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**ANALYSIS OF MIXED OXIDE FUEL
IRRADIATED IN EBR-II**

MEASURED VS. PREDICTED BURNUP

Hanford Engineering Development Laboratory

HANFORD ENGINEERING DEVELOPMENT LABORATORY
Operated by Westinghouse Hanford Company
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May 1978

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MEASURED AS PREDICTED BURNUP

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ABSTRACT

The calculation of burnup in mixed-oxide fuel pins irradiated in EBR-II is shown to agree with burnup measured by postirradiation radio-chemical analysis. The mean percent deviation is 0.12% with a variance of 2.49%. This gives a high level of confidence that HIST, which uses 91% of the nominal EBR-II power, provides an accurate estimate of burnup.

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I. INTRODUCTION

This report summarizes the results of an evaluation to determine how well calculations of burnup in mixed-oxide (U, Pu)O₂ fuel pins irradiated in EBR-II agree with burnup measured by post-irradiation radiochemical analyses.

The fission rates reported in the EBR-II operating guide⁽¹⁾ provide a basis for designing irradiation tests, but the run-by-run variations in the experimental loadings of EBR-II can cause significant deviations from the "guide". Furthermore, it has been reported⁽²⁾ that EBR-II actually operates at 9% lower power than the nominal 62.5 MW. Since the actual fission rates in a fuel pin play a major role in establishing the irradiation conditions and ultimately performance, it is essential that these rates be well known and that a consistent methodology for determining these rates be established. Furthermore, to transfer the EBR-II experience to a large reactor system, such as the Fast Flux Test Facility (FFTF), the estimates of fuel pin operating conditions in EBR-II must be as absolute as possible and not just comparable to other EBR-II tests.

The calculational consistency is provided at HEDL by the HIST version of SIEX⁽³⁾ to predict the steady-state performance of mixed oxide fuel irradiated in EBR-II. Power and burnup calculations are based on EBR-II run by run fission rates (transmitted from the EBR-II project to EBR-II experimenters since EBR-II Run 56) and a depletion method developed from physics considerations.

Burnup is defined as:

$$\text{Burnup (Atom percent fissioned)} = \frac{\text{number of fissions} \times 100}{\text{initial number of total heavy metal atoms}}$$

The energy deposited in the fuel is of prime concern for an evaluation of its irradiation performance and stability but is not germane to the present evaluations of calculated and measured burnup. The energy produced by a fuel will, in a reactor such as EBR-II, be 5 to 10% higher than the energy deposited because of losses to structural and coolant materials.

II. SUMMARY

This report verifies the reliability of the current HEDL methods used to estimate burnup in mixed-oxide $[(U, Pu)O_2]$ fuel pins irradiated in EBR-II. Therefore, the operating power is also reliably known, subject to the uncertainties in the energy deposited in the fuel.

The methods developed (contained within the computer code HIST) to predict burnup and power in EBR-II were verified by a comparison of predicted and measured burnups for 60 fuel sections from 52 pins. When the EBR-II run-by-run estimates of fission rates were reduced by 9%, the calculated values compared favorably with the measured values obtained by the fission product monitor neodymium-148. The results were insensitive to burnup level, axial location in the pin, and fuel enrichment.

III. METHODS USED TO MEASURE BURNUP

Neodymium-148 is produced as a fission product and is used as a fission monitor by measuring the ^{148}Nd and the residual heavy atom contents of a dissolved fuel specimen.⁽⁴⁾ The number of fissions in the fuel sample can be determined by using the ^{148}Nd fission yields for ^{235}U and ^{239}Pu and the ^{148}Nd present in the irradiated fuel sample.

Burnup values in atom percent (heavy metal) are calculated from isotopic mass spectrometric data on the basis of the following assumptions and nuclear constants:

- 1) Burnout and buildup of ^{148}Nd atoms from neutron capture reactions, other than fission, are neglected.
- 2) The plutonium is assumed to be all ^{239}Pu . (negligible amounts of ^{240}Pu are present).
- 3) The ^{235}U enrichment value, fuel composition, and the fission cross-sections are used to obtain weighted fission fractions for ^{235}U and ^{239}Pu fissions. All fissions are assumed to be from either ^{235}U or ^{239}Pu .
- 4) The following fission cross-section and ^{148}Nd fission yields (FY) for ^{235}U and ^{239}Pu in EBR-II neutron spectrum were used.

	Fission Cross-Sections (5)	¹⁴⁸ Nd FY (6)	Energy/Fission (7)
²³⁵ U	1.36 barns (σ_{f5})	1.75%(Y ₅)	203 MeV
²³⁹ Pu	1.64 barns (σ_{f9})	1.71% (Y ₉)	211 MeV

These assumptions have been shown to introduce minor errors only, compared to the overall uncertainty in burnup.

The method of calculating atom percent is as follows: Let A and B be the weight fractions of PuO₂ and UO₂ respectively in the mixed oxide fuel.

The fraction of fissions from ²³⁹Pu, F₉, is given by:

$$F_9 = \frac{A (\sigma_{f9})}{A (\sigma_{f9}) + B (\sigma_{f5}) Y_5} = \frac{A (1.64) \text{ barns}}{A (1.64) \text{ barns} + B (1.36 \text{ barns}) U_5}$$

where U₅ is the weight fraction of ²³⁵U, ²³⁵U/U.

And, the fraction of fissions from ²³⁵U, F₅, is given by

$$F_5 = \frac{B (\sigma_{f5}) U_5}{A (\sigma_{f9}) + B (\sigma_{f5}) U_5} = \frac{B (1.36 \text{ barns}) U_5}{A (1.36 \text{ barns}) + B (1.36 \text{ barns}) U_5}$$

Then, the average ¹⁴⁸Nd fission yield (Y_A) for the sample is given by

$$Y_A = F_9 Y_9 + F_5 Y_5 = F_9 (1.71\%) + F_5 (1.75\%)$$

The percent of original heavy metal atoms that have fissioned (at% burnup) is calculated using the number of ¹⁴⁸Nd atoms measured in the analyzed sample, N_{Nd}, and the number of heavy metal atoms measured in the analyzed sample, N_m. The number of fissions, N_F, which occurred in the sample is:

$$N_F = \frac{N_{Nd}}{Y_A/100}$$

Then, the atom percent burnup is calculated by:

$$\text{at\%} = \frac{N_F}{N_m + N_F} (100).$$

IV. METHOD USED BY HIST TO CALCULATE FUEL PIN BURNUP

The total burnup (comparable to the measured) is calculated in HIST by accumulating the individual burnup increments experienced during each run segment of EBR-II. In the relationship for burnup, MWd/MTM (= Pin power (MW) x time (d)/weight of metal (MTM)), the equivalent full power days of exposure (d) and the fabricated fuel metal weight (MTM) are well documented values that require no discussion. The fuel pin's energy production (MW) is the value which is determined by the code to calculate fuel pin burnup. The fuel pin's energy production (pin power) is derived as follows:

$$P_L = \sum P_I$$

where:

$$P_I = FR_I \times AXFAC \times W_I \times E_I \times 0.91$$

P_L = the linear heat rate (local pin power) of a fuel pin segment.
(HIST, as most fuel pin codes, divides the fuel pin axially into a number of segments to facilitate modeling the axial dimension.)

P_I = The energy contribution from each of four isotopes in the fuel accounted for by HIST; ^{235}U , ^{238}U , ^{239}Pu , and ^{240}Pu .

FR = Midplane (peak) isotopic fission rates. The sources for these fission rates are the EBR-II User's Guide⁽¹⁾ prior to EBR-II Run 56 and ANL calculated run-by-run after Run 56.

AXFAC = Axial power profile factor. HIST uses the User's Guide Revision 4⁽¹⁾ profile for applications prior to Run 56 and profiles provided by ANL⁽⁸⁾ starting with Run 56.

W = Isotopic weights in each fuel segment. For beginning of irradiation, HIST uses the fabricated ^{235}U weight and assigns the balance of uranium to ^{238}U . Fabricated weight values for ^{239}Pu and ^{241}Pu are lumped together as ^{239}Pu and the balance of the Pu is assigned to ^{240}Pu . After a period of exposure, HIST calculates (burnin/burnout) of the isotopes. The method used, correlated to EBR-II experience, determines the new isotopic weights based on previous weights, fission rates, and capture rates.

E_i = Isotopic energy releases. HIST uses 211 MeV/fission for ^{239}Pu and ^{240}Pu , 203 MeV/fission for ^{235}U , and 201 MeV/fission, for ^{238}U . To calculate fuel pin power HIST reduces the isotopic energy releases by a constant value of 9.2 MeV/fission to account for gamma energy loss.

0.91 = The fission rates in the User's Guide and those received run-to-run are normalized to an "advertised reactor power" (i.e., 50 or 62.5 MW). The factor, 0.91, is an adjustment to a more realistic power level.⁽²⁾

The HIST conversion of burnup in MWd/MTM to atom percent is as follows:

$$\text{Atom Percent Burnup} = \text{MWd/MTM} * \text{FAC}$$

$$\text{FAC} = 1.0/\bar{E}N * 100.$$

where:

FAC = conversion factor

$\bar{E}$ = average energy release per fission, MWd/fission

N = atoms per metric ton of metal, a/MTM

100. = conversion to percent

V. METHOD OF COMPARING CALCULATED BURNUP WITH MEASURED BURNUP

A statistical comparison of the measured and HIST-calculated burnup was conducted and the deviations of HIST from measured values was evaluated. (See Table I for tabulated data and results.)

The percent deviations were calculated using the following equation:

$$\text{Percent Deviation} = \frac{(\text{Measured Burnup} - \text{HIST Calc. Burnup})}{\text{HIST Calc. Burnup}} * 100$$

The percent deviation was compared for axial location (Figure 1), enrichment (Figure 2), and burnup level (Figure 3) to see if the deviation was dependent upon any of these variables. No dependence was found. The general agreement between HIST-calculated burnup values and measured burnup values was quite good (Figure 4).

At the time of this analysis only three pins which had been irradiated in EBR-II with the stainless steel reflector had been destructively examined. Therefore, there are not enough data to support a comparison of experimental burnup with HIST for pins irradiated only with the stainless steel reflector.

VI. CONCLUSION

The results of this analysis give a high level of confidence that HIST provides an accurate estimate of burnup and that using 91% of nominal power in calculations of burnup is consistent with the 148-Nd yields employed. Excellent agreement was shown to exist between HIST calculations and the actual measurements determined from destructive examination of irradiated pins. The mean percent deviation was 0.12% with a variance of 2.49%. The agreement between calculations and measurements was found to exist irregardless of burnup level, initial ^{235}U enrichment in the fuel or axial location of the burnup sample.

TABLE I
TABULATED DATA FOR STATISTICAL COMPARISON OF BURNUP

PIN ID	AXIAL LOCATION (INCH)	BURNUP		U235 ENRICHMENT (%)	PERCENT DEV ¹
		HIST	MEAS (ATOM %)		
PNL-03-08	6.75	2.662	2.782	0.72	4.51
PNL-03-23	6.75	2.707	2.832	0.72	4.62
PNL-03-27	1.75	2.383	2.367	0.72	-0.67
PNL-03-27	7.65	2.655	2.772	0.72	4.41
PNL-03-27	11.75	2.202	2.175	0.72	-1.23
PNL-03-33	6.75	2.698	2.802	0.72	3.85
PNL-04-01	6.75	4.337	4.387	45.0	1.15
PNL-04-20	6.75	4.317	4.294	45.0	-0.53
PNL-04-26	7.75	3.510	3.534	45.0	-0.68
PNL-04-26	6.75	4.121	4.304	45.0	4.44
PNL-04-26	12.75	3.189	3.123	45.0	-2.07
PNL-04-34	6.75	4.073	4.181	45.0	2.65
PNL-05-05	6.75	4.890	4.951	93.0	1.25
PNL-05-06	6.75	6.462	6.814	93.0	5.45
PNL-05-18	6.75	6.571	6.588	93.0	0.26
PNL-05-22	6.75	4.957	5.034	93.0	1.55
PNL-05-25	6.75	6.858	6.814	93.0	-0.64
PNL-05-31	1.75	4.438	4.478	93.0	0.90
PNL-05-31	7.75	4.922	5.064	93.0	2.89
PNL-05-31	11.75	4.077	4.159	93.0	2.01
PNL-05-35	6.75	4.952	5.044	93.0	1.86
PNL-5B-41	6.75	1.985	1.884	93.0	-5.09
PNL-5B-71	6.75	2.010	1.935	93.0	-3.73
PNL-07-10	0.41	2.027	2.055	45.0	1.38
PNL-07-10	6.75	2.496	2.568	45.0	2.88
PNL-07-10	12.95	1.878	1.880	45.0	0.11
PNL-08-11	6.75	5.982	5.878	93.0	-1.74
PNL-08-25	6.75	5.886	5.826	93.0	-1.02
PNL-08-28	6.75	5.783	5.713	93.0	-1.21
PNL-08-37	6.75	2.734	5.610	93.0	-2.16
PNL-08-38	7.10	2.838	2.903	93.0	2.29
PNL-09-30	6.75	4.700	4.939	30.0	5.09
PNL-10-23	6.75	5.126	5.134	65.0	0.16
PNL-10-63	6.65	5.347	5.440	65.0	1.74
PNL-11-12	6.75	3.037	3.087	65.0	1.65
PNL-11-20R	6.75	3.032	3.128	65.0	3.17
PNL-11-22	6.25	0.227	0.224	65.0	-1.32
PNL-11-26	7.25	0.216	0.217	65.0	0.46
PNL-11-36	7.25	0.226	0.225	65.0	-0.44
PNL-11-37	6.69	4.895	4.856	65.0	-0.80
PNL-11-48A	6.69	4.802	4.836	64.0	0.71
P-12-63K	6.63	3.613	3.387	92.0	-6.26

TABLE I (cont'd)

PIN ID	AXIAL LOCATION (INCH)	BURNUP		U235 ENRICHMENT (%)	PERCENT DEV ¹
		HIST	MEAS (ATOM %)		
PNL-17-06	6.00	3.261	3.323	65.0	1.90
PNL-17-07	6.50	3.338	3.375	65.0	1.11
PNL-17-33	6.50	3.212	3.210	65.0	-0.06
P-23A-21	6.75	4.726	4.918	64.0	4.06
P-23A-25	6.75	4.757	4.949	64.0	4.04
P-23A-26	6.75	2.379	2.325	64.0	-2.27
P-23A-28R	6.55	1.153	1.060	64.0	-8.07
P-23A-31	6.25	2.366	2.336	64.0	-1.27
P-23A-32	6.25	2.352	2.294	64.0	-2.47
P-23A-35	6.55	1.150	1.080	64.0	-6.09
P-23A-58B	6.55	1.174	1.121	64.0	-4.51
P-23B-49C	6.70	2.323	2.274	63.0	-2.11
P-23B-50C	6.53	2.265	2.212	63.0	-2.34
NUM-E-N029	6.75	2.435	2.501	76.0	2.71
NUM-E-N049	6.81	2.404	2.439	76.0	1.46
NUM-F-N070	8.06	4.125	3.942	76.0	-4.44
NUM-F-N159	6.25	4.227	4.169	76.0	-1.37
ANL-B-EW28	6.88	5.943	6.143	65.0	3.37

The Standard Deviation of the Error is 2.98%

The Mean of the Error is 0.28%

$$^1 \text{Percent Dev.} = \frac{(\text{Meas. BU} - \text{Calc. BU})}{\text{Calc. BU}} \times 100$$

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FIGURE 1. Comparison of the Deviations of Measured Burnup from Calculated Burnup as a Function of Axial Location of the Burnup Sample.

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FIGURE 2. Comparison of the Deviation of Measured Burnup from Calculated Burnup as a Function of ^{235}U Enrichment.

HEDL 7709-244.2

FIGURE 3. Comparison of the Deviation of Measured Burnup from Calculated Burnup as a Function of Burnup Level.

FIGURE 4. Comparison of HIST Predicted Burnup with Actual Measured Burnup.

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