to-cladding gap around the rod circumference at 30-degree intervals and of all major cracks in the fuel on three of the samples. Four of the samples were examined for possible massive hydriding.

The samples were first ground to a 600-grit finish and then swab-etched with a solution containing 56% lactic acid, 19% nitric acid, 7% hydrofluoric acid, and 18% water. If cracks on the inner diameter of the cladding were found, the samples were polished down to Linde A grade powder on the Syntron vibrapolisher. Photomicrographs were taken of the cladding as-polished, etched in bright field, and etched in polarized light using magnifications ranging from 100x to 500x. One sample was later removed from the mounting material and then the fuel was removed from the cladding. Sections of the cladding were analyzed for hydrogen content.

Another sample was sectioned longitudinally and the fuel was removed from the cladding. Replicas were made of the cladding inner diameter and the fuel outer surface. These replicas were examined with the scanning electron microscope.

APPENDIX J

INSTRUMENTATION POSTTEST CONDITION

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX J

INSTRUMENTATION POSTTEST CONDITION

The instrumentation on the test fuel rods, illustrated in Figure J-1, consisted of centerline thermocouples for Rods GC-1-001 and GC-1-002 and centerline ultrasonic thermometers for Rods GC-1-003 and GC-1-004, all located 0.47 m above the bottom of the fuel rod. Rod GC-1-004 contained one off-center thermocouple and Rods GC-1-001, GC-1-002, and GC-1-003 contained three off-center thermocouples, all ending 0.47 m above the bottom of the fuel rod. Three thermocouples ending 0.47 m above the bottom of the fuel rod were attached to the cladding of all rods, and two thermocouples ending 0.24 m above the bottom of the fuel stack were attached to the cladding of all rods. Table J-I presents a summary of the materials used in the fuel rod instrumentation.

The centerline ultrasonic thermometer in fuel Rod GC-1-004 was found to be broken in at least two places during destructive examination, explaining the loss of data from the power calibration portion of the test for this fuel rod. No apparent reason was determined during the posttest examination for the lack of response of the off-center thermocouple for this rod. All of the cladding thermocouples were found to be intact on both Rods GC-1-001 and GC-1-004.

Two samples each, were sectioned from fuel Rods GC-1-001 and GC-1-004 at the location of the junction of the instrumentation. These samples were ground through to show the location and condition of the thermocouple junctions. Figure J-2 shows the sample containing the junctions of the four internal thermocouples and the 0-, 120-, and 240-degree cladding thermocouples at several axial locations for Rod GC-1-001. The cladding thermocouple junctions were located above all of the internal thermocouple junctions. Table J-II lists the posttest locations of all of the thermocouple junctions. The design locations are shown for comparison.

The centerline and zero-degree off-center thermocouple sheaths in Rod GC-1-001 are shown in Figure J-3. Unidentified reaction layers were present on the external surface of the centerline thermocouple sheath. The centerline sheath wall thickness was 0.226 ± 0.001 mm, 0.003 mm less than the original wall thickness, and the off-center thermocouple sheath wall thickness was 0.140 ± 0.001 mm, 0.012 mm less than the original wall thickness. The 0-, 120-, and 240-degree cladding thermocouples at 471.7 mm are shown in Figure J-4. At this location, the junction of the 120-degree thermocouple had been ground through. The 0-degree thermocouple shows the end of the sheath below the junction, and the 240-degree thermocouple shows the bottom end of the weld, below the junction. The weld at the 0-degree junction penetrates two-thirds of the cladding wall.

The sample located 235.0 mm from the bottom of Rod GC-1-001 was sectioned to examine the 90- and 270-degree cladding thermocouple junctions. Figure J-5 shows the

Fig. J-1 Diagram of relative angular and axial locations of thermocouples and orientation of test fuel rods in 4x hardware for Gap Conductance Test GC 1-3.

INEL-A-1893

TABLE J-I
FUEL ROD INSTRUMENTATION

Instrumentation

Type K Cladding Thermocouples

Titanium sheath, Chromel-Alumel thermocouples were attached to the cladding of fuel Rods GC-1-001 and GC-1-004. MgO insulator. Wall thickness of sheath - 0.203 mm.

Type S Cladding Thermocouples

Titanium sheath, platinum-platinum 10% rhodium wires used for cladding thermocouples on fuel Rods GC-1-002 and GC-1-003. MgO insulator. Wall thickness of sheath - 0.203 mm.

Type S Internal Thermocouple

Tantalum sheath, platinum-platinum 10% rhodium wires used for off-center internal thermocouples in all fuel rods. BeO insulator. Diameter of sensor wires - 0.127 mm; wall thickness of sheath - 0.152 mm.

Centerline Thermocouple

Tantalum sheath, tungsten 5% rhenium-tungsten 26% for centerline fuel measurements in fuel Rods GC-1-001 and GC-1-002. BeO insulator. Diameter of sensor wires - 0.178 to 0.203 mm; wall thickness of sheath - 0.254 mm.

Ultrasonic Thermometer

Tungsten 22% rhenium sheath used for centerline fuel measurements in fuel Rods GC-1-003 and GC-1-004 with 2% thorated tungsten (ThO_2) for sensor. Diameter of sensor - 0.356 to 0.406 mm; wall thickness of sheath - 0.178 to 0.254 mm.

Fig. J-2 Transverse sample from fuel Rod GC-1-001 at several axial location,, showing internal and cladding thermocouple junctions and the condition of the junction welds.

TABLE J-II
AXIAL LOCATION OF INSTRUMENTATION FOR FUEL ROD GC-1-001^[a]

<u>Instrument Orientation</u>	<u>Posttest Location of Junction (mm from bottom of fuel rod)</u>	<u>Design Location of Junction (mm from bottom of fuel rod)</u>
0-degree internal thermocouple	463.6	474.5
120-degree internal thermocouple	463.6	474.5
240-degree internal thermocouple	465.1	474.5
Centerline thermocouple	463.6	474.5
0-degree cladding thermocouple	472.5	474.5
120-degree cladding thermocouple	between 471.1 and 471.7	474.5
240-degree cladding thermocouple	473.7	474.5
90-degree cladding thermocouple	246.7	244.6
270-degree cladding thermocouple	247.9	244.6

[a] A discussion of the uncertainty of the axial locations is presented in Appendix I.

sample at several axial locations as it was being ground through to locate the thermocouple junctions. The 90-degree cladding thermocouple first appeared at 245.9 mm, as shown in Figure J-5(b). The thermocouple weld had completely penetrated the cladding. Previously molten weld material was found in the gap between the fuel pellet and the cladding at this point. The 90- and 270-degree cladding thermocouple junctions are shown at 246.7 mm in Figure J-6. The junction of the 90-degree thermocouple was just starting to appear and the 270-degree thermocouple junction weld penetrated the cladding; however, both welds contained large pores which extended nearly to the inside of the cladding.

The 0-, 120-, and 240-degree cladding thermocouple junctions and the 240-degree internal thermocouple junction were examined in the sample located 463.6 mm from the

Fig. J-3 Centerline thermocouple sheath and zero-degree, off-center internal thermocouple sheath of sample located 465.3 mm from the bottom of fuel Rod GC-1-001.

(a) 0° Thermocouple

(b) 120° Thermocouple

(c) 240° Thermocouple

Fig. J-4 The 0-, 120-, and 240-degree cladding thermocouple junction welds of sample located 471.7 mm from the bottom of fuel Rod GC-1-004.

Fig. J-5 Transverse sample from fuel Rod GC-1-001 at several axial locations, showing cladding thermocouple junctions and the condition of the junction welds.

Fig. J-6 The 90- and 270-degree cladding thermocouple junction welds of sample located 246.7 mm from the bottom of fuel Rod GC-1-001.

bottom of Rod GC-1-004. The centerline ultrasonic thermometer also ended at about this location. Figure J-7 shows the sample at various axial locations. At 240 degrees, solidified weld material was evident on the inside of the cladding at 472.5 mm [Figure J-7(c)]. Figure J-7(d) shows that the 240-degree cladding thermocouple weld had entirely penetrated the cladding wall. The posttest and design thermocouple junction locations are presented in tabular form in Table J-III.

Two wires were present where only one should have been in the centerline ultrasonic thermometer, Figures J-7(a) through J-7(g). The ultrasonic thermometer sensor wire apparently broke in two places farther towards the top of the rod and the broken section slid down next to the original piece.

The cladding thermocouple welds are shown in Figure J-8. The 0- and 120-degree junctions were photographed at 474.0 mm. Figure J-8(c) shows the 240-degree thermocouple junction weld at 473.2 mm. The weld had entirely penetrated the cladding wall at this elevation, reducing the wall thickness to 0.76 ± 0.001 mm. Figure J-8(d) shows the 240-degree thermocouple weld at 474.0 mm.

A sample was sectioned from Rod GC-1-004 at 236.0 mm from the bottom of the rod in order to examine the area where the 90- and 270-degree thermocouple junctions were located. The sample, at various axial locations, is shown in Figure J-9. Figure J-10 shows the cladding junction welds at 244.0 mm from the bottom of the rod. The 90-degree thermocouple sheath stands off from the cladding a distance of 0.12 ± 0.001 mm on one side. A void of 0.24 mm in diameter exists in the cladding directly beneath the 270-degree thermocouple junction.

The posttest location of the drilled thermocouple holes was measured from 15x photographs. Table J-IV compares the pre- and posttest locations of the drilled holes for one location each, in fuel Rods GC-1-001 and GC-1-004. Figure J-11 is a diagram defining the variables reported in Table J-IV. The maximum change in the diameter of the drilled holes was 0.06 to -0.17 mm, the maximum change in the distance between the centerline hole and the off-center holes was 0.26 to 0 mm, and the maximum change in distance from the outside edge of the pellet to the drilled off-center holes was 0.01 to 0.18 mm. The drilled holes tended to decrease in diameter and the off-center holes tended to move towards the outside edge of the pellet.

Fig. J-7 Transverse sample from fuel Rod GC-1-004 at several axial locations, showing internal and cladding thermocouple junctions and the condition of the junction welds.

TABLE J-III

AXIAL LOCATION OF INSTRUMENTATION FOR FUEL ROD GC-1-004

<u>Instrument Orientation</u>	<u>Posttest Location of Junction (mm from bottom of fuel rod)</u>	<u>Design Location of Junction (mm from bottom of fuel rod)</u>
240-degree internal thermocouple	470.0 to 472.0	474.5
Centerline ultrasonic thermometer	not present	474.5
0-degree cladding thermocouple	473.2 to 474.0	474.5
120-degree cladding thermocouple	475.4 to 475.8	474.5
240-degree cladding thermocouple	474.0 to 475.4	474.5
90-degree cladding thermocouple	243.6 to 244.0	244.6
270-degree cladding thermocouple	245.0	244.6

Fig. J-8 The 0-, 120-, and 240-degree cladding thermocouple junction welds from sample of fuel Rod GC-1-004.

Fig. J-9 Transverse sample from fuel Rod GC-1-004 at several axial locations, showing cladding thermocouple junctions and the condition of the junction welds.

Fig. J-10 The 90- and 270-degree cladding thermocouple junction welds from sample located 244.0 mm from the bottom of fuel Rod GC-1-004.

TABLE J-IV

PRE- AND POSTTEST MEASUREMENTS OF THE DRILLED
INSTRUMENTATION HOLES FOR FUEL RODS GC-1-001 AND GC-1-004^[a]

	<u>D_C[b]</u>		<u>D₁[b]</u>		<u>D₂[b]</u>		<u>D₃[b]</u>		<u>C₁[c]</u>		<u>C₂[c]</u>		<u>C₃[c]</u>		<u>Y₁[d]</u>		<u>Y₂[d]</u>		<u>Y₃[d]</u>	
	<u>Pre-</u>	<u>Post-</u>	<u>Pre-</u>	<u>Post-</u>	<u>Pre-</u>	<u>Post-</u>	<u>Pre-</u>	<u>Post-</u>	<u>Pre-</u>	<u>Post-</u>	<u>Pre-</u>	<u>Post-</u>	<u>Pre-</u>	<u>Post-</u>	<u>Pre-</u>	<u>Post-</u>	<u>Pre-</u>	<u>Post-</u>	<u>Pre-</u>	<u>Post-</u>
	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>	<u>test</u>
Rod GC-1-001 (mm)	2.03	2.08	1.24	1.30	1.27	1.30	1.30	1.27	4.24	4.36	4.34	4.42	4.27	4.29	0.64	0.46	0.28	0.29	0.48	0.46
Rod GC-1-004 (mm)	2.18	2.01	1.45	1.36	--	--	--	3.76	4.02	--	--	--	--	0.81	0.68	--	--	--	--	--

[a] Accuracy ± 0.025 mm.

[b] Diameter of the off-center- and centerline-drilled holes as shown in Figure J-11.

[c] Distance between off-center- and centerline-drilled holes as shown in Figure J-11.

[d] Distance between off-center-drilled holes and edge of fuel pellet as shown in Figure J-11.

INEL-A-4980

Fig. J-11 Parameters used for pellet hole diameter measurements.

DISTRIBUTION RECORD FOR TREE-NUREG-1088

Internal Distribution

- 1 - Chicago Patent Group
9800 South Cass Avenue
Argonne, Illinois 60439
- 2 - C. A. Benson
Idaho Operations Office-ERDA
Idaho Falls, ID 83401
- 3 - R. J. Beers, ID
- 4 - P. E. Litteneker, ID
- 5 - R. E. Tiller, ID
- 6 - R. E. Wood, ID
- 7 - H. P. Pearson, Supervisor
Technical Information
- 8-17 - INEL Technical Library
- 18-37 - Authors
- 38-75 - Special Internal

External Distribution

- 16-77 - Saul Levine, Director
Office of Nuclear Regulatory Research, NRC
Washington, DC 20555
- 78-397 - Distribution under NRC-3, Water Reactor Safety Research
Fuel Behavior