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for U.S. Nuclear Regulatory Commission

**POWER-COOLING-MISMATCH TEST SERIES
TEST PCM-2
POSTIRRADIATION EXAMINATION**

S. L. SEIFFERT

March 1977

MASTER

EG&G Idaho, Inc.

IDAHO NATIONAL ENGINEERING LABORATORY

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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TREE-NUREG-1069 POWER-COOLING-MISMATCH TEST SERIES
TEST PCM-2 POSTIRRADIATION EXAMINATION

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POWER-COOLING-MISMATCH TEST SERIES.

TEST PCM-2:
POSTIRRADIATION EXAMINATION

by

S. L. Seiffert

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ABSTRACT

This report describes the results of the postirradiation examination of four 0.91-m long pressurized water reactor (PWR) type, UO_2 -fueled zircaloy-clad fuel rods tested in an in-pile experimental investigation of pre-and post departure from nucleate boiling (DNB) behavior of previously unirradiated fuel rods. None of the four fuel rods tested failed during testing or during reactor shut down. Visual and metallographic examination of the individual fuel rods indicated that the length of the high temperature zone of film boiling varied from rod to rod. Two of the four fuel rods showed evidence of damage by film boiling, characterized by oxide spalling and cladding collapse. Metallographic examination of these fuel rods showed internal cladding oxidation resulting from fuel-cladding reaction. Cladding embrittlement by oxidation is evaluated. A comparison of the cladding surface temperatures estimated metallographically for the separate fuel rods with cladding surface temperatures measured during testing and calculated from the Fuel Rod Analysis Program - Transient (FRAP-T) computer code is included.

SUMMARY

Four fuel rods were postirradiation examined, visually and metallographically, following testing in the Power-Cooling-Mismatch (PCM) Test Series, sixth in-pile investigation, Test PCM-2. The previously un-irradiated zircaloy clad UO_2 fueled rods were tested in a pressurized water reactor environment, simulated within the in-pile test loop at the Idaho National Engineering Laboratory Power Burst Facility (PBF), under power-cooling-mismatch and post departure from nucleate boiling (DNB) conditions. The four fuel Rods, UTA-0008, UTA-0009, UTA-0010, and A-0014 did not fail during reactor operation or following reactor shut down.

Postirradiation examination of the test fuel rods indicated that a black oxide surface coating was present on all four fuel rods. All four fuel rods exhibited a region of collapse in the high temperature zone, which experienced film boiling. Additional oxidation and oxide spalling occurred in the high temperature zones of fuel Rods UTA-0008 and A-0014. Bowing was observed in all four fuel rods.

Metallographic examination of the cladding microstructures of the four fuel rods indicated that two of the Rods, UTA-0009 and UTA-0010 operated in the 810 to 1115 K temperature range during the tests which were within the specified test temperature range. The other two fuel Rods, UTA-0008 and A-0014, operated during testing at temperatures above the $\alpha + \beta$ to β phase transformation of the zircaloy cladding and exhibited prior beta phase zircaloy microstructure in the high temperature film boiling zone. Temperatures calculated from parabolic rate law correlations for reaction layer buildup indicated that Rods UTA-0008 and A-0014 experienced cladding temperatures up to 1470 and 1350 K, respectively. Calculated cladding temperatures were compared with test thermocouple readings. Some circumferential variation in the cladding temperatures within the film boiling zone was indicated from this comparison. Cladding surface temperatures computed using the Fuel Rod Analysis Program-Transient (FRAP-T) computer code were compared with metallurgical results.

Embrittlement of the cladding in the high temperature film boiling zone by internal and external oxidation from UO_2 -Zr and Zr- H_2O reaction, respectively, was evaluated from the estimated cladding temperatures and test exposure time in film boiling using critical oxidation time criteria. The fuel rods were correctly predicted not to fail during the test.

The duplex UO_2 -Zr reaction layer formation was examined by electron microprobe. Two regions exhibiting anomalous second phase development were studied. The duplex reaction layer studied at the fuel-cladding interface was consistent with earlier reported results. Examination of the other regions indicated that a U-rich, U-Zr alloy had formed, filling a peripheral fuel pellet crack, and a U-rich, U-Fe-Ni alloy had developed locally at the tip of a section of cladding collapse into a fuel pellet interfacial gap.

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POSTIRRADIATION EXAMINATION RESULTS
FOR THE
POWER-COOLING-MISMATCH TEST-2

1. INTRODUCTION

EG&G Idaho, Inc., under contract to the Energy Research and Development Administration (ERDA), at the Idaho National Engineering Laboratory (INEL) is conducting fuel rod behavior studies in the Power Burst Facility (PBF) reactor as part of the Nuclear Regulatory Commission's Water Reactor Safety Research Fuel Behavior Program^[1]. Experimental data are being obtained from in-pile tests in the PBF reactor for the characterization and evaluation of fuel rod performance, and verification of analytical models developed to predict light water nuclear reactor fuel rod behavior under normal and postulated accident conditions.

The experimental program centers on the testing of single fuel rods and small clusters of fuel rods under power-cooling-mismatch (PCM), loss-of-coolant accident (LOCA), and reactivity initiated accident (RIA) conditions. The PCM Test Series^[2,3] of this experimental program is being conducted to characterize the behavior of unirradiated pressurized water reactor (PWR) type fuel rods under PCM conditions at power densities and flow conditions ranging from normal operating conditions to beyond departure from nucleate boiling (DNB).

Under postulated abnormal reactor operating conditions, an imbalance between the fuel heat generation rate and the coolant heat removal capability gives rise to changes in the fuel and cladding temperature distribution required to maintain equilibrium among the various heat transfer rates. This heat transfer imbalance, termed a power-cooling-mismatch accident, results from either over power conditions in the reactor core or undercooling situations at relatively constant reactor power, or a combination of both.

Small heat transfer imbalances in the nucleate boiling regime immediately re-equilibrate with only minor changes occurring in the fuel

and cladding temperature distributions. Larger imbalances may exceed the safe operating margin of a reactor and result in a boiling crisis^[4]. A boiling crisis appears as a basic change in the heat transfer rate as the boiling changes from sub-cooled nucleate or nucleate boiling to a transition boiling regime and finally to film boiling.

At the incipience of sub-cooled, or partial nucleate boiling, the fuel and cladding temperatures rise and then level off as a result of fully developed nucleate boiling. As the heat flux increases, transition, or partial film boiling appears; this is an unstable mode of heat transfer with nucleate and film boiling coexisting in the same region. Local temperature fluctuations occur as these boiling regimes intermittently appear. The maximum heat flux attainable between nucleate and transition boiling (incipience of the boiling crisis, i.e., departure from nucleate boiling, DNB) is called the critical heat flux (CHF)^[a]. If the fuel-cladding temperature remains below temperatures at which significant metal-water reactions occur, equilibrium between the heat generated in the fuel rod and the heat transferred to the coolant may possibly be reestablished with only a minor effect on the fuel rod behavior. However, sufficiently high temperatures may be reached during transition and stable, sustained film boiling to extensively oxidize the cladding. Oxygen embrittlement may result in fuel rod damage by brittle fracture.

Table I^[3] summarizes four categories of possible post DNB fuel rod behavior. Phenomenological processes which determine the category of post DNB fuel rod behavior expected during a PCM excursion are identified

[a] The critical heat flux ratio is the ratio of the calculated critical heat flux to the actual heat flux for the actual flow conditions. Current industry practice is to ensure that the calculated minimum critical heat flux ratio is such that there is a 95 percent probability with a 95 percent confidence that DNB has not been exceeded. For the W-3 correlation this translates to a minimum CHF ratio of 1.3^[5].

TABLE I

CATEGORIES OF POST DNB FUEL ROD BEHAVIOR DURING PCM EVENTS

<u>Category</u>	<u>Cladding Temp. Range (K)</u>	<u>Zircaloy Cladding Phase</u>	<u>Zirconium/Water Reaction</u>	<u>Cladding Ductility</u>	<u>Potential Fuel Rod Failure Modes</u>
1	< 810	Low temp α - phase	None	Normal	Fuel-cladding mechanical interaction induced cladding rupture.
2	810-1116	High temp α - phase	None	High	Large deformations to rupture followed by fuel melting [a].
3	1116-1225 ^[b]	$\alpha+\beta$ two phase region	Minimal	Low	Small deformations to rupture followed by fuel melting [a].
4	>1255	β - phase	Severe	High/Low ^[c]	Cladding oxidation and oxygen embrittlement. Large deformation to rupture followed by fuel melting [a].

[a] Cladding outward deformation or ballooning after the internal rod pressure exceeds the system pressure. A cold internal pressure of 5.52 MPa should be sufficient for PWR conditions.

[b] This temperature range is intended to bound the cladding ductility minimum that occurs within the $\alpha+\beta$ two phase region.

[c] The cladding ductility is initially high in β zirconium but will decrease rapidly as the zircaloy is embrittled by oxidation and oxygen absorption.

as cladding phase changes and the degree of cladding-water reaction, both of which influence cladding ductility. The principal variable controlling these changes is cladding temperature. Potential fuel rod failure modes are additionally dependent on rod internal pressurization. Maximum post-DNB cladding temperatures in the α -Zr microstructure range (810 to 1115 K) were sought during the test to determine low temperature cladding deformation data for model analysis.

The behavior and changes in fuel and cladding following the variety of abnormal thermal transient conditions attainable in reactor operation may be studied by posttest examination (both nondestructive and destructive) of the individual fuel rods.

This report describes the results of the postirradiation examination (PIE) on the first four-assembly, single-rod test of the PCM test series, PCM-2. Four separate single-fuel rod experiments were completed under the PCM Test Series^[6-10] prior to the PCM-2 Test. The objective of this postirradiation examination is to provide specific experimental data on the posttest condition of the fuel and cladding, and to supplement the test results.

1.1 General Description of Experiment Design, Conduct, and Test Results

The Test PCM-2 was conducted in the PBF reactor to characterize the behavior of four unirradiated PWR type fuel rods under simultaneous PCM and post DNB conditions at moderate power (46 kW/m). DNB was achieved by flow reduction methods whereby the coolant flow rate was decreased while maintaining a constant test fuel rod power.

The PBF driver core is designed to contain a centrally located tubular test region which operates as a neutron flux trap, permitting high power densities in tested fuels relative to the active core^[2]. Test fuel rod shrouds are positioned in a heavy-walled Inconel 718 tube designed to protect the driver core from potential fuel rod failure and to facilitate in-pile insertion and removal of experiments. The associated water loop simulates the operating conditions of a pressurized water reactor (PWR).

The test was performed with four test fuel rods each contained in a separate flow shroud positioned radially in the PBF in-pile tube (IPT). The radial positioning is illustrated in Figure 1 for the four-rod test assembly. The test assembly is designed to symmetrically position the four test fuel rods in the PBF in-pile tube and to allow easy removal following testing.

The Test PCM-2 assembly was instrumented for measurement of (a) coolant conditions, (b) fuel rod power, (c) fuel rod length change, (d) fuel rod internal pressure, (e) fuel centerline temperature, (f) cladding surface temperature, and (g) the instantaneous and integrated relative neutron flux in the region of the four fuel rod cluster. An instrumented fuel rod mounted inside its flow shroud (16.3 mm ID) is shown schematically in Figure 2. The experimental assembly is shown installed in the PBF in-pile tube test space in Figure 3. Each test fuel rod is rigidly fixed into the assembly at the top end-cap during testing, but is free to expand axially downward against a transducer to measure length changes.

The basic test sequence consisted of a thermal hydraulic calibration of fuel rod power versus the in-pile tube neutron flux, a preconditioning operation during which fuel to cladding gap conductance measurements were made, fuel rod aging, and sequential DNB testing. DNB conditions were obtained by either decreasing the coolant flow rate in small increments of approximately 5% at 60 second intervals, or by rapid flow reduction during about 16 seconds, while maintaining a nearly constant fuel rod power of about 46 kW/m. The nominal coolant inlet conditions were 600 K and 14.8 MPa.

Eight sequential flow reduction DNB test cycles were performed. Two of the fuel rods reached DNB during all eight cycles. One fuel rod achieved DNB during the second and succeeding cycles, while the remaining fuel rod reached DNB only during the final cycle. During the final test cycle, the four test fuel rods were allowed to remain in film boiling for over 60 seconds. A summary of the experimental results is presented

EGG-A-259

Fig. 1 Fuel rod circumferential orientation in the PBF in-pile tube test space.

Fig. 2 Test PCM-2 fuel rod and instrumentation shown installed in flow shroud.

EGG-B-975

Fig. 3 Test PCM-2 fuel rod and shroud assembly shown installed in the PBF in-pile test space.

in Table II. Additional more specific details of the experiment design, conduct, and results are contained in the Test PCM-2 Results Report^[11].

2. POSTIRRADIATION EXAMINATION

The general objective of the postirradiation examination of the PCM-2 fuel rods (identified as Rods UTA-0008, UTA-0009, UTA-0010, and A-0014) was to determine in detail the posttest condition of each fuel rod, and obtain specific information on the irradiation behavior of the fuel and cladding, supplementary to the main test results. The examination consisted of both nondestructive and destructive evaluation. The nondestructive examination included: (a) visual inspection and photographic documentation of the as-received rod test assembly and the separate fuel rods, (b) diametral measurements, (c) neutron radiography, (d) gross gamma scanning, (e) void volume determination, and (f) flux wire analysis. The destructive examination included analytical burnup determination from fuel rod sections and metallographic investigation of the cladding and fuel structure.

Following the in-pile testing at PBF, the PCM-2 fuel rod assembly was transferred to the hot cells for examination. In the hot cell, the test hardware was disassembled and each fuel rod was removed from its experimental shroud for visual examination through the hot cell window for gross damage and photo documentation. An in-cell periscope of about 4X magnification aided in this examination.

The flux wire was then removed for analysis. Diametral measurements were made along each fuel rod at two orientations, 90° apart. Following neutron radiography of fuel Rod A-0014, pulsed eddy-current (PEC) and gross gamma scans were performed. Fuel rod A-0014 was laser punctured and the internal gas was sampled, followed by void volume measurement prior to destructive examination.

After determining the void volume, fuel rod A-0014, together with the other three fuel rods, was epoxy-encapsulated in a separate stainless steel tube and sectioned into burnup analysis samples and metallographic samples. The burnup samples were sent to the Idaho Chemical Processing Plant (ICPP), a facility operated by Allied Chemical Company,

TABLE 11

SUMMARY OF DNB TEST RESULTS FOR TEST PCM-2

Flow Reduction No.	Flow Reduction Rate (%/sec)	Fuel Rod No.	Fuel Rod Peak Power (kW/m)	Inlet Coolant Temperature (K)	DNB Occurrence	Coolant Mass Flux at Onset of DNB (kg/s-m ²)	Time in DNB (sec)	Minimum Coolant Mass Flux (kg/s-m ²)	Time in Film Boiling [a] (sec)	Maximum ⁺ Indicated Cladding Surface Temperature (K)	Location ^[d] of Maximum Indicated Cladding Temperature (m)	Maximum ⁺⁺ Indicated Fuel Centerline Temperature (K)	Cladding* Elongation after DNB (mm)	Increase in Rod Internal** Pressure after DNB (MPa)	Maximum Indicated*** Plenum Temperature (K)
1	0.1	0008	46	601	No	---	0	849	0	629	0.686	1603	0	0	617
		0009	46	601	Yes	941	190	907	0	680	0.986	1812	[c]	0	617
		0010	46	601	Yes	930	220	936	0	680	0.635	2080	[c]	0	617
		0014	46	601	No	---	0	902	0	[b]	---	[b]	0	[b]	[b]
2	0.1	0008	46	601	No	---	0	820	0	629	0.686	1593	0	0	617
		0009	46	601	Yes	878	40	878	0	629	0.787	[c]	[c]	0	617
		0010	46	601	Yes	895	40	895	0	667	0.787	2075	[c]	0	617
		0014	46	601	Yes	896	40	863	0	[b]	---	[b]	0.14	[b]	[b]
3	3	0008	46	600	No	---	0	820	0	627	0.686	1653	0	0	616
		0009	46	600	Yes	884	50	878	0	634	0.787	1830	[c]	0	617
		0010	46	600	Yes	924	50	889	0	682	0.787	2085	[c]	0	617
		0014	46	600	Yes	846	50	824	0	[b]	---	[b]	0.02	[b]	[b]
4	3	0008	46	600	No	---	0	797	0	628	0.686	1653	0	0	617
		0009	46	600	Yes	907	30	837	0	672	0.787	1835	[c]	0	617
		0010	46	600	Yes	895	30	855	0	667	0.787	2070	[c]	0	617
		0014	46	600	Yes	874	30	802	0	[b]	---	[b]	0.14	[b]	[b]
5	3	0008	46	600	No	---	0	780	0	627	0.686	1655	0	0	617
		0009	46	600	Yes	878	25	901	0	713	0.787	1860	[c]	0	617
		0010	46	600	Yes	890	25	855	0	664	0.787	2050	[c]	0	617
		0014	46	600	Yes	863	25	785	0	[b]	---	[b]	0.21	[b]	[b]
6	3	0008	46	601	No	---	0	780	0	627	0.686	1655	0	0	617
		0009	46	601	Yes	878	20	839	0	641	0.787	1850	[c]	0	617
		0010	46	601	Yes	924	20	855	0	708	0.787	2080	[c]	0	617
		0014	46	601	Yes	891	23	802	0	[b]	---	[b]	0.16	[b]	[b]
7	3	0008	46	601	No	---	0	780	0	628	0.686	1655	0	0	617
		0009	46	601	Yes	890	12	837	0	730	0.787	1830	[c]	0	617
		0010	46	601	Yes	941	12	849	0	698	0.787	2075	[c]	0	617
		0014	46	601	Yes	946	15	802	0	[b]	---	[b]	0.18	[b]	[b]
8	3	0008	46.4	600	Yes	775	145	722	105	1315	0.635	2290	2.9	0.37	618
		0009	46.4	600	Yes	920	90	768	52	917	0.787	1900	[c]	0.18	618
		0010	46.4	600	Yes	980	60	780	50	875	0.787	2082	[c]	0.08	618
		0014	46.4	600	Yes	905	100	735	---	[b]	---	[b]	1.7	[b]	[b]

[a] Time that indicated cladding surface temperature exceeded 730 K.

[b] Fuel rod not instrumented.

[c] Instrumentation not functioning properly.

[d] Location is referenced to the bottom of the fuel stack.

+ Cladding temperature indicated by surface thermocouple.

++ Fuel centerline temperature indicated by ultrasonic thermometer.

* Cladding elongation was determined by an axial growth transducer (LVDT).

** Rod internal pressure was determined by a bellows type pressure transducer.

*** Plenum temperatures were indicated by a Chromel-Alumel (Type K) thermocouple.

located at the INEL, for analysis. The metallographic samples were mounted in Bakelite and prepared for examination of the cladding and fuel.

2.1 Pretest Fuel Rod Characterization

Pretest characterization and posttest measurements are required for evaluating and verifying rod performance models. The pretest measurements provide the as-built referential information for use in analytical models and comparison following posttest examination. Specific pretest characterization data for the unirradiated fuel rods are presented in Appendix A.

The test fuel rods were composed of 0.91-m long fuel stacks of sixty 93% theoretical density, 20% enriched UO_2 ceramic fuel pellets, each nominally 9.30-mm in diameter and 15.49-mm long. The pellets were contained in a zircaloy-4 alloy cladding tube of nominally 10.73-mm outside diameter and 0.61-mm wall thickness. The cladding and fuel of Rod A-0014 were not characterized so the nominal values listed for the instrumented rods must be used.

Three of the test fuel rods (UTA-0008, UTA-0009, and UTA-0010) were instrumented. Fuel rod instrumentation consisted of a tantalum-sheathed tungsten-rhenium centerline thermocouple or an (W/Re) ultrasonic thermometer, fuel rod gas plenum thermocouple, internal pressure transducer, and four titanium-sheathed chromel-alumel cladding surface thermocouples. The locations of instruments on the test fuel rods are outlined in Table III. Zircaloy-2 end-caps were welded to the ends of the cladding tube, with thermocouple and pressure transducer connections passing through the top end-caps.

The fuel centerline (C_L) thermocouple junctions were located at the same position as the respective 90° cladding surface thermocouple junctions. The nominal fuel cladding diametral gap was 0.2-mm for the assembled fuel rods. The centerline thermocouple holes were nominally

TABLE III

FUEL ROD INSTRUMENTATION FOR TEST PCM-2^[a]

Measured Parameters:	Internal Pressure	Plenum Temperature	Coolant Flow Rate	Coolant Outlet Temperature	Coolant Temperature Rise, ΔT	Fuel Centerline Temperature	Cladding Temperature	Fuel Rod Axial Growth
	0 to 17 MPa Pressure Transducer	Chromel-Alumel (Type K) TC	Turbine Flowmeter	Chromel-Alumel (Type K) TC	Copper-Constantan (Type T) ΔT TC	Ultrasonic Thermometer or W5Re/W26Re ^[c] Grounded Junction TC	Chromel- ^[c] alumel (Type K) TC	Linear Variable Differential Transformer (LVDT)
Fuel Rod UTA 0008	SN 142 ^[b]	SN 52690	SN 10094/299	SN 1001	SN DTC-3	UT SN 294 0.69m 0.686	0.635m- 0°:SN 16-14 0.686m- 90°:SN 22-06 ^[d] 0.889m-180°:SN 28-12 0.686m-270°:SN 26-11	SN 205
Fuel Rod UTA 0009	SN 143	SN 52700	SN 100095/229	SN 1005	SN DTC-4	TC SN 223 0.69m 0.686	0.635m- 0°:SN 32-02 0.686m- 90°:SN 25-10 0.787m-180°:SN 29-08 0.686m-270°:SN 33-05	SN 211
Fuel Rod UTA 0010	SN 144	SN 52694	SN 10092/225	SN 1003	SN DTC-8	TC SN 370 0.533m	0.686m- 0°:SN 32-03 0.533m- 90°:SN 29-07 0.686m-180°:SN 24-08 0.787m-270°:SN 28-29	SN 213
Fuel Rod UTA 0014	None	None	SN 10093/228	SN 1002	SN DTC-9	None	None	SN 210

[a] See Reference 11 for instrument calibration data.

[b] SN represents the serial number of particular instruments.

[c] Location is referenced with respect to the bottom of the fuel stack.

[d] The cladding TC's at 0.69m-270° are recessed thermocouple installations.

1.9-mm in diameter, penetrating 16 fuel pellets in fuel Rods UTA-0008 and UTA-0009 for a length of 0.246-m at the top end of the fuel stack, and penetrating 26 fuel pellets in UTA-0010 to a length of 0.40-m at the top end of the fuel stack. The fuel centerline thermocouples were located at 0.686-m from the bottom of the fuel stack for Rods UTA-0008 and UTA-0009, and at 0.533-m for UTA-0010. The internal fill gas volumes (including the pressure transducer and the transducer connection tube volumes) were 10.6, 10.4 and $10.0 \times 10^{-6} \text{ m}^3$ for the instrumented fuel Rods UTA-0008, UTA-0009, and UTA-0010, respectively. The fuel rods were pretest pressurized at ambient temperature with helium gas to 2.58 MPa. Fuel Rod A-0014, uninstrumented, was internally pretest pressurized with helium gas to 3.88 MPa.

Pretest radiographs of the fuel columns in Rods UTA-0009 and UTA-0010 are presented in Figures 4 and 5, respectively. The fuel pellets are numbered from the bottom of the stack in the sequence corresponding to Tables A-IV and A-V.

2.2 Visual and Photographic Inspection of the Rod Assembly

Following unloading and removal of the irradiated PCM-2 fuel rod shroud 4 assembly from the transfer cask into the hot cell, the separate shroud assemblies were visually examined through the hot cell window for evidence of damage. After disassembly and removal of each tested fuel rod from its shroud, the rods were visually inspected for gross damage. Each rod was then mounted on a display board and oriented for additional visual examination and photographic documentation. The fuel rods were oriented with respect to a reference notch located in the upper end-cap. For fuel Rods UTA-0008, UTA-0009, and UTA-0010, the zero degree cladding surface thermocouples were aligned with the end-cap notch. Composite appearances of the four fuel rods are presented in Figures 6 through 13 for the 0 and 180° orientations, respectively. Regions of surface oxidation, oxide spalling, and pronounced areas of collapse at fuel pellet interfaces are variously evidenced. Rod bowing is discussed in Section 2.3.

Fig. 4 Pretest radiograph of the fuel column in Test PCM-2 fuel Rod UTA-0009.

Fig. 5 Pretest radiograph of the fuel column in Test PCM-2 fuel Rod UTA-0010.

Fig. 6 Test PCM-2 fuel Rod UTA-0008 photographed from 0-degree orientation showing the posttest condition.

Fig. 7 Test PCM-2 fuel Rod UTA-0008 photographed from 180-degree orientation showing the posttest condition.

Fig. 8 Test PCM-2 fuel Rod UTA-0009 photographed from 0-degree orientation showing the posttest condition.

Fig. 9 Test PCM-2 fuel Rod UTA-0009 photographed in 180-degree orientation showing the posttest corcition.

Fig. 10 Test PCM-2 fuel Rod UTA-0010 photographed from 0-degree orientation showing the posttest condition.

Fig. 11 Test PCM-2 fuel Rod UTA-0010 photographed in 18C-degree orientation showing the posttest condition.

Fig. 12 Test PCM-2 fuel Rod A-0014 photographed from 0-degree orientation showing the posttest condition.

Fig. 13 Test PCM-2 fuel Rod A-0014 photographed in 180-degree orientation showing the posttest condition.

Fuel Rods UTA-0008 and A-0014 exhibited more readily identifiable surface damage in a region extending along both rods between 0.48 and 0.78-m from the bottoms of the fuel rods^[a]. Cladding collapse at fuel pellet interfaces, fuel pellet crack-chip boundaries, and spalling of the surface oxide are distinguishable within this zone on Rod UTA-0008. The collapse corresponds with the highest temperature region of the fuel rod. Surface flakes of oxide are still observed near 0.53 and 0.64-m on this fuel rod. Closer visual examination of the region of collapse and surface oxide spalling was made using the in-cell periscope with 4X magnification. Figure 14 presents composite photographs of the upper and lower boundaries of the collapse zone on Rod UTA-0008 as viewed through the hot cell periscope with the fuel rod oriented in a 0-90° position. The shiny zircaloy metal exposed by spalling of surface oxide, flakes of oxide remnants, and cladding collapse at fuel pellet interfaces are readily apparent. Note that the zero degree 0.69-m TC junction appears well attached to the cladding surface in this region.

Fuel Rod A-0014 was chosen for neutron radiography following testing. Figure 15 presents a composite photo of a neutrograph of the column. Cracking is evident along the column between fuel pellets 13 through 52. An open gap in the fuel column is present at pellet number 22 and pellet number 23 is fragmented (between 0.32 and 0.35-m from the bottom of the fuel column). This gap was not confirmed by subsequent gross gamma scanning. Apparently a shift in the fuel column during fuel rod transfer occurred to close the gap prior to gross gamma scanning (see Section 2.4.2).

2.3 Cladding Geometry

Temperature dependent properties of both the fuel and cladding alter the fuel rod high temperature behavioral characteristics, including the cladding geometry. Externally, cladding geometry changes are

[a] Note that observation of the gross surface damage is referenced to the bottom of the fuel rod. This allows ready identification from Figures 6 through 13.

(A) Upper Extent of Cladding Collapse and Surface Oxide Spall

(B) Lower Extent of Cladding Collapse and Surface Oxide Spall

Fig. 14 Collapse zone in the posttest Test PCM-2 fuel Rod UTA-0008 (0- to 90-degree orientation) showing (A) the upper extent, and (B) the lower extent of collapse at fuel pellet interfaces and surface spalled oxide as viewed through the hot cell periscope (4X).

Fig. 15 Neutron radiograph of Test PCM-2 fuel Rod A-0014 showing the fuel column and plenum region of the fuel rod. Note the fracture of fuel pellets along the column, and also the gap formed in Pellets 22 and 23, located between 0.32-m and 0.35-m from the bottom of the fuel stack.

exhibited as bow, and collapse during high temperature PCM testing conditions.

Three of the four fuel rods (UTA-0008, UTA-0010 and A-0014) showed noticable bowing. The bowed rods appeared closely misaligned in the same plane. The lower portion of the individual fuel rods was deflected in approximately the 90-270° plane, measured clockwise with respect to the zero degree orientation of the top end-cap. The direction of deviation was toward 200 to 270°. Bowing was roughly measured for Rods UTA-0008 and A-0014 only.

The bow in fuel Rod UTA-0008 was largest with the bottom length, beginning near 0.56-m from the bottom end-cap, deflected less than 20-mm from the centerline position toward 270°. Bow in Rod A-0014 appeared as a smooth kink beginning near 0.54-m from the bottom end-cap with upper and lower segments straight on each side of the point of kink. The maximum centerline deviation was measured roughly as less than 10-mm toward 200°.

Fuel Rods UTA-0009 and UTA-0010 were less bowed and the bow was not characterized. The pretest outside diameter of the fuel rod was a nominal 10.73 mm, as listed in Table A-I of Appendix A. This value may be compared with the posttest condition of each fuel rod. All four Test PCM-2 fuel rods showed some evidence of a region of collapse in the high temperature zone experiencing film boiling. The high temperature zone varied in location from rod to rod in the test assembly, roughly extending between 0.35 and 0.80-m above the bottom end-cap in fuel Rod UTA-0008 (exhibiting the largest region of collapse) to much shorter lengths in the other three fuel rods. The bottom of the fuel stack is located 35-mm above the bottom of the fuel rod. Succeeding measurements reported will be referenced from the bottom of the fuel stack.

2.3.1 Posttest Diametral Measurements

The outside diameter of each fuel rod tested was measured to determine the amount and extent of cladding collapse. Measurements were

made at orientations of 45 and 135° using a 0-1 inch (0-25.40-mm) micro-meter with an estimated accuracy of ± 0.001 inch (± 0.03 -mm). The outside diameters for both orientations of each fuel rod are plotted against the actual fuel column length in Figures 16 (UTA-0008), 17 (UTA-0009), 18 (UTA-0010), and 19 (A-0014), respectively. The separate regions of collapse are also apparent in the figures. Detailed outside diameter data are tabulated in Appendix B. The diametral reduction varies for the separate fuel rods, being located between 0.41 and 0.84-m for Rod UTA-0008, between 0.66 and 0.84-m for Rod UTA-0009, between 0.74 and 0.82-m for Rod UTA-0010, between 0.56 and 0.84-m for Rod A-0014. Fuel Rods UTA-0008 and A-0014 exhibited the largest amounts of collapse. The larger diametral values at the transition to collapse are associated with the heavier oxide layers in these regions as noted in the overall views of Figures 6 through 13.

The diametral reduction in Rod UTA-0008 is greater than nominally half the 0.20-mm diametral cold gap (0.160 to 0.165-mm at the two orientations). The region of greatest collapse in fuel Rod A-0014, between 0.56 and 0.69-m corresponds to the region seen in Figure 15 which exhibited circumferential fracture and gapping of the fuel pellets. The collapse observed in the four fuel rods appeared somewhat uneven, eccentric or elliptical across the cladding diameter. The overall reduction in diameter of Rod UTA-0010 is attributed to measurement error associated with in-cell handling.

2.3.2 Void Volume

Fuel Rod A-0014 was uninstrumented. The posttest void volume was measured to be $(7.2 \pm 0.2) \times 10^{-6} \text{ m}^3$. Table IV presents the results of the fission gas analysis for this fuel rod. No posttest void volume was obtained for fuel rods UTA-0008, UTA-0009 and UTA-0010.

Fig. 16 Postirradiation diametral measurements of Test PCM-2 fuel Rod UTA-0008.

Fig. 17 Postirradiation diametral measurements of Test PCM-2 fuel Rod UTA-0009.

Fig. 18 Postirradiation diametral measurements of Test PCM-2 fuel Rod UTA-0010.

Fig. 19 Postirradiation diametral measurements of Test PCM-2 fuel Rod A-0014.

TABLE IV

GAS ANALYSIS ON FUEL ROD A-0014

Elemental gas Constituent	H ₂	He	N ₂	O ₂	Ar	CO ₂	Kr	Xe
Analysis (mean concentration mol %)	< 0.01	93.0	0.08	0.01	6.9	0.01	[a]	[a]

[a] None detected.

2.4 Fuel Rod Power Profiles

The fuel rod power relative to the core power can have an important influence on the irradiation results of fuel rods tested during off-normal reactor operating conditions. The PCM-2 fuel rod power generation was determined individually for each of the four fuel rods tested by two methods: (a) a thermal hydraulic energy balance, dependent on single phase fuel rod coolant flow rate, pressure, inlet temperature, coolant temperature rise, and the neutron flux axial peak-to-average ratio, and (b) posttest chemical analysis of selected fuel rod segments. The thermal hydraulic power calibrations and fuel to cladding gap conductance measurements are discussed in detail in the PCM-2 Test Results Report^[10]. The fuel rod axial power profiles are determined correlative to the activity profiles obtained by (a) radiochemical analysis of fuel samples from each rod, (b) gross gamma scans of one of the fuel rods from the test and (c) the cobalt flux wire activation.

2.4.1 Analytical Burn Up Evaluation

The results of radiochemical analysis of five fuel samples from rod UTA-0009, and one or two from each of the other three fuel rods, are presented in Table V. The fissions per kilogram of total uranium, based on the 95-Zr isotope, are related to burnup in fissions per cubic metre and megawatt days per metric ton of uranium (MWd/t). These data are compared with the neutron flux axial profile in paragraph 2.4.3.

2.4.2 Gross Gamma Scans

The uninstrumented fuel Rod A-0014 was posttest gross gamma scanned to determine the axial activity profile. Since the rod was bowed, the rod was gamma scanned for two different orientations 180° apart to minimize the effect of the rod bowing. Figures 20 and 21 present the results of the gross gamma scans for two orientations, 0 and 180°, respectively. The activity profiles appear generally consistent with the expected axial power distribution. The periodic deviation from a

Fig. 20 Gross gamma scan of Test PCM-2 fuel Rod A-0014 (0-degree orientation).

Fig. 21 Gross gamma scan of Test PCM-2 fuel Rod A-0014 (180-degree orientation).

TABLE V

TEST PCM-2 RADIOCHEMICAL ANALYSIS RESULTS

Sample Location (metres from bottom of the fuel rod)	Isotopic Composition a/o					Fissions ^{235}U per kg of U_{total}	Fissions/ m^3 of UO_2 fuel	Burnup (MWd/t)
	^{234}U	^{235}U	^{236}U	^{238}U				
37 UTA-0008	0.457	0.087	19.285	0.206	80.383	$1.23 (+ 1.5 \times 10^{18}) 10^{20}$	$11.5(10^{23})$	45.6
UTA-0009	0.051	0.096	20.128	0.196	79.580	$5.50(+ 8 \times 10^{17}) 10^{19}$	$51.6(10^{22})$	20.4
	0.254	0.091	20.122	0.201	79.586	$1.05(+ 1 \times 10^{18}) 10^{20}$	$9.8(10^{23})$	38.9
	0.457	0.091	20.128	0.201	79.559	$1.23(+ 2 \times 10^{18}) 10^{20}$	$11.5(10^{23})$	45.6
	0.660	0.091	20.136	0.201	79.670	$9.43(+ 1.3 \times 10^{18}) 10^{19}$	$88.5(10^{22})$	34.9
	0.864	0.091	20.153	0.201	79.555	$4.77(+ 8 \times 10^{17}) 10^{19}$	$44.8(10^{22})$	17.7
UTA-0010	0.445	0.091	20.145	0.201	79.539	$1.27(+ 1.5 \times 10^{18}) 10^{20}$	$11.9(10^{23})$	47.0
	0.475	0.091	20.100	0.200	79.603	$1.22(+ 1.5 \times 10^{18}) 10^{20}$	$11.4(10^{23})$	45.2
A-0014	0.457	0.092	20.136	0.201	79.570	$1.26(+ 2 \times 10^{18}) 10^{20}$	$11.8(10^{23})$	46.7

smooth cosine curve in the gamma activity along the scan denote locations of fuel pellet interfaces. The presence of an axial gap in the fuel column would appear as a large negative deviation in the gamma activity at that location. The gap in the fuel column observed in the posttest neutrograph between 0.32 and 0.35-m from the bottom of the fuel stack is not identified in the gross gamma scans. A small negative deviation in the gamma activity near 0.80-m in the gross gamma scans is not identifiable as a gap in the fuel in the posttest neutrograph of Figure 15. This observation further supports the conclusion that the fuel column shifted as a result of handling prior to gamma scanning.

Results of the relative gamma activity along the scans compared to the average activity are presented in Tables C-I and C-II of Appendix C. The fuel rod axial power profile obtained from the above data is related to the axial neutron flux profile, an important input parameter to the FRAP-T code. The axial peak-to-average ratio data from Tables C-I and C-II indicate that the peak is located near 0.33-m from the bottom of the fuel stack with a peak-to-average activity ratio of 1.39.

2.4.3 Flux Wire Gamma Scan

The relative axial irradiation flux profile was measured for PCM-2 tests from a (0.510% Co)-Al flux wire attached to the experimental flow shroud of fuel Rod A-0014. The flux wire was removed posttest and gamma scanned. The thermal neutron flux is approximately proportional to the induced radioactivity of the wire. The results of this scan are presented in Table D-I of Appendix D. Table D-II lists the normalized axial neutron flux profile determined by the ratio of the local neutron flux to this average flux along the wire and smoothed by fitting to a Fourier series curve. A neutron axial peak-to-average ratio of 1.382 was determined from these data, with the axial peak located 0.457-m from the bottom of the fuel stack. The discrepancy between the location of the activity peak obtained from the cobalt flux wire and that obtained from gamma scanning (0.33-m) Rod A-0014 may be due to the fuel rod bow since the accuracy of the gamma scan is reduced when the distance from the fuel rod to the scanning detector slit varies.

For identical fuel pellets the axial neutron flux profile is directly proportional to the fuel rod axial power profile. Figure 22 presents a comparison of the burnup results from radiochemical analysis of fuel rod segments taken from Table V to the results of the axial neutron flux profile determined by gamma scanning the irradiated cobalt flux wire. The results of the comparison shown in Figure 22 demonstrate that in general, the expected axial power profile from radiochemical analysis appears consistent with the expected axial power profile based on the cobalt flux wire activation.

2.5 Metallographic Examination

Changes in the mechanical behavior affecting overall fuel rod performance result from modifications to the microstructure of the cladding and fuel induced by elevated temperatures. These changes arise from thermal gradients across the fuel and cladding, and from thermal expansion and contraction of the fuel stack following rapid transient heating and cooling. Microstructural changes may be deduced from metallographic examination of fuel rod segments.

2.5.1 Cladding and Fuel Structure

Microstructural changes in the zircaloy-4 cladding material and the UO_2 sintered fuel pellets are complex. The changes are strongly time and temperature dependent. Microstructural changes of interest to Test PCM-2 occur (a) in the cladding---by recrystallization (the nucleation and growth of strain-free grains within the strained lattice), grain growth (the enlargement of the recrystallized grains with time and temperature), and the alpha-Zr to beta-Zr phase transformations; and (b) in the fuel---by the initiation of thermal restructuring of the sintered UO_2 fuel as evidenced by grain growth, and pore migration. Depending on fuel rod design, operating history, test operating power, cladding collapse and the fuel-cladding diametral gap will range in size from an as-fabricated gap between the fuel and cladding to complete contact. Fuel fracture, shattering, and fragmentation accompany rapid heating and cooling.

Fig. 22 Comparison of local burnup from radio-chemical analysis of fuel rod sections with the axial neutron flux from the induced activity of the cobalt flux wire.

Each fuel rod was prepared for metallographic examination by encapsulating and epoxying it into a stainless steel tube. Selected rod segments were sectioned from the encapsulated fuel rod and mounted in Bakelite for cladding and fuel polishing, etching, and examination. The standard 32-mm diameter metallographic mounts were wet-grounded on successively finer grades of abrasive paper to 600-grit finish and swab etched for cladding examination and photographic documentation. The sample preparation was then extended to include polishing with "Linde A" powder on the Syntron vibra-polisher followed by etching for the UO_2 fuel microstructure, examination, and photomicrographic documentation. The details of sample preparation and sectioning locations are discussed in Appendix E.

Overall views of the transverse and longitudinal metallurgical samples examined and discussed in this report are shown in Figures 23 and 24. These illustrate the position from which each sample was sectioned from the intact, irradiated PCM-2 fuel rods. The sample locations are placed with respect to the bottom of the fuel rod, and the values presented in Tables E-I through E-IV have been adjusted to reference 35-mm with respect to the bottom of the fuel stack.

The metallographic samples were selected based on the posttest condition of the fuel rods. The selection was made to include various regions which remained at cooler operating temperatures during testing and regions which achieved DNB as indicated by thermocouple measurements of surface temperatures greater than $730\text{ K}^{[1]}$. Only Rods UTA-0009 and UTA-0010 achieved DNB during Cycle 1. Rods UTA-0009, UTA-0010 and A-0014 reached DNB during the succeeding seven Cycles. All four fuel rods indicated film boiling during the final eighth Cycle, (see Table II). Rod A-0014 was uninstrumented and its time in film boiling was not obtained directly. Rod UTA-0008 exhibited the largest zone experiencing high temperature film boiling, defined by the extent of collapse.

Cladding collapse into the fuel pellet interfaces (waisting) and surface thermocouple junctions are variously illustrated in Figure 23

Fig. 23 Overall view of the posttest Test PCM-2 fuel Rods UTA-0008 and UTA-0009 showing macrophotographic outlays of the metallographic samples examined and their sectioning locations along the fuel rods.

Fig. 24 Overall view of the posttest Test PCM-2 fuel Rods UTA-0010 and A-0014 showing macrophotographic outlays of the metallographic samples examined and their sectioning locations along the fuel rods.

for fuel Rods UTA-0008 and UTA-0009. Regions of the UO_2 fuel restructuring, revealed by oblique illumination of polished and etched fuel, together with fracturing (or cracking) of the fuel from thermal cycling are also observed in both Figures 23 and 24.

Fuel Rod UTA-0008

All of the samples sectioned for metallographic examination for this fuel rod were taken from locations within the high temperature film boiling zone which extended along the rod between 0.35 and 0.80-m from the bottom of the fuel stack. The microstructure of the cladding exhibited generally prior beta phase zircaloy, bounded on the OD and ID cladding surfaces with the development of oxygen-stabilized alpha-Zr bands.

Figure 25 shows the cladding and fuel microstructures from sample C-1 found in the region of the fuel rod near 0.48-m from the bottom of the fuel stack. The transverse section, Figure 25 (A), is illustrated for the cladding microstructure by Figure 25 (B) and for the fuel microstructures by Figures 25 (E) and (F). The cladding microstructure is that of prior beta phase material with OD and ID bands of oxygen-stabilized alpha-Zr. Figure 25 (C) illustrates the region of the UO_2 fuel pellet near the center where grain growth has occurred. Both transgranular fracture and fabrication porosity were observed. The fuel microstructure seen in Figure 25 (F) near the outer edge of the fuel pellet resembles that of unirradiated fuel. Fuel fragmentation has occurred near the cladding with the fracturing extending into the ID cladding layer of oxygen-stabilized alpha-Zr as seen in Figure 25 (C). The nearly 0.020-mm thick layer is very brittle due to oxygen uptake. Fuel fragments near the inside of the cladding often are attached to the cladding within the zone of film boiling. Attachment results by development of a UO_2 -Zr interaction layer adjacent to the cladding inner layer of oxygen-stabilized alpha-Zr, as seen in Figure 25 (D).

Fig. 25 Transverse section of Test PCM-2 fuel Rod UTA-0008, located 0.48-m from the bottom of the fuel stack, showing (A) a macrophotograph of the cladding and fuel, (B) a cross section of the cladding, (C) a composite view of the fuel fracturing extending into the cladding, (D) a UO₂ fuel fragment attached to the cladding, and (E) and (F) the fuel grains structure near the center of the fuel pellet and near the outer edge.

A transverse section (C-2) of the fuel rod taken at 0.53-m from the bottom of the fuel stack, is presented in Figures 26 for the cladding, and 27 for the fuel.

The microstructure seen in Figure 26 (B), (D), (F), (H), and (J) is mainly prior beta phase zircaloy bounded on the OD and ID by layers of oxygen-stabilized alpha phase zircaloy. The UO_2 -Zr reaction layer is present in various stages of morphology. In Figure 26 (C), the layer is quite well developed, exhibiting two well-defined layers adjacent to the ID cladding layer of oxygen-stabilized α -Zr. The various stages exhibited in Figure 25 (E), (G) and (I) are much less developed and appear largely associated with the fuel pellet periphery adjacent to the cladding. Figure 25 (C) further illustrates fuel fracturing extending 20 to 30- μm into the ID cladding layer of oxygen-stabilized alpha-Zr. In Figure 26 (E), a region of the cladding ID surface has developed pitting in the oxygen-stabilized α -Zr layer which appears to be associated with the build-up of the reaction layer into a fuel fracture crack. Previous electron microprobe work on a similar cavity formation in the cladding has revealed that zircaloy and uranium exchange locations with the cavity becoming U-rich while Zr concentration in the fuel reaction layer increases along the crack^[12]. In Figure 26 (G) and (I), reaction layer formation began to appear along fracture lines into the ID layer of oxygen-stabilized alpha-Zr prior to the development of a distinct dual reaction layer.

Figure 27 (A) presents the fuel microstructure observed near the outer edge of the fuel pellet. The fine grained UO_2 is similar to unirradiated fuel. About one third to midway into the center of the fuel pellet, a transition zone to grain growth appears. Representative fuel grain structure in this region is seen in Figure 27 (B). Near the center, large grains develop with connected porosity, preferentially formed along grain boundaries. Fracturing is also evident along the grain boundaries as seen in Figure 27 (C).

Fig. 26 Transverse section of Test PCM-2 fuel Rod UTA-0008, located 0.53 m from the bottom of the fuel stack, showing (A) a macrophotograph of the fuel and cladding; (B), (D), (F), (H), and (J) cross-sectional views of the cladding prior β -Zr microstructure at various circumferential locations; and (C), (E), (G), and (I) close-up views of selected microstructure from the cross-sectional views.

Fig. 27 Microstructural views of the UO₂ fuel from sample C-2, Rod UTA-0008, located 0.53-m from the bottom of the fuel stack, showing (A) fuel near the outer edge of the fuel pellet, (B) fuel near the transition zone to grain growth about midway toward the pellet center, and (C) grain growth near the center of the UO₂ fuel pellet.

Figures 28 and 29 present the microstructure of the cladding and fuel of sample C-3. These are located 0.58-m from the bottom of the fuel stack within the region which exhibited the greatest degree of cladding collapse. Microstructure locations in the transverse sample are identified in Figure 28 (A). Cladding microstructure exhibited in Figure 28 (B), (D), (E), and (G) is prior beta phase zircaloy bounded on the OD and ID surfaces by layers of oxygen-stabilized alpha zircaloy. The prior β -Zr illustrated, ranges from a cross-hatched (basket weave) microstructure mixed with needle-like platlets on the ID surface as in Figure 28 (B), to largely martensitic-like regions with alpha phase zircaloy intrusions into the prior beta phase material as seen in Figure 28 (E). Fuel fragments illustrated in Figure 28 (C) and (F) are attached to the cladding ID surface by the UO_2 -Zr reaction layer development. Figure 28 (C) exhibits a cavity in the ID oxygen-stabilized alpha-zircaloy layer filled with UO_2 -Zr reaction product.

The fuel microstructure is presented in Figure 29 (A). The composite figure across the 0 to 180° cross-section shows regions of fuel fracture and fragmentation near the outer edge of the fuel pellet, adjacent to the cladding, and large cracks with granular fragmentation toward the center of the fuel pellet. The region of grain growth and the transition regions to grain growth are apparent. Figure 29 (B) shows a higher magnification view of the region of fuel fragmentation near the cladding and the associated UO_2 -Zr reaction layer formation with fuel fracturing extending into the ID surface layer of oxygen-stabilized alpha-Zr. Figure 29 (C) and (D) illustrates the granular fracture of the larger grains near the center of the fuel pellet. Some regions of grain growth with accumulation of connected porosity along grain boundaries are present near areas of granular fragmentation of the UO_2 fuel as seen in Figure 29 (E).

Cladding collapse into the interface between fuel pellets was examined in a longitudinal sample C-4 (90° half) sectioned from the fuel rod between 0.61 and 0.63-m from the bottom of the fuel stack. The

Fig. 28 Transverse section of Test PCM-2 fuel Rod UTA-0008, located 0.58-m from the bottom of the fuel stack, showing (A) a macrophotograph of the cladding and fuel; (B), (D), (E), and (G) cross-sectional views of the cladding prior β -Zr microstructure; and (C) and (F) close-up views of UO₂ fragments attached to the ID cladding surface by UO₂-Zr reaction.

Fig. 29 Composite view of the transverse section C-3 from fuel Rod UTA-0008, located 0.58-m from the bottom of the fuel stack, showing (A) a composite view across the mid-plane (0- to 180-degree) of the transverse section illustrating fuel fracturing and restructuring, (B) close-up view of fuel fragmenting near the outer pellet edge together with a UO₂-Zr reaction layer development on the ID cladding surface, (C) and (D) fuel inter- and intragranular fracturing in the region of UO₂ grain growth, and (E) region of UO₂ grain growth with connected porosity long grain boundaries.

collapse is approximately uniform on both sides of the sample as seen from the macrophotograph of Figure 30 (A). Higher magnification of the collapse region reveals a prior beta phase microstructure with OD and ID surface bands of oxygen-stabilized alpha-Zr as seen in Figure 30 (B). The ID band of oxygen-stabilized alpha-Zr appears continuous around the collapse tip while the UO_2 -Zr reaction layer thins and disappears on both sides of the collapse tip.

In Figure 30 (C) and (E), fuel fragmentation is observed near the periphery of the fuel pellet. The fracturing is also observed to extend into the ID layer of oxygen-stabilized alpha-Zr, shown clearly in Figure 30 (E).

Deposition of a second phase material into a fuel crack paralleling the cladding is shown in Figure 30 (C). High magnification of the region of deposition reveals a definite grain structure. Electron microprobe analysis of the deposited material filling the crack indicates a U-Zr composition with uranium present in a somewhat larger concentration. Additional details of this analysis will be presented and discussed in Section 2.5.5.

Only a small amount of restructuring is observed in the UO_2 fuel near the center of the pellet and occurs as grain growth as shown in Figure 30 (F). An average grain size ranging from 20 to 30- μm was determined in this region compared to the fine-grained fuel microstructure near the outer edge which ranged from 4 to 8- μm in size.

Figure 31 (A) presents a composite view of the cladding collapse at the interfacial gap between fuel pellets. A reaction layer formation is seen built up on the collapse tip on the 180° side of the longitudinal section, illustrated by Figure 31 (B), but is not observed at the collapse tip on the opposite zero degree side seen in Figure 31 (E). The reaction formation of Figure 31 (B) is the first observed of this type in the PCM fuel rods examined to date. The formation appears to be three-dimensional, exhibiting definite grain structure in the central

Fig. 30 Longitudinal section (90-degree half) of Test PCM-2 fuel Rod UTA-0008, located between 0.61- and 0.63-m from the bottom of the fuel stack, showing (A) a macrophotograph of the fuel and cladding, (B) cladding collapse at a fuel pellet interface, (C) a composite view of the fuel fragmentation near the outer pellet edge with filling (healing) of a fracture line by a U-Zr alloy, (D) a close-up of the U-Zr alloy filler material exhibiting a definite grain structure, (E) region of fuel fracturing extending into the cladding, and (F) UO₂ grain structure near the fuel pellet centerline showing grain growth with inter- and intragranular fracturing.

Fig. 31 Composite view of the longitudinal section (90-degree half) C-4 from fuel Rod UTA-0008, located between 0.61- and 0.63-m from the bottom of the fuel stack, showing (A) a cross section of the cladding collapse at fuel pellet interfaces and the fuel pellets interfacial dish, (B) a close-up of the collapse tip (180-degree side) with a reaction layer at the collapse tip illustrating the three-dimensionalality of the buildup, and (D) the collapse tip on the opposite (0-degree) side exhibiting no anomalous reaction layer buildup.

region. Figure 31 (C) presents a higher magnification view of the central region exhibiting grain structure. Figure 31 (D) presents the region, refocussed to examine the outer edges. The edges exhibit a microstructure similar to the reaction layer formation normally observed between the fuel and cladding.

The reaction formation region has been examined by electron microprobe. This analysis indicates that the edge layer formation (see Figure 31 (D)) contains U and Zr, but no measureable quantity of Sn. This bi-layer formation is Zr-rich adjacent to the fuel. The large grained central region (see Figure 31 (C)) near the collapse tip appears to be rich in U with no measurable quantity of Zr. A significant quantity of Fe is indicated as present in this central region. Additional discussion will be presented in Section 2.5.5.

The second portion of the longitudinal Section C-4 (270° half) located at the same position (between 0.61 and 0.63-m from the bottom of the fuel stack) contained the centerline ultrasonic thermometer (W/22% Re) sheath. The UT sheath wall has fractured along a line approximately coincident with fuel pellet fracture. The fracture location in Figure 32 (A) is illustrated in the composite of Figure 32 (B). A close-up view of the sheath fracture and sheath surface degradation by cavitation and pitting is shown in Figure 32 (C). The fuel fracture, in Figure 32 (D), shows the fragmentation of the pellet periphery and propagation of the fracture into the ID layer of oxygen-stabilized alpha-Zr of the cladding. The ultrasonic centerline thermometer functioned properly during testing, and the sheath fracture is assumed to have occurred during quenching of the fuel rod following termination of the final DNB-film boiling operation.

A transverse section (C-5) of the fuel rod near the zero degree cladding surface thermocouple, located approximately 0.635-m from the bottom of the fuel stack, is shown in Figure 33 (A). The ultrasonic (W/Re) centerline thermometer sheath is also visible at this location. Cladding microstructures shown in Figure 33 (B), (C), and (D) exhibited prior beta phase zircaloy with OD and ID surface layers of oxygen-stabilized alpha-Zr. The UO_2 -Zr reaction layer between the cladding and

Fig. 32 Longitudinal section (270-degree half) of Test PCM-2 fuel Rod UTA-0008, located between 0.61- and 0.63-m from the bottom of the fuel stack, showing (A) a macrophotograph of the cladding and fuel with ultrasonic centerline TC, (B) a cross-sectional view of the cladding, fuel and centerline TC W/22% Re sheath illustrating failure of the TC sheath, (C) a close-up of the TC sheath degradation and fracture, and (D) a close-up of the fuel fracture intersecting the cladding with fracture extending into the ID layer of oxygen-stabilized α -Zr.

Fig. 33 Transverse section of Test PCM-2 fuel Rod UTA-0008, located 0.635-m from the bottom of the fuel stack, showing (A) a macrophotograph of the cladding and fuel with the 0-degree TC junction attachment, (B) and (C) cross-sectional views of cladding prior β -Zr, (E) and (F) fuel grain structure near the pellet periphery and near the center, respectively, and (G) a macrophotograph of the 0-degree, 0.63-m TC junction weld bead with a close-up at (H) of the laser weld attachment to the cladding.

fuel is not uniformly developed circumferentially. The alpha-Zr has formed intrusions into the prior beta phase material in various regions around the ID surface and is in-part illustrated in Figure 33 (D). The fuel grain structure near the outer edge of the fuel pellet resembles that of unirradiated fuel with average grain sizes ranging from 5 to 6- μm , as seen in Figure 33 (E). Similarly to the fuel near the center of the previously discussed sample, only limited fuel restructuring has occurred as evidenced by grain growth. Figure 33 (F) shows example fuel microstructure found near the center of the fuel pellet near the centerline thermometer sheath through-hole. The average grain size in this region ranges from 20 to 25- μm .

Figure 33 (G) presents a photomicrograph of the 0.635-m zero degree cladding surface thermocouple. None of the TC components (titanium sheath, tantalum barrier sleeve, insulation, or junction bead) were discernable even by successively grinding and observing microstructure changes with rod level changes. Apparently, the TC junction components were fused during the laser weld operation in fabrication. A greater magnification view is presented in Figure 33 (H) showing the region of laser weld attachment to the cladding. The weld surface has an oxide thickness approximately the same as the cladding surface thickness of ZrO_2 .

The 90 and 270° cladding surface thermocouples were located at 0.686-m from the bottom of the fuel stack, approximately coincident with the end location of the centerline ultrasonic thermometer (active element W/2% Th). The 270° TC junction is recessed in a nominally 0.30-mm deep groove to reduce localized temperature fluctuations associated with the cooling "fin" effect. Figure 34 (A) presents a transverse section taken at 0.69-m from the bottom of the fuel stack, ground and polished to expose the separate TC junctions, and the centerline active element of the ultrasonic thermometer. Cladding microstructure at this elevation is illustrated in Figure 34 (B) and (C) showing prior beta phase zircaloy with thin OD and ID bands of oxygen-stabilized alpha-Zr. The ID layer of oxygen-stabilized alpha-Zr is unevenly broken by alpha-Zr phase intrusion into the prior β -Zr region. The cladding surface in

Fig. 34 Transverse section of Test PCM-2 fuel Rod UTA-0008, located 0.69-m from the bottom of the fuel stack, showing (A) a macrophotograph of the fuel and cladding with the 0-degree and 90-degree TC junctions, (B) cross-sectional view of the cladding which exhibits collapse near a fuel fragment, (C) a cross-sectional view of the cladding which exhibits reaction layer degradation on the ID surface at a crack in the oxygen-stabilized α -Zr layer and (E) the fuel microstructure near the center of the fuel pellet with (F) the fuel microstructure near the outer pellet edge.

Figure 34 (B) shows evidence of collapse. The surface indentation and associated anomolous oxide formation correspond to the ID surface extruded fingerlet of cladding into a fuel crack. Fuel fracture intersects the ID cladding surface. The subsequent reaction degrades the layer of oxygen-stabilized alpha-Zr structure as illustrated in Figure 34 (D).

Fuel microstructure near the centerline thermometer through-hole appears basically unstructured as seen in Figure 34 (E) compared to the fuel microstructure near the pellet periphery which is typical of the preirradiated microstructure and illustrated in Figure 34 (F).

The region of collapse seen in Figure 34 (B) is illustrated in detail in Figure 35. A cross-sectional composite of the collapse region is presented in Figure 35 (A). Outer cladding surface indentations correspond to inner surface protrusions. Figure 35 (B) shows an extrusion of cladding material into a fuel crack. A UO_2 fuel fragment is attached to the cladding at that point by the UO_2 -Zr reaction layer present. Anomolous oxidation of the outer surface indentations is shown in Figure 35 (C) and (D).

Figure 36 (A) presents details of the recessed 270° 0.686-m thermocouple junction. A close-up of the TC junction components is seen in Figure 36 (B). Significant oxidation has occurred around defects in the laser weld attachment illustrated in Figure 36 (E) and (F), Thermal contact was good at points shown in Figure 36 (C) and (D), and the laser welds appeared to have been good since the cladding temperatures calculated from the surface oxide and oxygen-stabilized alpha-Zr layer formation differed by only 100 K from the actual measured thermocouple readings. Additional discussion of cladding temperatures will be presented in Section 2.5.2.

Fuel Rod UTA-0009

Fuel Rod UTA-0009 was an instrumented rod, with cladding surface thermocouples, a centerline thermocouple, and supplementary instrumentation.

Fig. 36 Detail of the recessed 0.69-m TC junction (Type K, Chromel-Alumel), located at the 270-degree orientation in Test PCM-2 fuel Rod UTA-0008, showing (A) a macrophotograph of the thermocouple junction seated in a 0.25-mm-deep groove, (B) a higher magnification illustrating the junction region and laser weld regions, (C) and (D) the cladding ridge in point contact with the TC sheath, and (E) and (F) oxidation formation in weld defects.

Metallographic samples sectioned from this rod were taken from the high temperature region experiencing cladding collapse between 0.65 and 0.90-m from the bottom of the fuel stack. Cladding microstructure and thermocouple junctions which indicated DNB were examined. The microstructure of the cladding was generally of the lower temperature variety, ranging from untransformed as-received stress-relieved material, to fully recrystallized alpha-Zr.

The 0.686-m 90 and 270° TC's briefly indicated DNB during the final test cycle. A transverse section taken at 0.69-m from the bottom of the fuel stack is presented in Figure 37 (A) which reveals the 90 and 270° TC junctions. The cladding microstructure observed in Figure 37 (B) is a mixture of the as-received, stress-relieved zircaloy and preequipped alpha phase zircaloy material. Microhardness measurements indicated a uniform circumferential hardness of about 201 DPH near the center of the cladding wall. Microhardness indentations in the cladding material are seen in Figure 37 (B) near the zero degree orientation. The fuel centerline thermocouple is seen in Figure 37 (C). Since the junction is at a slightly lower elevation than the exposed cladding surface TC junctions, it was not examined.

Fuel microstructure near the center of the fuel pellet is basically unrestructured as compared to Figure 37 (D) fuel, near the pellet center region, with Figure 37 (E) representing fuel near the periphery of the fuel pellet. Microhardness measurements give an average hardness near the center of the fuel pellet of 557 DPH which is generally in the range of hardness for unrestructured fuel found near the fuel pellet outer edge.

Figure 38 (A) presents a macrograph of the 0.686-m 90° TC junction. Details of the TC junction components are illustrated in Figure 38 (B). The laser weld attachment appears secure. Microhardness measurements of the weld material indicated an average hardness of 314 DPH which is considerably harder than the cladding hardness of 201 DPH. Cladding microstructure in the heat-affected zone adjacent to the weld attachment is very fine-grained pre-equipped zircaloy material.

Fig. 37 Transverse section of Test PCM-fuel UTA-0009, located 0.69-m from the bottom of the fuel stack, showing (A) a macrophotograph of the cladding and fuel, (B) a cross section of the cladding microstructure near the 0-degree orientation, (C) details of the centerline thermocouple and UO₂ fine-grain structure near the center of the fuel pellet, and (D) and (E) the UO₂ grain structure at different locations.

(0.69-m-TC)90° Macrograph
Etched, Bright Field (A)

Titanium-Sheathed, Magnesium Oxide
Insulated Chromel-Alumel (type K)
Spaded Junction Thermocouple

200 μ

Etched, Polarized Light (C)

20 μ

Etched, Polarized Light (B)

50 μ

Fig. 38 Detail of the 0.69-m TC located at the 270-degree orientation, showing (A) a macrograph of the titanium-sheathed, magnesium-oxide-insulated, Chromel-Alumel (Type K) spaded junction cladding surface thermocouple (1.17-mm outside diameter) laser welded to a 0.3-mm groove in the cladding, (B) a partial illustration of the TC junction, and (C) a higher magnification view of the cladding TC weld region exhibiting the heat-affected zone on Test PCM-2 fuel Rod UTA-0009.

Figure 39 (A) presents a macrograph of the 0.686-m 270° TC junction. Details of the TC junction components are illustrated in Figure 39 (B). The 270° TC junction is recessed in a nominally 0.30-mm groove cut into the surface of the cladding. The laser weld attachment appears secure. Microhardness measurements of the weld material gave an average hardness of 278 DPH which is not significantly different from the weld material found for the 90° TC. Cladding microstructure in the heat-affected zone is similarly very fine-grained preequipped zircaloy as illustrated in Figure 39 (C). Microhardness of this material indicates a hardness of 253 DPH which is similar to the hardness of the weld material, but differs considerably with the 201 hardness of the cladding wall.

Cladding wall temperatures based on oxide thicknesses measured at 1000X indicated higher surface temperatures than actually measured at the cladding surface TC's. The 90° TC indicated a maximum of 650 K with the calculated temperature determined to be 913 K (a temperature just below the 920 K temperature for recrystallization of the stress-relieved condition)^[13]. The 270° TC indicated a maximum temperature of 730 K while the calculated cladding temperature was 965 K (considerably above the recrystallization temperature). The actual temperature probably lies intermediate to these extremes with a value consistent with the presence of pre-equipped microstructure observed metallographically. Additional discussion of cladding temperature will be presented in Section 2.5.2.

A transverse section (L-2) taken from the region of largest cladding collapse near 0.74-m from the bottom of the fuel stack is presented in Figure 40 (A). The cladding microstructure is circumferentially uniform, exhibiting fully recrystallized alpha phase structure. Cross-sectional views of the cladding microstructure are presented in Figure 40 (B), (C), (D), and (E). The recrystallized alpha-Zr microstructure has a uniform circumferential hardness of 187 DPH, which is softer than the pre-equipped microhardness of 201 DPH of the preceding sample, L-1.

Fig. 39 Detail of the 0.69-m TC located at the 0-degree orientation showing (A) a macrograph of the titanium-sheathed, magnesium-oxide-insulated, Chromel-Alumel (Type K) spaded junction cladding surface thermocouple (1.17-mm outside diameter) laser welded to the cladding surface, (B) a partial illustration of the TC junction, and (C) a higher magnification view of the cladding TC weld region exhibiting the heat affected zone on Test PCM-2 fuel Rod UTA-0009.

The fuel is basically unrestructured with a uniform hardness of 772 DPH measured from the outer edge of the pellet to near the centerline TC through-hole. Supra-grain boundaries formed by segregation of macropores may be seen in Figure 40 (F) and (G). Such boundaries appear to be structurally weak since fracture along the boundary of porosity is common as a result of thermal cycling the fuel.

The region surrounded by such supra-grains appears relatively free of porosity. This type of fuel macrostructure is also observed in unirradiated fuel pellets^[14]. Supra-grain boundary formation is thus apparently associated with the sintering fabrication operation.

A transverse section (L-3) taken approximately 0.79-m from the bottom of the fuel stack is presented in Figure 41 (A). Grinding at the 0.79-m 180° TC junction has exposed a portion of the fuel pellet interfacial dish near the centerline. Fragmentation has occurred near that interface resulting in some loss of fuel in the central region. The cladding microstructure is circumferentially uniform with recrystallized alpha phase material present as illustrated by the representative microstructure of Figure 41 (B). Details of the 0.79-m 180° TC junction are presented in Figure 41 (C). Figure 41 (D) illustrates the separate TC components. The weld attachment to the cladding is good. The microstructure of the cladding in the heat affected zone next to the weld exhibits recrystallized alpha-Zr which has undergone growth as pictured in Figure 41 (E). Microhardness measurements of the laser weld and heat-affected zone of the cladding indicate average hardnesses of 196 DPH and 237 DPH, respectively. These values are compared and contrasted with the average hardness of the cladding wall in this sample of about 185 DPH.

Fuel Rod UTA-0010

Instrumented fuel Rod UTA-0010 exhibited very little cladding collapse. Cladding collapse occurred from about 0.69 to 0.81-m from the bottom of the fuel rod. This zone was assumed to coincide with the region of film boiling. The cladding 270° surface TC located at 0.787-m

Fig. 41 Transverse section of Test PCM-2 fuel Rod UTA-0009, located 0.79-m from the bottom of the fuel stack, showing (A) a macrophotograph of the fuel and cladding, (B) a cross section of the cladding recrystallized α -Zr microstructure, (C) detail of the 0.79-m TC at 180-degree, illustrated by (D) and (E) exhibiting a titanium-sheathed, magnesium-oxide-insulated, Chromel-Alumel (Type K) spaded junction cladding surface thermocouple (1.17-mm outside diameter) laser welded to the cladding.

from the bottom of the fuel stack indicated DNB. Some asymmetry in the film boiling patch is apparent since the 0.686-m zero degree TC registered DNB temperature spikes to 660 K during the final test cycle while the cladding thermocouples at 0.686-m 180° and 0.533-m 90° indicated only steady nucleate boiling. This asymmetry is verified metallographically by circumferential variations in the microstructure in any given sample. Samples examined metallographically from this fuel rod were sectioned from above, below, and within the cladding collapse region. The microstructure ranged from mixed stress-relieved and a pre-equiaxed material near the upper and lower collapse boundaries, to recrystallized alpha-Zr within the region of primary collapse and film boiling.

A transverse sample (E-1) sectioned near the lower boundary of the film boiling zone 0.65-m from the bottom of the fuel stack is presented in Figure 42 (A). The cladding microstructure is mixed stress-relieved and pre-equiaxed alpha phase zircaloy material as illustrated in Figure 42 (B) and is found around the entire circumference in this sample. Fuel microstructure shown in Figure 42 (C), (D), (E) and (F) taken from various regions in the fuel pellet is essentially unrestructured, similar to unirradiated fuel.

A transverse sample (E-2) sectioned within the lower boundary of collapse 0.72-m from the bottom of the fuel stack is presented in Figure 43 (A). The cladding microstructure in this sample is predominately mixed stress-relieved and pre-equiaxed alpha phase material with mainly pre-equiaxed zircaloy found near the zero degree orientation. A representative microstructure is seen in Figure 43 (B).

Macro-pore segregation into supra-grain boundaries is also a characteristic of the UO_2 fuel of this rod and is illustrated in the composite of Figure 43 (C). Some fuel fracturing is observed to follow the porous boundaries.

Fuel near the center of the fuel pellet is unrestructured and similar to unirradiated fuel as seen in Figure 43 (C).

Fig. 42 Transverse section of Test PCM-2 fuel Rod UTA-0010 located 0.65-m from the bottom of the fuel stack, showing (A) a macrophotograph of the fuel and cladding (B) the mixed stress-relieved and preequiated cladding microstructure, and (C), (D), (E), and (F) examples of the UO_2 fuel microstructure from various regions of the sample.

Fig. 43 Transverse section of Test PCM-2 fuel Rod UTA-0010, located 0.72-m from the bottom of the fuel stack, showing (A) a macrophotograph of the fuel and cladding, (B) the mixed stress-relieved and preequiaxed cladding microstructure, (C) a composite illustration of the fuel exhibiting radial cracking and supra-grain structure near the centerline TC through-hole.

Figure 44 (A) shows a transverse section taken in the region of greatest collapse 0.76-m from the bottom of the fuel stack. The polishing preparation has revealed the fuel pellet interfacial dish and fragmentation of the outer edge of the fuel pellet has resulted in some loss of fuel in these areas. The cladding microstructure in this sample is shown in Figures 44 (B), (C), and (D) from various circumferential locations. The microstructure varies from mixed stress-relieved and pre-equiaxed alpha-zircaloy in Figure 44 (B) near 200° circumferential orientation, to mixed pre-equiaxed and recrystallized alpha-Zr in Figure 44 (C) extending circumferentially from about 300° orientation through 0 to past 120° along the cladding, as in Figure 44 (D). Microhardness measurements of the various cladding microstructures indicate that the hardness of the pre-equiaxed material near 200° is 274 DPH, being circumferentially the same except in the predominately recrystallized alpha material near 90° which has a hardness of 230 DPH.

The fuel microstructure of Figure 44 (E) is unrestructured, and severely fragmented near the periphery as illustrated in the composite Figure 44 (F).

Figure 45 (A) shows a transverse section (E-4) taken from the upper boundary of the film boiling zone and region of collapse, 0.77-m from the bottom of the fuel stack. Cladding microstructural changes are illustrated in Figure 45 (B), (C), (D), and (E) varying from pre-equiaxed alpha phase zircaloy near 270° circumferential orientation through zero degrees to recrystallized α -Zr near 90° extending toward 180° along the cladding.

Microhardness measurements in these regions indicate that the hardness of the predominantly pre-equiaxed material near 180 and 270° is nominally 201 DPH. The region of recrystallized alpha-Zr near 90° has a nominal hardness of 248 DPH.

The fuel microstructure of this sample resembles that of unirradiated fuel. Figure 45 (F) presents a composite view of a partial cross-

Fig. 44 Transverse section of Test PCM-2 fuel Rod UTA-0010, located 0.76-m from the bottom of the fuel rod, showing (A) a macrophotograph of the fuel and cladding; (B), (C), and (D) the cladding microstructure at several orientations illustrating a transition from mixed stress-relieved and pre-equiaxed grain structure to mixed pre-equiaxed and recrystallized α -Zr; and (E) and (F) the fuel grain microstructure which is largely fragmented but exhibits a grain size similar to unirradiated fuel.

Fig. 45 Transverse section of Test PCM-2 fuel Rod UTA-0010, located 0.77-m from the bottom of the fuel stack, showing (A) a macrophotograph of the fuel and cladding; (B), (C), (D), and (E) the cladding microstructure as it varies around the circumference from stress-relieved material to recrystallized α -Zr; and (F) a composite of the UO₂ fuel containing supra-grains outlined by sintering porosity.

section of the fuel exhibiting the presence of supra-grain boundaries formed by segregation of macro-pores.

The 0.787-m 270° TC junction was ground separately for examination and a composite detail of the TC junction components is presented in Figure 46 (A) and (B). In Figure 46 (B), it is seen that some oxide had formed at weld defects near the TC sheath and at the cladding attachment. Despite this oxide formation, the junction attachment appears secure.

A transverse section (E-5) obtained from above the region of film boiling 0.82-m above the bottom of the fuel stack is presented in Figure 47 (A). The polishing preparation has revealed the fuel pellet interface. Peripheral fragmenting of the fuel has resulted in some loss. The microstructure found in the cladding is predominantly pre-equiaxed material as illustrated by Figure 47 (B). The average hardness of this material is 248 DPH which is comparable in hardness to that of the recrystallized alpha-Zr of the preceding sample.

Supra-grain structure is observed in the UO_2 fuel of this sample as seen in Figure 47 (C). Fracture along this porous boundary is illustrated in Figure 47 (D).

Fuel Rod A-0014

Fuel Rod A-0014 was uninstrumented. This fuel rod experienced cladding collapse between 0.53 and 0.83-m from the bottom of the fuel stack. It is assumed that the high temperature film boiling zone coincided with the collapse region. All metallographic samples examined were sectioned from within the zone of collapse. Cladding microstructure found in this region is prior beta phase zircaloy with OD and ID bands of oxygen-stabilized alpha-Zr.

A longitudinal section (U-1) taken between 0.60 and 0.62-m from the bottom of the fuel stack is presented in Figure 48 (A). The fuel pellets in this sample exhibit considerable fracture with fragment

Fig. 46 Low magnification macrophotograph of Test PCM-2 fuel Rod UTA-0010, showing (A) the 270-degree TC junction (Type K) located 0.79-m from the bottom of the fuel stack, and (B) details of the thermocouple components.

Fig. 47 Transverse section of Test PCM-2 fuel Rod UTA-0010, located 0.82-m from the bottom of the fuel stack, showing (A) a macrophotograph of the cladding and fuel, (B) the mixed stress-relieved and preequaxed cladding microstructure, (C) a composite of the fuel, and (D) a close-up of the supra-grain boundary fracture along porosity.

Fig. 48 Longitudinal section of Test PCM-2 fuel Rod A-0014, located between 0.60- and 0.62-m from the bottom of the fuel stack, showing (A) a macrophotograph of the fuel and cladding, (B) a cross section of the zircaloy cladding microstructure, (C) a detail of a fuel fragment attached to the cladding, (D) a composite photograph of the fuel and cladding illustrating fuel cracking and restructuring near the interfacial dish, (E) and (F) details of the fuel grain structure, and (G), (H), and (I) various regions of UO₂ grain growth.

displacement observed at the fuel pellet interfacial dish. Although significant collapse inward toward the fuel surface has occurred in this region, no collapse of the cladding into the fuel pellet interfacial gap is observed as illustrated in Figure 48 (D).

Cladding microstructure observed in Figure 48 (B) is that of prior beta phase-Zr with a well developed OD layer of oxygen-stabilized alpha-Zr. The ID layer is less distinct with alpha phase zircaloy intrusion into the region of prior beta phase zircaloy predominating. Fuel fragments from the pellet periphery are found attached at various locations to the ID cladding surface by the UO_2 -Zr reaction layer formation. Representative microstructure is presented in Figure 48 (C).

The radial extent of fuel restructuring is particularly evident in Figure 48 (D). Fuel microstructure from selected regions of the fuel pellet are presented in Figure 48. Figure 48 (E) shows the unrestructured fuel near the pellet periphery, Figure 48 (F) the transition region to grain growth, and Figure 48 (G), (H), and (I) the restructured regions of grain growth. Regions of anomolous or accelerated grain growth appear in the fuel, and have been identified as being an artifact of the preirradiation pellet fabrication^[10].

A transverse sample (U-2) sectioned 0.62-m from the bottom of the fuel stack is presented in Figure 49 (A). The microstructure of the cladding cross-section seen in Figure 49 (B) is prior beta phase zircaloy. The OD layer of oxygen-stabilized alpha-Zr is distinct and well developed, whereas, on the ID side, large alpha Zr phase platlets intruding into the prior beta phase material have nearly obscured the oxygen-stabilized alpha-Zr layer. Fuel fragments are also observed attached to the ID cladding surface by a UO_2 -Zr reaction layer as illustrated in Figure 49 (C). The region of fuel restructuring is seen in Figure 49 (D). An example of the UO_2 fuel microstructure obtained near the center of the

Fig. 49 Transverse section of Test PCM-2 fuel Rod A-0014, located 0.62-m from the bottom of the fuel stack, showing (A) a macrophotograph of the fuel and cladding, (B) a cross section of the cladding illustrating the zircaloy microstructure, (C) detail of a fuel fragment attached to the cladding, (D) a composite photograph of the cladding and fuel illustrating the region of fuel cracking and grain restructuring near the center of the fuel pellet, and (E) and (F) regions of UO_2 grain growth.

fuel pellet as presented in Figure 49 (E) and (F) which shows that fuel restructuring is limited to grain growth.

The transverse section (U-3) taken 0.66-m from the bottom of the fuel stack and presented in Figure 50 (A) exhibited a cladding microstructure similar to the preceding sample. The prior beta phase zircaloy in Figure 50 (B) is bounded on the OD and ID sides by distinct layers of oxygen-stabilized alpha-Zr. Alpha phase-Zr platlets intruding into the prior β -Zr region are still prominent. Fuel fragments are observed attached to the ID cladding surface at various locations by a UO_2 -Zr reaction layer as illustrated in Figure 50 (C).

Fuel microstructure near the outer pellet edge seen in Figure 50 (D) resembles that of unirradiated fuel. In the central restructured region of the UO_2 fuel pellet, grain growth is observed as illustrated in Figure 50 (E) and (F). Fracture of the fuel occurs by various modes and is observed in Figure 50 (E) as inter and intra-granular fracture along a line of macro-pores, i.e., along a supra-boundary.

A transverse sample (U-4) sectioned 0.71-m from the bottom of the fuel stack, near the upper boundary of collapse, is presented in Figure 51 (A). The cladding microstructure observed in this region is prior beta-Zr material. A distinct OD layer of oxygen-stabilized alpha-Zr is seen in Figure 51 (B). The ID layer of oxygen-stabilized alpha-Zr is, basically, indiscerable being comprised of alpha-Zr intrusions into the prior beta phase zircaloy.

Fuel microstructure near the periphery of the fuel pellet is fine-grained similar to the unirradiated fuel as seen from Figure 51 (C) and (D). Grain growth occurs in the central region of the fuel pellet. Considerable macro-porosity is also observed as illustrated in Figure 51 (E).

The transverse section (U-5) taken 0.76-m from the bottom of the fuel stack shown in Figure 52 (A) is located within the upper boundary

Fig. 50 Transverse section of Test PCM-2 fuel Rod A-0014, located 0.66-m from the bottom of the fuel stack, showing (A) a macrophotograph of the fuel and cladding, (B) a cross section of the cladding illustrating the zircaloy microstructure, (C) a detail of a fuel fragment attached to the cladding, and (D), (E), and (F) various regions of fuel grain restructuring and growth.

Fig. 51 Transverse section of Test PCM-2 fuel Rod A-0014, located 0.71-m from the bottom of the fuel stack, showing (A) a macrophotograph of the fuel and cladding, (B) a cross section of the cladding zircaloy microstructure, and (C), (D), and (E) various regions of the UO₂ fuel near the OD and toward the center of the fuel pellet inside the zone of grain restructuring.

Fig. 52 Transverse section of Test PCM-2 fuel Rod A-0014, located 0.76-m from the bottom of the fuel stack, showing (A) a macrophotograph of the fuel and cladding, (B) a cross section of the cladding microstructure illustrated at higher magnification of the OD band of recrystallized α -Zr by (C) and on the ID by (D), and the fine-grained UO₂ fuel at (E) with a localized region of grain growth.

of the collapse zone. Polishing preparation of the metallographic mount has revealed the pellet dish. Fragmenting near the outer pellet edge has resulted in some loss of fuel. The cross-sectional view of the cladding in Figure 52 (B) shows a predominantly two phase mixture of $\alpha + \beta$ zircaloy microstructure. This microstructure extends circumferentially. An OD band of recrystallized alpha-Zr is also present and extends circumferentially. These microstructures are further illustrated in Figure 52 (C) and (D).

The fuel in this sample is unrestructured, but does contain regions of anomolous or accelerated grain growth which was discussed earlier. Figure 52 (E) presents an example of such a region.

2.5.2 Cladding Surface Temperature Estimate

Instrumenting the fuel rods with cladding surface thermocouples attached at various locations along the rods gives test data of the surface temperatures reached at these specified locations. Evaluation and verification of the surface attached thermocouple performance may be made by metallographic examination of the thermocouple junction and adjacent cladding microstructure. Temperatures estimated from cladding microstructures may be compared to surface thermocouple temperature readings. Microstructure temperature estimates were made using structural characteristics such as the stress-relieved condition, recrystallized alpha-Zr material, and the presence of prior beta phase-Zr material.

Supplementary cladding surface temperatures may be estimated from the thicknesses of surface ZrO_2 and oxygen-stabilized α -Zr layers using parabolic rate law correlations relating the layer thicknesses to the temperature and time of exposure. These calculations are presented in Appendix F.

The results of these temperatures determinations are summarized in Tables VI, VII, VIII, and IX for fuel Rods UTA-0008, UTA-0009, UTA-0010, and A-0014, respectively. Figures 53, 54, 55, and 56 show cladding

Fig. 53 Cladding temperature axial profile estimated metallurgically for the Test PCM-2 fuel Rod UTA-0008.

Fig. 54 Cladding temperature axial profile estimated metallurgically for the Test PCM-2 fuel Rod UTA-0009.

Fig. 55 Cladding temperature axial profile estimated metallurgically for the Test PCM-2 fuel Rod UTA-0010.

Fig. 56 Cladding temperature axial profile estimated metallurgically for the Test PCM-2 fuel Rod A-0014.

TABLE VI

MICROSTRUCTURE AND TEMPERATURE ESTIMATES OBSERVED AT VARIOUS LOCATIONS ALONG TEST PCM-2 FUEL ROD UTA-0008

Sample Identification	C-1	C-2	C-3	C-4	C-5	C-6
Location from bottom of the fuel stack (m)	0.48	0.53	0.58	0.61-0.63	0.63	0.69
Cladding Micro-structure	prior β -Zr	prior β -Zr	prior β -Zr	prior β -Zr	prior β -Zr	prior β -Zr
Circumferential cladding temperature range from microstructure (K)	T>1250	T>1250	T>1250	T>1250	T>1250	T>1250
Calculated temperatures (Best Estimate) (K) [a]	1263	1467	1430	1457	1339	1278
Grain sizes of UO ₂ fuel (μ m)						
Near Center	~36	>32	30	~20	>22	--
Near OD	12	~8	--	5	5	8

[a] Average value based on several calculated temperatures (see Table F-1).

TABLE VII

MICROSTRUCTURE AND TEMPERATURE ESTIMATES OBSERVED AT VARIOUS LOCATIONS ALONG TEST PCM-2 FUEL ROD UTA-0009

<u>Sample Identification</u>	<u>L-1</u>	<u>L-2</u>	<u>L-3</u>
Location from bottom of the fuel stack (m)	0.69	0.74	0.79
Cladding Micro-structure	Stress-relieved zircaloy	Recrystallized α -Zr	Preeqiaxed, transition to recrystallized α -Zr
Circumferential cladding temperature range from microstructure (K)	$T < 920$	$920 < T < 1105$	$920 < T < 1105$
Calculated temperatures (Best Estimate) (K) [a]	948	978	948
Grain sizes of UO_2 fuel (μm)			
Near Center	~ 4	--	--
Near OD	4	--	--

[a] Average value based on several calculated temperatures (see Table F-II).

TABLE VIII

MICROSTRUCTURE AND TEMPERATURE ESTIMATES OBSERVED AT VARIOUS LOCATIONS ALONG TEST PCM-2 FUEL ROD UTA-0010

<u>Sample Identification</u>	<u>E-1</u>	<u>E-2</u>	<u>E-3</u>	<u>E-4</u>	<u>E-5</u>
Location from bottom of the fuel stack (in)	0.69	0.74	0.76	0.79	0.84
Cladding Micro-structure	Stress-relieved zircaloy	Stress-relieved zircaloy	Transition preequaxed to recrystallized α -Zr	Preequaxed transition to recrystallized α -Zr	Stress-Relieved transition to preequaxed zircaloy
Circumferential cladding temperature range from micro-structure (K)	T < 920	T < 920	920 < T < 1105	920 < T < 1105	T < 920
Calculated temperature (Best Estimate) (K) [a]	943	950	908	947	908
Grain size of UO ₂ fuel (μ m)					
Near Center	10	--	--	--	--
Near OD	5	--	--	--	--

[a] Average value on several calculated temperatures (see Table F-III).

TABLE IX

MICROSTRUCTURE AND TEMPERATURE ESTIMATES OBSERVED AT VARIOUS LOCATIONS ALONG TEST PCM-2 FUEL ROD A-0014

<u>Sample Identification</u>	<u>U-1</u>	<u>U-2</u>	<u>U-3</u>	<u>U-4</u>	<u>U-5</u>
Location from bottom of the fuel stack (m)	0.60 -0.62	0.62	0.66	0.71	0.76
Cladding Micro-structure	prior β -Zr	prior β -Zr	prior β -Zr	prior β -Zr	mixed recrystallized α -Zr to prior β -Zr
Circumferential cladding Temperature range from micro-structure (K)	T>1250	T>1250	T>1250	T>1250	1105 < T < 1250
Calculated Temperature (Best Estimate) (K) [a]	1280	1335	1344	1293	1189
Grain size of UO_2 Fuel (μm)					
Near Center	>25	>50	>50	--	>16
Near OD	8	--	--	--	4

[a] Average value based on several calculated temperatures (see Table F-IV).

temperatures as a function of axial location and were plotted using the calculated data from Tables F-I, F-II, F-III, and F-IV, corresponding to fuel rods UTA-0008, UTA-0009, UTA-0010 and A-0014, respectively.

The test thermocouples, laser welded to the cladding, were located at 0.64-m zero degree, 0.69-m 90°, 0.89-m 270° above the bottom of the fuel stack. Maximum thermocouple readings were recorded during the final DNB film boiling test cycle. These readings are shown on the plots.

Cladding temperatures determined from cladding samples adjacent to thermocouple junction locations in Rod UTA-0008 agreed well with maximum temperatures indicated by thermocouple instrumentation. From Tables VII and VIII, it is seen that Rods UTA-0009 and UTA-0010 remained within the 810 to 1115 K temperature range sought during the tests. Rods UTA-0008 and A-0014 exceeded this temperature range and achieved temperatures corresponding to the prior beta phase-Zr in the zircaloy-4 cladding. Within the high temperature collapse zone of Rods UTA-0008 and A-0014, UO_2 -Zr reaction occurred during high temperature operation when the fuel was in contact with the cladding.

The best estimate cladding temperatures for Rods UTA-0008, UTA-0010, and A-0014 as determined from metallurgical examination were compared to the maximum cladding temperature values computed by the Fuel Rod Analysis Program-Transient (FRAP-T2) computer code^[15].

DNB Cycle 8 was the only cycle of the test in which the fuel and cladding temperatures were allowed to attain a quasi-equilibrium before decreasing reactor power. Therefore, the measured test conditions for DNB Cycle 8 and the as-built fuel rod and shroud dimensions were used in the analysis. A description of the FRAP-T2 model and code input data is given in Appendix G.

Figures 57, 58, and 59 illustrate the comparison between the distribution of maximum post-DNB cladding surface temperatures computed by the FRAP-T2 code^[a] and the best estimate cladding surface temperatures estimated by metallography.

The FRAP-T2 calculated cladding temperatures for Rod UTA-0008 were generally about 200 K less than those estimated metallurgically. The measured cladding collapse region (0.41 to 0.84-m) agrees well with the calculated film boiling region.

The FRAP-T2 calculated cladding temperatures for Rod UTA-0010 were in good agreement with the four metallurgically derived values, but predicted that the film boiling would extend over a much longer region than measured.

The calculated cladding temperatures for Rod A-0014 were about 100 K less than the metallurgically determined values. The calculated film-boiling region was about 0.2-m longer than the measured region of cladding collapse.

2.5.3 Autoradiography

Autoradiographs from two fuel samples C-2 and C-4 of Rod UTA-0008 were made. Fuel sample C-2 was examined to determine if segregation of fissile material occurred in the vicinity of the UO_2 -Zr reaction layer which had begun to attach and develop into cracks along the ID cladding layer of oxygen-stabilized alpha-Zr, and to determine if a similar segregation of fissile material had occurred near the center of the fuel pellet which exhibited connected macroporosity along grain boundaries in a region of grain growth. Fuel sample C-4 was examined to determine if segregation of fissile material occurred in the anomalous UO_2 -Zr reaction

[a] The FRAP-T2 MOD 002 VER 07A and 7BEM version of the code was used in conjunction with MATPRO MOD 006.

Fig. 57 Comparison of cladding temperatures from FRAP-T calculations and from metallurgical examination of Test PCM-2 fuel Rod UTA-0008.

Fig. 58 Comparison of cladding temperatures from FRAP-T calculations and from metallurgical examination of Test PCM-2 fuel Rod UTA-0010.

Fig. 59 Comparison of cladding temperatures from FRAP-T calculations and from metallurgical examination of Test PCM-2 fuel Rod A-0014.

layer which developed at the surface of the ID cladding collapse protruding into the gap between fuel pellet interfaces, and to determine if a similar segregation of fissile material occurred in the region near the fuel pellet periphery where an anomolous deposition of material had filled a crack parallel to the cladding.

Figures 60 and 61 present the autoradiographs of these samples, C-2 and C-4, respectively. The autoradiographs of these samples show the principal features of fracture lines and the fuel pellet interfacial dish (appearing dark with respect to the background, possibly due to scattering and less fuel absorption of the fissile activity), and the region of fuel restructuring near the center of the fuel pellet (appearing lighter in background, due in part, to greater absorption of the fissile activity associated with the limited densification observed near the center of the fuel pellet).

The regions of interest, pointed out in the beginning of this subsection, do not appear in the autoradiographs. Apparently, the separate reaction layer development, limited restructuring of the fuel with associated segregation of macropores along grain boundaries, and the deposition of filler material in fuel cracks, identified with U of the fuel, do not result in localized accumulation of excess fissile material for these samples and under the test conditions employed.

2.5.4 Microprobe Analysis

Sample C-4 from Rod UTA-0008 was prepared for electron microprobe analysis to examine the reaction layer development near the tip of the cladding protruding into the interfacial gap between fuel pellets and the material deposited along the fuel cracks. Details of sample preparation are discussed in Appendix E.

Electron microprobe analysis scans were made across the anomolous fuel-cladding interfacial reaction layers adjacent to the collapse tip. Several scans were made at various locations through this region.

Fig. 60 Autoradiograph of the fuel from the Rod UTA-0008 metallographic sample C-2 (T-1556).

Fig. 61 Autoradiograph of the fuel from the Rod UTA-008 metallographic sample C-4 (T-1558).

Figure 62 presents the results of these scans for zirconium (Zr), uranium (U), tin (Sn), iron (Fe), and nickel (Ni). A qualitative description or interpretation of the reaction layer composition may be made. The reaction layer shown in Figure 62 (A) adjacent to the cladding away from the collapse tip exhibits the uranium-tin-zirconium composition similar to that observed in the previously tested and reported PCM-2A test fuel rod^[10]. This region is rich in uranium but contains a measureable quantity of Sn. Adjacent to the fuel, both the uranium and Sn levels decrease simultaneously with an increase in the quantity of Zr present. Due to background noise in the Sn ($L\alpha$) trace, the amount of tin which might extend into the fuel is inconclusively demonstrated.

Shown in Figure 62 (B) are scans closer to the collapse tip. The Zr scan indicates an intersection with the cladding collapse tip by a characteristic scan profile. The regions adjacent to the cladding, within the reaction deposition, contain significant quantities of U and Fe, but no measureable quantity of Sn is indicated. The variation in the magnitude of the U-traces seen in the figure is the result of beam shift during repeated scanning of the same region.

Scanning across the central portion of the collapse tip reaction deposition as seen in Figure 62 (C), reveals U and Fe without a detectable quantity of Zr. A small amount of Ni is also indicated. The side material reaction layers are seen to contain a U-Zr alloy composition, rich in Zr adjacent to the fuel.

The reaction layer development adjacent to the fuel-cladding interface may be understood on the basis of a UO_2 -Zr reaction, but the presence of a U-Fe-Ni material sandwiched into the fuel pellet interfacial gap and associated with the cladding collapse tip remains basically unexplainable. This region will be further studied to determine additional details.

The second region selected for study is located along the periphery of the fuel pellet, in a region which exhibits fragmentation of the UO_2

Fig. 62 Composite electron microprobe scans of the reaction layer deposition near the cladding collapse tip at the fuel pellet interfacial gap of Test PCM-2 fuel Rod UTA-0008.

fuel pellet associated with thermal stresses arising from transient heating and quenching of the fuel rod during PCM testing. A second phase material is observed deposited along the fuel crack in this region. Some details of this region were presented earlier in Figure 30. Figure 63 presents electron microprobe scan traces identifying various features of the deposition near the position of the fuel crack that intersects the UO_2 -Zr reaction layer. Similar scan traces are presented in Figure 64, identifying various features of the crack deposition material.

Near the cladding in the proximity of the UO_2 -Zr reaction layer, Figure 63, a larger concentration of Zr was indicated within the deposition material together with a measurable quantity of U. Sn which is present, tends to follow the Zr concentrations through the scanned region. Apparently, the deposited material, which is somewhat richer in Zr is a uranium-tin-zirconium alloy.

Further out in the fuel, as seen in Figure 64, the crack deposition material becomes more closely a U-Zr alloy, richer in U. No detectable amounts of Sn are indicated through this region.

Deposition material of this form has been noted in previous PCM metallographic investigations but has not been described due to the rather limited development of such regions along pellet periphery fuel cracks^[10]. The extensive development of the fuel crack filling observed here, indicates the importance of additional study of this phenomenon and similar depositions in other samples to determine the relationship it has to the UO_2 -Zr reaction layer development and to possible reaction product (uranium rich alloy) melting.

Fig. 63 Electron microprobe scan of the UO₂ fuel adjacent to the cladding in Test PCM-2 fuel Rod UTA-0008.

Fig. 64 Electron microprobe scan of the UO_2 fuel across a fuel crack containing an anomolous deposition of material which extends along the crack intersecting the UO_2 -Zr reaction layer between the fuel pellet edge and the cladding of Test PCM-2 fuel Rod UTA-0008.

3. DISCUSSION

The purpose of this report is to describe the observations, measurements, and methods required to establish the postirradiation condition of the four fuel rods tested in the PCM-2 Test. The examinations presented in this document include two general categories (a) preirradiation fuel and cladding characterization, and (b) postirradiation examination (both nondestructive and destructive investigations.)

The pretest characterization was used to provide a reference for comparing posttest data, so attention will focus on the latter investigations.

3.1 Posttest Condition

The posttest condition of each of the four tested fuel rods was established by visual examination, photodocumentation, cladding diametral measurements, neutron radiography and gross gamma scanning. All four fuel rods maintained their integrity during post-DNB film boiling operation, and following quenching during termination of the tests. Regions experiencing film boiling were characterized by an observable degree of surface oxidation, oxide spalling and cladding collapse. The film boiling zone has been arbitrarily established coincident with the cladding collapse region.

Cladding collapse was measured on all four fuel rods tested with variations in the extent of collapse dependent on cladding temperature. The film boiling region extended over a roughly 0.45-m length of fuel Rod UTA-0008, beginning near 0.35-m from the bottom of the fuel stack. The film boiling region was distinct, exhibiting oxide spalling and collapse into fuel pellet interfacial gaps. The film boiling region along Rod A-0014 extended approximately 0.27-m, beginning near 0.53-m from the bottom of the fuel stack. Cladding collapse into fuel pellet interfaces varied in circumferential extent except near the central portion of the zone. Shorter collapse zones were recorded for the other fuel rods of the test cluster.

Posttest neutron radiography of fuel Rod A-0014 showed evidence of fuel cracking and gaps in the fuel column. Subsequent gross gamma scanning of the fuel rod indicated that gaps in the fuel column seen in the neutron radiograph were no longer present. Apparent gaps did appear at other locations in the gross gamma scans, implying that the fuel stack was loose in this rod and shifted during handling.

A discrepancy due to rod bowing also appeared in determining the exact location of the power peak obtained from gross gamma scanning of Rod A-0014. The rod was gamma scanned in two orientations 180° apart to average out and minimize the effect of bowing.

3.2 Fuel Rod Performance

Metallographic samples were selected for study based on the posttest condition of the fuel rods. This study included various regions which remained at cooler operating temperatures during testing and regions which exhibited gross damage during post-DNB film boiling operation.

Examination of the cladding microstructures within the collapse zone of Rods UTA-0008 and A-0014 showed that they were primarily prior beta phase-Zr with OD and ID surface bands of oxygen-stabilized alpha-Zr. The surface layer of oxygen-stabilized α -Zr formed as a result of water-Zr reaction, while the ID layer of oxygen-stabilized α -Zr formed as a result of cladding-fuel contact from UO_2 -Zr reaction. Such regions experienced cladding temperatures above the $\alpha + \beta \rightarrow \beta$ transformation temperature of 1245 K, considerably in excess of the 810 to 1115 K range sought in the test.

Fuel Rods UTA-0009 and UTA-0010 remained within the 810 to 1115 K temperature bracket during testing. Cladding microstructures observed for these cooler operating fuel rods ranged from the untransformed, as-received, stress-relieved condition to recrystallized alpha-Zr in Rod UTA-0009, and from the mixed stress-relieved and pre-equiaxed alpha phase zircaloy near the upper and lower film boiling boundaries to

recrystallized alpha-Zr within the region of largest collapse in Rod UTA-0010. Microhardness values ranged from about 274 DPH in the pre-equiaxed material to 230 DPH in predominantly recrystallized alpha phase material. These values agree well with those obtained from similar cladding material in the PCM-2A test fuel rod^[10].

External reaction is characterized by surface development of ZrO_2 on the cladding. Cladding oxidation is characterized by the development of OD and ID bands of oxygen-stabilized alpha-Zr. The relative thickness of the ID band of oxygen-stabilized α -Zr is nominally the same as that of the OD band for the samples examined. A duplex interaction layer, formed by UO_2 -Zr reaction when the fuel and cladding are in contact is observed associated with the ID fuel-cladding interface when prior beta phase zircaloy microstructure is present in the cladding. No reaction layer development of this form is observed for lower temperature-associated cladding microstructures such as recrystallized alpha-Zr and the $\alpha + \beta$ two phase region.

In the high pressure PWR environment, the cladding collapses toward the expanding fuel column during test operation. Evidence of fuel-cladding contact and locking of the fuel column is indicated by reaction layer development, thermal cracking of fuel which extends into the brittle ID layer of oxygen-stabilized alpha-Zr, and collapse of the cladding into fuel pellet interfaces.

When collapse occurs extrusion of the cladding into cracks in the fuel may result, as demonstrated in Figure 35. Such extruded protrusions on the ID surface of the cladding appear as effective locking mechanisms of the fuel column.

Fuel pellet peripheral fragmentation by thermal fracture may serve to unlock the fuel as evidenced by partial diametral gap opening following thermal contraction of the fuel. Fragments of the fuel are often left attached to the cladding ID by UO_2 -Zr reaction layer formation (see for example Figure 35 (B)).

UO₂ fuel restructuring was observed in metallurgical samples sectioned from the film boiling zone. The restructuring is characterized by limited equiaxed grain growth near the central region of the fuel pellets up the thermal gradient.

Thermal shattering of the fuel is observed with localized grain fracture occurring in both inter- and trans-granular forms. Localized regions of connected macropores along grain boundaries also exhibited fracturing and appeared to be structurally weak (see Figure 29).

The presence of supra-grain boundaries formed by the segregation of macropores to pseudo-boundaries surrounding regions of varying UO₂ grain structure, essentially devoid of macroporosity, also appear to limit the structural integrity of fuel pellets since fracture along the supra-grains is observed (see Figure 40).

Cladding temperatures were estimated using parabolic rate law correlations which relate the thicknesses of ZrO₂ and the cladding OD layer of oxygen-stabilized alpha-Zr to the time and temperature of exposure (see Appendix F). These temperature data were used to establish best estimate temperatures presented in Tables VI, VII, VIII and IX. The methods of calculation produced cladding temperatures in reasonable agreement with microstructural estimates. The tabulated data in Tables F-I, F-II, F-III, and F-IV show that some circumferential variation in the calculated temperatures of individual samples occurs with differences as large as 150 K appearing from one side of the cladding to the other. Higher temperatures were usually located roughly 90° away from thermocouple junctions. Individual variations in calculated temperatures compared to thermocouple readings in the high temperature film boiling zone were 100 to 350 K apart. Variations noted for the lower temperature operating Rods UTA-0009 and UTA-0010 were somewhat smaller with less circumferential change. The large differences suggest that local cladding temperature suppression has occurred in the vicinity of the thermocouple junction by a possible cooling fin effect. Generally larger differences between temperatures calculated from layer

thickness and actual thermocouple readings were associated with recessed thermocouple junctions (0.69-m TC junctions, Rods UTA-0008 and UTA-0009). Thermocouple junctions laser welded to the surface of the cladding gave better agreement between calculated temperature and actual readings of the thermocouples at those locations. The discrepancy found for recessed junctions may possibly be due to a local disruption in the coolant flow associated with the cladding surface channel of the thermocouple recessing groove.

Fuel rod operation undergoing temperature conditions associated with film boiling, produced severe damage by external metal-water reaction and by internal reaction of the UO_2 fuel with the cladding. Investigation of the internal UO_2 -Zr reaction layer development was carried out using electron microprobe analysis. The reaction layer at the fuel-cladding interface was demonstrated by microprobe analysis to consist of two principal layers in agreement with previous work^[10,12]. The layer adjacent to the cladding was demonstrated to be low in Zr, but to contain a significant quantity of U, together with a measurable quantity of Sn (designated a U-rich, U-Zr-Sn alloy). The layer adjacent to the fuel at the interface was demonstrated to be low in U and Sn, but contained a large quantity of Zr (designated a Zr-rich, U-Zr alloy).

Two anomolous regions associated with the duplex reaction layer were studied. First a collapse-tip region where cladding had collapsed into the interfacial gap between fuel pellets and the associated material deposition was investigated. The periphery of the deposit at the collapse-tip closely resembled the composition of the UO_2 -Zr duplex reaction layer found at the UO_2 cladding interface. The material in the central portion of the deposit at the collapse-tip contained quantities of Fe and Ni with U, but no measurable amount of Zr or Sn (see Figure 62 (B) and (C)). The presence of such large amounts of Fe and Ni is not readily explainable on the basis of the cladding zircaloy composition and probably is related to either the presence of a near-by (undetected) metallic inclusion or possibly the brazing attachment of an adjacent thermocouple extension tube to the cladding.

The second anomolous region studied was along a fuel crack near the periphery of a fuel pellet where material deposition had occurred. Electron microprobe analysis of several locations along the deposit indicates a possible connection with UO_2 -Zr duplex reaction layer development at the fuel-cladding interface (see Figures 63 and 64). Probe traces for scans near the fuel-cladding interface show a U-Zr-Sn composition related to the UO_2 -Zr duplex reaction layer, with the Sn closely following the Zr concentrations. Farther out into the fuel, the second phase deposition material becomes U-Zr in composition, richer in U, but without measurable quantities of the other elements studied (Fe, Ni, or Sn).

Autoradiography of the regions discussed above indicated that no apparent segregation of fissile material is present. Additional features of these phenomena will be investigated.

Localized or general annealing, characterized by recovery of the stress-relieved cladding material and recrystallization lead to a loss in the cladding strength. Oxygen diffusion into the cladding as a result of the external metal-water reaction or from contact with the fuel becomes significant at higher cladding temperatures. Oxygen uptake strengthens the cladding but greatly decreases the ductility.

Embrittlement of the inside surface of the cladding occurred from reaction between the UO_2 fuel and the zircaloy cladding and on the outside surface from the H_2O zircaloy reaction. Visual evidence of such embrittlement is seen in macrographs showing fracture 20 to 30- μm into the OD and ID layers of oxygen-stabilized alpha-Zr (see Figures 25, 26, 28, 30, 35, 49, and 50).

Pawel has investigated criteria to establish failure thresholds based on the extent of cladding oxidation and subsequent embrittlement^[16]. Hobbins, et al, have shown that Pawel's embrittlement criteria may be applied to the PCM tests to predict fuel rod failure where oxygen embrittlement has occurred by a UO_2 -Zr reaction at the cladding-fuel interface, and by a H_2O -Zr reaction on the cladding exterior^[17].

Table X summarizes the results of the critical oxidation time calculations for the various PCM tests using the embrittlement criteria of Pawel. A correction factor determined by the relative wall thicknesses, the ratio $(0.610/0.686)^2$, has been applied to the critical time for each fuel rod to account for a thinner cladding wall used in the PCM tests. It is seen from Table X, that the exposure times in the film boiling regime for the fuel rods of the PCM-2 test are well below the critical exposure times for failure by embrittlement of the cladding. This result is in agreement with the post-irradiation examination results which showed that the fuel rods had not failed prior to disassembly of the test cluster, nor during subsequent remote handling.

TABLE X

COMPARISON OF MAXIMUM CLADDING EXPOSURE CONDITIONS WITH THE
CRITICAL OXIDATION TIME FOR EMBRITTLEMENT

Test	Maximum Cladding Temperature (K)	Time in Film Boiling (s)	Critical Oxidation Time (Corrected) (s)	Failure During or Following Test
8-1 RS	1540	660	35	Yes
CHF Scoping	1380	40	470	No
8-1 RF	1244	00	>800	No
PCM-2A	1400	210	420	No
PCM-2				
UTA-0008	1467	105	277	No
UTA-0009	978	52	>800	No
UTA-0010	950	50	>800	No
A-0014	1347	72	>800	NO

4. CONCLUSIONS

The posttest condition of the four PCM-2 fuel rods tested (UTA-0008, UTA-0009, UTA-0010, and A-0014) was established by visual and destructive examination. The structural integrity of the cladding of the fuel rods was found to be variously affected during stabilized post DNB (film boiling) operation. Evidence of structural damage was demonstrated by fuel rod bowing, cladding collapse onto the fuel and into fuel pellet interfaces, the degree of surface oxidation, and oxide spalling within the high temperature film boiling region of the separate fuel rods. None of the four rods tested failed during reactor operation or following reactor shutdown. Fuel pellet fracturing, and some apparent relocation of the fuel column was observed in the posttest neutron radiography of Rod A-0014.

Metallographic samples sectioned from each fuel rod and examined for cladding microstructure indicated that two of the four fuel rods, UTA-0009 and UTA-0010, effectively operated in the 810 to 1115 K temperature range (below the α to $\alpha + \beta$ transformation temperature) sought during the tests. The other two rods of the test cluster, UTA-0008 and A-0014, experienced cladding temperatures above the $\alpha + \beta$ to β transformation temperature range, 1245 K and above, with maximum temperatures up to 1467 and 1347 K, respectively.

Application of the test results to embrittlement criteria correctly indicated that the PCM-2 fuel rods operated within the critical oxidation limit for failure.

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APPENDIX A

PRETEST FUEL ROD CHARACTERIZATION

APPENDIX A

PRETEST FUEL ROD CHARACTERIZATION

Pretest measurements were made to characterize three of the four PCM-2 fuel rods. The design nominal physical characteristics of the fuel rod components are presented in this Appendix for model evaluation and verification.

The PCM-2 fuel rod component characterization data (nominal values) are presented in Table A-I.

The cladding ID and OD data are presented in Table A-II, III, and IV. The cladding ID was measured by air gaging (uncertainty $\pm 2.5 \text{ } \mu\text{m}$) at two angular orientations (0° and 90°) in 25.4-mm increments from the bottom of the 0.99-m long cladding tube. The average inside diameter was determined to be 9.50-mm. The OD was measured using a profilometer at two angular orientations (0° and 90°) for locations 25.4-mm., 0.31-m, 0.61-m, and 0.91-m from the bottom of cladding tube. The cladding outside-diameter was nominally 10.73-mm.

The physical characteristics (diameter, length, weight, density, and end-plane deviation) of the 60 PWR-type fuel pellets used for the PCM-2 fuel Rods UTA-0008, UTA-009, and UTA-0010 are presented in Tables A-V, VI and VII, respectively. The pellet length measurements were obtained by measuring the length between the upper and lower end dish, at the shoulder of each pellet. Both diametral and length measurements were performed with a Model BR-25, Bausch and Lomb optical gage to an assigned uncertainty of $\pm 0.005\text{-mm}$. Pellet mass data were obtained on analytical balance, measured to ± 1 milligram.

TABLE A-I

TEST PCM-2 FUEL ROD COMPONENT NOMINAL DESIGN DATA

Fuel

Ceramic grade, dished and sintered uranium dioxide pellets.

Enrichment (wt% U-235 of total U)	19.87 $\pm$ 0.03
Uranium content (wt% U)	88.1 $\pm$ 0.2
Density (mg/m ³)	10.2 $\pm$ 0.3
Pellet Diameter (mm)	9.30 $\pm$ 0.01
Pellet Length (mm)	15.5 $\pm$ 0.3
Dish Depth (mm)	0.33 (Nominal)
Total Impurities (ppm)	<364
O:U ratio	2.002 $\pm$ 0.002

Cladding

Zircaloy-4 alloy manufactured to ASTM Standard B 353-69, Grade RA-2, 50% cold worked and stress-relieved, nominal values.

Inside Diameter (mm)	9.5
Wall Thickness (mm)	0.61
Yield Strength (0.2% offset, MPa)	558
Tensile Strength (MPa)	744
Elongation (%)	18
Hardness (R _B)	96

End Cap Rod Stock

Zircaloy-2 alloy manufactured to ASTM Standard B 351-67, Grade RA-1, annealed, nominal values.

Yield Strength (0.2% offset, MPa)	341
Tensile Strength (MPa)	531
Elongation (%)	25
Hardness (BHN)	176

Compression Springs

Oil tempered chromium-vanadium alloy spring steel manufactured to ASTM Standard A 231-68, nominal values.

Wire diameter (mm)	1.04
Tensile strength (MPa)	2041
Spring outside diameter (mm)	9.02
Free length (mm)	60.3
Total number coils	17

Insulating End Spacers

Coors Porcelain Co., ceramic grade sintered alumina, nominal values.

Density (mg/m ³)	3.90
Compressive strength (MPa)	2496
Length (mm)	6.35
Diameter (mm)	9.27

TABLE A-II

TEST PCM-2 FUEL ROD CLADDING INSIDE AND OUTSIDE DIAMETER DATA
FOR UTA-0008

Distance from Bottom of Tube ^[a] (mm)	<u>Inside Diameter (mm)</u>		<u>Outside Diameter (mm)</u>	
	<u>0 degrees</u>	<u>90 degrees</u>	<u>0 degrees</u>	<u>90 degrees</u>
25.4	9.503	9.508	10.743	10.745
50.8	9.501	9.509		
76.2	9.501	9.508		
101.6	9.501	9.509		
127.0	9.502	9.507		
152.4	9.503	9.506		
177.8	9.503	9.506		
203.2	9.503	9.507		
228.6	9.505	9.506		
254.0	9.505	9.506		
279.4	9.504	9.507		
304.8	9.506	9.506	10.746	10.745
330.2	9.505	9.507		
355.6	9.505	9.505		
381.0	9.506	9.504		
406.4	9.505	9.506		
431.8	9.505	9.506		
457.2	9.505	9.505		
482.6	9.505	9.504		
508.0	9.504	9.507		
553.4	9.506	9.505		
558.8	9.508	9.503		
584.2	9.506	9.506		
699.6	9.504	9.506	10.747	10.746
635.0	9.502	9.509		
660.4	9.503	9.509		
685.8	9.504	9.508		
711.2	9.503	9.507		
736.6	9.504	9.505		
762.0	9.505	9.504		
787.4	9.505	9.505		
812.8	9.505	9.505		
838.2	9.507	9.502		
863.6	9.507	9.502		
889.0	9.506	9.503		
914.4	9.507	9.503	10.748	10.749

[a] The total tube length for Rod UTA-0008 was 990.6mm.

TABLE A-III

TEST PCM-2 FUEL ROD CLADDING INSIDE AND OUTSIDE DIAMETER DATA
FOR UTA-0009

Distance from Bottom of Tube ^[a] (mm)	Inside Diameter (mm)		Outside Diameter (mm)	
	0 degrees	90 degrees	0 degrees	90 degrees
25.4	9.508	9.512	10.737	10.743
50.8	9.511	9.508		
76.2	9.509	9.512		
101.6	9.507	9.510		
127.0	9.509	9.509		
152.4	9.506	9.511		
177.8	9.510	9.508		
203.2	9.508	9.510		
228.6	9.508	9.509		
254.0	9.508	9.507		
279.4	9.507	9.509		
304.8	9.507	9.508	10.742	10.734
330.2	9.509	9.509		
355.6	9.506	9.511		
381.0	9.508	9.510		
406.4	9.503	9.515		
431.8	9.504	9.511		
457.2	9.503	9.514		
482.6	9.501	9.516		
508.0	9.505	9.513		
533.4	9.508	9.513		
558.8	9.507	9.513		
584.2	9.510	9.509		
609.6	9.509	9.515	10.738	10.735
635.0	9.507	9.514		
660.4	9.511	9.513		
685.8	9.509	9.513		
711.2	9.514	9.511		
736.6	9.512	9.515		
762.0	9.512	9.513		
784.4	9.514	9.513		
812.8	9.515	9.501		
838.2	9.515	9.510		
863.6	9.517	9.512		
889.0	9.516	9.514		
914.4	9.519	9.512	10.738	10.735

[a] The total tube length for UTA-0009 was 990.6 mm.

TABLE A-IV

TEST PCM-2 FUEL ROD CLADDING INSIDE AND OUTSIDE DIAMETER DATA
FOR ROD UTA-0010

Distance from Bottom of Tube ^[a] (mm)	Inside Diameter (mm)		Outside Diameter (mm)	
	0 degrees	90 degrees	0 degrees	90 degrees
25.4	9.502	9.504	10.740	10.745
50.8	9.506	9.501		
76.2	9.506	9.505		
101.6	9.506	9.506		
127.0	9.506	9.505		
152.4	9.507	9.505		
177.8	9.506	9.508		
203.2	9.506	9.508		
228.6	9.507	9.507		
254.0	9.505	9.507		
279.4	9.504	9.506		
304.8	9.507	9.506	10.751	10.753
330.2	9.506	9.508		
355.6	9.505	9.506		
381.0	9.506	9.505		
406.4	9.506	9.506		
431.8	9.507	9.505		
457.2	9.507	9.504		
482.6	9.506	9.504		
508.0	9.507	9.503		
533.4	9.508	9.503		
558.8	9.506	9.505		
584.2	9.508	9.502		
609.6	9.510	9.502	10.752	10.751
635.0	9.508	9.503		
660.4	9.506	9.502		
685.8	9.504	9.504		
711.2	9.507	9.506		
736.6	9.508	9.508		
762.0	9.508	9.507		
787.4	9.507	9.506		
812.8	9.504	9.508		
838.2	9.505	9.507		
863.6	9.504	9.508		
889.0	9.502	9.508		
914.4	9.504	9.506	10.747	10.753

[a] The total tube length for Rod UTA-0010 was 987.45 mm.

TAB_E A-V

TEST PCM-2 FUEL ROD UTA-0008 FUEL PELLET PHYSICAL CHARACTERIZATION DATA

PELLET No. [a]	DIAMETER (cm)				LENGTH (cm)			WEIGHT (g)	GEOMETRIC DENSITY (g/cc)	IMMERSION ^[b] DENSITY (g/cc)	CENTERLINE DIAMETER TOP	HOLE (cm) BOTTOM
	TOP	CENTER	BOTTOM	AVERAGE	0°	90°	AVERAGE					
1	0.9294	0.9294	0.9294	0.9294	0.4669	0.4669	0.4716	3.182	10.3382	-----	0.0	0.0
2	0.9294	0.9294	0.9299	0.9296	1.5400	1.5385	1.5392	10.554	10.2193	-----	0.0	0.0
3	0.930	0.9299	0.9299	0.9300	1.5359	1.5337	1.5348	10.572	10.2566	-----	0.0	0.0
4	0.930	0.9304	0.9299	0.9301	1.5451	1.5413	1.5432	10.652	10.2734	-----	0.0	0.0
5	0.9294	0.9296	0.9296	0.9296	1.5448	1.5430	1.5439	10.580	10.2122	10.2470	0.0	0.0
6	0.9286	0.9291	0.9291	0.9290	1.5377	1.5418	1.5397	10.548	10.2229	-----	0.0	0.0
7	0.929	0.9291	0.9294	0.9292	1.5397	1.5367	1.5382	10.522	10.2026	-----	0.0	0.0
8	0.9299	0.9301	0.9299	0.9300	1.5372	1.5359	1.5366	10.517	10.1916	-----	0.0	0.0
9	0.9291	0.9299	0.9294	0.9295	1.5390	1.5436	1.5413	10.587	10.2593	-----	0.0	0.0
10	0.9299	0.9304	0.9301	0.9301	1.5410	1.5390	1.5400	10.562	10.2080	10.2604	0.0	0.0
11	0.9296	0.9299	0.9296	0.9297	1.5413	1.5375	1.5394	10.543	10.2036	-----	0.0	0.0
12	0.9296	0.9296	0.9294	0.9296	1.5408	1.5385	1.5396	10.557	10.2195	-----	0.0	0.0
13	0.9296	0.9299	0.9296	0.9297	1.5405	1.5446	1.5465	10.624	10.2541	-----	0.0	0.0
14	0.9299	0.9296	0.9299	0.9298	1.5858	1.5418	1.5438	10.589	10.2162	-----	0.0	0.0
15	0.9294	0.9294	0.9299	0.9296	1.5445	1.5413	1.5429	10.547	10.1973	10.2580	0.0	0.0
16	0.9295	0.9299	0.9299	0.9298	1.5413	1.5397	1.5405	10.563	10.2135	-----	0.0	0.0
17	0.9294	0.9296	0.9294	0.9295	1.5502	1.5481	1.5491	10.614	10.2121	-----	0.0	0.0
18	0.9295	0.9296	0.9294	0.9296	1.5453	1.5433	1.5446	10.600	10.2277	-----	0.0	0.0
19	0.9295	0.9294	0.9296	0.9296	1.5433	1.5395	1.5414	10.598	10.2468	-----	0.0	0.0
20	0.9294	0.9296	0.9299	0.9296	1.5433	1.5405	1.5419	10.589	10.2533	10.2684	0.0	0.0
21	0.9294	0.9296	0.9294	0.9295	1.5403	1.5370	1.5386	10.539	10.2102	-----	0.0	0.0
22	0.9295	0.9294	0.9296	0.9296	1.5436	1.5425	1.5430	10.613	10.2499	-----	0.0	0.0
23	0.9291	0.9294	0.9299	0.9295	1.5425	1.5413	1.5419	10.588	10.2555	-----	0.0	0.0
24	0.9295	0.9299	0.9294	0.9296	1.5462	1.5415	1.5438	10.587	10.2186	-----	0.0	0.0
25	0.9299	0.9296	0.9301	0.9299	1.5352	1.5370	1.5381	10.558	10.2233	10.2844	0.0	0.0
26	0.9294	0.9294	0.9299	0.9296	1.5352	1.5377	1.5385	10.564	10.2333	-----	0.0	0.0
27	0.9295	0.9299	0.9299	0.9298	1.5524	1.5499	1.5512	10.646	10.2222	-----	0.0	0.0
28	0.9294	0.9299	0.9301	0.9298	1.5471	1.5446	1.5458	10.620	10.2324	-----	0.0	0.0

TABLE A-V (continued)

PELLET No. [a]	DIAMETER (cm)				LENGTH (cm)			WEIGHT (g)	GEOMETRIC DENSITY (g/cc)	IMMERSION ^[b] DENSITY (g/cc)	CENTERLINE DIAMETER TOP	HOLE (cm) BOTTOM
	TOP	CENTER	BOTTOM	AVERAGE	0°	90°	AVERAGE					
29	0.9294	0.9294	0.9296	0.9294	1.5474	1.5461	1.5467	10.611	10.2271	-----	0.0	0.0
30	0.9294	0.9296	0.9299	0.9296	1.5441	1.5415	1.5428	10.589	10.2267	10.2838	0.0	0.0
31	0.9286	0.9284	0.9289	0.9286	1.5438	1.5400	1.5414	10.562	10.2331	-----	0.0	0.0
32	0.9294	0.9294	0.9299	0.9296	1.5405	1.5392	1.5399	10.579	10.2387	-----	0.0	0.0
33	0.9294	0.9296	0.9296	0.9296	1.5476	1.5448	1.5462	10.615	10.2307	-----	0.0	0.0
34	0.9294	0.9296	0.9299	0.9296	1.5403	1.5392	1.5397	10.573	10.2317	-----	0.0	0.0
35	0.9296	0.9294	0.9299	0.9296	1.5392	1.5362	1.5377	10.545	10.2188	10.2803	0.0	0.0
36	0.9296	0.9296	0.9299	0.9297	1.5469	1.5446	1.5457	10.621	10.2367	-----	0.0	0.0
37	0.9291	0.9296	0.9299	0.9296	1.5489	1.5469	1.5479	10.628	10.2329	-----	0.0	0.0
38	0.9291	0.9296	0.9296	0.9295	1.5405	1.5390	1.5397	10.573	10.2355	-----	0.0	0.0
39	0.9289	0.9294	0.9296	0.9293	1.5410	1.5392	1.5401	10.565	10.2296	-----	0.0	0.0
40	0.9294	0.9294	0.9294	0.9294	1.5448	1.5415	1.5432	10.593	10.2344	10.2670	0.0	0.0
41	0.9291	0.9294	0.9294	0.9293	1.5425	1.5410	1.5418	10.587	10.2396	-----	0.0	0.0
42	0.9284	0.9294	0.9296	0.9291	1.5395	1.5367	1.5381	10.548	10.2305	-----	0.0	0.0
43	0.9289	0.9291	0.9291	0.9290	1.5433	1.5392	1.5413	10.557	10.2196	-----	0.0	0.0
44	0.9296	0.9296	0.9294	0.9296	1.5436	1.5425	1.5430	10.582	10.2207	-----	0.0	0.0
45	0.9291	0.9294	0.9291	0.9292	1.5408	1.5392	1.5400	10.150	10.2297	10.2800	0.1778	0.1905
46	0.9294	0.9294	0.9294	0.9294	1.5395	1.5357	1.5376	10.123	10.2377	-----	0.1854	0.1930
47	0.9294	0.9296	0.9294	0.9295	1.5367	1.5349	1.5358	10.146	10.2305	-----	0.1778	0.1829
48	0.9296	0.9296	0.9296	0.9296	1.5352	1.5316	1.5334	10.103	10.2168	-----	0.1803	0.1880
49	0.9296	0.9296	0.9296	0.9296	1.5370	1.5319	1.5344	10.118	10.2309	-----	0.1803	0.1905
50	0.9291	0.9291	0.9291	0.9291	1.5380	1.5359	1.5370	10.091	10.1975	10.2465	0.1829	0.1880
51	0.9299	0.9296	0.9299	0.9298	1.5362	1.5334	1.5348	10.130	10.2420	-----	0.1829	0.1905
52	0.9301	0.9296	0.9296	0.9298	1.5405	1.5380	1.5392	10.144	10.2379	-----	0.1854	0.1930
53	0.9304	0.9299	0.9301	0.9301	1.5430	1.5408	1.5419	10.180	10.2542	-----	0.1930	0.1880
54	0.9296	0.9299	0.9296	0.9297	1.5400	1.5382	1.5391	10.127	10.2233	-----	0.1930	0.1854
55	0.9294	0.9291	0.9294	0.9293	1.5418	1.5413	1.5415	10.130	10.2256	10.2694	0.1930	0.1880
56	0.9299	0.9301	0.9301	0.9301	1.5321	1.5298	1.5310	10.088	10.2369	-----	0.1880	0.1930
57	0.9294	0.9294	0.9294	0.9294	1.5420	1.5403	1.5411	10.132	10.1824	-----	0.1753	0.1854

TABLE A-V (continued)

PELLET No. [a]	DIAMETER (cm)				LENGTH (cm)			WEIGHT (g)	GEOMETRIC DENSITY (g/cc)	IMMERSION ^[b] DENSITY (g/cc)	CENTERLINE DIAMETER TOP	HOLE (cm) BOTTOM
	TOP	CENTER	BOTTOM	AVERAGE	0°	90°	AVERAGE					
58	0.9291	0.9296	0.9294	0.9294	1.5367	1.5334	1.5350	10.096	10.1981	-----	0.1854	0.177
59	0.9291	0.9291	0.9296	0.9293	1.5344	1.5326	1.5335	10.103	10.2128	-----	0.1854	0.177
60	0.9294	0.9296	0.9296	0.9295	1.5377	1.5354	1.5366	10.141	10.2304	10.2619	0.1803	0.185

[a] Pellets numbered from bottom to top of fuel stack.

[b] Immersion in water

TABLE A-VI

TEST PCM-2 FUEL ROD UTA-0009 FUEL PELLETS PHYSICAL CHARACTERIZATION DATA

PELLET No. [a]	DIAMETER (cm)				LENGTH (cm)			WEIGHT (g)	GEOMETRIC DENSITY (g/cc)	IMMERSION ^[b] DENSITY (g/cc)	CENTERLINE DIAMETER TOP	HOLE (cm) BOTTOM
	TOP	CENTER	BOTTOM	AVERAGE	0°	90°	AVERAGE					
1	0.9299	0.9299	0.9299	0.9299	0.6111	0.5939	0.6025	4.061	10.2189	-----	0.0	0.0
2	0.9296	0.9299	0.9299	0.9298	1.5425	1.5387	1.5406	10.556	10.2070	-----	0.0	0.0
3	0.9299	0.9296	0.9299	0.9298	1.5420	1.5403	1.5411	10.576	10.2219	-----	0.0	0.0
4	0.9296	0.9301	0.9299	0.9299	1.5382	1.5342	1.5362	10.533	10.2115	-----	0.0	0.0
5	0.9299	0.9304	0.9296	0.9300	1.5405	1.5392	1.5399	10.546	10.1975	10.2750	0.0	0.0
6	0.9296	0.9296	0.9299	0.9297	1.5476	1.5458	1.5467	10.595	10.2909	-----	0.0	0.0
7	0.9294	0.9296	0.9299	0.9296	1.5425	1.5405	1.5415	10.568	10.2148	-----	0.0	0.0
8	0.9299	0.9296	0.9299	0.9298	1.5448	1.5428	1.5438	10.586	10.2136	-----	0.0	0.0
9	0.9291	0.9294	0.9299	0.9295	1.5433	1.5390	1.5411	10.556	10.2095	-----	0.0	0.0
10	0.9296	0.9299	0.9296	0.9297	1.5370	1.5352	1.5361	10.521	10.2046	10.2758	0.0	0.0
11	0.9301	0.9299	0.9394	0.9301	1.5395	1.5367	1.5381	10.545	10.2090	-----	0.0	0.0
12	0.9299	0.9201	0.9299	0.9300	1.5400	1.5357	1.5378	10.523	10.1890	-----	0.0	0.0
13	0.9294	0.9299	0.9301	0.9298	1.5448	1.5433	1.5441	10.570	10.1965	-----	0.0	0.0
14	0.9294	0.9301	0.9304	0.9300	1.5443	1.5415	1.5429	10.586	10.2156	-----	0.0	0.0
15	0.9296	0.9296	0.9299	0.9297	1.5451	1.5425	1.5438	10.587	10.2160	10.2774	0.0	0.0
16	0.9301	0.9304	0.9304	0.9303	1.5428	1.5405	1.5417	10.589	10.2197	-----	0.0	0.0
17	0.9307	0.9301	0.9304	0.9304	1.5423	1.5403	1.5413	10.627	10.2567	-----	0.0	0.0
18	0.9301	0.9304	0.9301	0.9302	1.5441	1.5403	1.5422	10.641	10.2681	-----	0.0	0.0
19	0.9301	0.9301	0.9291	0.9298	1.5413	1.5380	1.5396	10.591	10.2469	-----	0.0	0.0
20	0.9296	0.9301	0.9307	0.9301	1.5375	1.5367	1.5371	10.591	10.2562	10.3452	0.0	0.0
21	0.9307	0.9309	0.9309	0.9308	1.5380	1.5364	1.5372	10.632	10.2800	-----	0.0	0.0
22	0.9304	0.9301	0.9304	0.9303	1.5283	1.5255	1.5269	10.509	10.2417	-----	0.0	0.0
23	0.9304	0.9304	0.9307	0.9305	1.5418	1.5408	1.5413	10.603	10.2314	-----	0.0	0.0
24	0.9296	0.9299	0.9301	0.9299	1.5385	1.5364	1.5375	10.591	10.2596	-----	0.0	0.0
25	0.9307	0.9307	0.9301	0.9305	1.5342	1.5309	1.5325	10.575	10.2637	10.3404	0.0	0.0
26	0.9301	0.9301	0.9299	0.9301	1.5387	1.5370	1.5378	10.612	10.2730	-----	0.0	0.0
27	0.9301	0.9304	0.9304	0.9303	1.5489	1.5474	1.5481	10.667	10.2510	-----	0.0	0.0

TABLE A-VI (continued)

PELLET No. [a]	DIAMETER (cm)				LENGTH (cm)			WEIGHT (g)	GEOMETRIC DENSITY (g/cc)	IMMERSION ^[b] DENSITY (g/cc)	CENTERLINE DIAMETER TOP	HOLE (cm) BOTTOM
	TOP	CENTER	BOTTOM	AVERAGE	0°	90°	AVERAGE					
28	0.9296	0.9289	0.9251	0.9279	1.5390	1.5354	1.5372	10.519	10.2366	-----	0.0	0.0
29	0.9301	0.9299	0.9296	0.9299	1.5375	1.5339	1.5357	10.580	10.2610	-----	0.0	0.0
30	0.9301	0.9304	0.9301	0.9302	1.5403	1.5387	1.5395	10.641	10.2867	10.3526	0.0	0.0
31	0.9301	0.9301	0.9291	0.9298	1.5377	1.5367	1.5372	10.581	10.2533	-----	0.0	0.0
32	0.9304	0.9306	0.9304	0.9305	1.5329	1.5306	1.5317	10.714	10.4040	-----	0.0	0.0
33	0.9301	0.9304	0.9299	0.9301	1.5372	1.5354	1.5363	10.598	10.2679	-----	0.0	0.0
34	0.9291	0.9301	0.9301	0.9298	1.5347	1.5321	1.5334	10.535	10.2345	-----	0.0	0.0
35	0.9296	0.9299	0.9294	0.9296	1.5425	1.5395	1.5410	10.608	10.2577	10.3290	0.0	0.0
36	0.9301	0.9301	0.9301	0.9301	1.5306	1.5283	1.5295	10.528	10.2468	-----	0.0	0.0
37	0.9304	0.9309	0.9309	0.9307	1.5362	1.5342	1.5352	10.605	10.2696	-----	0.0	0.0
38	0.9299	0.9307	0.9307	0.9304	1.5309	1.5288	1.5298	10.569	10.2730	-----	0.0	0.0
39	0.9304	0.9296	0.9296	0.9299	1.5364	1.5342	1.5353	10.570	10.2538	-----	0.0	0.0
40	0.9299	0.9304	0.9301	0.9301	1.5392	1.5372	1.5382	10.582	10.2396	10.3014	0.0	0.0
41	0.9304	0.9307	0.9301	0.9304	1.5469	1.5441	1.5455	10.643	10.2439	-----	0.0	0.0
42	0.9304	0.9306	0.9304	0.9305	1.5415	1.5372	1.5394	10.577	10.2191	-----	0.0	0.0
43	0.9307	0.9299	0.9299	0.9301	1.5372	1.5354	1.5363	10.562	10.2335	-----	0.0	0.0
44	0.9307	0.9309	0.9304	0.9307	1.5428	1.5392	1.5410	10.595	10.2224	-----	0.0	0.0
45	0.9256	0.9274	0.9296	0.9275	1.5364	1.5342	1.5353	10.050	10.1929	10.2731	0.1829	0.1829
46	0.9296	0.9299	0.9299	0.9298	1.5420	1.5392	1.5406	10.133	10.1996	-----	0.1905	0.1803
47	0.9294	0.9289	0.9291	0.9291	1.5377	1.5357	1.5357	10.129	10.2617	-----	0.1930	0.1880
48	0.9299	0.9301	0.9296	0.9299	1.5420	1.5390	1.5405	10.142	10.2020	-----	0.1880	0.1803
49	0.9291	0.9296	0.9299	0.9296	1.5456	1.5425	1.5441	10.163	10.2213	-----	0.1854	0.1905
50	0.9291	0.9294	0.9294	0.9293	1.5408	1.5375	1.5391	10.138	10.2212	10.0734	0.1905	0.1778
51	0.9299	0.9296	0.9299	0.9298	1.5423	1.5405	1.5414	10.171	10.2276	-----	0.1778	0.1905
52	0.9291	0.9294	0.9294	0.9293	1.5397	1.5372	1.5385	10.117	10.2330	-----	0.1880	0.1930
53	0.9299	0.9299	0.9296	0.9298	1.5410	1.5397	1.5404	10.150	10.2074	-----	0.1778	0.1880
54	0.9301	0.9301	0.9304	0.9302	1.5377	1.5344	1.5361	10.106	10.2053	-----	0.1930	0.1829
55	0.9294	0.9294	0.9296	0.9295	1.5375	1.5357	1.5366	10.113	10.2204	10.3038	0.1829	0.1905
56	0.9299	0.9301	0.9294	0.9298	1.5408	1.5382	1.5395	10.142	10.2170	-----	0.1803	0.1905
57	0.9289	0.9286	0.9291	0.9289	1.5392	1.5357	1.5375	10.118	10.2453	-----	0.1930	0.1854

TABLE A-VI (continued)

PELLET No. [a]	DIAMETER (cm)				LENGTH (cm)			WEIGHT (g)	GEOMETRIC DENSITY (g/cc)	IMMERSION ^[b] DENSITY (g/cc)	CENTERLINE DIAMETER TOP	HOLE (cm) BOTTOM
	TOP	CENTER	BOTTOM	AVERAGE	0°	90°	AVERAGE					
53	0.9289	0.9286	0.9284	0.9286	1.5410	1.5385	1.5397	10.120	10.2256	-----	0.1829	0.1905
59	0.9296	0.9296	0.9299	0.9297	1.5410	1.5380	1.5395	10.173	10.2442	-----	0.1880	0.1803
60	0.9291	0.9291	0.9294	0.9292	1.5438	1.5400	1.5419	10.142	10.2379	10.2720	0.1930	0.1880

[a] Pellets numbered from bottom to top of fuel stack.

[b] Immersion in water.

TABLE A-VII

TEST PCM-2 FUEL ROD UTA-001C FUEL PELLET PHYSICAL CHARACTERIZATION DATA

PELLET No. [a]	DIAMETER (cm)				LENGTH (cm)			WEIGHT (g)	GEOMETRIC DENSITY (g/cc)	IMMERSION ^[b] DENSITY (g/cc)	CENTERLINE DIAMETER TOP	HOLE (cm) BOTTOM
	TOP	CENTER	BOTTOM	AVERAGE	0°	90°	AVERAGE					
1	0.9307	0.9301	0.9301	0.9301	0.4633	0.4735	0.4684	3.203	10.45C4	-----	0.0	0.0
2	0.9289	0.9291	0.9289	0.9290	1.5428	1.5438	1.5433	10.620	10.2EE6	10.3140	0.0	0.0
3	0.9297	0.9294	0.9291	0.9292	1.5512	1.5532	1.5522	10.710	10.2E96	-----	0.0	0.0
4	0.9304	0.9307	0.9307	0.9306	1.5372	1.5400	1.5386	10.584	10.2E96	-----	0.0	0.0
5	0.9296	0.9296	0.9294	0.9296	1.5370	1.5403	1.5386	10.600	10.2E72	-----	0.0	0.0
6	0.9294	0.9296	0.9294	0.9295	1.5367	1.5390	1.5378	10.535	10.2118	-----	0.0	0.0
7	0.9281	0.9284	0.9284	0.9283	1.5270	1.5309	1.5290	10.480	10.2443	10.2708	0.0	0.0
8	0.9299	0.9299	0.9299	0.9299	1.5497	1.5524	1.5511	10.702	10.27E3	-----	0.0	0.0
9	0.9291	0.9289	0.9286	0.9289	1.5451	1.5489	1.5470	10.643	10.2E76	-----	0.0	0.0
10	0.9291	0.9294	0.9294	0.9293	1.5352	1.5370	1.5361	10.532	10.2249	-----	0.0	0.0
11	0.9294	0.9294	0.9294	0.9294	1.5474	1.5497	1.5485	10.581	10.1E72	-----	0.0	0.0
12	0.9299	0.9294	0.9289	0.9294	1.5461	1.5494	1.5477	10.666	10.2743	10.3202	0.0	0.0
13	0.9284	0.9289	0.9291	0.9288	1.5481	1.5499	1.5490	10.582	10.1E79	-----	0.0	0.0
14	0.9299	0.9301	0.9299	0.9300	1.5395	1.5410	1.5403	10.599	10.2E99	-----	0.0	0.0
15	0.9294	0.9291	0.9291	0.9292	1.5319	1.5588	1.5453	10.666	10.2E94	-----	0.0	0.0
16	0.9281	0.9284	0.9284	0.9283	1.5349	1.5382	1.5366	10.562	10.27E1	-----	0.0	0.0
17	0.9295	0.9299	0.9296	0.9297	1.5370	1.5405	1.5387	10.550	10.2146	10.2991	0.0	0.0
18	0.9295	0.9299	0.9296	0.9297	1.5415	1.5423	1.5419	10.540	10.1E41	-----	0.0	0.0
19	0.9293	0.9294	0.9299	0.9297	1.5405	1.5418	1.5411	10.677	10.3E14	-----	0.0	0.0
20	0.9294	0.9296	0.9294	0.9295	1.5464	1.5474	1.5469	10.577	10.1E17	-----	0.0	0.0
21	0.9301	0.9299	0.9299	0.9300	1.5344	1.5364	1.5354	10.574	10.2E48	-----	0.0	0.0
22	0.9293	0.9301	0.9299	0.9300	1.5319	1.5339	1.5329	10.536	10.2E46	10.2904	0.0	0.0
23	0.9291	0.9296	0.9296	0.9295	1.5456	1.5474	1.5465	10.594	10.21C5	-----	0.0	0.0
24	0.9294	0.9296	0.9299	0.9296	1.5453	1.5474	1.5464	10.595	10.20E9	-----	0.0	0.0
25	0.9294	0.9296	0.9299	0.9296	1.5484	1.5499	1.5491	10.625	10.21E5	-----	0.0	0.0
26	0.9291	0.9296	0.9299	0.9296	1.5403	1.5418	1.5410	10.563	10.21E8	-----	0.0	0.0
27	0.9293	0.9296	0.9299	0.9298	1.5451	1.5469	1.5460	10.606	10.21E0	-----	0.0	0.0

TABLE A-VII (continued)

TEST PCM-2 FUEL ROD UTA-0010 FUEL PELLETT PHYSICAL CHARACTERIZATION DATA

PELLET No. [a]	DIAMETER (cm)				LENGTH (cm)			WEIGHT (g)	GEOMETRIC DENSITY (g/cc)	IMMERSION ^[b] DENSITY (g/cc)	CENTERLINE DIAMETER TOP	HOLE (cm) BOTTOM
	TOP	CENTER	BOTTOM	AVERAGE	0°	90°	AVERAGE					
28	0.9294	0.9296	0.9299	0.9296	1.5453	1.5481	1.5467	10.609	10.2199	-----	0.0	0.0
29	0.9296	0.9299	0.9299	0.9298	1.5464	1.5479	1.5471	10.514	10.1223	-----	0.0	0.0
30	0.9294	0.9299	0.9301	0.9298	1.5370	1.5377	1.5373	10.536	10.2087	9.9520	0.0	0.0
31	0.9299	0.9301	0.9301	0.9301	1.5453	1.5474	1.5464	10.610	10.2139	-----	0.0	0.0
32	0.9299	0.9301	0.9299	0.9300	1.5425	1.5451	1.5438	10.588	10.2117	-----	0.0	0.0
33	0.9296	0.9299	0.9296	0.9297	1.5377	1.5415	1.5396	10.536	10.1952	-----	0.0	0.0
34	0.9291	0.9294	0.9294	0.9293	1.5415	1.5441	1.5428	10.576	10.2221	-----	0.0	0.0
35	0.9296	0.9301	0.9299	0.9299	1.5418	1.5453	1.5436	10.210	10.2562	10.3432	0.1854	0.1854
36	0.9294	0.9299	0.9301	0.9298	1.5397	1.5441	1.5419	10.175	10.2339	-----	0.1854	0.1854
37	0.9294	0.9299	0.9296	0.9296	1.5347	1.5382	1.5364	10.137	10.2416	-----	0.1854	0.1880
38	0.9294	0.9299	0.9299	0.9297	1.5359	1.5382	1.5371	10.174	10.2556	-----	0.1829	0.1829
39	0.9301	0.9301	0.9296	0.9300	1.5438	1.5466	1.5452	10.204	10.2193	-----	0.1829	0.1803
40	0.9291	0.9296	0.9299	0.9296	1.5342	1.5372	1.5357	10.127	10.2160	-----	0.1829	0.1803
41	0.9296	0.9296	0.9296	0.9296	1.5466	1.5489	1.5477	10.206	10.2241	-----	0.1854	0.1829
42	0.9294	0.9291	0.9291	0.9292	1.5385	1.5408	1.5396	10.143	10.2307	-----	0.1854	0.1854
43	0.9301	0.9299	0.9299	0.9300	1.5428	1.5453	1.5441	10.190	10.2307	-----	0.1854	0.1854
44	0.9296	0.9294	0.9296	9.9296	1.5377	1.5425	1.5401	10.172	10.2487	-----	0.1854	0.1854
45	0.9296	0.9299	0.9301	0.9299	1.5420	1.5456	1.5438	10.187	10.2197	10.2606	0.1829	0.1829
46	0.9294	0.9296	0.299	0.9296	1.5349	1.5382	1.5366	10.134	10.2319	-----	0.1854	0.1854
47	0.9279	0.9291	0.9296	0.9289	1.5273	1.5362	1.5317	10.071	10.2132	-----	0.1854	0.1829
48	0.9299	0.9299	0.9299	0.9299	1.5354	1.5380	1.5367	10.141	10.2206	-----	0.1829	0.1829
49	0.9294	0.9296	0.9296	0.9296	1.5367	1.5387	1.5377	10.115	10.1955	-----	0.1829	0.1829
50	0.9296	0.9296	0.9296	0.9296	1.5349	1.5375	1.5362	10.129	10.2235	-----	0.1854	0.1829
51	0.9299	0.9299	0.9291	0.9296	1.5382	1.5403	1.5392	10.171	10.2403	-----	0.1829	0.1829
52	0.9294	0.9296	0.9296	0.9296	1.5314	1.5347	1.5330	10.093	10.2053	-----	0.1829	0.1829
53	0.9289	0.9294	0.9296	0.9293	1.5425	1.5461	1.5443	10.195	10.2381	-----	0.1829	0.1829
54	0.9289	0.9291	0.9291	0.9290	1.5372	1.5372	1.5395	10.086	10.2026	-----	0.1905	0.1880
55	0.9296	0.9294	0.9295	0.9295	1.5428	1.5436	1.5432	10.173	10.2023	-----	0.1829	1.1753
56	0.9296	0.9296	0.9294	0.9296	1.5357	1.5375	1.5366	10.116	10.2334	-----	0.1905	0.1880
57	0.9291	0.9289	0.9291	0.9290	1.5281	1.5306	1.5293	10.077	10.2425	-----	0.1854	0.1880

TABLE A-VII (continued)

TEST PCM-2 FUEL ROD UTA-C010 FUEL PELLET PHYSICAL CHARACTERIZATION DATA

PELLET No. [a]	DIAMETER (cm)				LENGTH (cm)			WEIGHT (g)	GEOMETRIC DENSITY (g/cc)	IMMERSION ^[b] DENSITY (g/cc)	CENTERLINE DIAMETER TOP	HOLE (cm) BOTTOM
	TOP	CENTER	BOTTOM	AVERAGE	0°	90°	AVERAGE					
58	0.9299	0.9299	0.9299	0.9299	1.5415	1.5433	1.5424	10.159	10.2420	-----	0.1930	0.1905
59	0.9296	0.9299	0.9296	0.9297	1.5359	1.5405	1.5382	10.165	10.2618	-----	0.1854	0.1905
60	0.9296	0.9299	0.9296	0.9297	1.5428	1.5451	1.5439	10.178	10.2196	10.3002	0.1829	0.1854

[a] Fuel pellets numbered from bottom to top of fuel stack.

[b] Immersion in water

APPENDIX B

PCM-2 FUEL ROD POSTTEST DIAMETRAL CHARACTERIZATION

APPENDIX B

PCM-2 FUEL ROD POSTTEST DIAMETRAL CHARACTERIZATION

To characterize the region of cladding collapse along each of the PCM-2 Rods UTA-0008, UTA-0009, UTA-0010, and A-0014, detailed posttest cladding outside diameter measurements were made along the fuel rods at two angular orientations (45° and 135°). These measurements are presented in Tables B-I for UTA-0008, B-II for UTA-0009, B-III for UTA-0010, and B-IV for Rod A-0014. The measurements are adjusted to reference with the bottom of the fuel stack which is located 0.035-m from the bottom of the fuel rod end-cap.

TABLE B-I

PCM-2

POSTTEST DIAMETRAL MEASUREMENTS - ROD UTA-0008

Location From Bottom of Fuel Stack	Orientation ^[a]	
	45°	135°
Metres	(mm)	(mm)
0.029	10.72	10.71
0.080	10.72	10.73
0.130	10.72	10.71
0.181	10.72	10.72
0.232	10.72	10.73
0.283	10.73	10.71
0.334	10.76	10.74
0.384	10.73	10.70
0.410	10.72	10.69
0.435	10.71	10.63
0.461	10.70	10.64
0.486	10.67	10.61
0.511	10.65	10.62
0.537	10.56	10.61
0.562	10.57	10.62
0.588	10.62	10.55
0.613		10.57
0.638	10.62	10.58
0.664	10.62	10.59
0.689	10.69	10.65
0.715		10.59
0.740	10.68	10.60
0.765		10.62
0.791	10.66	10.61
0.816		10.71
0.842	10.71	10.73
0.892	10.74	10.71
0.943	10.73	10.73
0.969	10.73	10.69

[a] Measurements were made using 0-1 inch (0-25.40-mm) micrometer with an estimated accuracy of ± 0.001 inches (± 0.03 -mm).

TABLE B-II

PCM-2

POTTEST DIAMETRAL MEASUREMENTS - ROD S/N UTA-0009

Location From Bottom of Fuel Stack	Orientation ^[a]	
	45°	135°
Metres	(mm)	(mm)
0.029	10.71	10.72
0.080	10.70	10.73
0.130	10.71	10.73
0.181	10.72	10.72
0.232	10.72	10.72
0.283	10.72	10.72
0.334	10.72	10.72
0.384	10.71	10.72
0.410	10.72	10.72
0.435	10.72	10.71
0.461		10.71
0.486	10.72	10.72
0.537	10.73	10.72
0.588	10.73	10.71
0.613	10.76	10.72
0.638	10.76	10.72
0.664	10.69	10.71
0.689	10.70	10.71
0.715	10.65	10.61
0.740	10.66	10.62
0.765	10.63	10.62
0.791	10.63	10.63
0.816	10.68	
0.842	10.70	10.70
0.892	10.70	10.70
0.943	10.73	10.72
0.969	10.73	10.74

[a] Measurements were made using a 0. inch (0-25.40-mm) micrometer with an estimated accuracy of ± 0.001 inches (± 0.03 -mm).

TABLE B-III

PCM-2

POTTEST DIAMETRAL MEASUREMENTS - RODS S/N UTA-0010

Location From Bottom of Fuel Stack	Orientation ^[a]	
	45° (mm)	135° (mm)
0.029	10.67	10.66
0.080	10.67	10.64
0.130	10.65	10.67
0.181	10.64	10.66
0.232	10.66	10.67
0.283	10.67	10.68
0.334	10.67	10.65
0.384	10.67	10.67
0.435	10.66	10.67
0.486	10.68	10.68
0.537	10.67	10.66
0.588	10.68	10.68
0.638	10.67	10.66
0.689	10.67	10.67
0.740	10.66	10.61
0.765	10.62	10.58
0.791	10.62	10.67
0.816	10.67	10.67
0.842	10.67	10.67
0.892	10.68	10.68

^[a] Measurements were made using a 0.1 inch (0-25.40-mm) micrometer with an estimated accuracy of ± 0.001 inches (± 0.03 -mm).

TABLE B-IV

PCM-2

POTTEST DIAMETRAL MEASUREMENTS - ROD S/N A-0014

Location From Bottom of Fuel Stack	Orientation ^[a]	
	45° (mm)	135° (mm)
0.029	10.72	10.74
0.080	10.73	10.76
0.130	10.72	10.74
0.181	10.72	10.72
0.232	10.72	10.72
0.283	10.72	10.73
0.308	10.72	10.73
0.334	10.72	10.72
0.359	10.72	10.72
0.384	10.74	10.72
0.410	10.73	10.72
0.435	10.73	10.74
0.486	10.73	10.72
0.537	10.73	10.72
0.562	10.70	10.72
0.588	10.67	10.67
0.613	10.62	10.67
0.638	10.64	10.65
0.664	10.65	10.64
0.689	10.67	10.67
0.715	10.67	10.72
0.740	10.69	10.72
0.765	10.65	10.73
0.791	10.70	10.71
0.816	10.71	
0.842	10.70	10.73
0.892	10.74	10.72
0.943	10.73	10.73
0.968	10.73	10.72

[a] Measurements were made using a 0-1 inch (0-25.40-mm) micrometer with an estimated accuracy of ± 0.001 inches (± 0.03 -mm).

APPENDIX C

GROSS GAMMA SCANS

APPENDIX C

GROSS GAMMA SCANS

The PCM-2 fuel Rod A-0014 was gamma scanned horizontally in the zero and 180 degree orientations to document the relative level of gamma-ray activity as a function of distance along the fuel stack. The scan was 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 (0.051×1.270 -mm) and the output of the NaI detector was recorded on the strip chart recorder as the fuel rod was driven past the collimator slit 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 ^{137}Cs source was monitored before and following the gamma scan to determine if any electronic drift in the initial and final data recording occurred during the scan.

The top and bottom of the fuel stack were identified by step-scanning past the detector-collimator. A rapid change in the gamma-ray intensity occurs at the end of the fuel stack. The fuel stack measured in this manner is 0.916 ± 0.005 -m compared to the 0.914 ± 0.003 -m measured during the fuel rod fabrication. Within the uncertainties of these measurements, no significant change in the fuel stack length is noted between the pre- and posttest values.

The results of the relative gamma activity (peak-to-average ratio) are given in Tables C-I for the zero degree orientation scan, and C-II for the 180° scan. The integrated areas of the scanned curves are $5.44 \times 10^{-2} \text{ m}^2$ and $5.25 \times 10^{-2} \text{ m}^2$ for the 0 and 180° scans, respectively. The respective average activities were 2.344, and 2.260 (arbitrary units).

TABLE C-I
GROSS GAMMA SCAN FOR TEST PCM-2 FUEL ROD A-0014
(0° Orientation)

Distance from bottom of fuel stack (Metres)	Peak Height (Arbitrary) Units	Normalized Peak height Activity (Peak)/Activity (Average) ^[a]
0.003	1.190	0.5077
0.0254	1.320	0.5632
0.0508	1.550	0.6613
0.0762	1.820	0.7766
0.1016	1.910	0.8150
0.1270	2.230	0.9515
0.1524	2.330	0.9942
0.1778	2.490	1.0624
0.2032	2.700	1.1520
0.2286	2.950	1.2587
0.2540	3.000	1.2800
0.2794	3.150	1.3440
0.3048	3.200	1.3654
0.3302	3.200	1.3654
0.3556	3.180	1.3568
0.3810	3.200	1.3654
0.4064	3.150	1.3440
0.4318	3.100	1.3227
0.4572	3.120	1.3312
0.4826	2.900	1.2374
0.5080	2.750	1.1734
0.5334	2.700	1.1520
0.5588	2.580	1.1008
0.5842	2.450	1.0454
0.6096	2.300	0.9814
0.6350	2.300	0.9814
0.6604	2.240	0.9558
0.6858	2.200	0.9387
0.7112	2.120	0.9046
0.7366	1.950	0.8320
0.7620	1.830	0.7808
0.7874	1.680	0.7168
0.8128	1.620	0.6912
0.8382	1.480	0.6315
0.8636	1.380	0.5888
0.8890	1.110	0.4736
0.9144	1.090	0.4651

[a] The average gamma activity was 2.344

TABLE C-II
GROSS GAMMA SCAN FOR TEST PCM-2 FUEL ROD A-0014
(180° Orientation)

Distance from bottom of fuel stack (Metres)	Peak Height (Arbitrary) Units	Normalized Peak height Activity (Peak)/Activity (Average) ^[a]
0.003	1.210	0.5354
0.0254	1.300	0.5752
0.0508	1.500	0.6637
0.0762	1.680	0.7434
0.1016	1.950	0.8629
0.1270	2.120	0.9381
0.1524	2.200	0.9735
0.1778	2.380	1.0531
0.2032	2.530	1.1195
0.2286	2.760	1.2213
0.2540	2.840	1.2567
0.2794	2.960	1.3098
0.3048	3.060	1.3540
0.3302	3.150	1.3939
0.3556	3.100	1.3717
0.3810	3.150	1.3939
0.4064	3.100	1.3717
0.4318	3.000	1.3275
0.4572	2.950	1.3154
0.4826	2.900	1.2832
0.5080	2.830	1.2523
0.5334	2.660	1.1770
0.5588	2.480	1.0974
0.5842	2.300	1.0177
0.6096	2.330	1.0310
0.6350	2.300	1.0177
0.6604	2.250	0.9956
0.6858	2.150	0.9514
0.7112	2.110	0.9337
0.7366	1.900	0.8407
0.7620	1.850	0.8186
0.7874	1.700	0.7522
0.8128	1.450	0.6416
0.8382	1.260	0.5575
0.8636	1.110	0.4912
0.8890	1.000	0.4425
0.9144	0.900	0.3982

[a] The average gamma activity was 2.260

APPENDIX D

FLUX WIRE GAMMA SCAN

APPENDIX D

FLUX WIRE GAMMA SCAN

A 0.510% Co-Al flux wire was attached to the A-0014 fuel rod/shroud 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 for one minute per measurement interval along the length of the wire, beginning at the bottom. The mean background count rate was 80 counts per minute. Table D-I lists the cobalt flux wire scan data.

The thermal neutron flux is approximately proportional to the induced radioactivity of the cobalt flux wire. The neutron time integrated flux was determined for a data point (0.391-m from the bottom of the wire), and was used to establish a conversion factor K_n for the scanning measurements. The (nvt) at 0.391-m was divided by the total counts per minute of that interval to give $k_n = 4.366 \times 10^{13}$. It has been assumed that the ratio of (nvt) at a point along the wire to the total counts per minute at that point remains a constant over the flux wire. To obtain the neutron fluence in neutrons/m², multiply $k_n \cdot$ (counts per minute). The neutron flux axial profile obtained from scanning the cobalt flux wire was used in the posttest FRAP-T analysis. Table D-I lists the normalized neutron flux axial profile that was obtained from scanning the cobalt flux wire at 7.6 mm intervals. A neutron flux axial peak-to-average ratio of 1.382 with the peak located at 0.457 m above the bottom of the fuel was determined by fitting a Fourier Series curve to the data (see Table D-II for details).

TABLE D-I
FLUX WIRE GAMMA SCAN DATA FROM TEST PCM-2

Location from bottom of wire		Location from bottom of wire	
(metres)	Counts Per Minute (10^4)	(metres)	Counts per Minute (10^4)
0.025	1.018	0.299	2.521
0.033	1.039	0.307	2.530
0.041	1.089	0.315	2.560
0.048	1.142	0.323	2.539
0.056	1.169	0.330	2.576
0.064	1.238	0.338	2.577
0.071	1.280	0.345	2.636
0.086	1.381	0.361	2.666
0.094	1.439	0.368	2.673
0.102	1.512	0.376	2.683
0.109	1.525	0.384	2.667
0.117	1.572	0.391	2.672
0.125	1.621	0.399	2.678
0.132	1.669	0.406	2.680
0.140	1.710	0.414	2.700
0.147	1.741	0.422	2.707
0.155	1.777	0.429	2.697
0.163	1.834	0.437	2.719
0.170	1.900	0.444	2.667
0.178	1.955	0.452	2.684
0.185	1.972	0.460	2.708
0.193	2.002	0.467	2.732
0.201	2.052	0.475	2.694
0.208	2.097	0.483	2.683
0.216	2.180	0.490	2.656
0.224	2.211	0.498	2.604
0.231	2.231	0.506	2.631
0.239	2.218	0.513	2.610
0.246	2.286	0.521	2.608
0.254	2.316	0.528	2.586
0.262	2.346	0.536	2.569
0.269	2.377	0.544	2.539
0.277	2.408	0.551	2.476
0.285	2.450	0.559	2.478

TABLE D-I (contd)

FLUX WIRE GAMMA SCAN DATA FROM TEST PCM-2

Location from bottom of wire (metres)	Counts Per Minute (10^4)	Location from bottom of wire (metres)	Counts per Minute (10^4)
0.292	2.492	0.566	2.396
0.574	2.393	0.803	1.419
0.582	2.355	0.810	1.362
0.589	2.324	0.828	1.317
0.597	2.341	0.826	1.294
0.605	2.315	0.833	1.243
0.612	2.306	0.814	1.191
0.620	2.265	0.843	1.144
0.627	2.215	0.856	1.092
0.635	2.202	0.864	1.051
0.643	2.179	0.871	1.018
0.650	2.125	0.879	0.990
0.658	2.096	0.887	0.919
0.666	2.057	0.894	0.892
0.673	2.021	0.902	0.841
0.681	2.032		
0.688	1.997		
0.696	1.947		
0.704	1.924		
0.711	1.900		
0.719	1.880		
0.726	1.846		
0.734	1.815		
0.742	1.763		
0.749	1.697		
0.757	1.655		
0.765	1.606		
0.772	1.572		
0.780	1.521		
0.787	1.497		
0.795	1.451		

$$k_n = 4.366 \times 10^{13} \text{ (nvt)/counts per minute}$$

TABLE D-II

TEST PCM-2 NEUTRON FLUX AXIAL PROFILE AS OBTAINED FROM
COBALT WIRE SCAN AND SMOOTHED BY FIT TO FOURIER SERIES

<u>Elevation</u> <u>(Meters above bottom of fuel)</u>	<u>Local Flux/Average Flux</u>
0.00	0.415
0.0305	0.551
0.061	0.647
0.0914	0.765
0.1219	0.844
0.1524	0.928
0.1829	1.013
0.2134	1.118
0.2438	1.171
0.2743	1.239
0.3048	1.295
0.3353	1.333
0.3658	1.357
0.3962	1.355
0.4267	1.375
0.4572	1.382
0.4877	1.317
0.5182	1.308
0.5486	1.253
0.5791	1.175
0.6096	1.146
0.6401	1.075
0.6706	1.028
0.7010	0.961
0.7315	0.892
0.7620	0.795
0.7925	0.718
0.8230	0.629
0.8534	0.532
0.8839	0.451
0.9144	0.329

APPENDIX E

METALLURGICAL SAMPLE PREPARATION

APPENDIX E

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 a fuel rod inside a 19.1-mm (ID) diameter stainless steel secondary tube. The stainless steel tube was prescribed with longitudinal orientation grooves and circumferential marks locating the metallographic sections. Longitudinal grooves on the outside diameter were machined and vibra etched to correspond to 0° and 90° orientations, respectively. Angular orientations of the fuel rod were maintained by aligning the zero degree surface thermocouple with the zero degree orientation groove of the secondary tube during epoxying. Viewed from the top of the fuel rod, 90° is located clockwise from the zero degree orientation.

The void between the fuel rod and the 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 at the plenum region to allow epoxying the fuel.

A vent was cut through the encasing tube down into the fuel rod near the lower end-plug. Epoxy was then injected under pressure (approximately 1.38 MPa) at the top end of the fuel rod until it emerged from the vent. The epoxy was then allowed to set overnight at ambient temperature prior to sectioning into metallurgical samples.

The fuel rod was sectioned using a "Cono" saw with 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.

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

The sectioning schedules for the four separate rods are presented in Tables E-I, E-II, E-III, and E-IV. Sections of the fuel rod identified for analytical burnup analysis were set apart for fuel removal to be later transferred to CPP for radiochemical analysis. The metallography specimens (previously identified by Vibra-tool marking) were additionally marked with black ink on the bottom surface and transferred to the metallography Hot cell for mounting, polishing, and examination. Most of the transverse sections were examined on the bottom surface, viewed looking toward the top end of the fuel rod.

Metallographic samples were mounted in Bakelite at 422 K and 29 MPa. Samples containing thermocouple junctions, scheduled for examination, were ground in 0.254-mm intervals and examined in the hot cell periscope until the junctions were located. They were then polished in the Automet together with the other mounted samples.

For cladding investigations, the samples were first ground to a 600 grit finish. They were then swab-etched with a solution containing 15 ml lactic acid, 5 ml nitric acid, 2 ml hydrofluoric acid, and 5 ml distilled water. Etching times up to 30 seconds were used. The cladding was then examined and photomicrographs obtained using bright field illumination to illustrate oxide layers, and polarized light to illustrate the various zircaloy microstructures: stress-relieved condition, re-crystallized alpha phase, prior beta phase material, and oxygen-stabilized alpha zircaloy. Magnifications ranging from 50X to 1000X were used. Macrophotographs of the samples were made through the hot cell periscope at approximately 6X magnification.

The sample preparation was then extended to include polishing 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. The fuel was examined and photomicrographs were made using bright field illuminations at magnifications ranging from 100X to 500X.

TABLE E-I

EXAMINATION SCHEDULE FOR TEST PCM-2 ROD UTA-0008

Sample Identification	Orientation	Sectioning Location (from bottom of Fuel Rod) Metres	Surface Examined	Comments
B-1	Transverse	0.457	- - - -	Burn-up analysis
C-1	Transverse	0.483	Bottom	Examine fuel and cladding structures.
C-2	Transverse	0.533	Bottom	Same as above
C-3	Transverse	0.584	Bottom	Same as above
C-4	Longitudinal	0.607-0.629	90° half [*]	Same as above
C-5	Transverse	0.635	Bottom	Same as above. Examine surface TC's (2).
C-6	Transverse	0.686	Bottom	Same as preceeding. Examine C _L TC

[*] 0° - 180° plane

Adjust sectioning locations 0.035-m to reference to the bottom of the fuel stack.

TABLE E-II

EXAMINATION SCHEDULE FOR TEST PCM-2 ROD UTA-0009

Sample Identification	Orientation	Sectioning Location (from bottom of Fuel Rod) Metres	Surface Examined	Comments
B-2	Transverse	0.051	- - -	Burn-up analysis
B-3	Transverse	0.254	- - -	Burn-up analysis
B-4	Transverse	0.457	- - -	Burn-up analysis
B-5	Transverse	0.660	- - -	Burn-up analysis
B-6	Transverse	0.864	- - -	Burn-up analysis
L-1	Transverse	0.686	Bottom	Examine cladding TC (2) and C _L TC. Examine cladding and fuel micro-structure, Determine cladding temperature.
L-2	Transverse	0.737	Bottom	Examine fuel and cladding structures. Determine cladding temperature.
L-3	Transverse	0.787	Bottom	Examine TC, fuel, cladding structure, and determine cladding temperature.

Adjust sectioning locations 0.035-m to reference to the bottom of the fuel stack.

TABLE E-III

EXAMINATION SCHEDULE FOR TEST PCM-2 ROD UTA-0010

Sample Identification	Orientation	Sectioning Location (from bottom of Fuel Rod) Metres	Surface Examined	Comments
B-7	Transverse	0.445	- - -	Burn-up analysis
B-8	Transverse	0.475	- - -	Burn-up analysis
E-1	transverse	0.686	Top	Examine cladding and fuel structures
E-6	Transverse	0.690	Top	Grind for TC junctions 0° and 180°
E-2	Transverse	0.737	Top	Examine cladding and fuel structures
E-3	Transverse	0.762	Bottom	Examine cladding in high temperature region
E-4	Transverse	0.787	Top	Same as above
E-7	Transverse	0.790	Bottom	Grind for TC junctions 270°
E-5	Transverse	0.838	Bottom	Examine cladding and fuel structures

Adjust sectioning locations 0.035-m to reference to the bottom of the fuel stack.

TABLE E-IV

EXAMINATION SCHEDULE FOR TEST PCM-2 ROD A-0014

Sample Identification	Orientation	Sectioning Location (from Bottom of Fuel Rod) Metres	Surface Examined	Comments
B-9	Transverse	0.457	- - -	Burn-up analysis
U-1	Longitudinal	0.603-0.622	90° half [a]	Examine fuel and cladding structures Determine clad temperatures.
U-2	Transverse	0.622	Bottom	Same as above
U-3	Transverse	0.660	Bottom	Same as above
U-4	Transverse	0.711	Bottom	Same as above
U-5	Transverse	0.762	Bottom	Same as above

[a] 0° - 180° plane

Adjust sectioning locations 0.035-m to reference to the bottom of the fuel stack.

Grain sizes in the UO_2 fuel structure were determined from photomicrographs of selected samples by the intercept method. The number of grain boundaries intercepting a 96-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 three observations was used for each grain diameter calculation. Some grain sizes were roughly estimated using a comparison method.

Metallography mount C-4(T-1558) was prepared for electron microprobe analysis. A carbon film was evaporated onto the surface of the mount to provide a conductive path to prevent surface electronic charge build up during probe examination. The sample was transferred from the TRA metallography hot cell to the microprobe laboratory at ARA-1. The sample was transferred remotely into a shielded microprobe for examination. Line scans for U (U-M β), Zr (Zr-L α), Ni (Ni-K α), and Sn (Sn-L α) were made across the fuel-cladding interface.

APPENDIX E

CLADDING SURFACE TEMPERATURE ESTIMATES.

APPENDIX F

CLADDING SURFACE TEMPERATURE ESTIMATES

The cladding surface temperatures were calculated using several kinetic correlations found in the literature for reaction layer thicknesses at the outside diameter. The correlations for reaction layer thicknesses are usually expressed by some form of the parabolic rate law

$$\underline{x} = \kappa_p t^{1/2} \quad (F-1)$$

where $\underline{x}$ is the thickness of the respective reaction layers in mm, t is the reaction time at the test temperature in seconds, and κ_p is a proportionality constant. The proportionality constant, κ_p is found empirically to vary as the square root of the diffusion coefficient, D , of the rate controlling process, the diffusion of oxygen in zircaloy. It is represented in the form

$$\kappa_p^2 = D = D^* \exp (-Q/RT) \quad (F-2)$$

where D^* is the pre-exponential diffusion coefficient (mm^2/sec), Q is the activation energy or heat of activation of the reaction process (cal / mole), R is the universal gas constant ($1.987 \text{ cal / mole} \cdot \text{K}$), and T is the temperature in Kelvin (K).

Cladding temperature estimates were based on outer diameter reaction layers using the following correlations:

$$(1) \underline{x}/t^{1/2} = 0.36 \exp (-6,793/T) \quad (F-3)$$

derived by Urbanic [F-1] for the ZrO_2 layer;

$$(2) \underline{x}/t^{1/2} = 3.90 \exp (-9,915/T) \quad (F-4)$$

developed by Urbanic [F-1] for the internal cladding outside diameter layer of oxygen-stabilized zircaloy layer, and;

$$(3) \ x/t^{1/2} = 8.412 \exp (-10,330/T) \quad (F-4)$$

from Pawel [F-2] for the combined thickness of ZrO_2 and oxygen-stabilized alpha layer represented by the summation

$$x = \Sigma (x_{ZrO_2} + x_{\alpha-Zr}) \quad (F-5)$$

Temperatures were calculated from layer thicknesses measured at several cladding positions on all metallurgical mounts sectioned from the fuel rod. When the ZrO_2 layer was missing (as a result of spalling in the high temperature region), calculations were based on the thickness of the oxygen-stabilized α -Zr layer. The time at temperature was taken from Table I of the text. The results of calculating cladding temperatures are presented in Tables F-I, II, III, and IV. Using the various correlations to determine cladding temperatures lead to variations with differences as large as 50K. The table includes best estimate temperatures determined by the mean from calculated values. Temperatures calculated from data in parentheses were not included in determining the best estimate temperature since they were arrived at by doubling the thickness of oxygen-stabilized alpha-zircaloy in the absence of surface oxide which had spalled off.

TABLE F - I

CLADDING TEMPERATURE ESTIMATES FOR TEST PCM-2 FUEL ROD UTA-0008

Sample Identification (Location from bottom of the fuel stack)	Orientation	Oxide Thickness	Alpha Layer Thickness	Alpha + Oxide Thickness	T_o (K) (*)	T_α (K) (**)	$T_{o+\alpha}$ (K) (***)	Best Estimate Temperature	
								T(K) Circumferen-	tial average
(metres)		(mm) [†]	(mm) [†]	(mm) [†]				[b]	
C-1	0°	C.010	0.010	0.020	1149	1196	1235	1172	
C.482-m	90°	C.011	0.011	0.022 [a]	1168	1210	1249	1189	
	180°	----	0.020	(0.040)	----	1305	(1346)	1305	<u>1263</u>
	270°	----	0.031	(0.062)	----	1384	(1428)	1384	
C-2	0°	----	0.063	(0.126)	----	1537	(1583)	1537	
C.533-m	90°	----	0.046	(0.092)	----	1465	(1510)	1465	
	180°	----	0.038	(0.076)	----	1425	(1469)	1425	<u>1467</u>
	270°	----	0.043	(0.086)	----	1451	(1495)	1451	
	280°	C.037	0.041	0.078	1476	1441	1474	1458	
C-3	0°	----	0.058	(0.116)	----	1517	(1563)	1517	
C.584	90°	----	0.044	(0.088)	----	1456	(1500)	1456	
	180°	----	0.028	(0.056)	----	1365	(1408)	1365	<u>1430</u>
	270°	----	0.031	(0.062)	----	1384	(1427)	1384	
C-4	0°(a) ⁽⁺⁾	0.036	0.049	0.085	1467	1479	1493	1473	
C.609-0.628-m	0°(b)	0.032	0.041	0.073	1431	1441	1461	1436	<u>1457</u>
		0.0375	0.0425	0.085	1480	1448	1493	1464	
C-5	0°	0.020	0.017	0.037	1302	1277	1333	1304	
C.635-m	0°	----	0.023	(0.046)	----	1329	(1371)	1329	

TABLE F - I (contd)

CLADDING TEMPERATURE ESTIMATES FOR TEST PCM-2 FUEL ROD UTA-0008

Sample Identification (Location from bottom of the fuel stack) (metres)	Orientation	Oxide Thickness (mm) ⁺	Alpha Layer Thickness (mm) ⁺	Alpha + Oxide Thickness (mm) ⁺	T_o (K) (*)	T_α (K) (**)	$T_{o+\alpha}$ (K) (***)	Best Estimate Temperature T(K) Circumfer- [b] tial average	
C-6 0.686-m	(350°) 0°	0.020	0.020	0.040	1302	1305	1346	1317	
	90°	0.014	----	----	1219	----	----	1219	
	180°	0.018	0.008	0.026	1276	1164	1275	1238	<u>1278</u>
	200°	0.020	0.012	0.032	1302	1222	1308	1277	
	250°	0.012	0.005	0.022	1263	1103	1249	1205	
	270°	0.030	----	----	1412	----	----	1412	

[a] Bracketed thicknesses were obtained by doubling the alpha layer thickness to determine an approximate combined thickness to use with the correlation by Pawel eq [F-5]. Temperatures calculated with these approximate thicknesses were not used to arrive at a best estimate temperature.

[b] Temperature averaged using T_o (K), T_α (K) and $T_{o+\alpha}$ (K)

+ The uncertainty in these thicknesses average ± 0.0010 -mm due primarily to the unevenness in the layers measured.

(*) Calculation based on Urbanic correlation eq [F-3].

(**) Calculation based on Urbanic correlation eq [F-4].

(***) Calculation based on Pawel correlation eq [F-5].

(+) Longitudinal samples were measured at the top (a), bottom (b) and near the fuel pellet interface (c).

TABLE F - II

CLADDING TEMPERATURE ESTIMATES FOR TEST PCM-2 FUEL ROD UTA-0009

Sample Identification (Location from bottom of the fuel stack)	Orientation	Oxide Thickness	Alpha Layer Thickness	Alpha + Oxide Thickness	T_o (K) (*)	T_α (K) (**)	$T_{o+\alpha}$ (K) (***)	Best Estimate Temperature T (K) Circumferen- tial average)
(metres)		(mm) [†]	(mm) [†]	(mm) [†]				
L-1	0°	0.002	----	----	948	----	----	948
0.686-m	90°	0.002	----	----	948	----	----	948
	180°	0.002	----	----	948	----	----	948
	270°	0.003	----	----	1004	----	----	1004
L-2	0°	0.0025	----	----	978	----	----	978
0.736-m	90°	0.0025	----	----	978	----	----	978
	180°	0.003	----	----	1004	----	----	1004
	270°	0.0025	----	----	978	----	----	978
L-3	0°	0.0015	----	----	911	----	----	911
0.787-m	90°	0.003	----	----	1004	----	----	1004
	180°	0.002	----	----	948	----	----	948
	270°	0.0025	----	----	978	----	----	978

† The uncertainty in these thicknesses average ± 0.0010 -mm due primarily to the unevenness in the layers measured.

(*) Calculation based on Urbanic correlation eq [F-3].

TABLE F - III

CLADDING TEMPERATURE ESTIMATES FOR TEST PCM-2 FUEL ROD UTA-0010

Sample Identification (Location from bottom of the fuel stack) (metres)	Orientation	Oxide Thickness (mm) [†]	Alpha Layer Thickness (mm) [†]	Alpha + Oxide Thickness (mm) [†]	T _o (K) (*)	T _α (K)	T _{o+α} (K)	Best Estimate Temperature T(K) circumferen- tial average)	
E-1 0.686-m	0°	0.001	----	----	866	----	----	866	
	90°	0.0035	----	----	1031	----	----	1031	
	180°	0.003	----	----	1007	----	----	1007	943
	270°	0.001	----	----	866	----	----	866	
E-2 0.737-m	0°	----	----	----	----	----	----		
	90°	0.002	----	----	950	----	----	950	
	180°	0.002	----	----	950	----	----	950	950
	270°	0.002	----	----	950	----	----	950	
E-3 0.762-m	0°	----	----	----	----	----	----		
	90°	0.002	----	----	950	----	----	950	
	180°	0.001	----	----	866	----	----	866	908
	270°	----	----	----	----	----	----		
E-4 0.787-m	0°	----	----	----	----	----	----		
	90°	0.0025	----	----	981	----	----	981	
	180°	0.0015	----	----	913	----	----	913	947
	270°	----	----	----	----	----	----		
E-5 0.838-m	0°	0.001	----	----	866	----	----	866	
	90°	0.002	----	----	950	----	----	950	908
	180°	0.002	----	----	950	----	----	950	
	270°	0.001	----	----	866	----	----	866	

† The uncertainty in these thicknesses average ± 0.0010 -mm due primarily to the unevenness in the layers measured.

(*) Calculation based on Urbanic correlation eq [F-3].

TABLE F - 1V

CLADDING TEMPERATURE ESTIMATES FOR TEST PCM-2 FUEL ROD A-0014

Sample Identification (Location from bottom of the fuel stack)	Orientation	Oxide Thickness	Alpha Layer Thickness	Alpha + Oxide Thickness	T_o (K) (*)	T_α (K) (**)	$T_{o+\alpha}$ (K) (***)	Best Estimate Temperature	
								T (K)	Circumferen- tial average)
(metres)		(mm) [†]	(mm) [†]	(mm) [†]					
165	U-1 0.602-0.622-m	180° (a) ⁽⁺⁾	----	0.015	(0.030) ^[a]	----	1288	(1329)	1288
		180° (b)	----	0.015	(0.030)	----	1288	(1329)	1288
		180° (c)	----	0.013	(0.026)	----	1264	(1305)	1264
	U-2 0.623-m	0°	----	0.017	(0.034)	----	1309	(1351)	1309
		90°	----	0.020	(0.040)	----	1338	(1380)	1338
		180°	----	0.022	(0.044)	----	1355	(1398)	1355
		270°	----	0.020	(0.040)	----	1338	(1380)	1338
	U-3 0.660-m	0°	----	0.021	(0.042)	----	1347	(1389)	1347
		90°	----	0.020	(0.040)	----	1338	(1380)	1338
		180°	----	0.021	(0.042)	----	1347	(1389)	1347
		270°	----	0.021	(0.042)	----	1347	(1389)	1347
	U-4 0.711-m	0°	----	0.015	(0.030)	----	1288	(1329)	1288
		90°	----	0.014	(0.028)	----	1276	(1317)	1276
		180°	----	0.016	(0.032)	----	1299	(1340)	1299
		270°	----	0.017	(0.034)	----	1309	(1351)	1309

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TABLE F - 1V (contd)

CLADDING TEMPERATURE ESTIMATES FOR TEST PCM-2 FUEL ROD A-0C14

Sample Identification (Location from bottom of the fuel stack)	Orientation	Oxide Thickness	Alpha Layer Thickness	Alpha + Oxide Thickness	T_o (K) (*)	T_{α} (K) (**)	$T_{o+\alpha}$ (K) (***)	Best Estimate Temperature	
								$\bar{T}$ (K)	Circuferen- tial average
(metres)		(mm) [†]	(mm) [†]	(mm) [†]					
U-5	0°	0.013	----	----	1244	----	----	1244	<u>1189</u>
0.762-m	90°	0.007	----	----	1117	----	----	1117	
	180°	0.011	----	----	1207	----	----	1207	
	270°	0.010	----	----	1187	----	----	1187	

[a] Bracketed thicknesses were obtained by doubling the alpha layer thickness to determine an approximate combined thickness to use with the correlation by Pawel eq [F-5]. Temperatures calculated with these approximate thicknesses were not used to arrive at a best estimate temperature.

+ The uncertainty in these thicknesses average ± 0.001 -mm due primarily to the unevenness in the layers measured.

(*) Calculation based on Urbanic correlation eq [F-3].

(**) Calculation based on Urbanic correlation eq [F-4].

(***) Calculation based on Urbanic correlation eq [F-5].

(+) Longitudinal samples were measured at the top (a), bottom (c) and near the fuel pellet interface (b).

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APPENDIX G

FRAP-T2 COMPUTER CODE CALCULATIONS

APPENDIX G

FRAP-T2 COMPUTER CODE CALCULATIONS

Pretest predictions were performed using the Fuel Rod Analysis Program Transient (FRAP-T2)^[G-1] computer code and reported in Reference G-2. Since the examination was not performed under the same test conditions used in the pretest predictions, a posttest analysis of the fuel rod behavior was made. FRAP-T is a FORTRAN IV computer code developed to describe the transient behavior of nuclear fuel rods during postulated accidents such as loss-of-coolant or power-cooling-mismatch. The FRAP-T versions used in this report are the second and third in a series of fuel codes planned for release at one-year intervals with each succeeding version incorporating the advancements made in fuel rod response analysis during that year.

DNB Power Cycle 8 was the only cycle of the test in which the fuel and cladding temperatures were allowed to attain a quasi-equilibrium before decreasing reactor power. Therefore, the measured test conditions for DNB Cycle 8 and the as-built fuel rod and shroud dimensions were used in the analysis. These input values are presented in Table G-I. The analytical model used to describe the fuel consisted of 15 axial nodes and 11 radial nodes. The nominal 1.9-mm diameter centerline hole used to position the fuel thermocouple was simulated by assigning a 1.9-mm diameter zero power generation region for the full length of the fuel stack. The four 1.17-mm diameter cladding surface thermocouple dimensions were included in calculating the coolant flow area and the hydraulic diameter, but not in the equivalent heated diameter.

The fuel rod axial power profile, presented in Table G-II, was obtained from a gamma scan of a cobalt flux wire which was located on the flow shroud of Rod A-0014.

The W3 CHF correlation^[G-3], the Groeneveld film boiling correlation^[G-4] for annuli, and the Ross-Stoute gap conductance model^[G-5] were utilized in the FRAP-T2 post-DNB calculations^[a]. The as-measured rod power and coolant mass flux histories for the entire cycle were used for Rod UTA-0008. The coolant mass flux histories used for Rods UTA-0010 and A-0014 duplicated the initial flow during the cycle and the decrease to the minimum measured coolant mass flux, but did not include increasing the coolant mass flux and decreasing the rod power to terminate DNB conditions. A constant rod power of 46.4 kW/m was used for the post-DNB calculations of Rods UTA-0010 and A-0014.

[a] The post-DNB analytical results were obtained using FRAP-T2, MOD 002 VER 07A and 7BEM in conjunction with MATPRO 006^[G-6].

TABLE G-I

FRAP-T COMPUTER CODE INPUT FOR POSTTEST ANALYSIS

<u>Fuel Rod</u>		<u>Rod UTA-0008</u>	<u>Rod UTA-0010</u>	<u>Rod A-0014</u>
<u>Fuel Region</u>	Active length	0.914 m	0.915 m	0.914 m
	Material	UO ₂	UO ₂	UO ₂
	Enrichment	20%	20%	20%
	Pellet height	15.240 mm	15.240 mm	15.240 mm
	Pellet diameter	9.30 mm	9.296 mm	9.296 mm
	Pellet shoulder radius	3.110 mm	3.110 mm	3.110 mm
	Dish Depth	0.330 mm	0.330 mm	0.330 mm
	Density	10275 kg/m ³	10255 kg/m ³	10275 kg/m ³
	Theoretical density	93.75%	93.57%	93.75%
	Roughness	2.159 microns	2.159 microns	2.159 microns
<u>Cladding Region</u>	Material	Zircaloy-4	Zircaloy-4	Zircaloy-4
	Cladding ID	9.506 mm	9.504 mm	9.498 mm
	Cladding OD	10.750 mm	10.750 mm	10.718 mm
	Roughness	1.143 microns	1.143 microns	1.143 microns
<u>Plenum Region</u>	Gas quantity	1.037x10 ⁻²	1.039x10 ⁻²	8.398x10 ⁻³
	moles helium		moles helium	moles helium
	Plenum volume	7.509x10 ⁻⁶ m ³	7.554x10 ⁻⁶ m ³	2.959x10 ⁻⁶ m ³
	Total backfill volume	10.626x10 ⁻⁶ m ³	10.044x10 ⁻⁶ m ³	6.0x10 ⁻⁶ m ³
	Gap pressure	2.579 MPa	2.57 MPa	3.882 MPa
	Spring Length	5.08x10 ⁻² m	5.08x10 ⁻² m	5.08x10 ⁻² m
	Spring coil OD	9.02x10 ⁻³ m	9.02x10 ⁻³ m	9.02x10 ⁻³ m
	Spring wire diameter	1.02x10 ⁻³ m	1.02x10 ⁻³ m	1.02x10 ⁻³ m
	Number of spring coils	17	17	17
<u>Flow Shroud</u>	Shroud ID	16.3 mm	16.3 mm	16.3 mm
	Coolant flow area	1.137x10 ⁻⁴ m ²	1.136x10 ⁻⁴ m ²	1.184x10 ⁻⁴ m ²
	Hydraulic diameter	4.564x10 ⁻³ m	4.560x10 ⁻³ m	9.251x10 ⁻³ m
	Equivalent heated diameter	1.347x10 ⁻² m	1.346x10 ⁻² m	1.407x10 ⁻² m
<u>Cycle 8 Test</u>	Coolant inlet temperature	600.1 K	600.1 K	600.1 K
<u>Conditions</u>	Coolant pressure	14.8 MPa	14.8 MPa	14.8 MPa
	Fuel rod peak power	46.4 kW/m	46.4 kW/M	46.4 kW/m

TABLE G-II

TEST PCM-2 AXIAL POWER PROFILE USED IN CALCULATIONS

<u>Elevation</u> <u>(m above bottom of fuel)</u>	<u>Local Power/Average Power</u>
0.0286	0.544
0.0762	0.698
0.1143	0.820
0.1524	0.928
0.1905	1.038
0.2286	1.122
0.2667	1.218
0.3048	1.295
0.3429	1.343
0.3810	1.351
0.4191	1.364
0.4572	1.382
0.4953	1.331
0.5334	1.284
0.5715	1.191
0.6096	1.146
0.6477	1.060
0.6858	0.985
0.7239	0.918
0.7620	0.795
0.8001	0.689
0.8382	0.579
0.8858	0.445

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