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ANALYSIS OF FUEL CLADDING CHEMICAL INTERACTION IN MIXED OXIDE FUEL PINS

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ANALYSIS OF FUEL CLADDING CHEMICAL INTERACTION IN MIXED OXIDE FUEL PINS

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In this paper an analysis is presented of the observed interaction between mixed oxide 75 w/o UO_2 - 25 w/o PuO_2 fuel and 316 - 20% CW stainless steel cladding in LMFBR type fuel pins irradiated in EBR-II. We will describe the test pins and their operating conditions, metallographic observations and measurements of the fuel/cladding reaction, and the development of a correlation equation relating depth of cladding attack to temperature and burnup. We will also show some recent data on cladding reactio in fuel pins with low initial O/M in the fuel and compare these with the correlation equation curves.

Fuel cladding chemical interaction (FCCI) has the effect of reducing the load bearing capability of fuel pin cladding by thinning of the cladding. It is essential for the design and prediction of fuel pin performance to develop analytical equations which relate the amount of cladding thickness loss to operating and fabrication parameters. Expressions have been developed and reported by workers in Germany, the United Kingdom, and the U. S. These expressions using results from irradiated fuel pins have all related depth of cladding attack to temperature. Some have also included burnup or time and fuel pin power parameters.

Cladding thickness loss from FCCI is being studied and measured at the Hanford Engineering Development Laboratory (HEDL) in a series of mixed oxide 316 - 20% cold worked stainless steel clad fuel pins irradiated in the EBR-II at high cladding temperatures to several burnup levels.

These tests designated the HEDL P-23A and P-23B are 37 pin subassemblies in Mark J-37 sodium by-pass EBR-II hardware. The fuel pins described in Figure 1 contain solid pellets of 25 w/o PuO_2-75 w/o UO_2 in a 34.3 cm long column. Each pellet is 0.53 cm long by 0.49 cm in diameter with dished ends and was fabricated by mechanical mixing, pressing and sintering. The pellet density is 90.5% of theoretical and the nominal planar smeared density is 85.5% of theoretical. Most of the pins contained fuel having an initial O/M of 1.985 but pins were also included in the tests having fuel with O/M ranging down to 1.95.

The analysis and development of the correlation described in this paper was performed on the results from fuel pins with an O/M of either 1.985 or 1.978, irradiated in the P-23A subassembly. Interim examinations were performed on the subassembly at three levels of exposure, thus permitting us to obtain data on FCCI at peak fuel burnups on 1.2, 2.4, and 5.0 at%. The cladding inside surface temperatures ranged from 410^{0}C at the sodium inlet and to 720^{0}C at the top of the fuel column. The analysis descrived in this paper is based upon the results of examination from three fuel pins, one at each of the three exposure levels. At the lowest burnup pin the initail fuel O/M was 1.985. On the other two pins at the higher burnups, the initial fuel O/M was 1.985.

Each pin was sectioned for metallographic examinations at five or six positions along the length of the fuel column. The samples were prepared using non aqueous grinding and polishing lubricants. The polished samples were visually examined on the metallograph and then photographed at 350x and 750x at 8 or 16 equally spaced positions around the circumference of the fuel-cladding interface. The depth of cladding attack was measured on each of these 8 or 16 750x photomicrographs. The next three figures, 2, 3, and 4 show typical microstructures of FCCI observed in the three pins analyzed. At the lower temperatures, Figure 2, all three pins showed essentially no attack of the cladding. At the intermediate temperatures, 600°C to 675°C, as shown in Figure 3 there is more reaction visible generally as matrix attack. At the highest temperature and with increasing burnup the reaction becomes more severe progressing with burnup from intergranular to a matrix type (Figure 4), which we term advanced or evolved matrix.

Because the reaction products in the matrix type reaction are in some cases loose and spread throughout the fuel to cladding gap, it becomes obvious that some criterion is necessary for measuring the depth of attack. Figure 5 shows how the criterion was chosen on cladding exhibiting matrix reaction. The fuel cladding interface shows no attack in certain locations, but immediately alongside there is significant matrix reaction. By examining a number of these places it was determined that the depth of matrix reaction attack of the cladding was approximately 1/2 the observed thickness of the matrix reaction product. The criterion was then chosen that the depth of attack into the cladding by matrix type reaction would be measured by assuming the original cladding inside surface was located in the middle of the reaction product. Intergranular attack was measured from the estimated original interface to the point of deepest intergranular penetration as shown in Figure 6. Where both matrix and intergranular attack occurred the depth of penetration was measured to include both at the point of deepest penetration. These measurements from each of the 8 or 16 high magnification photographs were average to obtain a single value for each cross section. These single values were thus an average of the maximum penetrations found at 8 or 16 positions around the fuel cladding interface.

Now I will describe the development of the correlation equation. It is recognized that the penetration of the cladding on each section of the fuel pin represents the accumulated effect of time at a varying temperature. Analysis of the time temperature relationship for each pin using EBR-II post run flow and fission rate data showed that the variations during reactor full power operation were approximate $\pm$ 20C^{o}. The cladding inside surface temperatures used in this analysis were calculated from fuel pin power based on the chemically measured fuel pin burnup, and the axial power variation determined from post irradiation gamma scanning of the fuel pins.

Figure 7 shows a tabulation of the results of cladding penetration measurements for each pin. In addition to the averaged cladding penetration we have shown the maximum penetration measured in the photomicrographs. In all cases except the lowest exposure the maximum penetration measured approximately twice the average.

Figure 8 shows the average penetration data plotted as a function of cladding inside surface temperature. Thus eachpoint represents a unique place along the fuel pin and a unique time averaged temperature. The points plotted indicate an increasing penetration with temperature starting from approximately 450 to 500^{o}C and an increasing penetration with burnup for a constant temperature. The form of the correlation equation was chosen to give an exponential temperature relationship and a power dependence on burnup. The data were analyzed using a non-linear regression analysis to give the equation shown in Figure 9. D is the penetration of the cladding in μm, B is the average fuel pin burnup in at% and T is the cladding inside surface temperature in °K. The burnup is to the one half power, or approximately to the square root of time, thus these data indicate a decreasing rate of penetration with time or burnup.

Figure 10 shows the data plotted and the curves of the equation for the three average burnups representing the plotted data. The curves and the data show reasonably good fit.

An important parameter that is not included in the current correlation is the initial fuel O/M level. Earlier work performed at HEDL on thermal flux irradiated fuel pins showed that reducing the initial fuel O/M significantly reduced the depth of cladding attack by FCCI. Figure 11 shows cladding attack data from three pins in the P-23B subassembly plotted for two O/M levels, 1.97 and 1.95, after irradiation to 2.4 at%. These data compared to the data for the P-23A fuel pin at the 1.985 O/M level at the same burnup shows that at a temperature of 700°C the average depth of penetration is reduced by a factor of 3 by reducing the O/M from 1.985 to 1.97 and by a further factor of 4 by reducing the O/M from 1.97 to 1.95. These data are at low burnup but the improvement is expected to continue to higher burnups.

In summary, Figure 12, these P-23A and P-23B pins represent a source of fuel-cladding attack data that are consistent in temperature, exposure, cladding, and fuel composition. Thus, much of the data scatter associated with selecting pins from a mixture of tests for analysis has been eliminated, and the resulting correlation is believed to be more reliable for predictive purposes. We have measured the depth of cladding attack from fuel cladding chemical interaction on fuel pins with 316 - 20% cold worked cladding irradiated to three different exposure levels and to cladding temperatures as high as 720°C. These results have been used to develop a correlation equation that shows depth of attack exponentially dependent on cladding inside surface temperature and dependent upon the burnup to approximately the 1/2 power. We have also shown that reducing the O/M of the starting fuel will have a pronounced effect of reducing the depth of cladding attack. With more data soon to be available from other HEDL irradiation tests we will expand the data base to 9.5 at% and include O/M as a variable.

DESCRIPTION OF EBR-II IRRADIATED FUEL PINS

FUEL

25 w/o PuO_2-75 w/o UO_2

O/M 1.985 → 1.95

MECHANICALLY MIXED

SOLID PELLET

- 90.4% TD
- DISHED ENDS
- 0.53cm LONG x 0.49cm DIAM.

34.3cm LONG FUEL COLUMN

FUEL PIN SMEARED DENSITY 85.5% TD

CLADDING

316SS-20% COLD WORKED

0.584cm OD x 0.038cm THICK WALL

OPERATING CONDITIONS

LINEAR POWER - 394 W/cm

CLADDING INSIDE SURFACE - 410°C TO 720°C

PEAK EXPOSURES - 1.2, 2.4, 5.0 AT. % BURNUP

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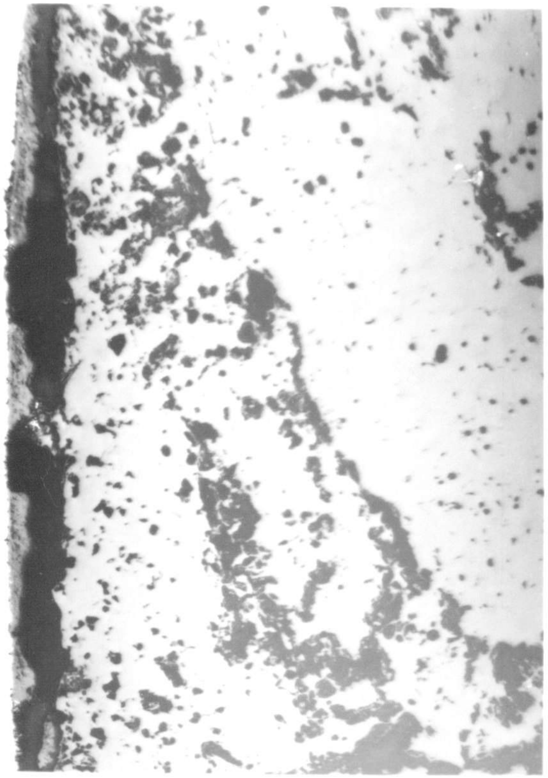
FIGURE 1

FUEL CLADDING INTERFACE

TEMPERATURE - 575^{0}C
BURNUP - 1.2 AT. %
INITIAL O/M 1.975



CLADDING

FUEL

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FIGURE 2

FUEL CLADDING INTERFACE

TEMPERATURE - 650°C
BURNUP - 2.4 AT. %
INITIAL O/M - 1.985

HEDL 7605-140.2

FIGURE 3

FUEL CLADDING INTERFACE

TEMPERATURE - 725^{0}C
BURNUP - 5.0 AT. %
O/M - 1.985

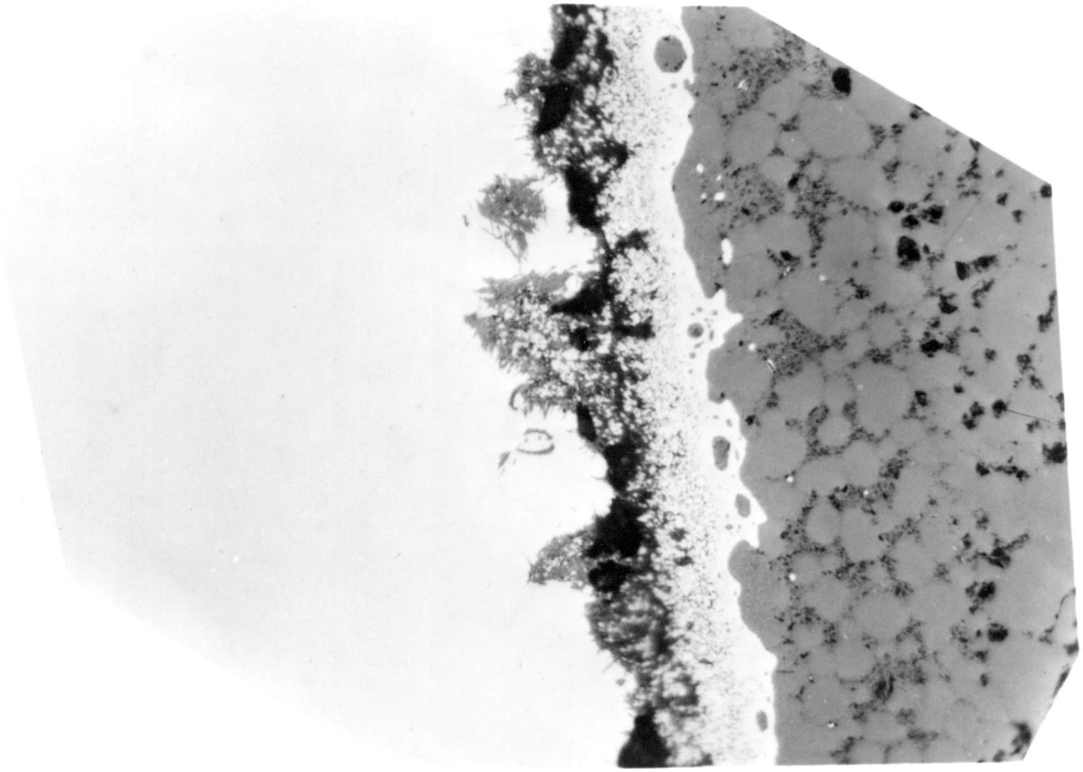

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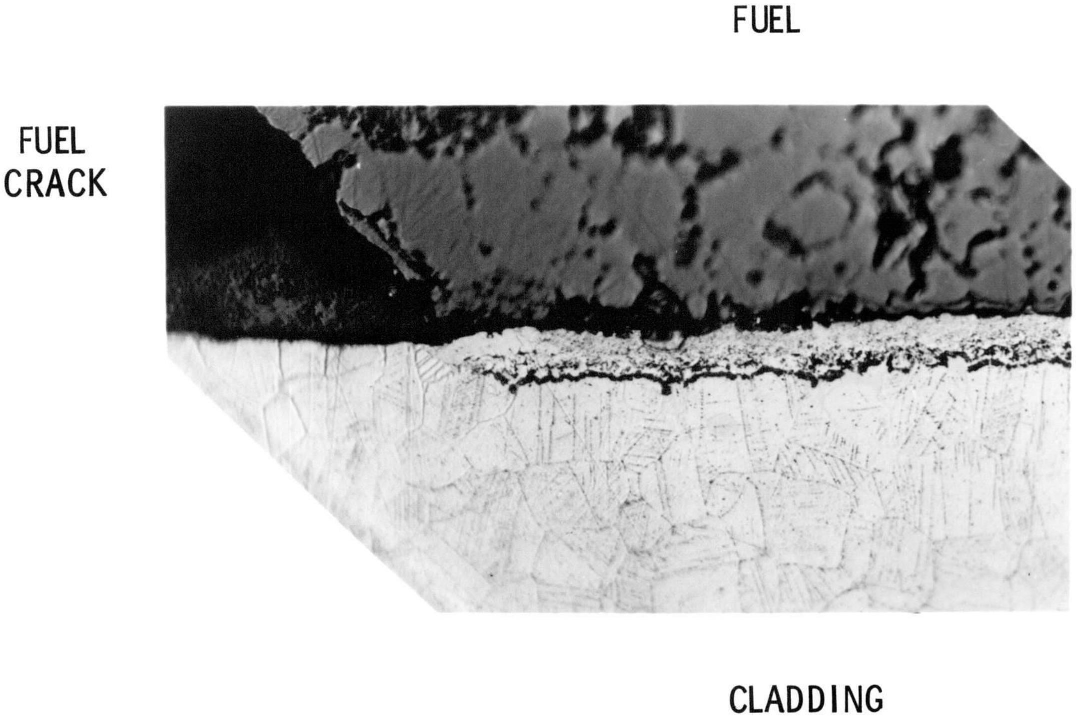
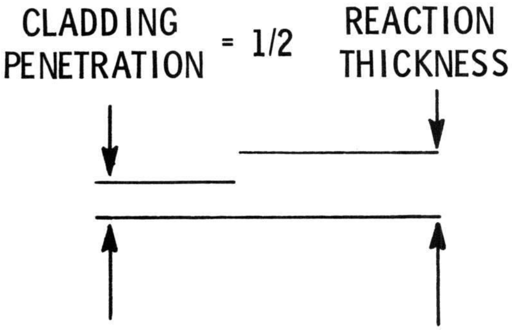
FIGURE 4

RELATIONSHIP OF CLADDING PENETRATION TO THICKNESS OF MATRIX REACTION





CLADDING PENETRATION = 1/2 REACTION THICKNESS

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FIGURE 5

MEASUREMENT OF FCCI CLADDING PENETRATION DEPTH

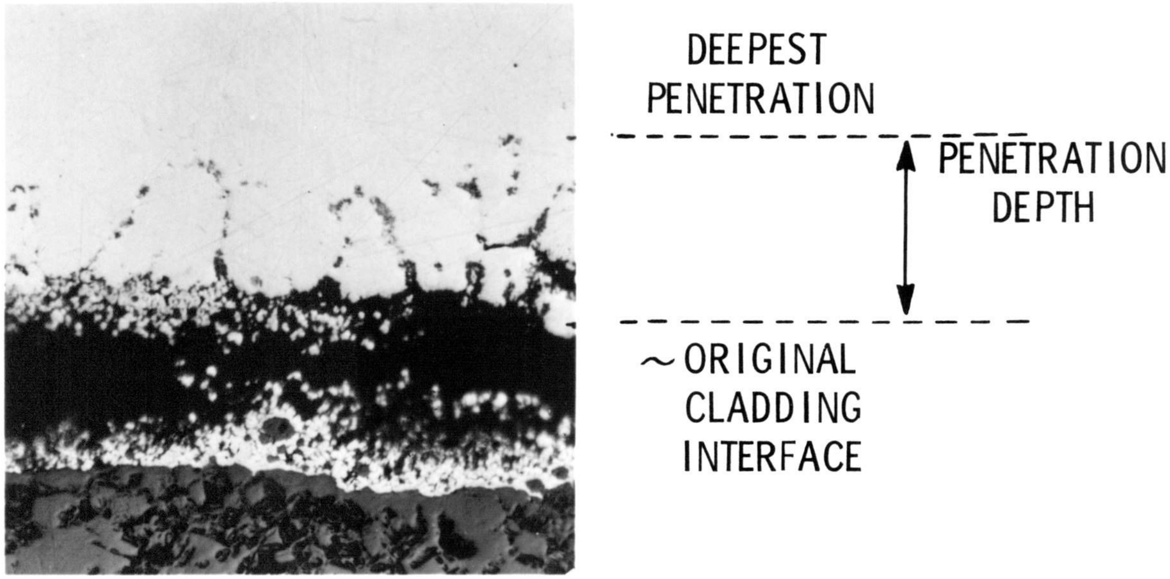

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FIGURE 6

LOSS OF CLADDING FROM FCCI

PIN	FUEL BURNUP - AT. %		CLADDING TEMPERATURE-^{o}C	DEPTH OF ATTACK - μm	
	AVG.	PEAK		AVG.	MAX.
P-23A-58B	1.0	1.2	440	0	0
			520	1.3	1.3
			588	3.2	6.4
			670	7.2	13.2
			718	13.5	38.1
P-23A-26	2.1	2.4	440	0	0
			520	1.3	1.3
			588	3.3	7.6
			670	9.0	12.7
			718	18.4	38.1
P-23A-25	4.6	5.0	421	0	0
			512	0	1.3
			590	9.4	17.8
			668	16.6	30.5
			700	21.9	33.0
			715	26.9	50.8

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FIGURE 7

DEPTH OF CLADDING PENETRATION BY FUEL CLADDING CHEMICAL INTERACTION

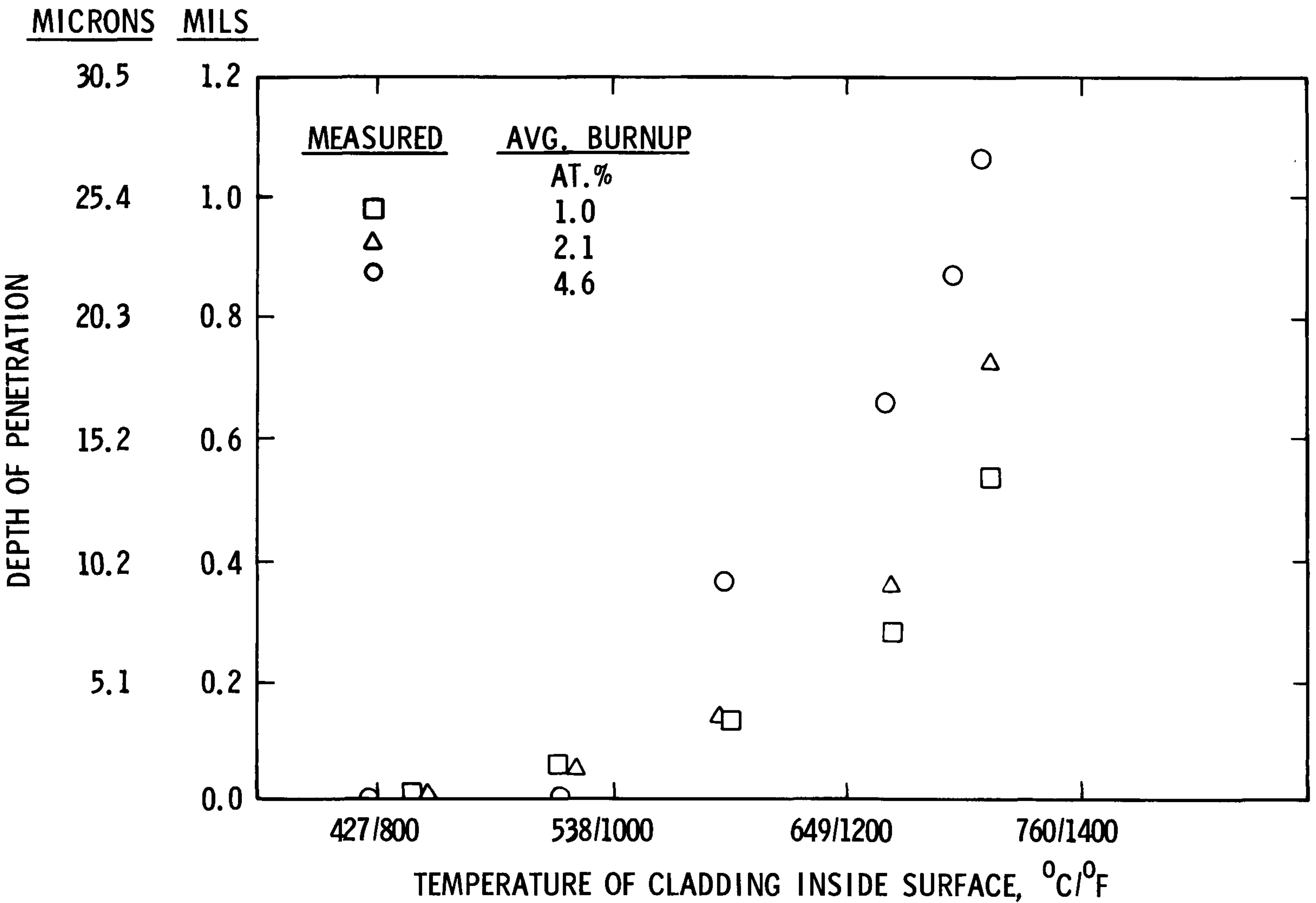

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FIGURE 8

CORRELATION OF CLADDING PENETRATION DEPTH FROM FCCI TO CLADDING TEMPERATURE AND FUEL BURNUP

$$D = 2.43\times10^{5}[B.U.]^{0.517}\exp[-\frac{9806}{T}]$$

D - AVERAGE DEPTH OF CLADDING PENETRATION - μm

B.U. - FUEL PIN AVERAGE BURNUP - AT. %

T - CLADDING INSIDE SURFACE TEMPERATURE - K

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FIGURE 9

COMPARISON OF CLADDING PENETRATION MEASURED WITH PENETRATION PREDICTED BY CORRELATION

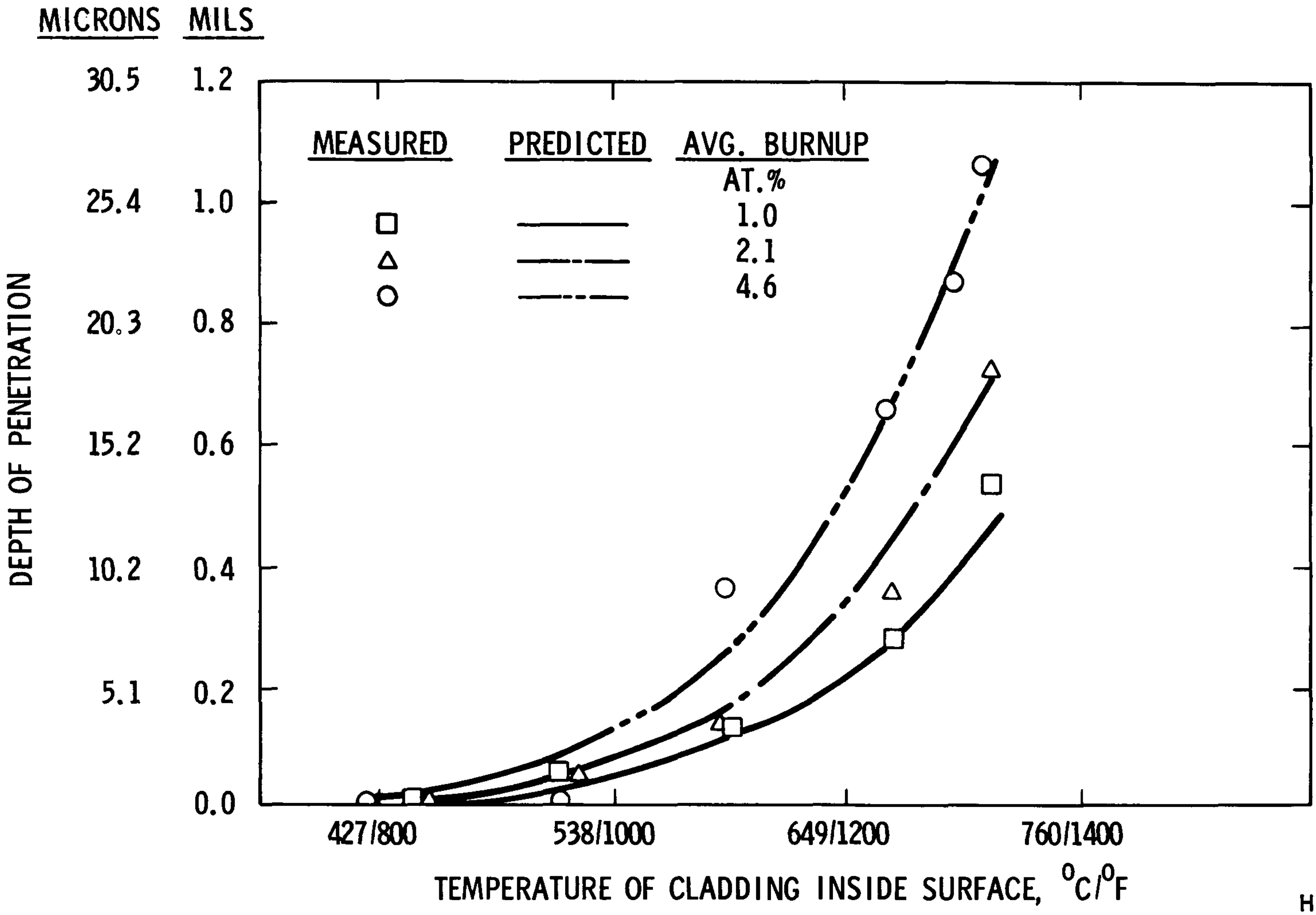

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FIGURE 10

COMPARISON OF FUEL O/M EFFECT ON DEPTH OF CLADDING PENETRATION AT 2.1 AT. % AVERAGE BURNUP

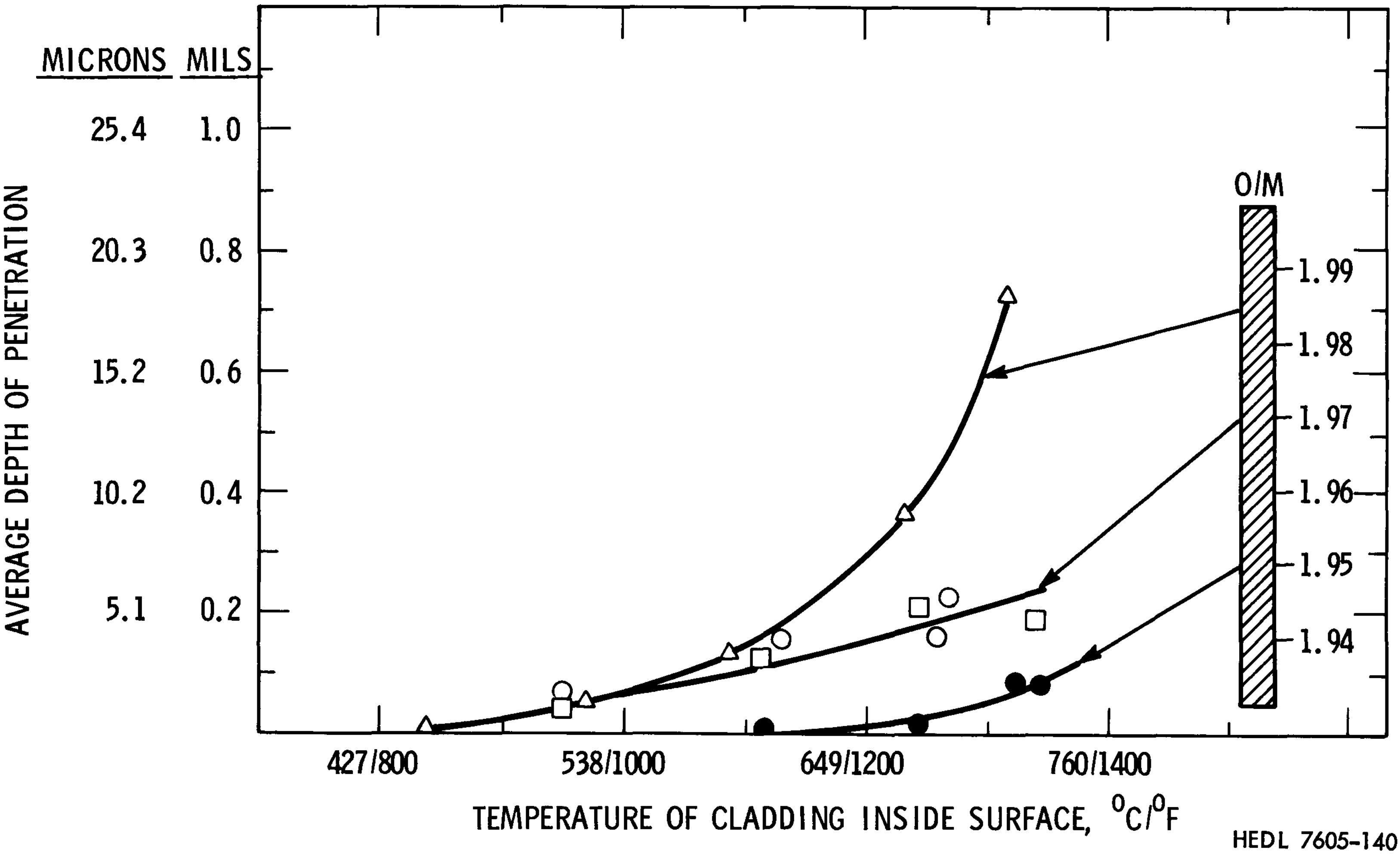

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FIGURE 11

SUMMARY OF ANALYSIS OF FUEL CLADDING CHEMICAL INTERACTION IN MIXED OXIDE FUEL PINS

- CONSISTENT DATA BASE
- MEASUREMENTS OF DEPTH OF CLADDING PENETRATIONS BY FCCI
  - 316-20% CW STAINLESS STEEL
  - EXPOSURES 1.2, 2.4, and 5.0 AT % PEAK BURNUP
- CORRELATION OF DEPTH OF PENETRATION

TO - CLADDING TEMPERATURE

- FUEL BURNUP

$$D = 2.43\times10^{5}[B.U.]^{0.517}\exp[-\frac{9806}{T}]$$

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FIGURE 12