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INTEGRAL HEAT RATE-TO-INCIPIENT MELTING IN $\text{UO}_2\text{-PuO}_2$ FAST REACTOR FUEL

Hanford Engineering Development Laboratory

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ABSTRACT

Analyses of integral power-to-melt tests, HEDL P-19 and P-20, are presented. These tests contained mixed-oxide, $\text{UO}_2\text{-PuO}_2$, fuel prototypic of fuel to be used in the driver fuel assemblies of the Fast Flux Test Facility, FFTF, and that could be used in initial Fast Breeder Reactors, FBR's. The experiments were irradiated in the Experimental Breeder Reactor #2, EBR-II, for the Hanford Engineering Development Laboratory, HEDL. The primary test variables are fabricated fuel-to-cladding gap size and accumulated fuel burnup to 1.1 at.%. At the beginning of the irradiation life of these fuel pins, burnups of about 0.01 at.%, the power required to cause incipient fuel melting, Q'_m varies from 18.3 to 14.8 kW/ft (600 to 486 W/cm) for fabricated diametral fuel-to-cladding gap sizes from about 0.0034 to 0.010 inch (0.086 to 0.25 mm). At higher burnups, 0.3 to 1.1 at.%, the thermal performance of the pins with large gaps has improved and Q'_m is at least 18.5 kW/ft (607 W/cm).

The observed improved thermal performance, with burnup, is analyzed based on results and conclusions drawn from sibling pins irradiated during the preconditioning phases of the P-20 test. These pins were not included in the overpower phase of the P-20 test. The primary cause of the improved thermal performance was found to be maturing fuel restructuring and rapid fuel-to-cladding gap closure. The favorable impact of these observations on the design and operation of FFTF and future FBR's is also reviewed.

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I. INTRODUCTION

This report presents detailed analyses made of the linear-heat-rate needed to cause incipient melting, Q'_m , of mixed-oxide fuel (75% UO_2 -25% PuO_2) typical of that to be used in the driver fuel of the Fast Flux Test Facility, FFTF (Figure 1). The results have general application to Fast Breeder Reactor, FBR, fuel pins containing similar fuel. The analysis is specifically concerned with the effects of fabricated fuel-to-cladding gap and accumulated fuel burnup up to 10,900 MWd/MTM (1.1 at.%) on the thermal performance of the fuel pins. These analyses are based on data from the HEDL P-19 and P-20 experiments which were irradiated in the Experimental Breeder Reactor #2, EBR-II, for the Hanford Engineering Development Laboratory, HEDL.

The capability of the fuel to operate at high power without melting is of interest to FBR's because reactor design limits normally require that there be a low probability of fuel melting during steady-state operation including overpower conditions. This requirement has a direct effect on the steady-state power limit of the fuel pin and the reactor. Optimization of this power capability is important to reactor thermal efficiency and economy of operation. Design factors, that are probably unnecessarily conservative because of a small data base, are applied in fuel temperature calculations causing a penalty in power limits that may not be needed. This uncertainty also causes very conservative fuel-to-cladding gap specification tolerances to be used which can increase fuel fabrication costs.

The HEDL P-19^(1,2) and P-20^(3,4) tests were conducted to develop integral thermal performance data for FFTF. The fuel pins and test operating conditions were as near prototypic of the FFTF design as possible, but at high enough heat rates to cause some fuel melting in a majority of the pins. The primary variable was fabricated fuel-to-cladding gap size because of the major uncertainty in calculating the temperature drop across the gap between the fuel and the cladding.

The P-19 and P-20 experiments represent a unique set of data in the United States fast reactor program. The tests use the known isotherm in the fuel, that occurs at the extents of fuel melting, to provide data for evaluating fuel thermal performance. Only one other test, the General Electric F-20⁽⁵⁾ test, provides this type of data. Complete results of the F-20 test remain to be published but are expected to extend the data range of the present analyses. Other possible methods for measuring fuel temperatures introduce "something extra", i.e. thermocouples or melt wires, into the fuel which may affect the results. Further, because of the high temperatures and severe environment involved, with attendant uncertainties in instrumentation response, tests using these other methods in fast reactor fuel have been used very little.

The initial results and analyses of the individual P-19 and P-20 tests with respect to Q'_{in} have been reported previously.⁽²⁻⁴⁾ The present report describes the collective analyses of these two tests, using more refined and consistent methods than previously applied. Also included are discussions of the observed behavior of the P-20 fuel throughout the test's three phases.

II. SUMMARY

The HEDL P-19 and P-20 tests were designed to provide "integral" power-to-melt data; the fuel pin fabrication parameters simulate present FFTF/FBR design conditions. The P-19 test was irradiated to investigate the effects of initial fuel-to-cladding diametral gap sizes, from 0.0034 to 0.010 inch (0.086 to 0.25 mm), on the linear-heat-rate needed to cause incipient fuel melting (power-to-melt), Q'_m , at beginning-of-life. The P-20 test was irradiated primarily to determine the effects of fuel burnup to 10,900 MWd/MTM (1.1 at.%) on Q'_m at several selected diametral gap sizes, 0.0035, 0.0055 and 0.0075 inch (0.09, 0.14, and 0.19 mm).

The pins were made with 75% UO_2 - 25% PuO_2 fuel pellets clad with 0.230 inch (5.84 mm) or 0.250 inch (6.35 mm) OD, 20% cold worked type 316 stainless steel. The P-20 test included pins fabricated with both pure helium (like P-19) and 18% Xe - 82% He fill-gases. Fabricated fuel microstructure was also varied.

HEDL P-19 and P-20 were irradiated in the EBR-II. P-19 was irradiated for a short period of time (ten minutes at peak power) to a peak fuel burnup of about 60 MWd/MTM (0.0062 at.%). The P-20 test involved three irradiation phases; the first two at high pin power (but less than Q'_m) to provide a source of well-characterized preirradiated pins (three burnup levels), and the third, similar to the P-19 test, to achieve melting at the fuel center-line in a portion of the pins.

Measurements of axial extents of fuel melting found in each test pin were used to derive Q'_m values. This was done by characterizing the local power and cladding temperature conditions at the axial extents of melting and normalizing to FFTF conditions.

The analysis of the two tests showed that at beginning-of-life conditions (60 to 90 MWd/MTM or about 0.01 at.%) there is dependence of Q'_m on fabricated

fuel-to-cladding gap size. The normalized Q'_m values varied from 18.3 kW/ft for gap sizes less than about 0.005 inch (0.13 mm) to 14.8 kW/ft for gaps as large as 0.010 inch (0.25 mm) (600 to 486 W/cm). The effect of having lower thermal conductivity fill-gas mixture (18% Xe - 82% He instead of pure He) was to significantly decrease Q'_m as expected.

The results of the higher burnup data show that by the time a burnup of about 3700 MWd/MTM (0.38 at.%) is reached, Q'_m is at least 18.5 kW/ft (607 W/cm) in a prototypic FFTF/FBR mixed-oxide fuel pin and is essentially independent of starting fuel-to-cladding gap size or composition of the fill gas. This represents, for the 0.0075 inch (0.19 mm) gap case, an improvement in Q'_m of about 20% relative to "fresh" fuel (60 to 90 MWd/MTM or about 0.01 at.%). This improvement comes about primarily by rapid closure of the fuel-to-cladding gap and by maturing of the fuel restructuring.

III. ANALYSES OF HEDL P-19 AND HEDL P-20 TEST RESULTS

This section summarizes the analyses of the HEDL P-19 and P-20 tests with respect to the linear-heat-rate-to-incipient fuel melting, Q'_m , which is also referred to as "power-to-melt". The analyses were designed to take advantage of the integral nature of these tests, which were conducted very near the conditions required in the fuel pin design of interest (FFTF driver type fuel pins). Some normalization of the data is necessary, however, so that data taken from different sized pins and at different coolant conditions can be compared. A revised version of the SIEX^(6,7) thermal performance computer code, SIEX-M1,⁽⁸⁾ was used in the final normalization calculations described in this report.

The present study incorporates many analytical refinements not used in preliminary analyses of the data⁽¹⁻⁴⁾ (i.e. special handling of fuel restructuring and use of the SIEX thermal performance code) and is the only one combining the results from both tests. P-19 ceramography was remeasured as part of these analyses to assure the same criteria were applied in interpreting the observations as were used for P-20 data. In addition, a change in power levels, from previous studies, used for the P-19 experiment (and thus P-20) was also made. This power adjustment reflects more detailed analyses⁽⁹⁾ made by the EBR-II project to establish actual reactor power and crosschecks⁽¹⁰⁾ made by HEDL on the apparent power level of other experiments in EBR-II.

A. SUMMARY OF THE HEDL P-19 TEST

The HEDL P-19 experiment was conducted in EBR-II to determine the effect of fabricated diametral fuel-to-cladding gap, from 0.0034 to 0.010 inch (0.086 to 0.25 mm), on Q'_m of mixed-oxide (25% PuO_2 - 75% UO_2) fuel pins under very rapid FBR startup conditions. P-19 was an encapsulated 19-pin subassembly consisting of eight "fresh" pins with cladding outside diameters (OD's) of 0.230 inch (5.84 mm), eight "fresh" 0.250 inch (6.35 mm) OD pins and three preirradiated pins. All pins were backfilled with pure

helium during fabrication. The fresh pins were clad with 316 stainless steel (20% cold worked) and were fabricated, where test parameters would allow, to RDT Standards for FBR fuel. Appendices A of References 2 and 3 summarize detailed fabrication data for the P-19 test pins. Table I shows fabrication data of direct interest to this analysis. The three preirradiated pins, from the PNL-1 and PNL-2⁽¹¹⁾ experiments represent a significantly different data set and are not included in the present analysis.

The P-19 test was conducted to simulate a fast startup to steady-state power. After a one hour hold period, power was increased rapidly an additional 15%. This level was held ten minutes and the reactor was then scrammed (see Figure 2) to quench the fuel structure.

The P-19 experiment (X108) was irradiated in row 2, position 2B1 in the EBR-II during reactor run 48E. The positions immediately adjacent to the test were occupied by EBR-II driver fuel assemblies.⁽¹²⁾

After irradiation, the P-19 pins were removed from EBR-II and neutron radiographed. This confirmed partial fuel melting in a number of pins. All 0.230 inch (5.84 mm) OD pins with fuel-to-cladding gaps equal to or less than 0.0055 inch (0.14 mm) had no fuel melting. The remaining 0.230 inch (5.84 mm) OD pins and all the 0.250 inch (6.35 mm) OD pins experienced partial fuel melting. The capsules were then returned to HEDL where detailed destructive examination was conducted.

Transverse fuel ceramographic samples were used to obtain measurements of fuel restructuring zone radii and residual fuel-to-cladding gaps. They were also used to obtain the radial extent of melting at the peak power locations of those pins experiencing partial fuel melting. However, power-to-melt data calculated from these sections were considered less accurate because of the uncertain influence of relocated molten fuel on local power. Further, the radial extent of central void formation at these locations is uncertain; melting has obliterated the central void formed by

TABLE I
SUMMARY OF FABRICATION PARAMETERS FOR EACH P-19 PIN

Pin Identifi- cation ^(a)	Nominal Diametral Fuel-to-Cladding Gap, mils (mm)	Average Fuel Pellet Density % TD ^(c)	Average Cladding OD, inches (cm)
P-19-2	7.8 (0.198)	90.75	0.230 (0.584)
P-19-3R	10.0 (0.254)	92.40	0.250 (0.635)
P-19-5	5.7 (0.145)	90.75	0.230 (0.584)
P-19-6	3.9 (0.099)	90.75	0.230 (0.584)
P-19-7R	6.2 (0.158)	92.40	0.250 (0.635)
P-19-8	9.6 (0.244)	90.75	0.230 (0.584)
P-19-13	7.8 (0.198)	90.75	0.230 (0.584)
P-19-20	9.7 (0.246)	90.75	0.230 (0.584)
P-19-24R	10.0 (0.254)	92.40	0.250 (0.635)
P-19-25R	8.0 (0.203)	92.40	0.250 (0.635)
P-19-26R	6.6 (0.152)	92.40	0.250 (0.635)
P-19-27R	4.0 (0.102)	92.40	0.250 (0.635)
P-19-28 ^(b)	3.4 (0.086)	92.40	0.250 (0.635)
P-19-30 ^(b)	7.0 (0.178)	92.40	0.250 (0.635)
P-19-33 ^(b)	4.9 (0.125)	90.75	0.230 (0.584)
P-19-35 ^(b)	7.2 (0.183)	90.75	0.230 (0.584)
P-19/PNL-1-11	6.0 (0.152)	89.45	0.240 (0.612)
P-19/PNL-2-16	6.1 (0.155)	90.57	0.238 (0.605)
P-19/PNL-2-18	5.9 (0.150)	90.05	0.238 (0.605)

^(a) All pins backfilled with helium and all fuel was high pressure pre-slugged except for that in P-19/PNL-11, P-19/PNL-2-16, and P-19/PNL-2-18.

^(b) Pellet surfaces in the as-sintered condition. All other pins contained ground pellets.

^(c) TD = Theoretical Density (~ 10.9 gm/cc) of the fuel.

restructuring. Since most of these peak power regions operated at much higher powers than Q'_m , melting is extensive even in adjacent fuel.

The axial extents of melting, as determined from longitudinal ceramographic sections, offered the best data for determining Q'_m since these sections were actually located where incipient melting occurred and experienced the least power variation due to molten fuel relocation. Local generated power and fuel temperatures are highest near the axial midplane and decrease toward each end of the fuel column. This ideally results in two axial extents of molten fuel from each fuel pin that can be used for deriving Q'_m values.

B. SUMMARY OF HEDL P-20 TEST

The primary purpose of the P-20 test was to determine the effect of burnup, up to 1.1 at.% (about 10,900 MWd/MTM) on power-to-melt, Q'_m , over a range of fuel-to-cladding gaps of interest to FFTF and FBR's. Table II summarizes the experiment variables and general fabrication parameters. Table III summarizes specific pin data.

The pins with 0.0035, 0.0055, or 0.0075 inch (0.09, 0.14 or 0.19 mm) fuel-to-cladding diametral gaps constitute the main portion of the test since these span the present allowable range in FFTF driver fuel pins. These pins were backfilled with pure helium to permit a direct comparison of the results with the HEDL P-19 results. Several pins with 0.0075 inch (0.19 mm) fuel-to-cladding gaps and back-filled with 82% He-18% Xe were included to assess the effect of "tag" gas on thermal performance. [FFTF driver and FBR fuel pins will be "tagged" with a 90% He-10% (Xe+Kr) mixture with predetermined ratios of certain Xe and Kr isotopes for a given sub-assembly to allow identification of "leakers" in the event of a cladding breach.] In addition, pins were included with fuel columns made up of different diameter pellets (mixed gap) to evaluate axial "smoothing" of Q'_m , and with fuel fabricated by low pressure preslugging⁽¹³⁾, to determine

TABLE II

SCOPE OF THE HEDL P-20 THERMAL PERFORMANCE TEST

General Parameters

Cladding

316 20% CW stainless steel

0.230 inch (5.84 mm) OD x 0.015 inch (0.38 mm) wall thickness

Fuel

75% UO_2 - 25% PuO_2

Preslugged (high pressure) same as P-19

O/M - 1.96

Pellet density ~91% [similar to P-19, 0.230 inch (5.84 mm) OD pins]

He bonded to cladding

13.5 inch (34.3 cm) fuel column length

Subassembly

19 encapsulated pins

Shroud tubes

Main Variables

Fuel burnup, three increments to 10,900 MWd/MTM (1.1 at.%)

Fuel-to-cladding diametral gap [0.0035 to 0.0096 inch (0.9 to 0.24 mm)
Phase I & II] [0.0035 inch (0.9 mm), 0.0055 inch (0.14 mm) and
0.0075 inch (0.19 mm) Phase III]

Secondary Variables

Fill gas, pins with 18% Xe Tag

Fuel fabricated structure, pins with low pressure preslugged fuel

HEDL P-19 fuel batch

Mixed fuel-to-cladding gaps in the same pin

One high burnup PNL-2 pin [304 SS cladding 0.250 inch (6.35 mm)
OD x 0.016 inch (0.41 mm) wall]

TABLE III

SUMMARY OF FABRICATION PARAMETERS FOR PINS IN EACH PHASE OF P-20

PIN IDENTIFICATION ¹	NOMINAL DIAMETRAL FUEL-TO-CLADDING GAP, MILS (mm)	AVERAGE FUEL PELLET DENSITY, ³ % TD	PLENUM FILL GAS ⁴	PHASE ⁵		
				I	II	III
P-20-1	7.6 (0.193)	90.7	He	X		
P-20-2R	7.6 (0.193)	91.0	He	X		X
P-20-3	7.6 (0.193)	90.9	He	X	X	
P-20-4	7.6 (0.193)	90.6	He	X	X	X
P-20-5	7.6 (0.193)	90.8	He		X	
P-20-7	7.6 (0.193)	91.1	He			X
P-20-8	7.6 (0.193)	90.6	He		X	X
P-20-9	7.4 (0.187)	91.2	Xe+He	X		
P-20-10	7.6 (0.193)	91.2	Xe+He	X		X
P-20-11	7.5 (0.191)	91.1	Xe+He	X	X	
P-20-12	7.5 (0.191)	91.3	Xe+He		X	
P-20-13	7.4 (0.187)	91.1	Xe+He			X
P-20-15	7.7 ² (0.196)	91.4	He		X	
P-20-18	M 5.5 ² (0.140)	91.4	He	X		
P-20-19	M 5.4 ² (0.137)	91.3	He	X		X
P-20-20	M 5.6 ² (0.142)	91.3	He	X	X	
P-20-21	M 5.5 ² (0.140)	91.2	He		X	
P-20-22	M 5.6 ² (0.142)	91.4	He			X
P-20-24	5.6 (0.142)	90.8	He	X		
P-20-25R	5.6 (0.142)	91.2	He	X		X
P-20-26	5.5 (0.140)	91.1	He	X	X	
P-20-27	5.6 (0.142)	91.0	He	X	X	X
P-20-28	5.5 (0.140)	91.2	He		X	
P-20-29	5.6 (0.142)	91.3	He		X	X
P-20-30	5.5 (0.140)	91.0	He			X
P-20-32	3.6 (0.091)	90.6	He	X		
P-20-33	3.6 (0.091)	90.6	He	X		X
P-20-34R	3.5 (0.089)	91.1	He	X	X	
P-20-35	3.5 (0.089)	90.7	He	X	X	X
P-20-36	3.6 (0.091)	90.6	He		X	
P-20-37	3.5 (0.089)	90.6	He		X	X
P-20-39	7.6 (0.193)	91.5	He			X
P-20/19-1R	9.6 (0.244)	90.8	He		X	
P-20/19-14	3.8 (0.097)	90.8	He		X	
P-20/19-21	7.6 (0.193)	90.8	He			X
P-20/19-23	3.8 (0.097)	90.8	He	X		
P-20/19-34	7.2 (0.183)	90.8	He			X
P-20/PNL-2-5	6.0 (0.152)	91.7	He			X

¹All fuel pins have 0.230 inch (0.584 cm) cladding OD's except the PNL-2-5 pin which has 0.250 inch (0.635 cm)

²M 5.5 = Mixed gap pin; Mixed gap sizes over four inch length near axial mid-plane with indicated gap in remainder of fuel column.

³Fuel for pins P-20-15 and P-20-39 was fabricated with low pressure preslugging techniques, all other P-20 fuel was made with high pressure preslugging methods. TD = Theoretical Density (~10.9 gm/cc) of the fuel.

⁴He = 100% Helium, Xe + He = 18.3% Xenon + 81.7% Helium.

⁵Phase I, Subassembly #X169A; Phase II, Subassembly X169; Phase III, Subassembly #X169B.

the impact on Q'_m of varying the type of porosity. Other pins in the test, which were unirradiated spares from the HEDL P-19 test were used to provide the internal calibration of the HEDL P-20 test to the P-19 test. Also, a pin from the PNL-2⁽¹¹⁾ assembly, with a fuel burnup of 65,000 MWd/MTM (6.7 at.%), was included to help assess Q'_m at high burnup.

Detailed fabrication descriptions of those pins whose data were used in the analyses are given in Appendix C of Reference 3. These pins were the same design as the 0.230 inch (5.84 mm) OD pins used in the P-19 experiment; however, different fuel fabrication lots were used. The results from the mixed gap P-20 pins and the PNL 2-5 pin will not be discussed in this report because analyses on these are incomplete.

The P-20 test was conducted in three phases (see Figure 3). The purpose of Phases I and II was to accumulate fuel burnup under steady-state conditions. The peak fuel pin linear power in these phases was about 13.75 kW/ft (438 W/cm). After the first phase, some pins were removed and unirradiated pins added so that three different burnup levels were achieved (see Table IV). Phase III was then conducted using pins from each of the three burnup levels, plus six "fresh" pins and the PNL-2 fuel pin.

The Phase III portion of the test was scheduled to be conducted with the same power-time history as in the P-19 test (Figure 2). However, several of the hold times were longer (Figure 4) than in the P-19 test because of reactor operating requirements. These are of no consequence to the test results because they occurred at low powers. The EBR-II core loading for this phase was adjusted⁽¹⁴⁾ to obtain at least the same pin power levels as the P-19 test. As will be shown later, fuel burnup and Q'_m data indicate that the powers in the P-20 test were actually significantly higher than those in the P-19 test.

After Phase III irradiation was completed, the pins were neutron radiographed and shipped as rapidly as possible to Los Alamos Scientific Laboratory (LASL) for nondestructive examination. Destructive examination

TABLE IV

Summary of P-20 Irradiation Conditions

	EBR-II		Equivalent Full Power Days	Approximate Accumulated Burnup MWd/MTM (At%)	Reactor Full Power Cycles
	Run No.	Test Posi- tion			
Phase I	61A	3F2	12.4	3700 (0.38)	2.
Phase II	59B	3F2	23.7	7200 (0.74)	6.
Phase I + II	---	---	36.1	10,900 (1.12)	8.
Phase III	62E	1N1	0.26	90 (0.0093)	1.

followed at both HEDL and LASL. Table V summarizes analysis of neutron and betatron radiograph data. Later ceramography confirmed these observations.

Using neutron radiography, betatron radiography, ceramography and autoradiography, the axial extents of fuel melting were determined by the methods used in the analysis of the P-19 test.

C. CERAMOGRAPHIC DATA FROM HEDL P-19 AND P-20

The positions to remove longitudinal ceramography sections, used to identify the axial extents of melting, were located based on the appearance of the central voids observed on the neutron radiographs and betatron radiographs (see Figures 5 and 6). The sections were mounted in plastic and ground to the longitudinal centerline of the pin. Reimpregnation minimized fuel "fall-out" and "pull-out". Photomacrographs, α and β - γ autoradiographs, and 75x photomosaics of the surfaces in the polished and etched conditions were prepared for each section.

From this ceramography, the axial extents of melting* were located. Figures 5 and 6 show examples of the data used to find the axial extents of melting. Reference 3 includes examples from additional P-20 pins. Appendix A describes the fuel characteristics used to locate the axial extent of fuel melting. Appendix E summarizes the positions of the axial extents of fuel melting (which correspond to the location for incipient fuel melting).

*The axial extent is defined as the furthest distance fuel melting is observed from the axial peak power position. In most cases in this report, this is taken with respect to the local central void (see Appendix A). To be valid for use in calculating Q'_m values, the axial extent must be at least 0.13 inch (7.6 mm) back from the ends of the fuel column because of the complications of two-dimensional heat flow in these regions.

TABLE V
FUEL MELTING RESULTS FOR THE PHASE III HEDL P-20 TEST PINS

Preirradiated Burnup, MWd/MTM (At%)	Total Pins	Pure He Pin Fill Gas					18% Xe-82% He Pin Fill Gas 7.5*	Comments
		3.5 (0.089)*	5.5 (0.14)*	7.5 (0.19)*	Mixed	Other		
~0	7	--	1	2**	1	2***	1	All pins had fuel melting
3700 (0.38)	5	1	1	1	1	--	1	Only the 3.5 mil (0.089 mm) gap pin had fuel melting
7200 (0.74)	3	1	1	1	--	--	--	No fuel melting
10900 (1.1)	3	1	1	1	--	--	--	No fuel melting
65000 (6.7)	1	--	--	--	--	1	--	PNL-2-5 had fuel melting

*As built, nominal fuel-to-cladding diametral gap size, mils (mm)

**One pin contained low pressure preslugged fuel

***P-19 spare pins, 7.2 and 7.6 mil (0.18 and 0.19 mm) gaps

In order to normalize the Q'_m data, estimates of the central void and columnar grain radii are needed near the axial extents of melting. These estimates are taken in fuel where no melting occurred. The central void size was also used to find the axial extent of melting with respect to the central void. If a transverse ceramography section (which allows the most accurate measurement of radial regions) was not available, the longitudinal sections used for measurement of axial extents of melting, or sibling pin data were used. Table E-III in Appendix E summarizes these data.

Measurements of the radial extents of melting from the transverse ceramography sections, taken near the axial midplane of the fuel columns, while not used to derive final Q'_m values, make a good check of trends and the magnitude of the Q'_m data derived from the axial extent data. Measurements of central void (which are actually shrinkage cavities when melting has occurred) radii, melt radii, columnar grain region radii and fuel-to-cladding gaps, taken from transverse ceramography from the P-19 and P-20 pins, are tabulated in Tables E-IV and E-V of Appendix E. The measurements from P-19 have been discussed in Reference 2. The measurements from P-20 are discussed in Appendices C and D.

D. CONDITIONS REQUIRED TO CAUSE INCIPIENT FUEL MELTING AT THE AXIAL EXTENTS OF MELTING

The fuel operating conditions (pin power and coolant temperature) affecting the fuel temperatures must be accurately characterized at the locations of axial melting. The uncertainty in operating conditions reflects directly in the derived Q'_m values.

Peak pin powers, in the HEDL P-19 experiment, are based on a detailed study⁽¹²⁾ made by Argonne National Laboratory, ANL. Previous preliminary studies of P-19 used these powers reduced by a factor of 0.94, to account for a bias in the thermal balance made on the EBR-II coolant system. For the present analysis, the factor of 0.91 was used because of more recent

detailed analyses⁽⁹⁾, which included data for the specific reactor run of this experiment. In addition, comparisons⁽¹⁰⁾ of pin powers derived from measured burnup, and pin powers calculated (in a similar manner to that used for P-19) for other HEDL fuel tests show the 0.91 figure to be the most accurate.

The P-19 pin powers (reduced by 9%) were chosen as the base from which to normalize both sets of test data, because of the in-dept analysis⁽¹²⁾ made for the P-19 experiment by the ANL EBR-II project. For the P-20 test, ANL did not perform special detailed post-irradiation analyses, though they did provide general fission rate maps. As described in Appendix B, the HEDL P-20 peak pin powers were derived from results of the spare P-19 pins used in P-20; compared to the behavior of similar pins in the P-19 test. Normalization of the pin powers of the two tests, using the response of the P-19 fuel pins, eliminates the calculational uncertainties that would be introduced by attempting to calculate, on a theoretical basis, the effects on pin power of the differences in the EBR-II core environment between when the P-19 experiment was run (May 1971) and when the P-20 experiment was completed (March 1973). An increase of nine percent, over pin powers in the P-19 test, was calculated as necessary to explain the fuel melting observed in the P-19 sibling pins in the P-20 test. The magnitude of this difference in power was verified by comparing measured fuel burnup values with the time-power history of each test.

Appendix B also reviews the method used to define the axial power distributions for the HEDL P-19 pins and the HEDL P-20 pins in Phase III. From the axial power profiles and the peak power of each pin, the local power, thus Q'_m , at each axial extent of melting was found. The values were corrected upward slightly, based on the increased amount of fuel, if a fuel plug was present in the central void at the location of the axial extent of melting.

The Q'_m values* derived from the axial extents of melting and power profiles are summarized in Tables E-I and E-II of Appendix E, and are shown in Figures 7 and 8. Values from the P-20 pin with xenon tag gas are not valid for axial extents of melting since this pin had centerline fuel melting from the top to the bottom of the fuel column. Thus, Q'_m for this pin must be less than the powers at the ends of the fuel column, and points corresponding to these powers form an "upper bound" of Q'_m . Only one P-20 pin with burnup prior to Phase III had fuel melting. The maximum powers reached by similar fuel pins that experienced no melting (based on a study of radiographs and transverse fuel ceramography) are included in Figure 8. These peak power values establish a "lower bound" of Q'_m for these pins (i.e., Q'_m is greater than these peak power values). Similarly, "lower bound" points are shown in Figure 7 for the P-19 fuel pins that did not melt.

In order to characterize the cladding temperature to associate with the axial extents of melting, the coolant flow rates for each pin must be determined. It was calculated, accounting for the .91 factor previously noted, that there was a coolant mass flow rate of 1340 lb/hr (607.8 kg/hr) at 800°F (427°C) for each pin in P-19, and a coolant mass flow rate of 768 lb/hr (348.4 kg/hr) at 800°F for each pin in Phase III of the P-20 test. Appendix B summarizes briefly how these flow rates were derived. Tables E-I and E-II of Appendix E show the calculated coolant temperature at each axial extent of melting based on pin power, coolant flow rate and axial power profile.

*These values are "deposited" powers. Thus they represent the total energy deposited in the test assemblies per fission (about 193 MeV or 30.92 pJ), not the total energy generated in the reactor core per fission from the test assembly's fuel (about 202.6 MeV or 32.46 pJ). The difference is due to energy being deposited in the reactor blanket and reflector and to highly enriched fuel elements in the EBR-II core producing more gamma related energy than they absorb (Reference 12).

E. NORMALIZATION OF POWER-TO-MELT DATA

The Q'_m data were normalized to a single set of parameters for direct use of the data in reactor design applications. Parameters pertinent to FFTF were selected as follows:

- Cladding ID temperature, 1060°F (570°C) [equivalent to the hot channel midplane temperature in FFTF operating at 115% of normal power with a 600°F (315.6°C) coolant inlet temperature]
- Plenum temperature, 1060°F
- Pellet density, 90.4% TD
- Cladding and fuel geometry, 0.230 inch (5.84 mm) OD cladding.

A modified version of SIEX-M1,⁽⁸⁾ [an updated version of the SIEX⁽⁶⁾ code] was used for the normalization calculations. For the majority of the data, the normalization needed minimal calculations since the tests were designed to be as near the selected FFTF conditions as possible. The normalization of the data from the 0.250 inch (6.35 mm) OD fuel pins to the smaller, 0.230 inch (5.84 mm) OD size represents the greatest adjustment needed.

Figure 9 indicates the normalization method used. Basic steps followed were:

1) The fuel-to-cladding gap conductance model, H, was adjusted in the SIEX-M1 code thermal simulation, at the location of the axial fuel melting extent, with all other variables (i.e., local power, central void size, pellet density, local cladding temperature, measured restructuring, etc.) held constant, until incipient fuel melting was calculated. [Note: Adjustment was made by changing the value of one of the calibration constants in the gap conductance model.^(6,8)]

2) Normalization values were entered for fuel pellet density, cladding ID temperature, and plenum temperature. Also, for the 0.250 inch (6.35 mm) fuel pins, the fuel and cladding sizes were adjusted.

3) The local linear power was then adjusted until incipient melting (Q'_m normalized) was again calculated.

For the 0.230 inch (5.84 mm) OD fuel pin data, the only adjustment made by the code to the gap conductance was for the effect of temperature on the local gas thermal conductivity and the gas pressure in the fuel-to-cladding gap. For the data from 0.250 inch (6.35 mm) OD pins that were in P-19, SIEX-M1 was used to recalculate a new hot gap when normalizing to the 0.230 inch (5.84 mm) size and to adjust for temperature changes affecting gap conductance. In addition, 0.018 cc of N_2 and 0.035 cc of Ar, at standard temperature and pressure (STP) conditions were assumed to be in the plenum gas for all normalizations. This assumption was consistent with post-test measurements from P-19 and P-20. This gas is assumed to come from gases absorbed by the fuel during fabrication.

Figures 10 and 11 show the normalized Q'_m data for the two experiments.

F. DISCUSSION OF POWER-TO-MELT RESULTS

Figure 10 summarizes the normalized data for the "fresh" (60 to 90 MWd/MTM or 0.0093 to 0.0062 at.%) pins from the HEDL P-19 and P-20 experiments. The agreement between the two sets of data is good except for the 0.0055 inch (0.14 mm) fuel-to-cladding diametral gap pin from the P-20 test. The trend observed is for Q'_m to increase with decreasing fabricated fuel-to-cladding gap size up to a certain gap size (about 0.0045 inch or 0.114 mm) and then to become a constant value. This is interpreted as the heat being transferred, at first only through the gas in the gap, then the fuel and cladding surfaces coming in contact with each other (on a microscopic level) resulting in a "transition" region, and finally, a constant transfer system being established consisting of both solid-to-solid contact and conductivity through the gas. The final constant value at small gap sizes is the result of the fuel yielding before enough stress is built-up to plastically strain the cladding, thus, there is no further increase in interface pressure. This interpretation

is based on measured profilometry of the cladding OD's where no cladding diameter change was found in any of the P-19 and P-20 test pins when compared to original dimensions.

The reason for the lower result in Q'_m from the P-20 pin with the 0.0055 inch (0.14 mm) fuel-to-cladding diametral gap is not clear. A possible cause for this behavior follows. The fuel and cladding at operating temperatures at Q'_m will come into contact if the fabricated diametral gap is approximately 0.0055 inch (0.14 mm) or less. The mechanisms of heat transfer change at contact from thermal conduction through gas, to a combination of conduction through the gas, and solid-to-solid conduction through contacting microscopic points of the surfaces. The P-20 pin in question is in this "transition" region between no contact and contact at a constant interface pressure, the latter causing improved conductivity. Thus, the lower result for P-20 could be indicating a sensitivity to slight differences between the test fuel pins in roughness and waviness of the fuel and cladding surfaces. However, this cannot be confirmed at this time because surface roughness of the fuel and cladding in both tests was not measured. Although the rest of the Q'_m data for this and smaller gap sizes are from normalized data from the P-19 0.250 inch (6.35 mm) OD pins, the "lower bound" points from the P-19 pins with 0.230 inch (5.84 mm) OD and no fuel melting, substantiate the normalized points from the 0.250 inch OD pins.

The pin in P-20 with low pressure preslugged fuel appears to have a slightly higher Q'_m than the high pressure preslugged fuel. This is consistent with the fuel restructuring results, described in Appendix C, for P-20 Phase I and II pins. Fuel restructuring in these pins was found to be slightly less in the low pressure preslugged fuel, indicating lower temperatures in this type of fuel. Rather than these small differences, observed in performance, being all a result of high and low pressure preslugging, they may, in part, be the result of other unintentional differences in the fuel batches. The low pressure preslugged fuel had 0.5% higher density (hence it had a potentially higher thermal conductivity than

the other fuel), and less nonhelium gases absorbed during fabrication than the high pressure preslugged fuel. This last condition could lower fuel conductivity in the high pressure preslugged fuel if the gases were retained in the fuel or lower the fuel-to-cladding gap conductance initially if the gases were released. The nonhelium gases, exclusive of hydrogen, have thermal conductivities an order of magnitude less than that of helium.

Figure 11 shows the normalized results from the pins with the three levels of burnup from the HEDL P-20 test. The improvement in normalized Q'_m for the 18% xenon tagged pin is more than 25% in going from the upper bound of the "fresh" pin Q'_m , Figure 10, to the lower bound of the Phase I pin irradiated to 3700 MWd/MTM (0.38 at.%), Figure 11.

The P-20 preirradiated pin from Phase I, with a 0.0035 inch (0.09 mm) diametral gap, was the only pin which experienced fuel melting. The axial extents of melting were located at positions which operated at power levels within one percent of the peak power of the pin. Thus, the peak power region was very close to incipient melting. From the data in Figure 11, including the lower bound pins in which there was no fuel melting, we conclude that the effect of fabricated fuel-to-cladding gap size on the power-to-melt is no longer a dominant variable after a short time of irradiation. The apparent reason for this is described in the following section.

Application of these results to FFTF/FBR fuel performance prediction shows the data's significant implications. Viable fuel pin fabrication processes require diametral gaps whose tolerances exceed 0.005 inch (0.13 mm). It has been necessary to allow for the reduction in Q'_m in the thermal design of fast reactor fuel pins, as well as to employ centerless grinding of the fuel pellets, in order to control pellet OD's to tight tolerances. The test results now indicate that it is possible, after a short conditioning period (less than 3700 MWd/MTM or 0.38 at.%), not only to increase the thermal rating of the FBR at least 20% but, if a reduced power is used initially, to relax restrictive limits, due to Q'_m , on the maximum fabricated gap size.

G. DISCUSSION OF PROPOSED FUEL BEHAVIOR WITH BURNUP, BASED ON P-20 PHASE I AND II RESULTS

A sibling (similar fuel in an identical pin) of each preirradiated P-20 pin in Phase III was nondestructively and destructively examined. In addition to these sibling pins, several other pins with different gap sizes and burnup levels of interest were also examined. Typically the pins were:

- Neutron and betatron radiographed
- Precision gamma scanned
- Punctured for recovery of fission gas
- Sectioned for burnup analysis and ceramography

A review of the ceramography and fission gas release data is described in Appendix C. Conclusions drawn from pins in Phase I and II as they affect Q'_m are:

1) The residual fuel-to-cladding diametral gap (gap measured during destructive examination⁽¹⁵⁾) rapidly approaches 0.001 to 0.0025 inch (0.025 to 0.064 mm), at a burnup of less than 3700 MWd/MTM (0.38 at.%). At higher burnups, the gap is observed to continue to close but at a much slower rate. It is believed the fuel and cladding are in contact (zero hot gap) by the end of Phase I, when operating at power levels equal to or greater than those in Phase I. The observed small amount of continued reduction in the residual gaps with burnup is believed to be the effect of lower fuel temperatures, caused by improved gap conductance, as burnup is accumulated beyond the Phase I level. The lower temperatures affect the fuel thermal expansion resulting in the fuel contracting less from the cladding as the pin power is reduced.

2) The columnar grain region apparently forms early, before the hot gaps close. This reflects a marked dependence on the fabricated gap size; being larger in fuel pins fabricated with larger gaps. Additional columnar restructuring does not occur beyond Phase I burnup.

3) Measurements of the equiaxed grain growth region show little original fuel-to-cladding gap dependence, indicating that this region is principally formed after the majority of gap closure has occurred.

4) The amount of fission gas released from the fuel to the gas plenum in pins from Phase I (3700 MWd/MTM or 0.38 at.%) shows a direct dependence on fabricated fuel-to-cladding gap size. However, for pins from Phase II (7200 MWd/MTM or 0.74 at.%) and Phase I plus II (10900 MWd/MTM or 1.12 at.%), release values are inversely dependent on original gap size. This leads to the conclusion, since fission gas release from the fuel is expected to be very dependent on fuel temperatures, that fuel temperatures were, for a major portion of Phase I, lower in the pins fabricated with smaller gaps. However, at higher burnup levels (Phase II and Phase I plus II), fuel temperatures were higher in the pins fabricated with small gaps.

Thus, all these data imply that peak fuel temperatures occurred early in irradiation followed by decreasing fuel temperatures. This was due to rapid fuel-to-cladding gap closure with proportionally more closure for larger gaps. By 3700 MWd/MTM (0.38 at.%) burnup, the hot fuel-to-cladding gaps are closed. The residual gaps continue to be slightly smaller after this because of fuel temperatures decreasing somewhat with time. The final residual diametral gaps are in a fairly uniform range, from 0.001 to 0.0025 inch (0.025 to 0.064 mm).

Similar postirradiation examinations were made to pins preirradiated in Phase I and/or II and then operated in the overpower, Phase III. The results of these examinations are reviewed in Appendix D. The following summarizes observations from these data and conclusions that pertain to Q'_m response:

1) There was little, if any, significant difference in measured residual fuel-to-cladding gaps between these pins and the sibling pins, previously discussed, that were not in Phase III. The only difference observed was a slight trend for pins fabricated with smaller gaps to have larger

residual gaps, than the sibling pins, after the Phase III overpower. This is consistent with the previous conclusion, drawn from the data on pins that were only in Phase I and/or II, that the hot gaps are closed at heat rates equal to or greater than those in Phase I and II. Thus, the resulting residual gaps observed are the results of differential thermal expansion of the fuel and cladding. If the pins with the small fabricated gaps are operating with hotter fuel than the pins fabricated with large gaps, it would be expected that the fuel will contract more on shutdown in the pins with smaller original gaps.

2) Columnar grain and central void measurements showed no significant change from the sibling data from pins not in Phase III. Thus, no additional fuel restructuring, due to the Phase III overpower, occurred in these pins. It is likely the temperature at the terminus of the columnar grain region never exceeded initial values, even at the overpower, due to pronounced gap closure.

3) Fission gas release from the fuel to the gas plenum in these pins confirmed the dependences observed in the sibling Phase I and II pins. The Phase III exposure caused an additional two-to-six percent fission gas release for the majority of pins. Consistent with the premise that the pins fabricated with smaller gaps are operating hotter; these pins, in many cases, released more additional gas than comparable pins with larger gaps.

Thus, this second set of data confirms the conclusions drawn from the data taken from the pins irradiated only in Phase I and/or II.

Section II of Appendix D reviews the fuel restructuring, gap closure, and fission gas release of the "fresh" fuel pins in Phase III of the P-20 test. A comparison is also made between the restructuring data from the fresh fuel and the preirradiated fuel. From these studies, it was concluded that in the fresh pins the columnar grain regions and central voids are still maturing, and that the residual fuel-to-cladding gaps in the fresh pins are all at least slightly smaller than the fabricated gaps.

The interpretations given above, of behavior of the gap and the maturing of the fuel restructuring, explain the significant improvement in power-to-melt observed with just the Phase I preirradiation. From these, the reason for the burnup behavior of Q'_m and the other observations can be explained. To summarize (also see Appendix C):

The fuel temperatures, including the fuel centerline temperature, are at first (beginning of irradiation) very dependent on fabricated gap size. Fuel temperatures of pins fabricated with small fuel-to-cladding gaps are less than ones fabricated with larger gaps. After a short period of time, however, rapid gap closure puts the fuel and cladding in contact (resulting in all the residual gap sizes being about the same). Thus, the temperature drop across the gaps become very similar for all the pins and these drops are less than at the beginning of irradiation, especially for large gap pins. The extents of the columnar grain regions apparently form prior to this gap closure resulting in the pins with small gaps having significantly smaller columnar grain regions. As burnup accumulates, the restructured regions mature and the fuel cracks heal in the restructured zones, moving part of the fuel-to-cladding gap volume to the central void. This forms central voids larger than can be explained just by densification of the fuel pellets in the columnar grain region;⁽¹⁶⁾ larger gaps lead to larger central voids. Since the hot gaps are now closed or nearly closed, the temperature change across them must be about the same and the temperature increase across the fuel itself controls the differences in fuel centerline temperatures. The fuel in pins fabricated with the smaller gaps, have smaller columnar grain regions and central void radii so they will operate at higher centerline temperatures. This follows from the increased thermal conductivity of the higher density columnar grain regions and the larger central voids (i.e., shorter heat paths) that result in the fuel with larger columnar grain regions.

The above explains the main reason why the fuel pin, having a 0.0035 inch (0.09 mm) diametral gap and irradiated in Phase I, later melted in Phase III while larger gap pins with the same preirradiation burnup and even having Xe tag gas did not. This pin had the smallest initial gap and highest

fuel smeared density* of the group of Phase I pins in Phase III. It had the least columnar grain (note data Appendix C and D) and central void formation. Therefore, this fuel pin operated at higher fuel temperatures than the other pins once the fuel-to-cladding gaps were closed.

The relatively higher temperatures in the P-20 preirradiated fuel pins with smaller initial gaps were further enhanced by the slightly higher specific power of the small gap pins because of higher fuel smeared density. The P-20 fuel pellets were all about the same density so a decrease in fuel-to-cladding gap size in the same size cladding tube results in a higher fuel smeared density and increased linear power.

None of the pins preirradiated to higher burnups, 7200 MWd/MTM or 0.74 at.% (Phase II) and 10,900 MWd/MTM or 1.12 at.% (Phases I and II), and irradiated in Phase III experienced fuel melting. This is due to further small improvements in thermal performance probably caused by improved heat transfer between the contacting fuel and cladding surfaces (caused by creep of the contacting surface microscopic asperities and/or buildup of solid fission products in the voids between these contacting asperities).

H. POWER-TO-MELT RESULTS FROM RADIAL EXTENTS OF MELTING

Figure 12 shows the normalized Q'_m values derived from radial extents of melting measured near the fuel column midplanes of "fresh" pins, tabulated in Tables E-IV and E-V of Appendix E. The radial extent data were normalized with a method similar to that used for the axial extent data. Since there is no way to directly calculate the columnar grain density at the location of the radial melting extents (the central void observed is actually a molten fuel shrinkage cavity), the average of values found near the axial extents of melting were used. None of the powers used to derive Q'_m values were corrected for molten fuel plugs that were probably present during part of the irradiation.

*Fuel smeared density: Mass of fuel divided by the corresponding volume within cladding ID, $(\text{Fuel mass per unit length, } L) / \left(\frac{[\text{Clad ID}]^2 \times \pi}{4} \right)$

In general, the trends and magnitudes for Q'_m calculated from these data are in good agreement (see Figure 11) with those derived from axial extent data. Note the higher Q'_m result, compared to the results from the axial extent analysis, for the P-20 pin with a 0.0055 inch (0.14 mm) gap. This type behavior (Q'_m being higher where the actual interface pressures were high due to the local power being higher than Q'_m) adds credence to the theory proposed in Section III, F about the resulting low Q'_m values derived from the axial extents of melting from this pin. Other assumptions for fuel restructuring and local power, due to changes caused by molten fuel plugs, can change the results from these sections significantly. Thus, no further analysis was made using these data.

No plot of Q'_m values from radial extents from higher burnup pins is made since it follows that they would be the same as Figure 11; only one pin actually experienced any fuel melting and this was, in effect, at incipient melting.

I. EXPECTED UNCERTAINTY IN POWER-TO-MELT VALUES DERIVED FROM AXIAL EXTENTS OF MELTING

A good estimate of the uncertainty involved in the derivation of Q'_m from the axial extents of melting can be made from the uncertainty in calculating the local power at these points. The uncertainties in the location of the melt extent and coolant temperature at these positions are minor compared to the power uncertainty.

Reference 12 stated the uncertainty in calculating pin powers in P-19, to which all data were normalized, to be about 10%. However, a 6% uncertainty, which was noted to be directional, was included in this estimate for determining the actual EBR-II reactor power level. More recent analyses⁽⁹⁾ of this "uncertainty" have shown it to be a real bias in the system of $9 \pm 2\%$. Powers in this report were corrected downward for the 9%, as described in Section III, D.

It is estimated, combining the uncertainty in the calculation of absolute peak pin power with the uncertainty in locating and calculating local powers at the axial extents of melting, that the absolute uncertainty in the Q'_m values is on the order of $\pm 6\%$. In addition to this uncertainty, there is an uncertainty in measured fabricated diametral gap size on the order of ± 0.0003 inch (± 0.008 mm).

J. MATHEMATICAL FIT OF NORMALIZED DATA

For design purposes, it is helpful to have a simple mathematical expression of the normalized Q'_m data as a function of fabricated gap. A cubic equation was "fit" to the data in Figure 10, for pins that had 100% He fill-gas at the start-of-life ("upper" and "lower" bound data was not included). The final expression that resulted for this fresh fuel data was:

$$P_F = 16.31 + 1.543G - .353G^2 + .0188G^3$$

$$3 \leq G \leq 10$$

$$[P_{F1} = 535.1 + 1993G_1 - 1.795 \times 10^4 G_1^2 + 3.764 \times 10^4 G_1^3]$$

$$[0.076 \leq G_1 \leq 0.254]$$

$$P_F = Q'_m \text{ a "fresh" pin with 100\% He fill-gas, kW/ft}$$

$$[P_{F1} = P_F \text{ in W/cm}]$$

$$G = \text{Fabricated diametral gap, mils}$$

$$[G_1 = G \text{ in mm}]$$

and is plotted along with the data in Figure 13. The cubic form was chosen for its representation of the data shape and its ease of application. No physical reason is implied by its use.

If a correction for 10% Xe tag gas is made, typical of the fill-gas composition of FFTF driver pins, the curve shown in Figure 14 is predicted. Here, the difference between the tagged and untagged cases is based on differences predicted by the calibrated SIEX-M1 code.⁽⁸⁾ This version of the SIEX code was calibrated to the Q'_m data developed in this report, and incorporates updated material properties and residual fuel-to-cladding gap models calibrated specifically to the P-19 and P-20 data. The resulting cubic equation representing this curve is:

$$P_{FT} = 17.28 + .834G - .285G^2 + .0171G^3$$

$$3 \leq G \leq 10$$

$$[P_{FT}] = 567.0 + 1.077 \times 10^3 G_1 - 1.449 \times 10^4 G_1^2 + 3.424 \times 10^4 G_1^3]$$

$$[0.076 \leq G_1 \leq 0.254]$$

$$P_{FT} = Q'_m \text{ for a "fresh" pin with 10\% Xe tag, kW/ft}$$

$$[P_{FT}] = P_{FT} \text{ in W/cm]}$$

$$G = \text{Fabricated diametral gap mils}$$

$$[G_1 = G \text{ in mm}]$$

Figure 14 displays the adjusted cubic curve.

For the higher burnup data (between 3700 and 10,900 MWd/MTM, or 0.38 and 1.12 at.%), from Figure 11, a very conservative linear expression, actually representing a lower bound, can be implied by using the single set of Q'_m data points and the "lower bound" data points (which are lower than Q'_m). The expression resulting is:

$$P_B = 19.3 - .125G$$

$$3 \leq G \leq 10$$

$$[P_{B1} = 633. - 4.10G]$$

$$[0.076 \leq G_1 \leq 0.254]$$

P_B = Minimum Q'_m for a fuel pin with burnup between 3700 and 10,900 MWd/MTM (0.38 and 1.12 at.%), kW/ft

$$[P_{B1} = P_B \text{ in W/cm}]$$

G = Fabricated diametral gap, mils

$$[G_1 = G \text{ in mm}]$$

and is shown in Figure 15. Based on the results for the 18% Xe tagged pin and predictions from the SIEX-M1 code, this expression is valid for both pins fabricated with 100% He fill-gas or 10% Xe-90% He fill-gas. The trend of this line through the data does not reflect the predictions of the calibrated SIEX-M1 code nor the actual Q'_m values of preirradiated fuel. It is representative only of the minimum Q'_m implied by the P-20 data.

IV. CONCLUSIONS

Figure 10 illustrates the conclusions that can be drawn from the "fresh" pin data from HEDL P-19 and P-20. With fresh fuel (burnup of 60 to 90 MWd/MTM or 0.0062 to 0.0093 at.%), there is a definite dependence of Q'_m on fabricated fuel-to-cladding gap size. The data show a decrease in Q'_m values as the fabricated fuel-to-cladding diametral gap increases beyond 0.005 inch (0.13 mm). This is interpreted to be due to the fuel and cladding no longer being in contact and the heat being transferred only through a gas gap. Normalized Q'_m values ranged from about 18.5 kW/ft (607 W/cm) to 14.5 kW/ft (475 W/cm) over the diametral fuel-to-cladding gap range of 0.003 to 0.010 inch (0.08 to 0.254 mm), for fuel pins back-filled with helium.

The primary conclusion that can be drawn from the higher burnup data, based on this analysis, is illustrated in Figure 11. By the time 3700 MWd/MTM (0.38 at.%) is reached, the linear heat-rating-to-melting, Q'_m , is at least 18.5 kW/ft (607 W/cm) and is independent of starting gap size. This is at least a 20% relative improvement over the results found for the "fresh" pins fabricated with pure He fill gas, at a diametral gap of 0.0075 inch (0.13 mm). The improvement in Q'_m observed for the 18% xenon gas tagged pin was over 25%, from under 15.3 kW/ft (501 W/cm) "fresh" to over 18.3 kW/ft (600 W/cm) at 3700 MWd/MTM (0.38 at.%). This improvement in thermal performance with initial burnup is caused primarily by maturing of the fuel restructured regions and early fuel-to-cladding gap closure. The latter eliminates the initial fabricated fuel-to-cladding gap, in the range tested, as a major variable affecting Q'_m after a small burnup is accumulated.

These test results verify previous less refined analyses and have significant implications about the performance predictions for FFTF/FBR type fuel. The higher burnup data indicate that with a short conditioning period (less than 12 full power days or 3700 MWd/MTM, 0.38 at.% with several full power cycles) thermal rating of a FBR with $\text{PuO}_2\text{-UO}_2$ fuel could be increased by 20%. Further, if this mode of operation is used, restrictive limits on maximum fabricated gap size, due to Q'_m behavior, can be relaxed.

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VI. FIGURES

FFTF DRIVER FUEL PIN

FIGURE 1. Schematic Illustration of the FFTF Driver Fuel Pin.

Photo No. 779905-1

HEDL 7506-117.8

FIGURE 2. Power History During HEDL P-19 Test.

Photo No. 7711280-3

HEDL 7611-54.11

FIGURE 3. Peak Power History for a Nominal HEDL P-20 Pin.

Photo No. 771275-6

FIGURE 4. Power-Time History for HEDL P-20 Phase III.

Photo No. 7711280-2

FIGURE 5. Regions at Axial Extents of Fuel Melting in HEDL P-20/19-34 (etched longitudinal ceramography, betatron radiography, and neutron radiography with arrows locating positions of axial extents of melting).

Photo No. PNL740686-5

FIGURE 6. Regions at Axial Extents of Fuel Melting in HEDL P-20-33 (etched longitudinal ceramography, betatron radiography, and neutron radiography with arrows locating positions of axial extents of melting).

Photo No. PNL740686-1

FIGURE 7. Q'_m Data Derived From Axial Extents of Melting in Pins Included in the HEDL P-19 Test.

Photo No. 779905-11

HEDL 7611-54.22

FIGURE 8. Q'_m Data Derived from Axial Extents of Melting in Pins Included in the HEDL P-20 Test.
Photo No. 770572-11

STEP 1 MATCH ORIGINAL CONDITIONS

HEDL 7710-146.1

FIGURE 9. Normalization of Q'_m values.

Photo No. 7711280-1

FIGURE 10. Normalized Q'_m Values for "Fresh" Fuel.

Photo No. 7710426-2

HEDL 7709-116.5

FIGURE 11. Normalized Q'_m Values for Fuel with Significant Burnup.

Photo No. 779905-5

HEDL 7709-116.6

FIGURE 12. Normalized Q'_m Values Calculated from Radial Extents of Melting in "Fresh" Pins.

Photo No. 77990

HEDL 7709-116.7

FIGURE 13. Cubic "Fit" of Q'_m Data from "Fresh" Pins Normalized to FFTF Conditions with Helium Fill-Gas.

Photo No. 779905-7

HEDL 7709-116.8

FIGURE 14. Cubic "Fit" of Q'_m Data from Fresh Pins Adjusted to FFTF Conditions with 10% Xe Tag Gas.

Photo No. 7710426-3

HEDL 7709-116.9

FIGURE 15. Fit of "Lower Bound" Q'_m Data with Burnups to 10900 MWd/MTM (1.12 at.%). Photo No. 779905-9

APPENDIX A

INDICATOR OF EXTENTS OF FUEL MELTING
IN HEDL P-19 AND P-20

APPENDIX A

INDICATORS OF EXTENTS OF FUEL MELTING IN HEDL P-19 AND P-20

The purpose of this appendix is to review the type of indicators that were used for the determination of the extents of melting found in this report. Both radial and axial extents will be discussed. Appendix K of Reference 1 describes some general observations on molten fuel boundaries and data from other tests.

Radial Extent of Melting as Determined from Transverse Ceramography

Transverse ceramography sections removed from selected axial locations of once molten fuel pins were mounted in clear resin and polished. Macro-photographs (Figure A-1), autoradiographs (β - γ , Figure A-2) and a 75X photomosaic (Figure A-3) were then made from the sample in this condition. A strong chemical etch was then used. This etch ($80 \text{ H}_2\text{O}_2(30\%)20 \text{ H}_2\text{SO}_4$) had shown a quality of accenting molten fuel zones. The sample then had another 75x photomosaic (Figure A-4) made from it in this state (usually with oblique lighting which further accentuated the molten fuel zone).

The main determining features for the extents of melting were:

- 1) β - γ autoradiographs: The largest distinct radius of the activity-depleted (white) zone in the annulus of active (dark) and depleted zones in the molten region was taken as an indicator of furthest extent of melting. The active and depleted zones (Figure A-2 and A-6) are believed to correspond to concentrations of Ruthenium. [The extent of an enriched zone in the α autoradiography (Figure A-9) indicates the extent of melting at shutdown. However, it is usually indistinct.]
- 2) As-polished Ceramography: The extent coincides with the furthest extent of a zone in the fuel free of small pores (Figure A-3). This can also be seen in Figure A-5, an etched sample.

References

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HEDL P-19, Compiled by R. D. Leggett, HEDL-TME 71-92, Hanford
Engineering Development Laboratory, Richland, WA, June 1971.

FIGURE A-1. Example of Macrophotography of a Transverse Fuel Section in "As-Polished" Condition (P-19-35, Sample D).

Photo No. 7611090-1

FIGURE A-2. Example of β - γ Autoradiograph of a Transverse Fuel Section (P-19-35, Sample D).

FIGURE A-3. Example of Photomosaic (Originally 75X) of a Transverse Fuel Section in "As-Polished" Condition (P-19-35, Sample D).

Photo No. 712292-2

FIGURE A-4 Example of Photomosaic (Originally 75X) of a Transverse Fuel Section Chemically Etched $[80\text{H}_2\text{O}_2(30\%)20\text{H}_2\text{SO}_4]$ (P-19-35, Sample D).

**MAXIMUM EXTENT
OF MELTING**

**FUEL THAT WAS
MOLTEN AT SHUTDOWN**

FIGURE A-5. Ceromographic Appearance of an Etched Section D from HEDL P-19-35 (This area is at the center of the fuel. Oblique illumination was used).

Photo No. 724481-1

FIGURE A-6. Example of Molten Zone Extent Indicator on β - γ Autoradiograph (note white continuous band around molten annulus).

A-12

FIGURE A-7. Example of Molten Fuel Axial Extent in "As-Polished" Longitudinal Sample (P-19-27R, Sample H-1).

Photo No. 713022-2

A-13

FIGURE A-8. Example of Molten Fuel Axial Extent After Chemically Etching a Longitudinal Sample (molten fuel is to the left; note dendritic structure).

Photo No. 713022-1

ALPHA
10X

BETA-GAMMA
10X

FIGURE A-9. Examples of Molten Fuel Indicators Present in Autoradiography of Longitudinal Fuel Section (P-20/19-34G).

Photo No. PNL 753945-1

A-15

POINT B: AXIAL EXTENT OF MELTING
WITH RESPECT TO THE
CENTRAL VOID

POINT A: AXIAL EXTENT OF FUEL PLUG

HEDL 7707-15

FIGURE A-10. Axial Extent of Melting with Respect to the Central Void (P-19-27R, Sample H-1).

Photo No. 775869-1

APPENDIX B

CHARACTERIZATION OF COOLANT FLOW RATES, AXIAL POWER PROFILES AND NORMALIZED PIN POWERS

APPENDIX B

CHARACTERIZATION OF COOLANT FLOW RATES, AXIAL POWER PROFILES AND NORMALIZED PIN POWERS

Coolant Flow Rates in HEDL P-19 and P-20 Assemblies

The flow rate of coolant, assumed in the present analysis, for the P-19 assembly was based on ANL calculations. These, in turn, were based on a pretest flow test made on the assembly and reactor operating conditions. The flow rate of the sodium coolant (after correction for the 0.91 factor) was calculated to be 1340 lb/hr (607.8 kg/hr) at 800°F (427°C). Tests on the type of assembly used for P-19 and P-20, with shroud tubes, have shown that there is an equal split of coolant to each pin. Thus, no mixing or pin-to-pin bias need to be accounted for.

The flow rate in the P-20 Phase III assembly was calculated based on pretest flow measurements on the assembly and on the measured reactor core coolant pressure drop during irradiation. This calculation yielded a coolant flow rate of 768 lb/hr (348.4 kg/hr) at 800°F (427°C).

Axial Power Profile for HEDL P-19

The axial power profile used for the HEDL P-19 fuel pins was based on a curve taken from an EBR-II Users Guide⁽¹⁾ for ^{235}U fission rates. This was confirmed with a series of measured burnup values taken from the P-19-33 fuel pin. This pin experienced no fuel melting. Figure B-1 shows this curve and the results of the burnup analyses, which were based on Nd-148. Although the burnup values measured in this manner will have a large absolute uncertainty, the relative values should be very accurate. This will be noted in the following section.

Gamma scan results from P-19-33 and other P-19 fuel pins also confirmed the axial profile shown in Figure B-1.

Axial Power Profile P-20 Phase III

The axial power profile for Phase III was derived from burnup samples taken from four "fresh" pins used in this portion of the test. Samples were taken at various axial locations along the length of the fuel column and then were analyzed for fuel burnup based on Nd-148. Where melting was present in the fuel column, samples were taken where large shrinkage cavities existed (determined by neutron and betatron radiography). This minimized the possibility of fuel from other locations moving into the burnup sample location and remaining there affecting the burnup measurement. Fuel pins irradiated in a fast flux environment should exhibit a uniform radial burnup profile, thus, fuel that relocated out of a section will not affect the burnup measurement.

The burnup results for each of four pins were normlized to peak values, and these data were then fit with a fourth order polynomial, shown in Figure B-2.

While the uncertainty expected for these low burnup levels (about 90 MWd/MTM or 0.0093 at.%) is fairly large (about $\pm 30\%$) the precision of the measurements was shown to be much better than this. An exchange of a number of HEDL P-19 and P-20 burnup samples between the HEDL and LASL chemistry laboratories showed the largest disagreement in measured burnup to be only four percent. The average disagreement found between seven cross-checks was less than one percent.

The power profile in Figure B-2 agreed with the profile determined from Zr-95 gamma scan results, but was somewhat different (shifted 0.4 inches toward the top and no peaking at the ends) from the curve described for fission rates of ^{235}U taken from the EBR-II Users Guide.⁽²⁾ This result is not unexpected since P-20 Phase III had a special EBR-II core loading and was experimental (no axial stainless steel reflectors) fuel rather than the driver fuel discussed in the guide.

HEDL P-20 Peak Pin Powers Normalized to HEDL P-19 Powers

Peak pin powers for P-20 pins were first calculated from post-run fission rate maps provided by the ANL EBR-II project. These were multiplied by 0.91 as noted in the main text, Section III, C. From the powers and the axial power profile derived above, calculations of local power-to-incipient fuel melting, Q'_m , were made for the two "fresh" spare P-19 pins used in P-20 Phase III. Q'_m values were normalized to FFTF conditions of 90.4% T.D. pellet density and 1060°F (571.1°C) cladding ID temperature as described in Section III, D of the main text. These results were then compared to normalized Q'_m values found in the HEDL P-19 test for similar gap size pins. The average difference in normalized Q'_m values was found to be 12.6% lower for the P-20 values. This indicated, since the normalized Q'_m values should be the same for both experiments with the same fuel-to-cladding gap size and the same fuel, that the powers calculated for P-20 were too low. Because of this analysis and the supporting data described below, the P-20 pin powers were normalized to the P-19 powers. Thus relative comparisons of Q'_m could be made. The P-19 pin powers were chosen as the base to normalize to instead of the P-20 powers because of the in-depth analysis made of P-19 by ANL.⁽³⁾ No such analysis existed for P-20. Adjustment factors were applied to the P-20 powers until normalized data from the two P-19 pins, included in Phase III of the P-20 test, agreed with normalized Q'_m values from P-19 work. The P-20 pin powers had to be increased by eleven percent (2% higher than the original fission rate values supplied by ANL) to make the two sets of test data agree. This adjustment resulted in the calculated peak pin powers in the P-20 test being 9% higher than those in similar pins in the P-19 test.

The results from Nd-148 burnup analysis from P-19 and P-20 substantiate that the P-20 test was running at a higher power. Burnup measurements from both experiments, as was noted in the previous section on axial power profile, are very consistent and have been cross-checked for precision. The ratio of burnup measurements from the two tests should be an accurate value. Taking the average of the peak burnups from a number of similar pins from

each experiment and dividing by the integrated area under the reactor power-time history, (i.e., the total megawatt-hours for the reactor) Figures 2 and 4 of the main text, it is found:

$$\frac{\text{P-19}}{.0061 \text{ at.\%}} = \frac{287.4 \text{ MW-hr}}{2.12 \times 10^5 \text{ at.\% MW-hr}}$$

$$\frac{\text{P-20}}{.0094 \text{ at.\%}} = \frac{393.5 \text{ MW-hr}}{2.39 \times 10^5 \text{ at.\% MW-hr}}$$

This indicates, assuming a linear relation between reactor power level and fuel burnup, that P-20 was operating at 12.7% higher power than P-19. Burnup was accumulating this much faster per megawatt-hour in the test fuel of the P-20 test. This confirms the magnitude of the absolute power difference between the P-19 and P-20 tests. The final difference relative to P-19 test pin power calculated using normalized Q'_m of the P-19 pins in the P-20 test was 9%. This is a more conservative value than the 12.7 value indicated by the burnup, hence its use in the final analysis.

Correction of Local Power for Molten Fuel Plugs

If a once molten fuel plug was present at the axial extent of melting, the local power used for Q'_m was increased (see Section III, D of the main text) by the ratio of the areal size of the plug to the areal cross-section of the fuel pellet. This was a small correction in most cases, corresponding to typically an additional 2.5% of power.

The power at the upper extent of melting in the P-20-33 pin, the only preirradiated pin with fuel melting, was the only Q'_m value not adjusted for the fuel plug observed. The power at the axial extents of melting, with no plug correction, is one percent less than peak pin power because the axial power and temperature gradients are very flat in this region. Adjusting the local power at the axial extent of melting for the fuel plug would raise the calculated Q'_m above the peak power of the pin. But, the peak power

location must have had incipient melting prior to this location. This follows since, if the power needed to cause melting was greater than the peak power, no melting would have occurred and no plug would have formed to create the higher power at this upper extent. The assumption not to correct for the plug is conservative and is consistent with the lower axial extent of melting. It is believed this plug may have been deposited after fuel melting occurred by some axial transport mechanism other than that observed in the fresh fuel. The central void above this upper extent is narrower than that of the sibling pin examined after Phase I exposure, but there are no signs of melting. This, perhaps, indicates some fuel vapor transport mechanism is acting in this region where temperatures are almost at the melting point over a substantial axial distance.

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HEDL 7611-54.13

FIGURE B-1. Axial Power Profile for HEDL P-19 Pins.

Photo No. 771275-13

HEDL 7611-54.12

FIGURE B-2. Axial Power Profile for HEDL Phase III Pins Based on Burnup Analyses.

Photo No. 770572-5

APPENDIX C

SUMMARY OF RESULTS FROM ANALYSIS OF CERAMOGRAPHY
AND FISSION GAS RELEASE FROM PHASES I AND II OF
HEDL P-20

APPENDIX C

SUMMARY OF RESULTS FROM ANALYSIS OF CERAMOGRAPHY AND FISSION GAS RELEASE FROM PHASES I AND II OF HEDL P-20

The purpose of Phase I and II of HEDL P-20 was to accumulate fuel burn-up under steady-state power conditions of about 14 kW/ft (460 W/cm). After each phase, some pins were removed and others added so three burnup levels (as noted in the main text) were achieved. For each Phase I and II pin used in Phase III, a sibling pin was examined without Phase III exposure. Additional pins of interest, spare P-19 pins having .0096 inch (0.24 mm) and .0038 inch (0.097 mm) diametral gaps were also irradiated and examined. These highly characterized pins provide valuable data on fuel restructuring and fuel pin response under well-defined conditions. The behavior of these pins must be known before the performance of the P-20 preirradiated Phase III pins can be fully understood. The following summarizes the analysis of ceramography samples and fission gas release from these Phase I and II pins. Appendix D discusses the behavior of the sibling pins that were irradiated in Phase III.

Analyses of Ceramography

Each of the pins irradiated in Phase I and/or II had three transverse fuel ceramography sections taken from it at approximately 1.5 inches (3.8 cm), 6.25 inches (15.9 cm), and 12.0 inches (30.5 cm) above the bottom of the fuel column. Along with other data, a 75x photomosaic was made from each of these samples in both the polished and etched condition. Examples of the etched (with "stain" etch) samples from "Phase II only" (7200 MWd/MTM or 0.74 at.%) pins are shown in Figures C-1 and C-2. Each set of mosaics for a sample were then measured for central void, columnar grain region and equiaxed grain region extents, and for residual fuel-to-cladding gap sizes.

Figures C-3 and C-4 summarize the results of the measurements of the central void and columnar grain region radii. From this, within the scope

and limitations of the test, the following interpretations and conclusions with respect to the columnar grain region and gap conductance were drawn:

1) There is no increase in columnar grain region size with time or burnup. The maximum extent was reached by the end of Phase I. This would indicate the temperature drop across the fuel-to-cladding gap is not increasing with time (assuming a constant columnar grain formation temperature).

2) As would be expected, there is a trend of increasing region size as the fabricated gap size increases, indicating the maximum fuel temperatures are dependent on original gap size. However, there is a leveling off of this increase at gap sizes greater than 0.0075 inch (0.19 mm).

3) The 18% Xe tagged pins showed slightly larger, about 6%, region sizes than the untagged pins. This shows, as expected for a 0.0077 inch (0.20 mm) starting gap, an increased temperature drop across the gap resulting in higher fuel temperatures. Again, however, there is no increase of region size with time.

4) The low pressure preslugged fuel results show a slightly smaller restructured region (with a 0.0077 inch or 0.20 mm fabricated gap) than the high pressure preslugged fuel. The difference between the performance of the two fuel types is minimal.*

Thus, maximum fuel temperature appears to occur at beginning-of-life, (BOL). From then on, there is an improvement (or, at worst, no change) in the overall heat transfer from the fuel-to-cladding. These maximum temperatures

*The small difference observed could be accounted for, in part, by the low pressure preslugged fuel being 0.5% higher in density (hence a potentially higher thermal conductivity than the other) and/or because this fuel also had less absorbed nonhelium gases from fabrication, i.e., if there is an effect on gap conductance or fuel thermal conductivity from absorbed gases early in the life of the pin, this effect would be smaller for the low pressure preslugged fuel.

result in the formation of the maximum extents of the columnar grain regions. Analyses of measurements of this region relate to this maximum temperature condition in the fuel not necessarily to the end-of-test (EOT) conditions (or time-averaged conditions) of the fuel as is sometimes assumed.

Results from the central void measurements indicate a marked dependence on gap size and, for the most part, follow columnar grain size trends. However, the effects of gap voidage moving to the central void,⁽¹⁾ as will be discussed later, are affecting the central void sizes also. This is evidenced in the proportionally larger central void of the 0.0096 inch (0.24 mm) gap pin, while its columnar grain region is no larger than the 0.0075 inch (0.19 mm) gap fuel.

Figure C-5 summarizes the results of the "equiaxed" grain region measurements. This region is identified in this study as the region where gas (assumed to be fission gas) has noticeably collected on the fuel grain boundaries. This region, the extent of which is most likely dependent on an isotherm and time, is probably much slower forming than the columnar grains, which are formed by fabricated porosity migrating up the thermal gradient. The "equiaxed" region extent is also much more difficult to discern, especially with the high pressure preslugged fuel structure. Thus, the scatter of the measurements can be expected to be greater than that observed for the columnar grain region measurements. Conclusions that may be drawn from Figure C-5 for the equiaxed grain region data are:

- 1) There appears to be only a slight dependence on original fabricated gap size.
- 2) There is a small increase in region size with time.
- 3) There is no observable consistent effect of the Xe tag or the low pressure preslugged fuel on the radius of the equiaxed grain region.

These conclusions suggest that the equiaxed grain regions matured after the fuel temperatures had decreased from their peak values and the fuel-to-cladding gaps, as will be shown in the next paragraph, were about the same for all the pins. This would cause the isotherm needed for the region to form to be at about the same radial location in all the pins.

Figure C-6 shows the results of measurements of the residual fuel-to-cladding gap. These were measured in a manner similar to that described in Reference 2. Conclusions which may be drawn from these data are:

1) There is a rapid closure of the fuel-to-cladding gap early in life that results in all the residual gap sizes coming to about the same 0.001 to 0.0025 inch (0.025 to 0.064 mm) diametral gap size range by the end of Phase I. Then there is a small amount of additional closure. It is believed that the resulting similar cold gap sizes are indicative of the hot gaps being closed, i.e., the differential thermal expansion of the fuel and cladding, after coming in contact, results in this residual gap size upon cooling to room temperature.

2) Apparently, fuel-to-cladding gap closure depends on local power, time/burnup/reactor cycle and original gap size, as noted in Reference 2. These parameters would be related to the response of the fuel coming out of contact with the cladding on cooldown rather than to closure mechanisms.* Note the difference in measurements at the three axial positions in Figure C-6.

*The larger residual gap sizes observed in the lower power end sections may be caused by the smaller columnar grain zones at these locations. This results in the uncracked central portion of the fuel (which is essentially the columnar grain zone) being smaller. Greater contraction of the outer fuel surface at these end sections can ensue on shutdown, resulting in the observed larger residual gaps; while the hot gaps at all three axial levels in the fuel column are closed (see Reference 7).

These data on gap size support the preceeding conclusions drawn from the restructuring region data; there is a maximum gap size (maximum temperature drop across the gap) at BOL that accounts for early maximum fuel temperatures that decrease with time. By the end of Phase I, the hot gaps are closed and the residual gaps are all very similar in size.

In summary, the ceramography data lead to the conclusion that, within the range of this test, there is a maximum fuel-to-cladding gap size very early in life, resulting in a maximum temperature drop across the gap and maximum fuel temperatures. This maximum accounts for the extent of the columnar grain region. There is then rapid fuel-to-cladding gap closure that results in the residual gap size levels seen in Figure C-6. After that, the residual gap size is fairly stable, because the hot gaps are closed, and the maturing (as gas is formed) "equiaxed" grain region forms as observed in Figure C-5. The columnar extent does not change with time since the maximum temperatures at BOL are never surpassed. The fission gas release values found substantiate these conclusions as described in the following paragraphs.

Fission Gas Release

Figure C-7 summarizes the results of the calculation of the fission gas release based on measurements of fission gas recovered and fuel burnup from Phase I and II pins. A summary of the fission yields and constants used is given in Table C-I. The dependence of percent fission gas release for "Phase I only" pins shows the expected decreasing trend with decreasing gap size. There would be less gas released in pins with lower fuel temperatures (i.e., small gaps). However, for the "Phase II only" and Phase I plus II pins there is an unexpected increase in percent fission gas release in going from large to small original gaps.

The reason for this burnup dependent behavior can be explained in light of the data and conclusions already reviewed. That is, see Figure C-8, the

TABLE C-I

CONSTANTS USED TO CALCULATE FUEL BURNUPS OF P-20
PHASE I AND II PINS AND FISSION GAS GENERATION

	Average-Fission Cross-Section ⁽³⁾	Nd-148 Fission Yields ⁽⁴⁾	Total Energy Per Fission Deposited in the Reactor* ⁽⁵⁾	Gas Fission Yields	
				Xe	Kr
^{235}U	1.36 barns (1.36×10^{-28} m)	1.75%	203 MeV (32.5 pJ)	21.73%	4.82%
^{238}U	0.0855 (0.0855×10^{-28})	1.93	201 (32.2)	21.35	3.08
^{239}Pu	1.64 (1.64×10^{-28})	1.71	211 (33.8)	23.17	2.36

* Based on Reference 6, it is assumed the energy deposited in the fuel pin is about 9.2 MeV/fission (1.47 pJ/fission) less than the total energy deposited in the reactor core, blanket, and reflector. Thus, pin powers are based on energy deposited in the test fuel pin; while burnup, when reported in MWd/MTM, is based on total generated energy.

fuel temperatures, including the fuel centerline temperature (T_C), are, at first, very dependent on fabricated gap size; fuel temperatures of pins fabricated with small gaps are less than ones fabricated with large gaps ($T_C^S < T_C^L$), which is substantiated by the measurements of columnar grain radii. After a short period of time however, the rapid gap closure puts the fuel and cladding in contact bringing all the residual gap sizes to about the same overall dimensions. Thus, the temperature drop across the gaps, ΔT_{GAP} , becomes very similar for all the pins. As further burnup occurs, the mechanism proposed in Reference 1 occurs. The fuel cracks heal in the restructured zones moving part of the fuel-to-cladding gap volume to the central void. This forms central voids larger than can be explained just by densification of the columnar grain region; larger gaps lead to larger central voids. It is also noted that the columnar grain regions are smaller in the small gap pins than in the large gap fuel pins. Since the hot gaps are now closed or nearly closed, the temperature drop across them must be about the same and the drop across the fuel itself controls the differences in fuel centerline temperatures. The fuel in the smaller gap pins has less restructuring so it will run at higher centerline temperatures, ($T_C^S > T_C^L$) Figure C-8 (see also Section II of main text).

The mechanisms mentioned above would lead to the small gap pins actually operating at higher fuel temperatures than the larger gap pins resulting in the observed fission gas behavior. This same conclusion was noted in the main text due to the behavior of the Phase I pins in Phase III (i.e., only the 0.035 inch or 0.09 mm fuel-to-cladding gap pin had fuel melting while larger gap pins did not).

Fuel smeared density* and original gap size are then the actual controlling influences on fuel temperature after BOL operation; with fuel temperatures

*It is noted for these P-20 pins that a decrease in original fuel-to-cladding gap size means an increase in smeared density since there is a constant fuel pellet density. Smeared density has been shown to be the controlling factor in central void size⁽¹⁾. Lower smeared density leads to larger central voids and lower fuel centerline temperatures.

increasing with decreasing gap size and decreasing with decreasing smeared density. The opposite would be true at the beginning of life. Thus, since gas release is expected to be time, grain structure and fuel temperature dependent, the drop in temperature in the large gap pins after BOL could cause the observed fission gas release results.

This concept of fuel temperature behavior is further supported by the results of the measured extents of equiaxed grain regions all being about the same size for all the different gap sizes. The distance from the equiaxed grain boundary isotherm to the central void edge will be greater for small gap pins (i.e. smaller central void), suggesting higher fuel centerline temperatures. Results from sibling pins irradiated in Phase III also confirm this behavior as discussed in Appendix D.

Possible Fuel Melting During Phase I and II

Figure 10, in Section III of the main text, shows the "upper bound" of Q'_m found for the P-20 pins with Xe tag to be below 14.2 kW/ft (466 W/cm). This would indicate a very high probability of fuel melting when fresh siblings of these pins were irradiated in Phase I and II. The sizes of the central voids and columnar grain regions of the tagged pins suggest some melting did occur, confirming the validity of the analysis of the axial extent data. The following observations are made:

- 1) The measured central void sizes, Figure C-3, at the 6.25- and 12-inch (15.9- and 30.5-cm) levels for the tagged pin are the same or slightly larger than those measured from pins with the same gap size but with no tag gas. However, at the bottom sections (1.5-inch or 3.8-cm level), the measured central voids for the tagged pins are significantly smaller than the untagged pins.

2) The measured columnar grain region radii, Figure C-4, of the tagged fuel pins are almost always significantly larger than similar untagged pins at all three axial levels.

Thus, from the columnar grain region measurements, the central voids are expected to be larger than for similar untagged pins; this does not agree with the measured values. The lower sections (at 1.5 inch or 3.8 cm) from the tagged pins have consistently smaller central void radii. It is very likely that a small amount of fuel melting occurred in the tagged pins, relocating some fuel toward the bottom of the fuel column. This increased the amount of fuel in the columnar grain region of these lower sections and decreased the central void size by increasing the local smeared fuel density.

No microstructural confirmation (such as once molten fuel boundaries as described in Appendix A) of this melting was expected, nor was any found. The fuel is expected to restructure "through" any solidified molten fuel plugged regions resulting in a normal columnar grain and central void, with no "melt" indicators. As previously noted, due to the rapid improvement in heat transfer, it would be expected that the fuel would only be molten for a small portion of either Phase I or II. Gamma scan data were examined for evidence of fuel relocation but results were inconclusive.

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12 INCHES (30.5 cm) FROM BOTTOM
FUEL COLUMN

6.250 INCHES (15.9 cm) FROM BOTTOM
FUEL COLUMN

1.50 INCHES (3.81 cm) FROM BOTTOM
FUEL COLUMN

10 mm

HEDL 7709-116.3

FIGURE C-1. Etched Transverse Fuel Ceramography From HEDL P-20-5.

Photo No. 779905-3

12 INCHES (30.5 cm) FROM BOTTOM
FUEL COLUMN

6.250 INCHES (15.9 cm) FROM BOTTOM
FUEL COLUMN

1.50 INCHES (3.81 cm) FROM BOTTOM
FUEL COLUMN

10 mm

HEDL 7709-116.4

FIGURE C-2. Etched Transverse Fuel Ceramography From HEDL P-20-36.

Photo No. 779905-4

HEDL 7709-116.12

FIGURE C-3. Measured Fuel Central Void Radii From HEDL P-20 Phase I and II Pins.

HEDL 7709-116.13

FIGURE C-4. Measured Columnar Grain Region Radii from HEDL P-20 Phase I and II Pins.

Photo No. 779905-13

HEDL 7709-116.14

FIGURE C-5. Measured Equiaxed Grain Region Radii from HEDL P-20 Phase I and II Pins.

Photo No. 779905-14

HEDL 7709-116.15

FIGURE C-6. Measured Residual Diametral Fuel-to-Cladding Gaps from HEDL P-20 Phase I and II Pins.

Photo No. 779905-15

HEDL 7611-54.15a

FIGURE C-7. Percent Fission Gas Release Found for HEDL P-20 Phase I and II Pins.

Photo No. 775793-3

FIGURE C-8. Fuel and Temperature Behavior with Burnup. Photo No. HEDL L-499-1

APPENDIX D

CERAMOGRAPHY AND FISSION GAS RELEASE
RESULTS FROM HEDL P-20 PHASE III PINS

APPENDIX D

CERAMOGRAPHY AND FISSION GAS RELEASE RESULTS FROM HEDL P-20 PHASE III PINS

I. PHASE I AND II PINS IRRADIATED IN PHASE III

A. CERAMOGRAPHY

Appendix C summarized the measurements of ceramography and fission gas release from pins examined after Phase I and II of the P-20 test. Each of these pins had three transverse ceramography samples prepared from it. Similarly, those pins included in Phase III that were also in Phase I and/or II had three transverse ceramography samples prepared. The samples were taken at the same location as before [i.e., 1.5 inches (3.8 cm), 6.2 inches (15.8 cm) and 12.0 inches (30.5 cm) above the bottom of the fuel column]. The samples were prepared in a manner similar to that described in Appendix A and C. Photography was limited however, due to time and budget constraints. Eight photographs at 75X were taken every 45° around the fuel-to-cladding gap with the sample in the "as-polished" condition, and a 75X photomosaic of the whole ceramography surface was made in the etched state (see Figures D-1 and D-2). [Samples (Figure D-1) prepared at LASL were etched with a stain etch while those (Figure D-2) prepared at HEDL were etched with a cathodic vacuum etching technique.] This coverage allowed, in each case, the measurement (see Table E-V) of the fuel-to-cladding residual gap, the central void radius, and the columnar grain region radius, as well as a check for any once molten fuel zones.* Measurements of the equiaxed grain region radii were not made from these samples because of the lack of an "as-polished" transverse photomosaic which is needed to identify this region.

*Only one of these pins showed fuel melting from Phase III that was the pin fabricated with a 0.0035-inch (0.089-mm) diametral gap that was previously irradiated in Phase I, P-20-33 (see main text for details).

Figures D-3 and D-4 show the results of measuring the central void and columnar grain radii from the Phase III samples, and how they compare to the pins that were only in Phase I and/or II. From this data, it is observed that there is no significant increase in fuel restructuring between pins examined after Phase I and II, and sibling pins irradiated in Phase III.

Figure D-5 summarizes the measurements of residual fuel-to-cladding gaps. These agree closely with measurements from the "Phase I and/or II only" pin samples. Both form a constant band ranging from about 0.0025 to 0.00075 inch (0.064 to 0.019 mm) diametrically. [The two measurements over 0.0025 inch (0.064 mm) are strongly suspected to be enlarged due to preparation problems with the samples.] The fact that the two sets of data agree so closely substantiates the hypothesis that the hot gaps were closed at these burnups even before the overpower is applied. The observed residual gap is thus due to differential thermal expansion of the fuel and cladding. Had the hot gaps been open at the Phase I and II power level, additional closure of the residual gaps would have been expected in comparing the two sets of data because of the additional full power cycle and the overpower operation during Phase III.

The residual gap data in Figure D-5 indicates there may be a slight trend for the Phase III pins to have increasing residual gap size with decreasing fabricated gap size. This trend could be the result of higher fuel temperatures and smaller restructuring regions which are expected in those pins fabricated with small gaps at these burnup levels (see Appendix C and the main text). These operating conditions would result in more residual gap developing in the small gap pins because of the greater contraction of the hotter fuel from the cladding on cooling down (see Reference 1 for example).

B. FISSION GAS RELEASE

Figure D-6 shows the resulting fission gas release from the "Phase I and/or II only" pins compared to the sibling pins which also experienced

Phase III. See Appendix C for fission yields used. The fuel in the pins experiencing Phase III released more fission gas, as expected, due to the higher fuel temperatures. Those Phase III pins, with smaller fabricated gaps, released a comparatively greater percentage because of the Phase III over-power. This is again consistent with the previously proposed behavior. The pins fabricated with small gap sizes experienced higher fuel temperatures than those with large gaps after the initial irradiation (less than 3700 MWd/MTM or 0.38 at.%). This Phase III data confirms the general dependence on burnup and fabricated gap size found from "Phase I and/or II only" pins.

C. SUMMARY PHASE I, II AND III PINS

In summary, the data from pins irradiated in Phase I and/or II and then in the overpower phase, Phase III, show:

- 1) There is no significant additional columnar grain growth or increase in central void size caused by the additional irradiation and overpower. This is interpreted as the temperature and temperature gradient at the columnar grain region boundary present being too low to cause any additional growth. Temperatures here were probably lower at this radius than at the beginning-of-life because the hot fuel-to-cladding gaps were closed.
- 2) The residual fuel-to-cladding gaps are essentially unchanged from "Phase I and/or II only" pin data. A slight trend of increasing residual gap size with decreasing fabricated gap size may be present, however, it is about the magnitude of the scatter of this type of data. It is hypothesized that because of this and other substantiating evidence, all the fuel-to-cladding gaps during operation are closed at the Phase I and II power levels and above.

- 3) Fission gas release from these pins was several percent higher than those pins that experienced only Phase I and/or II. A greater increased release was found for the smaller gap pins. All these results are consistent with the interpretation of fuel behavior developed in Appendix C, and summarized in Section III, C. Thus, all the test data (the fuel melting behavior of the Phase I and II pins in Phase III, the fuel restructuring, residual gaps and the fission gas release measurements from all three phases) can be explained in general by the theory for behavior proposed in Appendix C.

II. FRESH FUEL PINS IRRADIATED IN PHASE III

A. CERAMOGRAPHY

Midplane transverse ceramography sections from fresh fuel pins irradiated in Phase III were prepared in a similar manner to those samples previously described. Examples of the photomosaics of the etched samples are shown in Figures D-7, D-8 and D-9. All these fresh pin samples were measured (Table E-V) for columnar grain region extents, residual fuel-to-cladding gaps and molten fuel radial extents. Central voids, which were random molten fuel shrinkage cavities, were measured. Because these are of no direct value to fuel performance evaluations they will not be further discussed.

Figure D-10 shows the extent of columnar grain growth at the fuel column midplane of the pins examined after Phase I and/or II, compared to the radial extent of growth in fresh fuel included in Phase III. It should be remembered that no difference was observed in fuel restructuring between the "Phase I and/or II only" pins and the siblings to these pins that were also irradiated in Phase III, Figure D-4. Figure D-10 shows the fresh fuel formed extensive columnar grain regions during Phase III, but the extents are, in general, slightly less than similar pins irradiated in Phase I and II, where long periods of steady-state operation were experienced.

It was further observed in the fresh fuel ceramography, that some lenticular voids are still moving in the columnar grain region up the temperature gradient to the center; this is not observed in the Phase I and/or II pins irradiated in Phase III, except in a limited fashion near the tips of healed cracks. It is concluded that this observation is indicative of the columnar grain region still maturing (lenticular voids still moving fabrication porosity) in the fresh fuel pins due to the short irradiation time and overpower involved in Phase III.

Residual gap sizes from the fresh pins in Phase III are shown in Figure D-11. The amount of closure measured is from 0.0001 to 0.0027 inch (0.0025 to 0.069 mm) and appears fairly random in nature. However, all the residual fuel-to-cladding gaps are smaller than fabricated; no indication of enlargement is observed. The difference in gap closure between the fresh Phase III pins and the Phase I and II pins can be explained comparing Figures D-1 and D-8. Fuel cracking and the subsequent crack healing in the columnar grain region appears to be the dominant mechanism of gap closure. Note the four healed cracks in the fuel in Figure D-1 compared to the lack of similar cracks in the fuel in Figure D-8.

Figures D-12 and D-13 show the central void and columnar grain region measurements used in developing the final relations for Q'_m in this report (see Table E-III through E-V). These measurements are important to normalizing calculations on the Q'_m data and analyses where the temperature drop across the gap and the fuel must be calculated individually. These measurements were made in unmolten fuel just beyond the axial extents of fuel melting or at the fuel column midplanes of those pins that experience no fuel melting. These measurements were taken at positions operating at powers corresponding to Q'_m values for each pin (see main text).

Figure D-12 shows there is significant difference in columnar grain region sizes at the Q'_m locations, between the fresh fuel and the fuel irradiated in Phase I and/or II prior to Phase III. Part of this difference

is due to local power levels. As seen in Figure D-10, the midplanes of the fuel columns of all the P-20 Phase III pins have developed similar size columnar grain regions. However, at the axial extents of melting in the fresh fuel pins with the larger gaps, the local power levels, at Q'_m , are significantly lower because melting occurs near the ends of the fuel column and there is less fuel restructuring. Thus, in the test pins, lower gap conductance values result in lower Q'_m values that occur closer to the ends of the fuel columns, which further reduces Q'_m because of less extensive columnar grain region formation.

As Figure D-13 shows, the measured central voids of the preirradiated pins are much larger than the fresh fuel. The reasons for this are believed to be increased columnar grain region size (Figure D-12), the further densification of the columnar grain zone, and the movement of fuel-to-cladding gap volume to the central void by fuel crack healing mechanisms.⁽²⁾ This latter reason is inferred because of the steep increase in central void size with fabricated gap size of the preirradiated fuel as compared to the fresh fuel. As noted previously, the larger central voids in the preirradiated fuel increases Q'_m substantially and contributes significantly to the higher Q'_m of the preirradiated pins.

B. FISSION GAS RELEASE

Figure D-14 summarizes the volume of fission gas recovered from each fresh Phase III pin. The amount of fission gas released and generated at this low a burnup (about 90 MWd/MTM or 0.009 at.%) is very small. A wide range of gap sizes is not available from these pins, only two gap sizes are represented. The limited observations that can be made from this data show it to be consistent to what would be expected (i.e. gas release dependent on fuel temperature). Gas release decreases with decreasing gap size (which decreases the temperature drop across the gap) and is increased by Xe tag gas being present (which increases the temperature drop across the gap).

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FIGURE D-1. Etched Transverse Sample at 12 Inches (30.4 cm) from the Bottom of the Fuel Column of HEDL P-20-2R (0.0076 inch or 0.193 mm original gap, etched with 10 HCl-10 HBr-1HF).

Photo No. 741232-2

FIGURE D-2. Etched Transverse Sample from Near the Midplane of the Fuel Column of HEDL P-20-25R (0.0056 inch or 0.142 mm original gap, cathodic vacuum etch).

Photo No. 735904-1

HEDL 7709-116.17

FIGURE D-3. Comparison of Central Void Radii in Pins from Phase I and II Before and After Phase III.

Photo No. 779905-17

HEDL 7709-116.18

FIGURE D-4. Comparison of Measured Columnar Grain Region Radii in Pins from Phase I and II Before and After Phase III.

Photo No. 779905-18

HEDL 7709-116.16

FIGURE D-5. Comparison of Measured Residual Fuel-to-Cladding Gap Sizes in Pins from Phase I and II Before and After Phase III.

Photo No. 779905-16

HEDL 7611-54.15

FIGURE D-6. Percent Fission Gas Release Found for HEDL P-20 Phase I and II Pins After Phase III.

Photo No. 775793-2

FIGURE D-7. Etched Transverse Sample from Near the Fuel Column Midplane of HEDL P-20-7 (0.0076 inch or 0.193 mm original gap, etched with 10HCl-10HBr-1HF).

Photo No. 740801-8

FIGURE D-8. Etched Transverse Sample from Near the Midplane of the Fuel Column of HEDL P-20/19-34 (0.0072 inch or 0.183 mm, original gap etched with 10HCl-10HBr-1HF).

Photo No. 741232-10

FIGURE D-9. Etched Transverse Sample from Near the Fuel Column Midplane of HEDL P-20-39 (0.0076 inch or 0.193 mm original gap, low pressure preslugged fuel, etched with 10HCl-10HBr-1HF).

Photo No. 741232-11

HEDL 7706-225.1

FIGURE D-11. Comparison of Measured Fabricated and Residual Fuel-To-Cladding Gap for Fresh Fuel in Phase III.

Photo No. 778855-5

HEDL 7708-199.3

FIGURE D-12. Measured Columnar Grain Region Radii Used in Q_m^1 Analyses from the Axial Extents of Melting.

Photo No. 778855-4

FIGURE D-13. Measured Central Void Radii Used in Q'_m Analyses from the Axial Extents of Melting. HEDL 7708-199.1

HEDL 7706-225.2

FIGURE D-14. Fission Gas Release from Fresh Fuel Pins in Phase III.

Photo No. 7788-1-6

APPENDIX E

TABULAR SUMMARIES OF TEST DATA

TABLE E-I

PEAK PIN POWERS AND AXIAL EXTENTS OF MELTING FOR HEDL P-19 PINS

Pin Identity	Peak Pin Power kW/ft, (W/cm)	Bottom Axial Extent of Melting			Top Axial Extent of Melting		
		Location ¹	Local Power ² kW/ft, (W/cm)	Coolant Temp Deg. F, (Deg. C)	Location ¹	Local Power ² kW/ft, (W/cm)	Coolant Temp. Deg. F., (Deg. C)
P-19-2	16.6 (545)	2.84 (7.21)	15.8 (518)	726. (385.6)	9.78 (24.84)	15.4 (505)	799. (426.1)
3R	19.5 (640)	0.35 (0.89)	16.0 (525)	704. (373.3)	12.32 (31.29)	15.7 (515)	843. (450.6)
5	17.1 (561)	---	---	---	---	---	---
6	17.1 (561)	---	---	---	---	---	---
7R	20.3 (666)	1.61 (4.09)	18.0 (591)	718. (381.1)	11.27 (28.63)	17.3 (568)	839. (448.3)
8	16.4 (538)	2.49 (6.32)	15.5 (509)	723. (383.9)	10.48 (26.62)	14.8 (486)	805. (429.4)
13	16.6 (545)	3.33 (8.46)	16.1 (528)	732. (388.9)	9.41 (23.90)	15.7 (515)	796. (424.4)
20	16.5 (541)	3.87 (9.83)	16.0 (525)	737. (391.7)	10.64 (27.03)	14.8 (486)	807. (430.6)
24R	19.7 (646)	0.59 (1.50)	16.1 (528)	706. (374.4)	12.60 (32.00)	15.1 (495)	848. (453.3)
25R	20.1 (660)	0.83 (2.11)	16.8 (551)	709. (376.1)	12.01 (30.51)	16.1 (528)	846. (452.2)
26R	20.4 (669)	1.84 (4.67)	18.4 (604)	720. (382.2)	10.68 (28.13)	18.2 (597)	833. (445.0)
27R	20.4 (669)	2.33 (5.92)	18.8 (617)	727. (386.1)	10.18 (25.86)	18.5 (607)	828. (442.2)
28	20.7 (679)	2.35 (5.97)	18.9 (620)	727. (386.1)	10.70 (27.18)	18.0 (591)	835. (446.1)
30	20.0 (656)	1.11 (2.82)	17.2 (564)	712. (377.8)	11.35 (28.83)	17.1 (561)	838. (447.8)
33	16.8 (551)	---	---	---	---	---	---
35	16.5 (541)	3.26 (8.28)	16.0 (525)	731. (388.3)	8.84 (22.45)	16.0 (525)	790. (421.1)

(1) Distance from bottom of fuel column in inches (cm).

(2) Powers corrected for once molten fuel plugs if present in ceramography.

TABLE E-II

PEAK PIN POWERS AND AXIAL EXTENTS OF MELTING FOR PHASE III HEDL P-20 PINS

Pin Identity	Preconditioning Phase	Peak Phase III Pin Power kW/ft ¹ , (W/cm)	Bottom Axial Extent of Melting			Top Axial Extent of Melting		
			Location ²	Local Power ⁴ kW/ft., (W/cm)	Coolant Temp Deg. F., (Deg. C)	Location ²	Local Power ⁴ kW/ft., (W/cm)	Coolant Temp Deg. F., (Deg. C)
P-20-2R	I	18.1 (594)	---	---	---	---	---	---
4	I & II	17.9 (587)	---	---	---	---	---	---
7	NONE	18.0 (591)	0.70 (1.78)	15.4 (505)	713. (378.3)	11.50 (29.21)	15.1 (495)	934. (501.1)
8	II	17.7 (581)	---	---	---	---	---	---
10	I	17.9 (587)	---	---	---	---	---	---
13	NONE	18.0 (591)	0.10 ³ (0.25)	14.9 (489)	703. (372.8)	13.30 ³ (33.78)	13.9 (456)	966. (518.9)
25R	I	18.3 (600)	---	---	---	---	---	---
27	I & II	18.1 (594)	---	---	---	---	---	---
29	II	18.2 (597)	---	---	---	---	---	---
30	NONE	18.4 (604)	1.35 (3.43)	16.5 (541)	725. (385.0)	10.92 (27.74)	15.9 (522)	929. (498.3)
33	I	18.6 (610)	4.98 (12.65)	18.4 (604)	802. (427.8)	7.51 (19.08)	18.6 (610)	859. (459.4)
35	I & II	18.4 (604)	---	---	---	---	---	---
37	II	18.5 (607)	---	---	---	---	---	---
39	NONE	18.0 (591)	1.73 (4.39)	16.5 (541)	731. (388.3)	10.06 (25.55)	16.3 (535)	907. (486.1)
P-20/19-21	NONE	17.9 (587)	1.22 (3.10)	15.9 (522)	724. (384.4)	11.58 (29.41)	15.2 (499)	937. (502.8)
P-20/19-34	NONE	18.0 (591)	1.60 (4.06)	16.0 (525)	731. (388.3)	10.87 (27.61)	16.2 (532)	923. (495.0)

(1) Powers normalized to P-19 powers as described in Appendix B.

(2) Distance from bottom of fuel column in inches (cm).

(3) "Axial extents of melting" for this Xenon tagged pin extended into the two dimensional heat transfer region at each end of the fuel column. Thus the fuel can be considered to have melted through the top and bottom of the fuel column.

(4) Powers corrected for once molten fuel plug is present in ceramography.

TABLE E-III

ESTIMATES OF RESTRUCTURING AT AXIAL EXTENTS OF MELTING

Pin Identity	Top Axial Extent of Melting			Bottom Axial Extent of Melting		
	Radius Central Void, Inches, (mm)	Radius Columnar Grain, Inches, (mm)	Calculated ² Columnar Grain Region Density, %TD ³	Radius Central Void, Inches, (mm)	Radius Columnar Grain Inches, (mm)	Calculated ² Columnar Grain Region Density, %TD ³
P-19-2	.014 (0.36)	.061 (1.55)	96.4	.015 (0.38)	.060 (1.52)	98.0
3R	.016 (0.41)	.073 (1.85)	96.9	.016 (0.41)	.073 (1.85)	97.2
7R	.015 (0.38)	.068 (1.73)	97.4	.015 (0.38)	.061 (1.55)	98.6
8	.017 (0.43)	.063 (1.60)	98.0	.016 (0.41)	.062 (1.58)	98.0
13	.014 (0.36)	.061 (1.55)	98.0	.015 (0.38)	.060 (1.52)	98.0
20	.017 (0.43)	.062 (1.58)	97.3	.016 (0.41)	.062 (1.58)	97.4
24R	.008 (0.20)	.067 (1.70)	93.1	.008 (0.20)	.067 (1.70)	92.9
25R	.018 (0.46)	.071 (1.80)	98.5	.009 (0.23)	.068 (1.73)	93.6
26R	.017 (0.43)	.066 (1.68)	98.2	.015 (0.38)	.060 (1.52)	98.6
27R	.014 (0.36)	.057 (1.45)	98.4	.012 (0.31)	.060 (1.52)	96.1
28	.008 (0.20)	.058 (1.47)	94.5	.009 (0.23)	.057 (1.45)	94.5
30	.015 (0.38)	.065 (1.65)	97.9	.013 (0.33)	.065 (1.65)	96.0
35	.016 (0.41)	.064 (1.63)	96.6	.015 (0.38)	.067 (1.70)	96.0
P-20-7	.015 (0.38)	.065 (1.65)	96.9	.015 ¹ (0.38)	.064 (1.63)	96.9
13	.015 (0.38)	.071 (1.80)	98.0	.015 (0.38)	.070 (1.78)	98.0
30	.018 (0.46)	.065 (1.65)	98.5	.018 ¹ (0.46)	.060 (1.52)	98.5
33	.012 (0.31)	.072 (1.83)	93.5	.019 (0.48)	.074 (1.88)	96.5
39	.016 (0.41)	.068 (1.73)	97.1	.016 ¹ (0.41)	.064 (1.63)	98.2
P-20/19-21	.012 (0.31)	.065 (1.65)	93.9	.015 (0.38)	.068 (1.73)	96.0
P-20/19-34	.017 (0.43)	.065 (1.65)	96.1	.014 (0.36)	.061 (1.55)	97.8

(1) The central void at the bottom section was obliterated by molten fuel relocation. In this case the central void size from the top of the pin was used, see Appendix A.

(2) Based on densification of columnar grain needed to form central void. Densities were limited to no higher than 98.5% TD based on observations of grain region.

(3) TD = Theoretical Density (~10.9 gm/cc) of the fuel.

TABLE E-IV

MEASUREMENTS FROM TRANSVERSE CERAMOGRAPHY FROM HEDL P-19

Pin Identity		Location ⁽¹⁾ , Inches, (cm)	Fabricated Diametral Fuel-to-Clad Gap, Mils, (mm)	Pellet Density % TD ⁽²⁾	Measured Postirradiation Values			
					Central Void Radius, Inches, (mm)	Molten Region Radius, Inches, (mm)	Columnar Grain Region Radius, Inches, (mm)	Diametral Fuel-to-Clad Gap, Mils, (mm)
P-19-2	B	6.1 (15.5)	7.9 (0.201)	90.4	.025 (0.64)	.037 (0.94)	.071 (1.80)	5.6 (0.142)
	D	7.5 (19.1)	7.7 (0.195)	90.9	.023 (0.58)	.031 (0.79)	.068 (1.73)	5.6 (0.142)
P-19-5	B	6.1 (15.5)	5.7 (0.145)	90.7	.018 (0.46)	0.0	.066 (1.68)	4.0 (0.102)
	D	7.3 (18.5)	5.8 (0.147)	91.6	.019 (0.48)	0.0	.065 (1.65)	5.8 (0.147)
	F	8.0 (20.3)	5.7 (0.145)	91.2	.017 (0.43)	0.0	.061 (1.55)	4.0 (0.102)
	G	8.5 (21.6)	5.8 (0.147)	91.1	.018 (0.46)	0.0	.063 (1.60)	4.8 (0.122)
P-19-6	B	6.1 (15.5)	3.8 (0.097)	90.7	.014 (0.36)	0.0	.062 (1.58)	2.8 (0.071)
	C	7.0 (17.8)	3.9 (0.099)	90.9	.014 (0.36)	0.0	.059 (1.50)	2.7 (0.069)
	D	7.4 (18.8)	3.9 (0.099)	91.4	.015 (0.38)	0.0	.060 (1.52)	3.6 (0.091)
	E	7.9 (20.1)	4.0 (0.102)	90.7	.015 (0.38)	0.0	.062 (1.58)	2.9 (0.074)
	F	8.4 (21.3)	3.9 (0.099)	91.0	.015 (0.38)	0.0	.055 (1.40)	2.8 (0.071)
	G	8.9 (22.6)	3.7 (0.094)	90.3	.013 (0.33)	0.0	.055 (1.40)	3.3 (0.084)
P-19-8	B	6.1 (15.5)	9.8 (0.249)	90.6	.018 (0.46)	.038 (0.97)	.073 (1.85)	8.2 (0.208)
P-19-24R	B	6.1 (15.5)	10.0 (0.254)	92.1	.007 (0.18)	.045 (1.14)	.083 (2.11)	4.2 (0.107)
P-19-25R	B	6.1 (15.5)	8.0 (0.203)	92.4	.039 (0.99)	.048 (1.21)	.083 (2.11)	4.9 (0.124)
	D	7.3 (18.5)	8.0 (0.203)	92.5	.031 (0.79)	.035 (0.89)	.080 (2.03)	4.1 (0.104)
P-19-26R	B	6.1 (15.5)	6.1 (0.155)	92.6	.025 (0.64)	.028 (0.71)	.075 (1.91)	4.0 (0.102)
	D	7.4 (18.8)	6.1 (0.155)	92.1	.027 (0.69)	.047 (1.19)	.079 (2.01)	3.1 (0.079)
	E	7.8 (19.8)	6.1 (0.155)	92.9	.030 (0.76)	.036 (0.91)	.076 (1.93)	4.1 (0.104)
	F	8.2 (20.8)	6.1 (0.155)	92.8	.005 (0.13)	.030 (0.76)	.073 (1.85)	3.6 (0.091)
P-19-27R	B	6.1 (15.5)	4.1 (0.104)	92.2	.013 (0.33)	.040 (1.02)	.073 (1.85)	2.7 (0.069)
	D	7.3 (18.5)	4.0 (0.102)	92.8	.029 (0.74)	.033 (0.84)	.074 (1.88)	3.3 (0.084)
	E	8.0 (20.3)	4.1 (0.104)	92.0	.020 (0.51)	.027 (0.69)	.073 (1.85)	2.8 (0.071)
	F	8.2 (20.8)	4.1 (0.104)	92.7	0.0	.036 (0.91)	.073 (1.85)	2.5 (0.064)
	G	8.6 (21.8)	4.0 (0.102)	92.6	.022 (0.56)	.029 (0.74)	.070 (1.78)	3.7 (0.094)
P-19-28	B	6.1 (15.5)	3.3 (0.084)	92.2	0.0	.034 (0.86)	.071 (1.80)	3.4 (0.086)
	D	7.3 (18.5)	3.4 (0.086)	92.0	0.0	.038 (0.97)	.073 (1.85)	2.6 (0.066)
	E	8.0 (20.3)	3.3 (0.084)	92.7	.027 (0.69)	.036 (0.91)	.073 (1.85)	2.5 (0.064)
	F	8.2 (20.8)	3.6 (0.091)	93.0	.022 (0.56)	.028 (0.71)	.071 (1.80)	2.8 (0.071)
	G	8.6 (21.8)	3.4 (0.086)	92.6	.009 (0.23)	.034 (0.86)	.073 (1.85)	2.0 (0.051)
P-19-30	B	6.1 (15.5)	7.1 (0.180)	92.5	.039 (0.99)	.052 (1.32)	.079 (2.01)	3.0 (0.076)
	C	6.9 (17.5)	7.2 (0.183)	92.3	.037 (0.94)	.049 (1.24)	.081 (2.06)	3.0 (0.076)
	D	7.6 (19.3)	7.1 (0.180)	92.5	.007 (0.18)	.051 (1.30)	.082 (2.08)	2.9 (0.074)
P-19-33	C	6.1 (15.5)	5.1 (0.130)	90.8	.017 (0.43)	0.0	.064 (1.63)	3.4 (0.086)
	D	6.9 (17.5)	5.0 (0.127)	91.2	.017 (0.43)	0.0	.063 (1.60)	5.0 (0.127)
	E	7.6 (19.3)	5.0 (0.127)	90.8	.016 (0.41)	0.0	.065 (1.65)	5.4 (0.137)
	F	8.2 (20.8)	5.0 (0.127)	90.6	.017 (0.43)	0.0	.063 (1.60)	4.5 (0.114)
	G	8.7 (22.1)	5.0 (0.127)	90.7	.014 (0.36)	0.0	.059 (1.50)	4.4 (0.112)
P-19-35	B	6.1 (15.5)	7.3 (0.185)	90.8	.023 (0.58)	.030 (0.76)	.069 (1.75)	4.9 (0.124)
	D	7.6 (19.3)	7.2 (0.183)	89.9	0.0	.031 (0.79)	.069 (1.75)	6.5 (0.165)
	E	8.2 (20.8)	7.1 (0.180)	90.7	.008 (0.20)	.032 (0.81)	.069 (1.75)	5.9 (0.150)

(1) Inches (cm) from bottom of fuel column

(2) TD = Theoretical Density (~10.9 gm/cc) of the fuel

TABLE E-V

MEASUREMENTS FROM TRANSVERSE CERAMOGRAPHY FROM HEDL P-20 PHASE III

Pin Identity		Location ⁽¹⁾ , Inches, (mm)	Fabricated Diametral Fuel-to-Clad Gap, Mils, (mm)	Pellet Density % TD ⁽²⁾	Measured Post Irradiation Values			
					Central Void Radius, Inches, (mm)	Molten Region Radius, Inches, (mm)	Columnar Grain Region Radius, Inches, (mm)	Diametral Fuel-to-Clad Gap, Mils, (mm)
P-20-7	D	6.5 (16.5)	7.6 (0.193)	90.9	0.010 (0.25)	0.047 (1.19)	0.080 (2.03)	5.4 (0.137)
-13	E	6.4 (16.3)	7.6 (0.193)	91.6	0.0	0.053 (1.35)	0.083 (2.11)	6.9 (0.175)
-30	E	6.5 (16.5)	7.3 (0.185)	91.1	0.0	0.034 (0.86)	0.073 (1.85)	4.4 (0.112)
-39	D	6.6 (16.8)	7.7 (0.196)	91.3	0.020 (0.51)	0.041 (1.04)	0.076 (1.93)	4.7 (0.119)
P-20/P-19-21	D	6.2 (15.8)	7.6 (0.193)	90.9	0.017 (0.43)	0.041 (1.04)	0.073 (1.85)	5.0 (0.127)
P-20/P-19-34	E	6.7 (17.0)	5.6 (0.142)	91.2	0.024 (0.61)	0.041 (1.04)	0.077 (1.96)	7.1 (0.180)
P-20-2R	D	1.5 (3.8)	7.5 (0.191)	91.1	0.026 (0.66)	0.0	0.078 (1.98)	1.8 (0.046)
	G	6.2 (15.8)	7.5 (0.191)	91.3	0.027 (0.69)	0.0	0.081 (2.06)	1.3 (0.033)
	L	11.9 (30.2)	7.7 (0.196)	91.5	0.023 (0.58)	0.0	0.075 (1.91)	1.6 (0.041)
P-20-4	D	1.5 (3.8)	7.6 (0.193)	91.0	0.025 (0.64)	0.0	0.074 (1.88)	1.1 (0.028)
	G	6.2 (15.8)	7.6 (0.193)	91.2	0.029 (0.74)	0.0	0.080 (2.03)	0.7 (0.018)
	L	11.9 (30.2)	7.6 (0.193)	90.4	0.028 (0.71)	0.0	0.079 (2.00)	0.9 (0.023)
P-20-8	D	1.5 (3.8)	7.7 (0.196)	91.5	0.026 (0.66)	0.0	0.078 (1.98)	1.3 (0.033)
	G	6.2 (15.8)	7.7 (0.196)	90.5	0.029 (0.74)	0.0	0.083 (2.11)	1.1 (0.028)
	L	12.0 (30.5)	7.6 (0.193)	90.6	0.027 (0.69)	0.0	0.079 (2.01)	1.1 (0.028)
P-20-10	D	1.5 (3.8)	7.7 (0.196)	91.5	0.025 (0.64)	0.0	0.084 (2.13)	1.8 (0.046)
	G	6.2 (15.8)	7.6 (0.193)	91.4	0.027 (0.69)	0.0	0.087 (2.21)	1.4 (0.036)
	L	12.0 (30.5)	7.7 (0.196)	91.0	0.027 (0.69)	0.0	0.081 (2.06)	2.2 (0.056)
P-20-25R	D	1.5 (3.8)	5.6 (0.142)	91.3	0.022 (0.56)	0.0	0.075 (1.91)	2.4 (0.061)
	G	6.2 (15.8)	5.6 (0.142)	91.1	0.023 (0.58)	0.0	0.079 (2.01)	1.9 (0.048)
	L	12.0 (30.5)	5.6 (0.142)	91.1	0.022 (0.56)	0.0	0.077 (1.96)	2.1 (0.053)
P-20-27	D	1.5 (3.8)	5.7 (0.145)	90.9	0.022 (0.58)	0.0	0.072 (1.83)	1.5 (0.038)
	G	6.2 (15.8)	5.6 (0.142)	91.0	0.026 (0.66)	0.0	0.078 (1.98)	1.9 (0.048)
	L	12.0 (30.5)	5.8 (0.147)	91.1	0.026 (0.66)	0.0	0.075 (1.91)	2.4 (0.061)
P-20-29	D	1.5 (3.8)	5.7 (0.145)	91.3	0.023 (0.58)	0.0	0.074 (1.88)	1.7 (0.043)
	G	6.2 (15.8)	5.6 (0.142)	91.4	0.026 (0.66)	0.0	0.078 (1.98)	1.3 (0.033)
	L	12.0 (30.5)	5.6 (0.142)	91.2	0.023 (0.58)	0.0	0.076 (1.93)	1.8 (0.046)
P-20-33	B	1.5 (3.8)	3.5 (0.089)	91.2	0.018 (0.46)	0.0	0.068 (1.73)	2.2 (0.056)
	D	6.0 (15.2)	3.5 (0.089)	90.1	0.020 (0.51)	0.0	0.078 (1.98)	2.1 (0.053)
	H	11.9 (30.2)	3.8 (0.097)	90.4	0.019 (0.48)	0.0	0.073 (1.85)	2.7 (0.069)
P-20-35	D	1.5 (3.8)	3.6 (0.091)	90.1	0.016 (0.41)	0.0	0.070 (1.78)	2.3 (0.058)
	G	6.2 (15.8)	3.5 (0.089)	90.5	0.020 (0.51)	0.0	0.077 (1.96)	3.2 (0.081)
	L	12.0 (30.5)	3.5 (0.089)	90.8	0.020 (0.51)	0.0	0.073 (1.85)	1.5 (0.038)
P-20-37	D	1.5 (3.8)	3.4 (0.086)	90.2	0.017 (0.43)	0.0	0.069 (1.75)	1.7 (0.043)
	G	6.2 (15.8)	3.4 (0.086)	90.7	0.019 (0.48)	0.0	0.074 (1.88)	1.1 (0.028)
	L	12.0 (30.5)	3.5 (0.089)	90.5	0.021 (0.53)	0.0	0.073 (1.85)	1.0 (0.025)

(1) Inches (cm) from bottom of fuel column

(2) TD = Theoretical density (~10.9 gm/cc) of the fuel.

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E. N. Heck	W/E-3
J. M. Henderson	W/E-8
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D. M. Hoyt	W/E-1
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L. A. Lawrence	W/E-1
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J. Muraoka	W/F-119

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L. A. Pember	W/A-72
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W. E. Roake	W/E-2
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W. F. Sheely	W/C-44
D. P. Schively	W/FED-119
F. R. Shoher	W/E-6
I. Z. Stone	W/E-1
J. P. Taylor	W/E-7
J. E. Tobin	W/E-1
D. F. Washburn	W/E-10
E. T. Weber	W/A-63
J. W. Weber	W/E-1

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