HEDL-SA-2206-FP

CONF-801107--49

FUEL-CLADDING CHEMICAL INTERACTION IN MIXED-OXIDE FUEL AT HIGH BURNUP

MASTER

L. A. Lawrence, J. W. Jost

October 1980

DISCLAIMER

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

American Nuclear Society

November 16-21, 1980

Washington, D.C.

HANFORD ENGINEERING DEVELOPMENT LABORATORY
Operated by Westinghouse Hanford Company, a subsidiary of Westinghouse Electric Corporation, under the Department of Energy Contract No. EY-76-C-14-2170

COPYRIGHT LICENSE NOTICE
By acceptance of this article, the Publisher and/or recipient acknowledges the U.S. Government's right to retain a nonexclusive, royalty-free license in and to any copyright covering this paper.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

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

DISCLAIMER

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

FUEL-CLADDING CHEMICAL INTERACTION IN MIXED-OXIDE FUEL AT HIGH BURNUP

L. A. Lawrence, J. W. Jost

The correlation for depth of fuel-cladding chemical interaction (FCCI) in mixed-oxide fuel pins[1] was expanded with the addition of examination data at high burnups from the HEDL-P-23A, -23B, and -23C, and HEDL-P-15 subassemblies irradiated in EBR-II.[2] (SLIDE 1). Fabrication and operating parameters for the tests are summarized in the next slide (SLIDE 2). The 75 wt% UO_2 - 25 wt% PuO_2 fuel was enriched to 65 wt% in ^{235}U in the P-23 series and was natural, i.e., .71 wt%, for the HEDL-P-15 pins. O/M's ranged from 1.938 to 1.984 with the bulk of the data between 1.96 and 1.98. Fuel pins operated to a peak burnup of 14.5 at.% with local cladding inner surface temperatures to 725°C with exposure times to 675 equivalent full power days. Heat rates were ∿400 W/cm for the P-23 series and ∿200 W/cm for the HEDL-P-15 pins.

The expansion of the HEDL FCCI data base is summarized in the next slide (SLIDE 3). The data base was extended to a peak burnup of 14.5 at.% for the high O/M of 1.984 and to a peak burnup of 7.1 at.% for the low O/M of 1.938. Data from the fourth interim examination of the HEDL-P-15 test extended the data base to 2.8 at.% burnup[3] for high cladding temperatures (∿700°C) and low heat rates (∿150 W/cm).

The depth of interaction was measured on each sample using total cladding thickness techniques. The next slide (SLIDE 4) summarizes the measurement technique used for depth of interaction. A "nominal" depth of interaction was obtained by averaging the measurements of the minimum thickness on photographs of the cladding at eight equally spaced locations on the circumference of each metallographically prepared sample and subtracting this value from a similarly established reference cladding thickness. The photographic coverage for each sample was on a fixed grid. In addition, if there were major variations within

a given sample the photographic coverage was increased accordingly. Samples for determining the reference thickness were removed from each fuel pin at a location ~25 cm above the top of the fuel column. Examinations of unirradiated cladding have shown significant variations (i.e., on the order of ± 10 - 12 microns) in total cladding thickness around the circumference of the samples due primarily to manufactured tubing eccentricity. The averaging technique used to define the depth of interaction tends to reduce the data scatter due to as-fabricated cladding thickness variations. A maximum depth of interaction was also determined for each sample.

The next slide (SLIDE 5) lists the fabrication and irradiation parameters considered for the correlation. In the case of ^{235}U enrichment and heat rate, only two data sets were available, i.e., P-23 series and P-15. These data were too limited to develop any correlation with enrichment and heat rate. For burnups and cladding temperatures several different definitions were possible.

Fuel pin cladding temperatures varied during irradiation due to changes in the irradiation environment from cycle-to-cycle, alteration in the subassembly due to scheduled interim examinations, and depletion of fissile atoms with burnup. The peak cladding temperature for a P-23A pin irradiated to ~10 at.% burnup is shown in the next slide (SLIDE 6) as an example.

Several definitions for cladding temperature and burnup were considered for the operating conditions to describe the data (SLIDE 7). A calculated local burnup was selected for each sample. Measured burnup values using ^{148}Nd have been shown to agree within ± 3% with values calculated based on reactor supplied fission rate data. A time averaged cladding inner surface temperature was selected to describe the samples.

The correlation of the depth of interaction with fabrication and operating parameters was revised. The first step was to use the same equation form and techniques developed for the original correlation.[1] Other models, such as an exponential temperature dependence, were considered but rejected since they did not result in an improved fit to the data.

The revised correlation for depth of interaction, shown in the next slide (SLIDE 8) is:

$D = 0.3198\ (O/M - 1.935)(B + K)(T - 739)$ For $O/M > 1.935$, $B > 0$, $T > 739$
(For conditions outside this range, D is zero).

Where:

D = depth of interaction (microns)
O/M = initial as-fabricated oxygen-to-metal ratio
B = local fuel burnup (at.%)
K = constant (a function of the confidence level for maximum depth of interaction)
T = time averaged local cladding inner surface temperature (K)

The revised correlation is very similar to the original equation,[1] in that when K = 0 the value predicted by D is the median value for the measured "averaged" depths of interaction. The maximum depth of interaction for a given sample is less than or equal to the value predicted by the correlation with the confidence level determined by the value of K. The values of K were empirically determined and, therefore, are approximate confidence levels.

K	Approximate Confidence Level, %
16.67	95
13.98	90
4.33	50

The predicted and measured maximum depths of interaction at the 95% confidence level, shown in the next slide (SLIDE 9), indicate that the model adequately accounts for the measured depths of interaction without being overly conservative.

The differences between the measured and predicted maximum depths of interaction are plotted as a function of burnup in the next slide (SLIDE 10). The differences are evenly divided around the zero line indicating that the linear burnup dependence is a good statistical approximation to the data base.

The depth of interaction was calculated for a typical breeder reactor fuel pin operating at a peak cladding inner surface temperature of 700°C to

a peak burnup of 8 at.% (SLIDE 11). Axial burnup and cladding temperature profiles are shown in the upper curves. The maximum depth of interaction is ~50 microns at the 95% confidence level for an O/M = 1.97, considered to be the upper end of most fuel specifications. The maximum depth of attack occurs approximately 3/4 of the way up the fuel column where a combination of burnup (or heat rate) and cladding temperature produces the most severe conditions. For an initial O/M = 1.95 the maximum depth of interaction is in the range of 20 microns to 25 microns, which is a significant reduction in depth of interaction.

The final topic I would like to discuss are some observations from the examinations of the highest burnup (14.5 at.%) and O/M pins in the data base. The most extensive FCCI in the HEDL EBR-II reference fuel program, shown in the next slide (SLIDE 12), was observed in the peak cladding temperature sample from P-23A-18. The character of the interaction was similar to that observed in other high O/M P-23A pins at lower burnups.[1] However, the depth of the interaction and extent of the reaction product zone in the fuel-cladding gap are greater. Local areas of deeper matrix interaction seen in P-23A-18 were also observed but to a lesser extent, in the corresponding lower burnup P-23A fuel pins.[4] Total cladding thickness measurements for P-23A-18 indicate a maximum cladding thickness loss of 135 microns (5.3 mils). It should be noted that this represents the most extensive FCCI seen in the program and is not representative of the majority of the data. This fuel pin is being discussed because it provides some insight into fuel pin lifetimes.

The pin had not breached but the condition of the cladding suggests that P-23A-18 was at the end-of-life. Detailed examinations of the cladding inner surface in the area of deeper local interaction revealed an incipient cladding crack, shown in the next slide (SLIDE 13). Etched cladding structure in the area of the crack showed no significant change in carbide precipitates, compared to the rest of the cladding, and no large intermetallic precipitates. Therefore, local high cladding temperatures are not suspect as the cause of the incipient crack. The crack, 85 microns (3.4 mils) deep, when combined with the extensive cladding attack represents a significant reduction in cladding thickness to 165 microns (6.5 mils).

In conclusion (SLIDE 14), the HEDL FCCI correlation has been expanded to peak burnups up to 14.5 at.%. Increases in depth of interaction were found to be linear with burnup to approximately twice the FFTF goal burnup. Examinations of the peak burnup pin P-23A-18 indicates that it was very close to a true end-of-life breach, demonstrating a substantial burnup capability for FFTF reference design mixed-oxide fuel[2] operating at high cladding temperatures.

REFERENCES

1. L. A. Lawrence, J. W. Weber, and J. L. Devary, "Fuel-Cladding Chemical Interaction in Mixed-Oxide Fuel," Proceedings of the International Conference on Fast Breeder Reactor Fuel Performance, pp. 432-444, Monterey, CA, March 5-8, 1979.

2. R. D. Leggett, E. N. Heck, P. J. Levine, R. F. Hilbert, "Steady-State Irradiation Behavior of Mixed-Oxide Fuel Pins Irradiated in EBR-II," Proceedings of the International Conference on Fast Breeder Reactor Fuel Performance, pp. 2-16, Monterey, CA, March 5-8, 1979.

3. J. W. Hales, L. A. Lawrence, "Performance of Commercially-Produced Mixed-Oxide Fuels in EBR-II," HEDL-SA-2190S, For Presentation at the Washington, D.C., ANS Meeting, November 17-21, 1980.

4. L. A. Lawrence, J. W. Weber, and J. L. Devary, Analysis of Fuel-Cladding Chemical Interaction in Mixed-Oxide Fuel at High Burnup, HEDL-TME 78-66, Hanford Engineering Development Laboratory, Richland, WA, July 1978.

FUEL-CLADDING CHEMICAL INTERACTION (FCCI) IN MIXED-OXIDE FUEL AT HIGH BURNUP

L. A. LAWRENCE, J. W. JOST

FUEL-CLADDING CHEMICAL INTERACTION (FCCI) AT HIGH BURNUP

HEDL FCCI WASTAGE CORRELATION FOR REFERENCE MIXED-OXIDE FUELS EXPANDED WITH THE ADDITION OF HIGHER BURNUP DATA

- HEDL-P-23A, -23B, -23C AT PEAK BURNUPS TO 14.5 AT.%
- HEDL-P-15 AT PEAK BURNUPS TO 2.8 AT.%

(SLIDE 1)

FABRICATION AND IRRADIATION PARAMETERS

FUEL	75 WT% UO_2 - 25 WT% PuO_2
	^{235}U ENRICHMENT: 65 WT% (P-23 SERIES)
	NATURAL: (P-15)
	O/M = 1.938 TO 1.984
	SMEARED DENSITY = 85%
CLADDING	TYPE 316 - 20% CW STAINLESS STEEL
	5.84 MM OD BY 5.08 MM ID
IRRADIATION	REACTOR: EBR-II
	PEAK BURNUP TO 14.5 AT.%
	LOCAL CLADDING ID TEMPERATURES TO 725°C
	PEAK HEAT RATES: 400 W/CM (P-23 SERIES)
	200 W/CM (P-15)
	RESIDENCE TIME TO 675 EFPD*

*EQUIVALENT FULL POWER DAYS

(SLIDE 2)

EXPANSION OF FCCI DATA BASE

- P-23 SERIES
  - 54 DATA SETS FROM 14 PINS
    - PEAK BURNUP 14.5 AT.% FOR O/M = 1.984
    - PEAK BURNUP 7.1 AT.% FOR O/M = 1.938
- HEDL-P-15
  - 11 DATA SETS FROM 7 PINS
    - PEAK BURNUP 2.8 AT.% FOR O/M = 1.97
- DATA BASE
  - ORIGINAL: 153 DATA SETS FROM 42 PINS
  - EXPANDED: 218 DATA SETS FROM 63 PINS

(SLIDE 3)

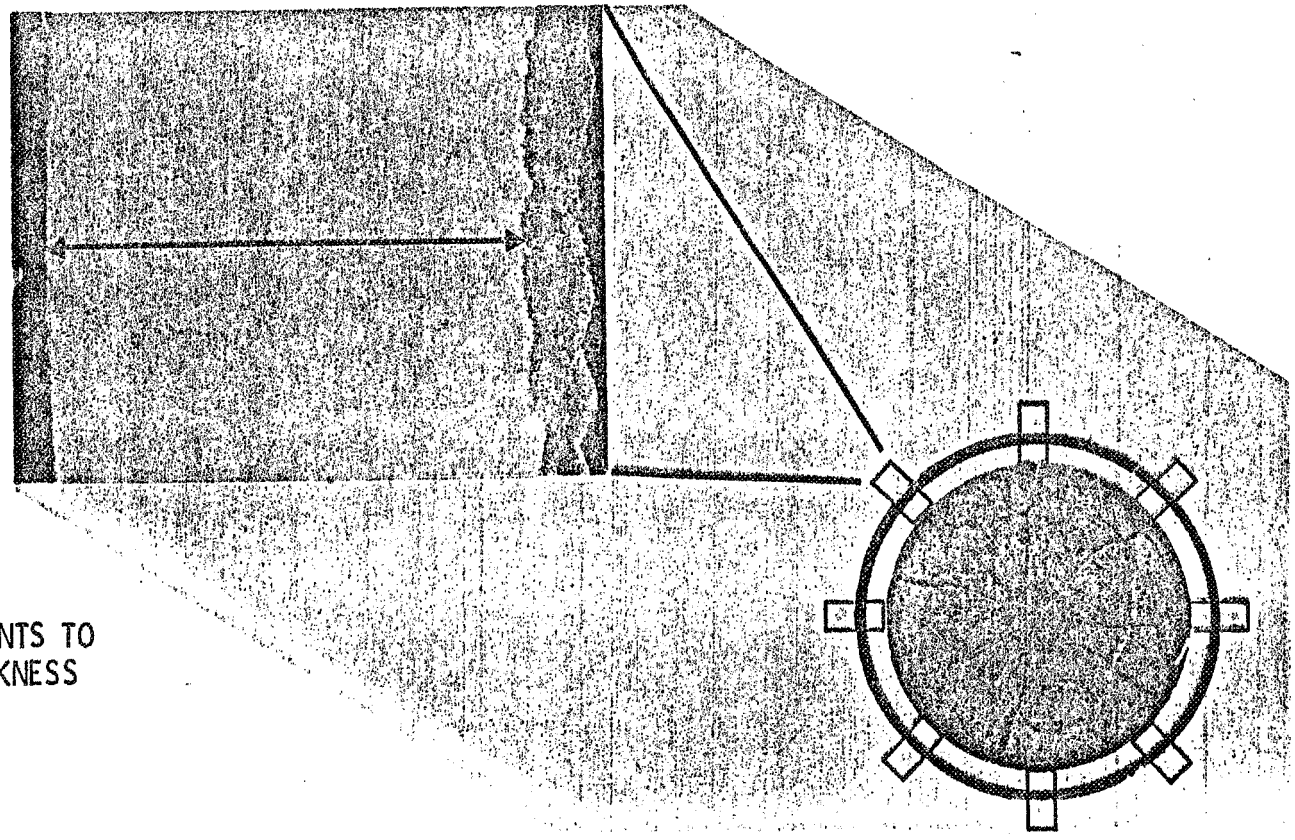
MEASUREMENT OF DEPTH OF INTERACTION

MEASURE MINIMUM THICKNESS ON EACH PHOTOGRAPH

MEASURE MINIMUM THICKNESS FOR THE SAMPLE

AVERAGE THE 8 MEASUREMENTS TO OBTAIN A "NOMINAL" THICKNESS

ESTABLISH A REFERENCE THICKNESS FOR EACH PIN WITH A CLADDING SAMPLE OUTSIDE THE FUELED PORTION OF THE PIN



EIGHT CLADDING THICKNESS PHOTOGRAPHS TAKEN ON A REGULAR GRID FOR EACH SAMPLE IN THE POLISHED CONDITION

HEDL 7911-060.14

(SLIDE 4)

PARAMETERS CONSIDERED FOR CORRELATION

FABRICATION

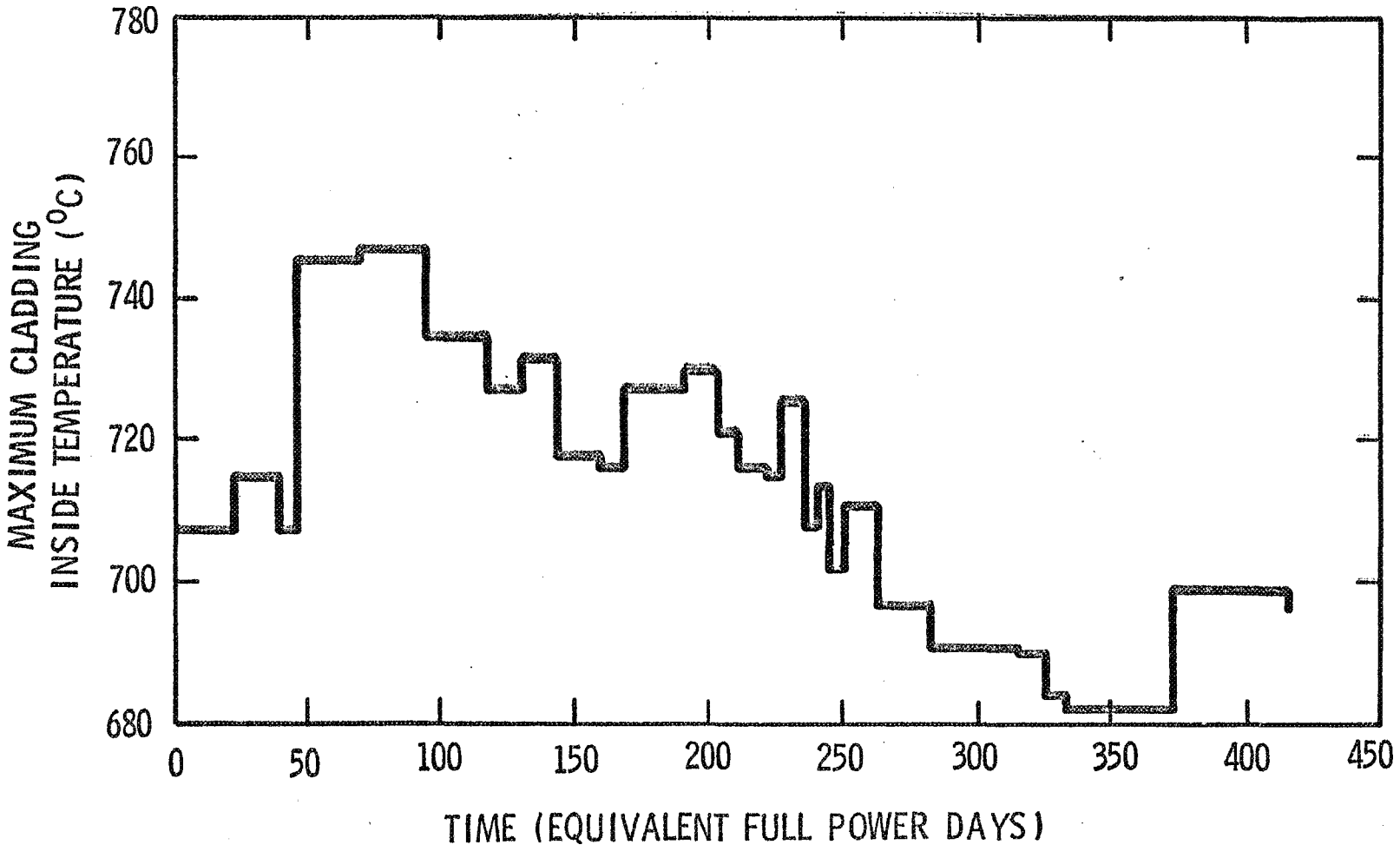
- OXYGEN-TO-METAL RATIO
- ^{235}U ENRICHMENT

IRRADIATION

- BURNUP
- CLADDING TEMPERATURE
- HEAT RATE
- RESIDENCE TIME

(SLIDE 5)

PEAK CLADDING INNER SURFACE TEMPERATURE HISTORY OF P-23A-20



(SLIDE 6) HEDL 7911-060.12

OPERATING PARAMETERS FOR CORRELATION

BURNUP

* - CALCULATED

- MEASURED ($^{148}_{ND}$)

- PIN AVERAGED

* - LOCAL

CLADDING TEMPERATURES

- BEGINNING-OF-LIFE

- END-OF-LIFE

* - TIME AVERAGED

- BURNUP AVERAGED

- AVERAGE OF FIRST AND LAST CYCLE

- EFFECTIVE÷BASED ON AN ASSUMED FORM OF THE EQUATION

---

*SELECTED FOR CORRELATION

(SLIDE 7)

CORRELATION OF DEPTH OF INTERACTION

$$D = .3198\,(O/M - 1.935)\,(B + K)\,(T - 739)$$

FOR $O/M > 1.935$, $B > O$, $T > 739$

FOR CONDITIONS OUTSIDE THIS RANGE, D IS ZERO

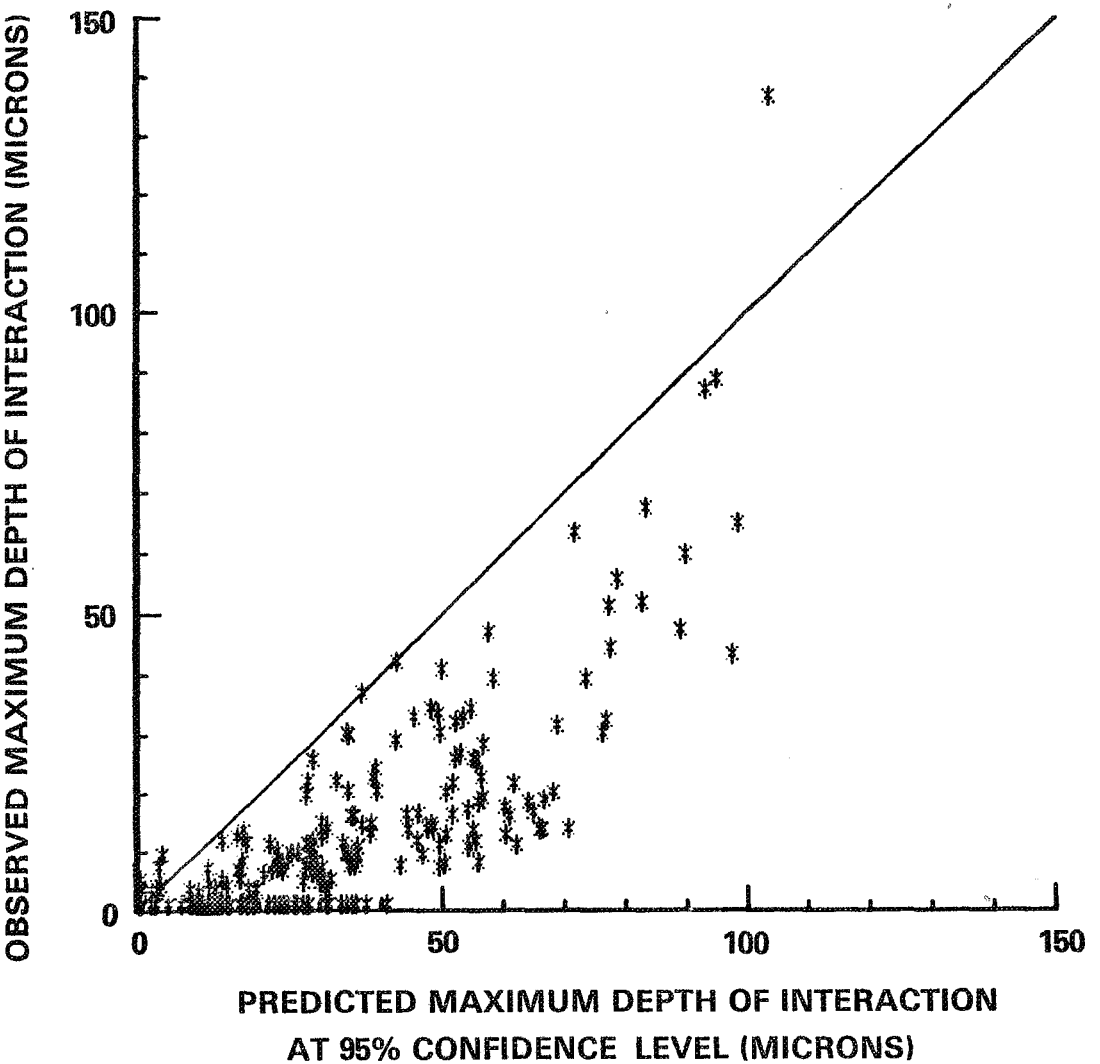
	K	APPROXIMATE CONFIDENCE LEVEL, * %
D = DEPTH OF INTERACTION (MICRONS)		
O/M = INITIAL AS-FABRICATED OXYGEN-TO-METAL RATIO	16.67	95
B = LOCAL FUEL BURNUP (AT. %)	13.98	90
K = CONSTANT (A FUNCTION OF THE CONFIDENCE LEVEL FOR MAXIMUM DEPTH OF INTERACTION)	4.33	50
T = LOCAL TIME AVERAGED CLADDING INNER SURFACE TEMPERATURE (K)		

*CONFIDENCE LEVEL EMPIRICALLY DETERMINED

HEDL 8010-157.5

(SLIDE 8)

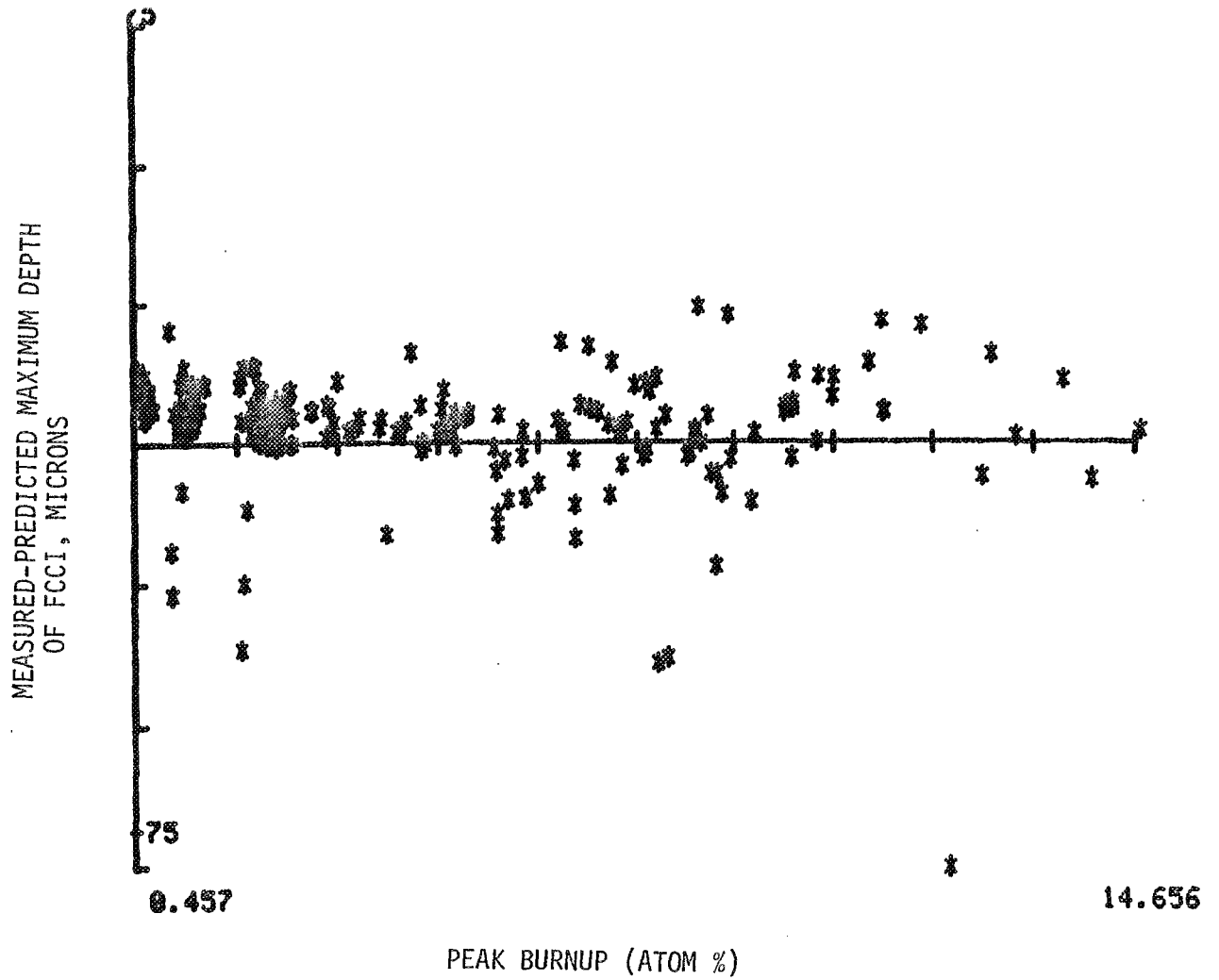
MEASURED AND PREDICTED (95%)
MAXIMUM DEPTH OF INTERACTION



HEDL 8003-337.5

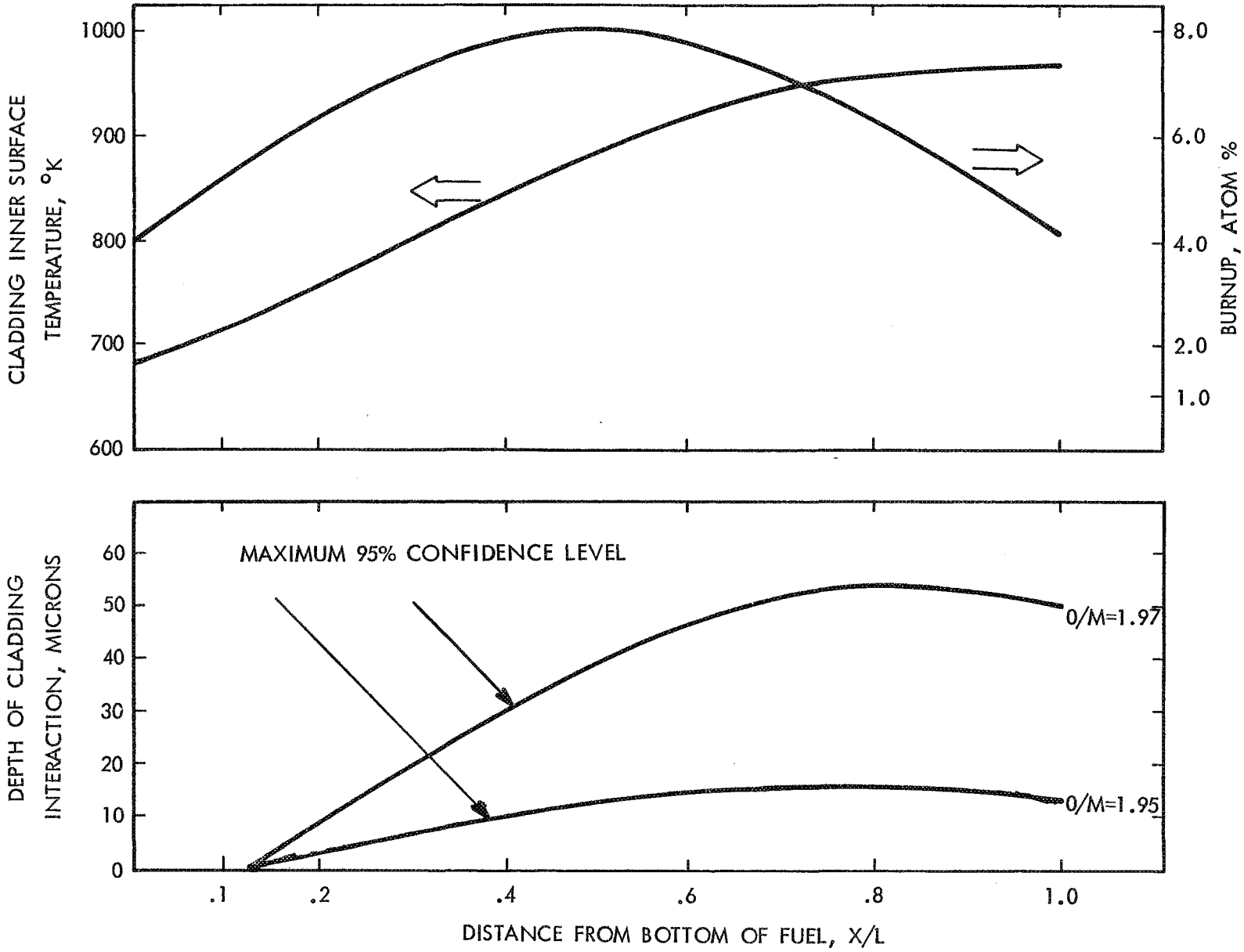
(SLIDE 9)

MEASURED AND PREDICTED MAXIMUM DEPTHS OF FCCI



(SLIDE 10)

PREDICTED DEPTH OF INTERACTION FOR A BREEDER REACTOR FUEL PIN



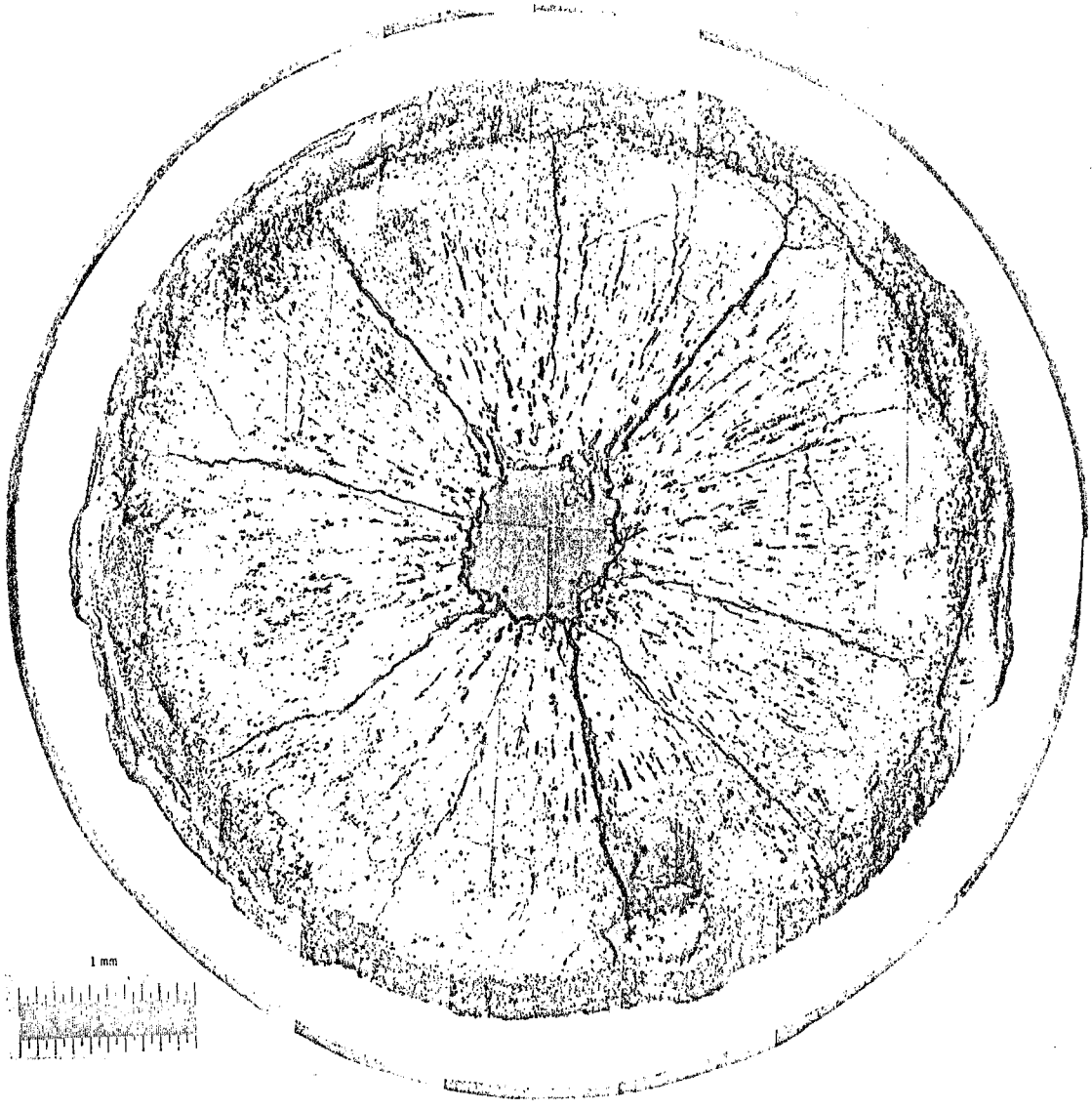
HEDL 7901-096.2

(SLIDE 11)

FCCI AT HIGH BURNUP

P-23A-18

O/M = 1.984

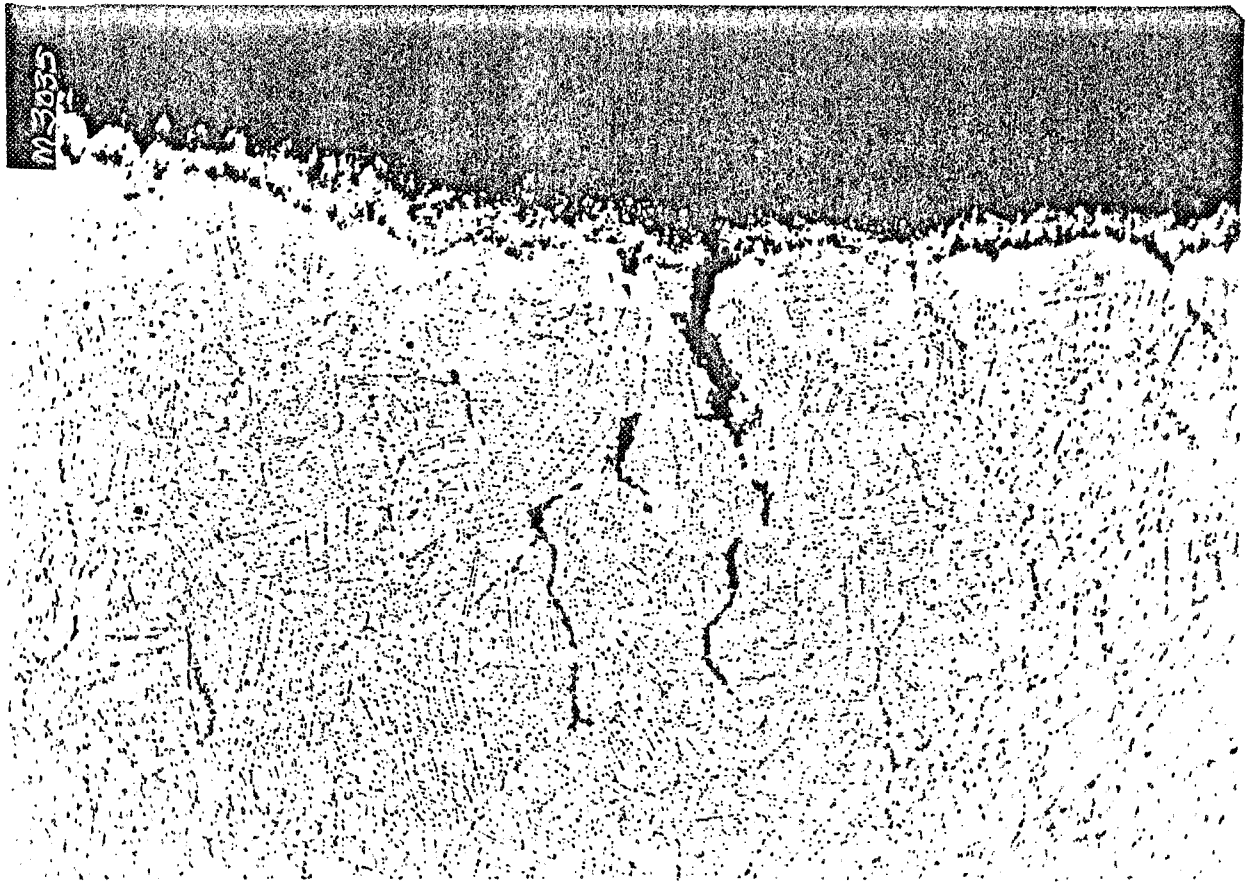


PEAK BURNUP 14.5 at%

PEAK CLADDING 695°C
ID TEMPERATURE

(SLIDE 12)

CLADDING STRUCTURE
P-23A-18



25 microns

(SLIDE 13)

SUMMARY AND CONCLUSIONS

- THE HEDL FCCI WASTAGE CORRELATION WAS EXPANDED TO INCLUDE DATA WITH PEAK BURNUPS TO 14.5 AT.%.
  - INCREASES IN DEPTH OF INTERACTION WERE LINEAR WITH BURNUP TO APPROXIMATELY TWICE THE FFTF GOAL BURNUP.
- EXAMINATIONS OF THE HIGH O/M = 1.984 PEAK BURNUP PIN (P-23A-18) INDICATED IT WAS VERY CLOSE TO A TRUE END-OF-LIFE BREACH DEMONSTRATING A SUBSTANTIAL BURNUP CAPABILITY.