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Westinghouse Astronuclear Laboratory

**PERFORMANCE OF WANL SUPPLIED
FUEL ELEMENTS IN PEWEE-1**

(Title Unclassified)

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Westinghouse Astronuclear Laboratory

PERFORMANCE OF WANL SUPPLIED FUEL ELEMENTS IN PEWEE-1

(Title Unclassified)

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ABSTRACT (U)

(U) This report describes the results of detailed post-operational examination and performance analysis of WANL supplied PEWEE-1 fuel elements. It was found that interpretations of fuel performance were complicated by surface corrosion and fuel bead hydrolysis effects. After these effects were considered, the general bore performances of all WANL elements were found to be uniformly good and qualitatively as predicted by the qualifying electrical corrosion test data. Surface corrosion losses were found to be primarily related to the thickness of OD NbC coatings; the thicker the coatings the lower the losses. Fuel bead hydrolysis effects in WEFF-GEM coated elements produced pinhole and/or corrosion pocket damage which in turn was found to be related primarily to NbC bore coating defects, cracks and/or thickness parameters.

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1.0 INTRODUCTION (U)

(U) PEWEE-1, the first in a series of compact nuclear reactors, was operated at full power at NRDS on December 4, 1968. The PEWEE reactors were designed at the Los Alamos Scientific Laboratory (LASL) primarily for the test and development of NERVA/ROVER fuel elements and reactor hardware components.

(U) One-hundred-thirty of the fuel elements in PEWEE-1 were supplied by the Westinghouse Astronuclear Laboratory (WANL). These fuel elements, representing technological developments in both coatings and matrices, were outgrowths of the earlier NRX reactor test series and subsequent fuel development activities.

(U) The purpose of this report is to describe the performance of the WANL supplied fuel elements based on the results obtained from a joint LASL-WANL post-operational program. The post-operational results are presented summarily in the text; detailed weight loss and visual examination data for individual elements are given in Appendix A. Metallographic studies of some aspects of fuel element corrosion, particularly that of the hot end region (25-50 inches), have not yet been completed at LASL. An addendum to this report will be issued based on the LASL study.

(U) No attempt has been made to assess the performance of the LASL fuel elements in PEWEE-1. Data on these elements have been included only as necessary to show the general corrosion trends in the core. Considerable emphasis has been given in this report to the data and analyses required to determine the bore corrosion performance of the WANL elements. Consequently, bore weight losses have been estimated for each element by applying corrections to the measured weight losses for mechanically induced and/or surface corrosion losses as indicated by the post-operation observations. No attempt has been made to determine bore weight loss "performance indices" as in previous NRX post-operational experience. ⁽¹⁾ The bore losses of LASL elements have not yet been reported and the core average radial trends needed for performance index calculations have not been established.

2.0 PEWEE-1 CORE MAKEUP AND FABRICATION HISTORY OF WANL SUPPLIED FUEL ELEMENTS (U)

(CRD) The PEWEE-1 core pattern was assembled at LASL per LASL Drawing 43Y-15000ZD1. The WANL supplied fuel elements were fabricated according to WANL Drawing 939J028.

2.1 PEWEE-1 CORE MAKEUP (U)

(CRD) The general inventory of fueled and unfueled elements in PEWEE-1 is given in Table 2-1. The 130 WANL fueled elements represented nine fabrication types and seventeen bore coating batches. They were located in the C, E, F, G, H, and L rows of the core, spanning a core radius of 1.99 to 7.42 inches. The description of WANL supplied fuel elements is given in Table 2-2 and their location in the core is depicted in Figure 2-1 and Table 2-3. For comparison, an inventory of LASL supplied fuel elements by fabrication type is given in Table 2-4.

(CRD) A group of three fuel elements was glued at the cold end to each of 28 unfueled central elements in a "standoff" design. This design produced a gap of approximately sixty mils between the hot end exit face of the fueled elements and the inlet face of the corresponding pedestals. The standoff unfueled centrals were WANL supplied, located exclusively in the F and D rows as shown in Figure 2-1. Fifty-five WANL supplied fuel elements (plus 29 LASL elements) were glued to the A, B, and F faces of the Westinghouse Astronuclear Core Operations (WNCO) centrals as indicated in the legend to Figure 2-1. None of the WEF-1 GEM elements from bore coating batches B219, B220, or B223 nor the Y12 GEM elements were involved in glued clusters. DOW Epoxy 500 was used to bond elements; the resin was applied in the general axial region of 0.5 to 1.5 inches from the inlet end on at least two faces of each fuel element involved.

2.2 FABRICATION HISTORY OF WANL SUPPLIED FUEL ELEMENTS⁽²⁾ (U)

(CRD) The processing of WANL supplied PEWEE-1 elements included coordination of WNCO, Y12, and WEFF facilities to produce the desired matrix/U loading/coating variable combinations described in Table 2-2. The production effort was culminated in the period December 7, 1967, through April 15, 1968, with the delivery of a total of 184 elements, including core candidates, spares, test elements, and evaluation samples. The raw materials and WNCO processing procedures used are tabulated in Tables 2-5 and 2-6. All U-235 loadings of 525 mg/cc in both standard and niobium resinate impregnated matrices were extruded at WNCO^{*}, those of 477 and 269 mg/cc in standard and 2.5 v/o NbC additive matrices were extruded at Union Carbide, Y-12 Division^{*}. The standard extrusion batch formulation of PEWEE-1 elements was 85 parts of cross-blended Type W graphite flour to 15 parts of carbon black, GA fuel beads, and 27 percent "varcum" catalyzed with maleic anhydride.

(CRD) The WNCO elements were extruded at a pressure of 95 ± 10 tons and a rate of 100 ± 10 inches per minute. Cure, bake, graphitization, leaching, and machining procedures were identical to those used for NRX-A6 fuel element processing. A summary of permeability data for Y12 and WNCO elements is presented in Table 2-7.

(CRD) PEWEE-1 production included three successful manufacturing modifications: 1) the use of a 75 w/o NbC - 25 w/o C composite tip, 2) a higher hydrogen-to-salt ratio chemistry for the standard high temperature NbC bore/OD coating sequence (GED), and 3) a new low temperature NbC coating process using methane in the coating gases (GEM process).

* PEWEE-1 elements extruded at WNCO had Serial Numbers 57000 to 57999. PEWEE-1 elements extruded at Y12 had Serial Numbers 58000 to 58999.

(CRD) The aft (hot) end of the WANL supplied PEWEE-1 fuel elements utilized a one-inch long transition tip. This tip consisted of an unfueled nineteen-hole hexagonal graphite section approximately 0.6 inch long brazed to a 75 w/o - 25 w/o C composite wafer approximately 0.4 inch long. The tip was supplied as a unit to WNCO; the unfueled graphite end was brazed to the fuel element (Station 51) using -325 mesh molybdenum powder.*

(CRD) All of the PEWEE-1 fuel elements were O.D. coated. The elements coated at WNCO and WEFF were sequentially bore coated and then O.D. coated without removing the elements from the coating furnace. At Y12, the O.D. coating was deposited first and the bore coating last with different coating furnaces being used for each operation.

(CRD) The WNCO GED, WEFF GEM, and Y12 GEM bore/O.D. sequential coating of elements was accomplished using temperatures, coating times, and chemistry ratios as summarized in Table 2-8. The typical bore coating profiles for the elements tested in PEWEE-1 are compared by major types in Figure 2-2. Tables 2-9 and 2-10 give coating batch average profiles for both bore and O.D. from beta backscatter data.

(CRD) As indicated by Figure 2-2, the bore coatings generally tend to be thickest in the Y12 GEM coated elements followed by the WEFF GEM and WNCO GED types. The batch average thickness profile for GED batches C397 and C398 (eighteen elements) are plotted separately from the other WNCO GED batches (eight batches, 75 elements) since the NbC thicknesses in these two batches were decidedly different. The coating thickness profile typical of the HED coated elements tested in NRX-A6 has been included in Figure 2-2 to indicate the thicker NbC coatings in the hot end region for the WANL PEWEE-1 elements. The data in Table 2-10 indicates a general trend of O.D. NbC thickness of Y12 GEM > WNCO GED > WEFF GEM. The O.D. coating in the extreme hot end region (51-52 inches) of the Y-12 GEM elements is decidedly thicker than that on the other WANL supplied elements.

* Brazing procedure: Tip-to-element joint induction heated to a surface temperature of 2425°C, held for ten seconds and allowed to cool. A 1500 psi compression load was maintained throughout the thermal cycle.

(CRD) The bores in WANL supplied GED coated elements were all overcoated with molybdenum using a modified procedure with a total coating gas flow 24 percent above that used for NRX-A6 elements due to the increased PEWEE-1 bore diameter. The resultant axial distribution of molybdenum was similar to that produced in NRX-A6 and XE-2 fuel elements; that is, approximately $\frac{2}{3}$ of the total weight of molybdenum per element was deposited in the axial region 0-25 inches. The average incremental weight of molybdenum retained in the bores by coating batch is tabulated in Table 2-11.

Figure 2-1. (CRD) Core Location of WANL-Supplied Fueled and Unfueled Elements in PEWEE-1 (U)

Figure 2-2. (CRD) Typical Bore Coating Thickness Profiles for WANL PEWEE-1 Fuel Elements (U)

TABLE 2-1 (CRD)

PEWEE-1 GENERAL INVENTORY OF FUELED AND UNFUELED ELEMENTS (U)

A. Total Number Elements (Filler Elements Excluded)	529
B. Total Number Unfueled Central Support Elements	127 [*]
C. Total Number Fueled Elements	402
a. Number WANL Supplied	130
b. Number LASL Supplied	272

^{*} Twenty-eight unfueled centrals along with associated pedestals and hot end hardware were supplied by WANL.

TABLE 2-2 (CRD)
 WANL SUPPLIED FUEL ELEMENTS IN PEWEE-1 (U)

<u>Bore-O.D. Coating Type</u>	<u>Matrix Type</u>	<u>Nominal Uranium Loading mgms/cc</u>	<u>Nominal Bore Diameter mils</u>	<u>No. In Core (Rows)</u>	<u>NbC Bore Coating Batches</u>
GED + X (WNCO)	Std. (W)	525	110	35 (C, E, F, G)	C396, M136, L314, F387
	Res. (W)	525	110	17 (C, E, F, G)	C398, L313
	Add. (Y)	477	110	24 (G, H)	M138, M139
	Add. (Y)	269	110	17 (L)	C397, M137
GEM (WEFF)	Std. (W)	525	112	6 (C, E)	B224
	Res. (W)	525	110	6 (C)	B218
	Add. (Y)	477	112	6 (G, H)	B223
	Add. (Y)	269	110	13 (L)	B219, B220
GEM (Y-12)	Std. (Y)	269	110	6 (L)	8561W, 8562W

* GED + X: G end diffusion coating of bores and O.D. surfaces with NbC followed by bore over-coating with Mo; performed at Westinghouse Astronuclear Core Operations, Cheswick.

GEM: G end, low temperature, methane assisted coating of bores and O.D. surfaces with NbC; performed at Westinghouse Experimental Fuel Facility and at Y-12.

** Std: Normal flour, thermax, and varcum matrix
 Res: Standard matrix impregnated with niobium resinate
 Add: Standard matrix with 2.5 v/o NbC powder additive
 (): Indicates matrix manufacturer.

TABLE 2-3 (CRD)

RADIAL DISTRIBUTION OF WANL SUPPLIED PEWEE-1 FUEL ELEMENTS (U)

NbC Bore Coating Batch	Number of F.E. in Radial Increment (Inches)									Total In Core
	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	
C396	-	1	1	8	2	-	-	-	-	12
F387	-	-	-	1	1	-	-	-	-	2
L314	-	1	-	9	4	-	-	-	-	14
M136	-	-	-	7	-	-	-	-	-	7
C398	-	-	1	4	4	-	-	-	-	9
L313	-	-	-	1	7	-	-	-	-	8
C397	-	-	-	-	-	-	-	9	-	9
M137	-	-	-	-	-	-	-	8	-	8
M138	-	-	-	-	6	6	-	-	-	12
M139	-	-	-	-	-	12	-	-	-	12
B218	-	3	3	-	-	-	-	-	-	6
B219	-	-	-	-	-	-	-	8	-	8
B220	-	-	-	-	-	-	-	5	-	5
B223	-	-	-	-	4	2	-	-	-	6
B224	-	1	-	5	-	-	-	-	-	6
8561	-	-	-	-	-	-	-	4	-	4
8562	-	-	-	-	-	-	-	2	-	2

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TABLE 2-4 (CRD)

LASL SUPPLIED FUEL ELEMENTS IN PEWEE-1 (U)

	<u>Type</u>	<u>Number</u>
A.	Standard Matrix, 19-Hole, 110 Mil Bore	237
a.	LASL GEM + GED + X	204
b.	LASL GEM + GED	2
c.	LASL GEM + Zr GED + X [*]	8
d.	Y-12 GEM (Nb Bromide Method)	5
e.	LASL Zr GEM + Zr GED + X [*]	6
f.	LASL Zr GEM + Zr GED [*]	6
g.	LASL GEM + GED + X (High Temperature Fuel Beads)	3
h.	LASL GEM + GED (High Temperature Fuel Beads)	3
B.	Phoebus IB Type, TIC in No. 10 Hole, 19-Hole, 110 Mil Bore	
	LASL HED + X	20
C.	Standard Matrix, 12-Hole, 110 Mil Bore (N Row Peripherals)	
	LASL GEM + GED + X	12
D.	Six-Inches UC ZrC at Cold End, 19-Hole, 110 Mil Bore	
	LASL Zr GEM + Zr GED + X [*]	3

* Q Coated Elements

TABLE 2-5 (CRD)

PEWEE-1 RAW MATERIALS (U)

<u>Materials</u>	<u>Specification</u>	<u>Supplier</u>
Special Uranium Particles	PDS 30050-C	General Atomics
Graphite Flour	PDS 30046-B	Great Lakes Carbon Company
Carbon Black	PDS 30047-B	R. T. Vanderbilt Company, Inc.
Furfuryl Alcohol	PDS 30048-B	Varcum Chemical Company
Maleic Anhydride	PDS 51300-AB (Rev. C)	Fisher Scientific Company
Niobium Pentachloride	(1) PDS 30052-C	Atomergic Chemetals (CIBA), P.O. No. 59-NUB-80372 & 90177
	(2) GFE (S.O.Y. 84327)	Union Carbide Nuclear Corporation, Y-12 Plant
	(3) 33Y-7266V	Union Carbide Nuclear Corporation, Y-12 Plant
Anhydrous Hydrogen Chloride	PDS 52217-Ap (Sub B)	Frontier Chemical Company, Air Products and Chemicals
Hydrogen	PDS 3057-F	Air Products and Chemicals
Argon	PDS 52118-BA (Sub A)	Air Reduction Sales
Molybdenum Hexacarbonyl	PDS 30095	Climax Molybdenum Company
Transition Tip	910E185	WANL
Brazing Powder (For Tips)	PDS 30179-1	Fansteel Metallurgical Corporation
Niobium Carbide Powder	PDS 30104-D	Kawecki Chemical Company

TABLE 2-6 (CRD)

PEWEE-1 PROCESS PROCEDURES (U)

<u>AFF No.</u>	<u>Title</u>
1. 1010	Material Preparation and Dry Carbon Ingredient Blending
2. 1013	Procedure for Proof Testing Strength of Brazed Joint at Element/Tip Interface
3. 1020	Catalyzed Binder Preparation
4. 1025	Batch Formulation
5. 1030	Mixing Procedure
6. 1040	Extrusion Procedure
7. 1050	Cure Procedure
8. 1060	Bake Procedure
9. 1065	Procedure for Induction Brazing Tips to As-Graphitized Elements
10. 1066	Procedure for Cantilever Shear/Flexure Testing Ultimate Strength of Tip Brazing Operator Qualification Samples
11. 1070	Graphitizing Process for Unfueled and Fueled Graphite Shapes (35-Element "E" Furnace)
12. 1080	Procedure for Leaching of Fueled Graphite Shapes
13. 1091	Coating of Unfueled Graphite Support Blocks, Insulating Cups, and Washers
14. 1095	Sequential Bore/O.D. Coating of Fueled Graphite Shapes
15. 1110	Procedure for Packing and Shipment of Final Machined and Coated Elements
16. 1140	Final Bore Processing of Fueled Graphite Shapes
17. 1160	Procedure for Loading Low Temperature Furnace Saturators
18. 1270	Graphitizing Process for Fueled and Unfueled Graphite Shapes (74-Element AE Furnace)

TABLE 2-7 (CRD)
 PEWEE-1 FUEL ELEMENT PERMEABILITY (U)

Supplier	Fuel Element Loading	Ranges of Leak Rate (cc/min) (As Leached)								Total Fuel Elements Evaluated
		0-99	%	100-169	%	170-199	%	200 & Over	%	
WNCO	525	112	36	131	42	28	9	39	13	310
Y12	477	34	44	43	56	0		0		77
Y12	269	59	81	7	10	1	1	6	8	73

TABLE 2-8 (CRD)

COATING PARAMETERS FOR BORE/O.D. SEQUENTIAL OPERATIONS
AT WNCO, WEFF, AND Y12 (U)

		Min. Time	Coating Gas Concentration (Liters/Minute/Element)					Coating Temperature (°C)				
			Ar	HCl	H ₂	CH ₄	Salt*	No. 1	1" No. 2	26" No. 3	52" No. 4	No. 5
WNCO GED	Bore	14 Hrs.	1.00	0.50	0.136	-	0.060		1385	1515	1755	-
	O.D.	2.5 Hrs.	2.30	0.83	0.12	-	0.060		1495	1555	1620	-
WEFF GEM	O.D.	5 Hrs.	4.59	0.75	0.077	0.018	0.090	985	1015	1030	1050	1055
	Bore	14 Hrs.	4.59	0.75	0.077	0.060	0.090	925	965	1030	1055	1055
Y12** GEM	O.D.	8 Hrs.	4.50	0.75	0.080	0.020	0.087		1027	1098	1142	
	Bore	28 Hrs.	4.50	0.75	0.082	0.020	0.086		1050	1136	1160	

* WNCO GED - WEFF GEM coating salt was NbCl₅ with HCl.
Y12 GEM coating salt was NbBr₅ with HBr.

** During Y12 GEM coating, No. 2, No. 3, and No. 4 temperature readings were taken at 3.0, 29.0, and 43.0 inches, respectively.

TABLE 2-9 (CRD)
 WANL PEWEE-1 ELEMENTS BATCH
 AVERAGE BORE COATING PROFILES (U)

NbC Bore Batch	NbC Average Thickness, Mils/Axial Station ^(*)														
	7.5	10.5	13.5	16.5	19.5	22.5	25.5	28.5	31.5	34.5	37.5	40.5	43.5	46.5	49.5
C396	.79	.79	.85	.90	1.00	1.05	1.15	1.25	1.35	1.55	1.75	1.98	2.25	2.43	2.62
C397	1.20	1.22	1.20	1.24	1.22	1.28	1.34	1.46	1.62	1.87	2.10	2.23	2.43	2.66	2.91
C398	1.59	1.62	1.57	1.50	1.49	1.46	1.46	1.51	1.71	1.90	2.06	2.20	2.39	2.48	2.68
L313	.80	.90	.90	.98	1.00	1.06	1.11	1.18	1.34	1.56	1.74	1.89	2.16	2.26	2.36
L314	.72	.80	.84	.88	.92	.97	1.01	1.10	1.25	1.46	1.63	1.81	2.03	2.27	2.56
M136	.79	.80	.85	.90	1.00	1.00	1.13	1.25	1.39	1.35	1.80	2.03	2.26	2.50	2.66
M137	.85	.90	.94	1.00	1.03	1.09	1.14	1.24	1.43	1.73	1.93	2.06	2.31	2.51	2.59
M138	1.13	1.21	1.23	1.26	1.26	1.30	1.45	1.49	1.66	1.88	2.02	2.18	2.36	2.54	2.75
M139	.69	.73	.79	.82	.88	.92	.98	1.10	1.29	1.60	1.82	2.05	2.29	2.47	2.78
F387	.80	.80	.90	.90	.95	1.00	1.10	1.15	1.25	1.45	1.70	1.90	2.10	2.30	2.50

* Beta backscatter data, 3-inch increments

TABLE 2-9 (CRD) (Continued)

 WANL PEWEE-1 ELEMENTS BATCH
 AVERAGE BORE COATING PROFILES (U)

NbC Bore Batch	NbC Average Thickness, Mils/Axial Station ^(*)														
	7.5	10.5	13.5	16.5	19.5	22.5	25.5	28.5	31.5	34.5	37.5	40.5	43.5	46.5	49.5
B218	.67	.77	.87	1.02	1.22	1.47	1.73	1.97	2.20	2.40	2.53	2.63	2.72	2.82	2.93
B219	.60	.67	.70	.83	1.01	1.14	1.35	1.58	1.80	1.99	2.14	2.30	2.41	2.60	2.83
B220	.60	.66	.78	1.03	1.30	1.66	2.02	2.34	2.62	2.88	3.02	3.10	3.18	3.22	3.30
B223	.63	.65	.73	.85	1.03	1.25	1.52	1.75	2.02	2.22	2.35	2.35	2.45	2.48	2.53
B224	.68	.70	.80	.90	1.15	1.25	1.50	1.77	2.00	2.18	2.32	2.38	2.48	2.48	2.52
	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5					
8561	1.2	1.9	2.6	3.0	3.0	2.8	2.7	2.7	2.8	2.7					
8562	.9	1.3	1.7	2.2	2.4	2.6	2.7	2.7	2.7	2.7					

* Beta backscatter data, 3-inch increments for WEF GEM, 5-inch for Y-12 GEM

TABLE 2-10 (CRD)

WANL PEWEE-1 COAT BATCH AVERAGE - O.D. COATING THICKNESS PROFILES (U)

NbC Bore Batch	NbC Average Thickness Mils Per 3-Inch at Station														
	7.5	10.5	13.5	16.5	19.5	22.5	25.5	28.5	31.5	34.5	37.5	40.5	43.5	46.5	49.5
C396	0.50	0.50	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
C397	0.50	0.50	0.50	0.55	0.55	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
C398	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.60
L313	0.60	0.60	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
L314	0.50	0.50	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
M136	0.55	0.55	0.55	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
M137	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
M138	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
M139	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
F387	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.60
B218	0.40	0.40	0.50	0.50	0.50	0.50	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
B219	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
B220	0.30	0.30	0.40	0.40	0.40	0.40	0.40	0.40	0.35	0.35	0.35	0.35	0.35	0.35	0.35
B223	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
B224	0.30	0.30	0.30	0.35	0.35	0.35	0.35	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40

TABLE 2-10 (CRD) (Continued)

WANL PEWEE-1 COAT BATCH AVERAGE - O.D. COATING THICKNESS PROFILES (U)

NbC Bore/OD Batch	NbC Average Thickness Mils Per 5-Inch at Station						
	3.5	13.2	22.8	32.5	42.4	47.2	51.2
8561/ 7661	0.40	0.65	0.65	0.65	0.75	0.65	1.35
8562/ 7662	0.40	0.65	0.60	0.65	0.75	0.75	1.90

TABLE 2-11 (CRD)

MOLYBDENUM WEIGHT DISTRIBUTION IN WANL GEDX PEWEE-1 ELEMENTS (CRD)

Bore/Mo Batch	Average Weight Molybdenum per 5-Inch Increments, grams										Avg. Wt. Mo, Grams 0-52
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	
C396/174	0.17	0.29	0.71	0.90	0.71	0.58	0.29	0.29	0.17	0.08	4.15
C397/177	0.18	0.32	0.78	0.99	0.78	0.64	0.32	0.32	0.18	0.09	4.60
C398/178	0.18	0.32	0.77	0.98	0.77	0.63	0.31	0.31	0.18	0.09	4.52
L313/175	0.18	0.31	0.76	0.97	0.76	0.63	0.31	0.31	0.18	0.09	4.48
L314/177	0.15	0.26	0.62	0.79	0.62	0.51	0.26	0.25	0.15	0.07	3.67
M136/174	0.16	0.29	0.70	0.89	0.70	0.58	0.29	0.29	0.16	0.08	4.11
M137/175	0.14	0.24	0.60	0.76	0.60	0.49	0.24	0.24	0.14	0.07	3.50
M138/179	0.17	0.30	0.73	0.93	0.73	0.60	0.30	0.30	0.17	0.09	4.32
M139/179	0.17	0.29	0.71	0.90	0.71	0.58	0.29	0.29	0.17	0.08	4.17
F 387/178	0.18	0.31	0.75	0.95	0.75	0.62	0.31	0.30	0.18	0.09	4.47

3.0 PEWEE-1 REACTOR TEST AND WANL FUEL ELEMENT TEMPERATURES (U)

(CRD) PEWEE-1 was operated successfully for two twenty-minute cycles at power levels of approximately 500 M.W. each, in Test Cell C, NRDS on December 4, 1968^{*}. The test was restarted for a third twenty-minute cycle but was aborted at about sixty percent full power when some evidence of structural damage was noted in the exhaust plume. Immediately preceding the two full power runs, a two-minute thermal calibration run at 95 percent of full power was performed. On this basis, PEWEE-1 was operated for a total of about 62 minutes achieving four cycles to sixty percent of full power or above.

(CRD) During the two full power cycles, the core operated at or near design conditions^{**} with a total drum roll out of about fourteen degrees. Two exceptions from design conditions were noted: 1) An increase in temperature with increasing core radius which was somewhat larger than predicted, and 2) the "center of gravity" of axial fission distribution shifted upstream in the elements with the result that 51.4 percent of the energy was generated in the first 24 inches of fuel as opposed to the 49 percent predicted.

(CRD) Final analysis of PEWEE-1 fuel element temperatures has not been reported by LASL. Current temperature estimates have been based on the following types of information:

- a. Thermocouple and thermocapsule data as shown in Figure 3-1;
- b. Axial fission distribution from gamma and radiochemical measurements as shown in Figure 3-2;

^{*} A total of 4.77×10^{22} (+5%) fissions were generated during the power tests, EP III. This corresponds to a fission power integral of approximately 1.49×10^6 M.W. seconds.

^{**} Design Condition	Flow, Lbs/Sec	Pressure, psia	Temperature, °R
Core Inlet	31.05	785	281
Tie Rod, Inlet Manifold	10.37	1025	57
Nozzle Chamber	41.42	629	3300
Core Exit, Fuel	27.55	-	4500
Core Exit, Tie Rod	10.37	-	500

- (CRD) c. Barium 140 fission product retention parameter data as shown in Figure 3-3; and
d. Fuel bead migration information from various metallographic and microradiographic studies as depicted in Figures 3-4 and 3-5.

(CRD) In general, all of the temperature data indicated that there was a rise in fuel element temperature of about 200°R – 400°R from the center of the core to the core periphery as depicted in Figure 3-1. The location of the WANL supplied fuel elements is indicated. The best estimate for the operating regime of the axial temperature profiles for the WANL elements is given in Figure 3-6; the WANL elements operated at maximum fuel element temperatures between 4500°R (2230°C) and 4700°R (2330°C), with the maximum temperatures occurring roughly in the 40–45 inch axial region. The axial temperature distributions obtained in the NRX-A6 fuel elements are included in Figure 3-6. By comparison, a) the WANL PEWEE-1 elements operated at maximum temperatures roughly 100° – 200°R higher than those in NRX-A6, and b) the axial temperature distribution in the PEWEE-1 elements was shifted upstream about 3–5 inches from that in the A6 elements.

(CRD) There were no indications of fuel bead migration in the WANL elements. In fact, the only elements with any indication of "test induced" migration were some of the LASL elements deliberately orificed to run at approximately 150°R hotter temperatures (see Figure 3-3). In the latter elements, only spotty fuel bead migration was reported by LASL personnel, indicative of temperatures no higher than 4900°R (2450°C). Typical microradiographic and metallographic results obtained on fuel beads in WANL elements are portrayed in Figures 3-4 and 3-5.

(CRD) Ba^{140} retention data confirmed the general lack of bead migration, although LASL J-11 personnel believe the presence of O.D. coatings made this type of data difficult to interpret. The retention data trends with core radius indicated in Figure 3-3 show a general drop in retention of Ba^{140} (a rise in fuel element temperature) in elements located roughly in the L row to the core periphery.

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Figure 3-1. (CRD) Radial Variations in PEWEE-1 Fuel Temperatures as Measured by LASL Instrumentation (U)

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Figure 3-2. (CRD) Axial Fission Distribution in PEWEE-1 Fuel Elements (U)

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Figure 3-3. (CRD) Ba¹⁴⁰ Retention Parameter Versus Core Radial Location for PEWEE-1 Fuel Elements (U)

STATION 35

STATION 40

STATION 45

Figure 3-4. (CRD) Microradiographs of 15-Mil Wafers from Stations 35, 40, and 45 Inches of WANL PW-1 Fuel Element 525-57089, Core Position 030C1, Nb Resinate GEM Coat, Batch B218. Typical of All WANL Elements Examined; There Is No Migration Indicated in the Fuel Beads. (CRD)

A

B

C

D

E

A. 250X, STATION 49, 525-57217, CORE POSITION 330 E3, STD. MATRIX GED-X COATING BATCH M136

B. & C. 250X, STATION 44, 525-57127, CORE POSITION 030C2, Nb RESINATE MATRIX, GEM COATING BATCH B218. NOTE BINDER ATTACK AND CORROSION OF PYROSHELLS IN B, A VIEW OF REGION NEAR OD SURFACE OF ELEMENT. C SHOWS BEADS AT INTERIOR COOLANT CHANNEL

D. 50X AND E (250X), STATION 41, 269-58238, CORE POSITION 090L5, 2.5 v/o NbC ADDITIVE MATRIX, GEDX COATING BATCH M137. VIEW D SHOWS UNMIGRATED BEADS (BEAD SHELLS) AT AND IN OD WEBBING REGION. VIEW E SHOWS TYPICAL UNMIGRATED BEAD BUT WITH BINDER ATTACK AND CORROSION OF PYROSHELL AT OD SURFACE

Figure 3-5. (CRD) Photomicrographs Showing the Typical Conditions of Fuel Beads in the Hot End Region of WANL-Supplied Fuel Elements Tested in PEWEE-1 (U)

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Figure 3-6. (CRD) Best Estimate of Axial Temperature Distributions in WANL-Supplied PEWEE-1 Fuel Elements (U)

4.0 POST OPERATIONAL EXAMINATION RESULTS (U)

(U) The joint LASL-WANL post-operational examinations on PEWEE-1 fuel elements were performed in the R-MAD building, NRDS, and the Wing 9 hot cell complex, CMB14, LASL. Disassembly of the core, INSIPID photography (In Situ Photography In Depth)*, whole element weighing, and ASP (Axial Surface Photography)* were accomplished in the upper bay, R-MAD. All of the core fueled and unfueled central elements along with LASL reactor hardware components were then shipped to Wing 9 at Los Alamos where various hot cell and J-11 radiochemical examinations were performed.

(U) A summary of the examinations performed on the WANL supplied elements is given in Table 4-1. Selected WANL fueled elements were returned to the E-MAD hot cells at NRDS for special sectioning, photography, and metallography to determine surface corrosion losses. Four WANL unfueled elements were also returned to E-MAD for flexure testing, the results of which will not be discussed in this report.

(CRD) There were three "firsts" achieved in the fuel element examinations for PEWEE-1:

- 1) One hundred percent (100%) of all elements recovered intact from the core received MULE (Mass Per Unit Length) measurements.
- 2) Whole Element Radiography (WER) was performed on all but twelve of the core elements.
- 3) An inert gas heat treatment (800°-1000°F for one hour) was moderately successful in "unsticking" the glued clusters.

(CRD) Electrical resistance (PDE), WER, and microradiographic results were intended to help establish temperature conditions in the core (i.e., to determine whether fuel migration had occurred) and to aid in interpretation of axial corrosion performance. As was mentioned in Section 3.0, there was very little evidence of fuel migration in the fuel beads of PEWEE-1.

* INSIPID photographs were taken as various layers of the core were uncovered during disassembly; ASP photographs were taken on 70 mm film showing full length views of all six faces of each intact fuel element after removal from core.

The data from the WER study was found to be more useful as an indicator of the axial distribution of internal corrosion pockets (see Table 4-4 for summary results). A typical example of WER photography on a WANL element containing corrosion pockets is shown in Figure 4-1. PDE data on WANL elements essentially gave electrical resistance profiles which reflected incremental weight losses and cold end radiation effects as depicted in Figure 4-2.

(CRD) Incremental weight loss profiles were obtained by computer programming of pre-reactor/post-reactor MULE data. These measurements were quite successful. Some difficulty was reported by LASL GMX-1 personnel with respect to an apparent bias between pre- and post-reactor MULE data on some elements. This was particularly true for the WANL 2.5 v/o NbC additive matrix elements. The problem was apparently due to the fact that the pre- and post-reactor test profiles were measured in two different MULE facilities at LASL.

(U) The heat treatment at the cold end (Stations 0-3.5 inches) of the glued clusters was performed in nitrogen, the aim being to destroy the integrity of the resin bond. The treatment was only moderately successful as it was usually necessary to use a spatula to obtain final separation. All of the glue joints were intact after the reactor test and there was no detectable change in the hot end "offset gap" for the WANL elements.

4.1 GENERAL DISASSEMBLY AND HOT CELL OBSERVATIONS (U)

(CRD) As the fuel elements were removed from the core, it was apparent that O.D. coatings were frequently flaked and corrosion had occurred in two general axial regions on the surface of most of the fuel elements:

- a. A mid-band region spanning roughly Stations 8-15 inches (see Figures 4-3 and 4-4)
- b. A hot end tip region (see Figures 4-5, 4-6, and 4-7).

(CRD) The corrosion in these two regions varied in severity from element to element and from face to face. MULE data on both LASL and WANL elements reflected this variation in the two regions. One-inch incremental gross weight loss profiles for a few WANL and LASL elements selected at various core radii are shown in Figure 4-8. Typically, the principal axial regions of weight loss displayed by all WANL PEWEE-1 fuel elements were

1) 0-25 inches, 2) 25-50 inches, and 3) 50-52 inches. Maximum gross incremental losses (grams per inch) varied considerably from element to element for the 0-25 and 50-52 inch regions but were relatively constant for the 25-50 inch region.

(CRD) Another pattern of corrosion noted for the WANL elements was a tendency for WEFF GEM coated elements to pinhole. The pinholes appearing on the surface in ASP film are shown in Figure 4-9. In most cases, the pinholing was most dense in the axial region 15-25 inches, although in some cases pinholes were observed in the hot end region (25-40 inches) as shown in Figure 4-10. A plot of mid-band pinholes for various WANL GEM coated elements and two batches of GED-X coated elements as a function of core radial position is shown in Figure 4-11. While it is difficult to interpret this plot due to the limited bore batch radial distribution and a lack of LASL pinhole data to establish core radial trends, it is concluded that radial location was not a major contributor to pinhole formation in the WANL elements. Occasional pinholes were noted in the WNCO GED-X elements as indicated in Figure 4-11, the density of pinholes in these elements being much less than for the WEFF GEM coated elements. A summary of pinholing for all WANL coating batches is given in Table 4-2. The occurrence of high pinhole densities in the WEFF GEM coated elements was not surprising since it had been demonstrated at WNCO before the reactor test (with follow-on experiment, FOX₂ elements) that these elements were prone to hydrolyze, i.e., the hydrolysis of certain fuel beads caused local flaking of the bore coatings and these defects subsequently became sites for corrosion pocket and pinhole formation during both reactor and electrical corrosion testing. Data comparisons of reactor pinholing and corrosion test pinholing are given in Table 4-3 for the various WANL supplied batches. As remarked previously, the WER

data proved to be a good indicator of internal corrosion pocket formation. Comparing the WER data and pinhole densities tabulated in Table 4-4 for WANL batches, there is a fairly good correspondence for elements of high pinhole densities such as in the GEM coated elements.

(CRD) Some general observations on the comparative gross weight loss performance of the WANL and the LASL elements can be made. (No comparison of pinholing in WANL and LASL elements can be made since pinhole statistics for the LASL elements are not available.)

Figure 4-12 is a plot of core average gross weight losses versus one-inch core radial increments. The weight loss averages for the two general WANL coating types (GEM versus GED X) are superimposed at corresponding radii for comparison. The gross weight losses of the WANL elements generally lie above the core average. It should be emphasized, however, that the gross loss is not a good indicator of bore corrosion performance since most of the WANL elements were affected either by mechanical losses, surface corrosion losses, corrosion pocket formations, or by molybdenum blowdown losses.

(CRD) In general, the "best" performing elements in PEWEE-1 with respect to gross weight losses, pinholing, hot end tip behavior, and surface corrosion were the Y-12 GEM coated elements and the LASL ZrC coated elements. The listing of whole element (0-52 inches) gross weight losses by coating matrix types is given in Table 4-5. Typical MULE incremental gross loss profiles for a WANL supplied Y-12 GEM coated element and for a LASL ZrC coated element are shown in Figure 4-13 illustrating the generally lower gross weight losses in the mid-band region (10-15 inches) and the hot end "tip" region (50-52 inches) for these element types. Neither of these types showed any appreciable surface corrosion or O.D. coating flake in the mid-band or hot end tip regions; the typical surface condition in the hot end tip regions is illustrated in Figure 4-14 and in the mid-band in Figure 4-15.

(CRD) Two types of "mechanical" damage occurred in the WANL PEWEE-1 fuel elements which necessitated a correction to the gross weight loss calculations to reflect "gross corrosion losses." In the first of these, some of the elements lost their hot end tips either by mechanical

stress or corrosion weakening. In the second type, some of the WANL elements which were "glued" to central unfueled elements were damaged on the cold ends (pieces missing) when spatulas were used to separate the elements after the "ungluing" heat treatment. Both types of corrections were determined by visual examinations of the affected areas on ASP 70 mm film. The elements involved and the corrections estimated from ASP are given in Tables 4-6 and 4-7. In all subsequent discussions of weight loss in this report, it is to be understood that these corrections have been made.

(CRD) In order to determine bore corrosion weight losses for molybdenum overcoated elements, corrections by the amount of Mo blowdown losses due to reactor operation were also necessary. The estimate of this correction for the WANL GED-X coated elements in PEWEE-1 was based on previous reactor experiences with the HED-X coated elements in NRX-A6,⁽⁴⁾ i.e., approximately sixty percent of the Mo originally present before the reactor test was "blown down" or lost during reactor testing. The five-inch incremental corrections for Mo loss on the basis of WANL coating batch averages were obtained from the distributions given previously in Table 2-11, Section 2.2. Whole element Mo loss corrections (0-52 inches) for the WANL elements involved ranged from 2.84 to 2.27 grams, averaging 2.52 grams per element. The cold end, hot end, and Mo blowdown correction data were used along with surface corrosion estimates (discussed in subsequent parts of this section) to obtain bore corrosion loss estimates for all WANL supplied elements.

(CRD) Some fueled elements and several unfueled central elements were observed to be broken upon removal from the core. For PEWEE-1, the term "broken" (to differentiate from the cold end and hot end damage discussed above) means that the element was fractured at some axial position between the one inch and 51 inch station. A total of 45 PEWEE-1 fuel elements, fourteen of which were WANL supplied, were found to be fractured in this manner, the fracture appearing to be either mechanically induced or due to corrosion weakening. The axial location and condition of the fractures in the WANL elements as determined by Kohlmorgen examinations is tabulated in Table 4-8. Eleven of the WANL elements involved

in the fractures were WEFF GEM coated with the fracturing typically occurring in the regions of high pinhole and internal corrosion pocket densities. A photograph illustrating the typical corrosion pocket weakening effect in a GEM element is portrayed in Figure 4-16. Particularly in the mid-band region, surface corrosion losses also contributed to weakening and element fracture as indicated by Figure 4-17. In some cases the fractures appeared to be purely mechanical as in Figure 4-18. The visual evidence indicated that in no case did any of the WANL elements corrode completely through during the reactor operation. The fresh or uncorroded regions noted on all fracture surfaces indicated that final separation occurred due to some form of mechanical stress. None of the fractured elements in the above category were weighed or photographed on ASP at R-MAD. Likewise, none were measured in MULE at LASL.

(CRD) Some light inter-element bonding was in evidence during disassembly of PEWEE-1. Figure 4-19 shows O.D. coating adherence in a region of soot and PyC deposits on the surface of a fuel element. Soot and PyC deposits were noted in the general 20-30 inch axial region on a high percentage of the core elements, suggesting that interstitial surface corrosion with its attendant "methane reaction" deposition of carbon had occurred during the reactor test. A tighter bond of similar character was observed between most of the non-O.D. coated NRX-A6 fuel elements⁽⁵⁾.

4.2 MID-BAND REGION CORROSION DATA (0-25 INCHES) (CRD)

(CRD) The MULE-measured gross weight loss profiles indicated that variably high one-inch incremental losses ranging from approximately 0.2 to greater than 4 grams per inch were occurring in roughly the 10-15 inch axial region of the WANL elements. General ratings of the matrix/coating types on the basis of averaged 10-15 inch gross losses were as follows:

Coating - Matrix

Approximate 10-15 inch gross loss

GEM-STND.	10.7 grams
GEM-ADD.	3.6 - 9.0 grams
GEM-RES.	2.5 grams
GED-STND.	2.3 - 3.6 grams
GED-ADD.	1.0 - 2.2 grams
GED-RES.	1.3 - 1.8 grams
YGEM-STND.	1.0 - 2.0 grams

(CRD) ASP visual data indicated that part of this loss was due to surface corrosion, the surface contribution varying with the type of element. The WEFF GEM elements mid-band behavior was complicated by having both high pinhole densities and surface corrosion losses while the GED-X elements showed varying surface corrosion losses. Typically, the surface corrosion appeared as streak, edge, face, or channel exposure types very similar to that observed on the surfaces of non-O.D. coated elements in previous NRX reactor tests. (1, 5)

The surface corrosion in the mid-band region was recorded during ASP visuals of each WANL element; each face type was recorded by axial occurrence, and by visual estimates of severity (light, moderate, or heavy). The data was used to determine a qualitative "surface performance rating" (PR) for the 0-25 inch region for all WANL elements photographed on ASP. The ratings were averaged for each WANL coating batch, loading, matrix, and coat type and are presented in Table 4-9. It is apparent that the order of the mid-band surface PR's is somewhat similar to those of the 10-15 inch gross weight loss ratings given above, indicating that surface losses apparently have played a part in differentiating the performance of some of the batches, notably those with GEM coats and those with standard matrixes. There also appears to be some variation of PR with uranium loading. On analysis of mid-band surface PR change with core location did not show any definite trends in surface damage with respect to core radius. Additional emphasis was placed on the significance of surface corrosion losses when the coolant channels of selected WANL elements were examined. The overall results of these examinations are tabulated summarily in Table 4-10. Figures 4-20 and 4-21 show the typical bore conditions

for the various WANL coating-matrix types, indicating no significant differences in the character of coolant channel corrosion in the mid-band region with the exception of corrosion pocket formation in the WEFF GEM coats and the center channel corrosion in the standard matrix GED-X coated elements. The high incremental losses in the 10-15 inch axial region of several WANL elements can not be explained by the amount of corrosion visible around the coolant channels, i.e., a significant part of these losses is occurring in the outer webbings at the element surfaces.

(CRD) It is difficult to judge the extent or character of low magnitude channel corrosion in macroscopic views of split elements. Metallographic examinations of a limited number of samples from the 0-25 inch region for several types of WANL elements revealed that mild bore corrosion, appearing generally as binder carbon attack or very light corrosion through-cracks, occurred in the GED-X elements in regions of high incremental gross weight losses (see photomicrographs at Station 14, Figure 4-22). The GEM elements displayed gross pocket corrosion typical of that produced by fuel bead pop-outs (hydrolyzed fuel beads) in these same regions (see Figure 4-23). In both GEM and GED-X types, O.D. surface corrosion in the form of pockets, crack corrosion, and binder attack were identified in several samples. The surface corrosion, except for very severe cases, was not physically connected with the bore corrosion. An unusual phenomenon identified in many of the metallography samples from the 0-25 inch region was that the binder attack corrosion at the bore coating-matrix interface was more severe at the outer channels than at the center channel, the condition illustrated in Figure 4-22. Exceptions to this were elements from coating batches L314 and C396 which displayed the most severe center channel corrosion in the mid-band region of all WANL supplied elements (see Figure 4-24).

(CRD) The relative surface corrosion-bore corrosion results discussed in the foregoing paragraphs suggested during the early post-mortem period that a separate study was needed to make some quantitative estimate of surface corrosion weight losses, at least in the 0-25 inch axial region. For this purpose, twelve WANL elements representing several degrees of surface corrosion severity (light, moderate, and heavy) and geometric forms (streak, edge, face, and

coolant channel exposure) in the mid-band were selected and shipped to E-MAD. The elements were sectioned transversely in regions of surface damage into one-inch or 1/2 inch increments. Photographs of the ends of these sections were taken and used for geometric determination of the surface weight loss factors associated with the various types of surface damage recorded from ASP. Typical end photographs are shown in Figure 4-25 to 4-27, illustrating some surface corrosion examples of varying severity and geometric form as selected from ASP visuals. The method of analysis and the factors determined in the E-MAD studies are listed for the three matrix-loading types in Appendix Tables A-1 and A-2. Appendix Figures A-1 and A-2 are sketches of typical transverse sections used in the analysis. These factors were applied to recorded ASP visual results and estimates were made of surface losses for each element on the basis of observed axial occurrence.

(CRD) It should be noted that two types of surface oriented corrosion were found to have occurred from study of the end photographic and metallographic samples, i.e., a matrix loss, and a binder carbon loss (see Figures A-1 and A-2). Since the axial distribution of surface binder loss could not be accurately determined except by exhaustive transverse sectioning, no attempt has been made to account for it in this report. In addition to the lack of a surface binder loss correction, there was also evidence of missing matrix material having occurred under intact, non-flaked O.D. coatings (see Figure A-1); the occurrence would not be noted on ASP film*. Under these circumstances, it is believed that the surface loss estimates for the WANL elements are too low in all axial regions involved.

(CRD) The 0-25 inch ASP recorded pinhole data for WANL supplied coating batches were summarized in Table 4-2. The GEM coated elements had pinhole densities in this region 6 to 60 times higher than those of the GED-X elements. The typical axial distribution of

(*) In several instances on LASL and WANL element surfaces, both in the mid-band and hot end (35-45 inch) regions, examples of dimpled, or spotty flaked O.D. coating were observed. When some of these were sectioned, surface matrix loss and binder loss were usually observed. Examples of sectioning results on two LASL elements are shown in Figures 4-28 and 4-29.

pinholes by batch for the GEM coated elements was depicted in Figure 4-10; the most severe pinholing occurring in the 10-20 inch region of NbC additive elements from Batch B219. The most extensive axial involvement of pinholing was also related to B219 elements. Appendix Tables A-3 and A-4 give the 5-inch axial distribution of pinhole averages for each WANL supplied bore coating batch.

4.3 HOT END REGION CORROSION DATA (25-50 INCHES) (CRD)

(CRD) The ASP visuals of the 25-50 inch region revealed only occasional O.D. coating flaking and surface corrosion. Surface loss estimates were made on the same basis as described in Section 4.2 for the 0-25 inch region. Corrections to obtain average bore corrosion losses on a five-inch basis by bore coating batch were made. The very limited metallography performed in this region indicated that binder corrosion was still occurring at the O.D. coat-matrix interface and, in fact, may have been more severe than that in the mid-band region. This binder carbon loss is interpreted as having been caused by diffusion corrosion. Again, no attempt was made to correct for surface binder loss in the region and therefore the estimated surface corrosion correction is probably too low. Very few WANL elements were sectioned transversely in the hot end region but the surface losses displayed by the LASL elements in Figure 4-29 are believed to represent the condition of some of the WANL elements also.

(CRD) Axial split element examinations and limited metallography revealed that three categories of 25-50 inch bore corrosion were observed (Table 4-10, Figures 4-20 and 4-21):

- 1) The WNCO and Y-12 GEM elements with mild diffusion losses and very limited corrosion through coating cracks.
- 2) The general GED-X element with relatively more severe diffusion losses and light to moderate corrosion through coating cracks.
- 3) The elements from batches C396 and L314 with relatively heavier ring corrosion in the center channel (see Figure 4-30).

As in the mid-band region the limited metallography indicated that the bore corrosion was more severe in the outer channels than in the center channel on most elements excluding those from the standard GED-X batches.

(CRD) Pinholing was very limited in the 25-50 inch region based on the results given in Table 4-2. There were cases of corrosion pocket formation observed in the hot end region, but with the exception of elements from coating batch B219 the occurrences were random with respect to coating batch or type.

4.4 CORROSION IN THE REGION 50-52 INCHES (CRD)

(CRD) Visual ASP examinations of the "transition tip" region revealed that corrosion damage typically was evident on the surface of the unfueled graphite, extending occasionally upstream past the fuel-transition zone but hardly ever downstream into the composite section. Early in the past-operational study this damage was categorized during ASP visuals into two qualitative types per element per face, i.e., "heavy" and "moderate." (Typical examples of these two types of damage were shown in Figures 4-5 through 4-7). Hot end tip performance ratings (HEPR) were calculated as shown in Table 4-11.

(CRD) Based on a face-by-face categorization of tip damage, the WANL supplied elements fell roughly into three groups: those with predominantly heavy damage (GEM's), those with moderate damage (GED-X), and those with no apparent or limited damage (Y-12 GEM and M136 GED-X).

(CRD) Various analyses of the ASP hot end tip data did not indicate any consistent variations with core location or radius. The trends appeared to indicate a differentiation in performance by coating type and particularly with respect to O.D. coating thickness, since the "best" performers (Y-12 GEM's) had greater than 1-mil O.D. thickness in this region while the "worst" (WEFF GEM's) had only about 0.3 to 0.4 mil O.D. coat thickness. The data did not specify, however, whether the cause of the damage was internal or external in nature.

(CRD) Examination of split 50-52 inch sections for all coating types was performed on the WANL elements. The results indicated that the most severe corrosion effect occurred in the outer webbings of the graphite transition section as shown in Figures 4-31 through 4-34. Corrosion of the internal bores was normally of the same type and order of magnitude as that

occurring in the 49-51 inch region (note Figure 4-31 in particular) of the elements. The only corrosion occurrences of any depth noted at the fuel-transition or transition-composite joints were occasional pockets of small to moderate size as shown in the metallographic study in Figure 4-35. None of the pockets found intersected the surface in any of the 36 WANL elements examined. In all the WANL elements examined, there was no evidence of fuel bead migration in the braze region. There were some beads migrated in the Y-12 joint regions but it is believed this migration existed in the pre-reactor test condition.

(CRD) The most conclusive evidence of the cause of the hot end damage was obtained in some "tip grind" metallographic studies performed at E-MAD on 50-52 inch samples. In this study, several element samples were ground in progressive stages and examined to trace the depth and/or origin of corrosion. Consistently, on those samples with both moderate and heavy damage to a face, the corrosion appeared to originate on the surface of the outer webbing at the position of "thinnest" O.D. coating. This position appeared to be at about 51.6 to 51.7 inches, just upstream of the transition to composite joint as shown in the metallographic montage in Figure 4-36. A macroscopic view of one of the tip grinds is shown in Figure 4-37, also indicating the typical occurrence of the outer web corrosion prevalent in the WANL elements.

(CRD) After consideration of the ASP, split element, and metallographic data it was concluded that the majority of the hot end "transition tip" damage in the WANL elements was of a surface corrosion origin. Based on this, it was deemed necessary to correct the 50-52 inch MULE losses to demonstrate realistically the bore performance in this region. At the same time, the "surface loss" value obtained for each element would then allow a more quantitative analysis of hot end coating or matrix performance. Since there were no end photography studies made of the tip region, it was decided to estimate the 50-52 inch bore losses on the basis of MULE data and thereby obtain an estimate of the surface loss in the region.*

* Checks were made on surface losses determined by this means by estimating surface losses from ASP surface visuals using loss factors for unfueled graphite. The results from both methods showed fair agreement.

The surface loss for 50-52 inches was determined from the MULE data as follows:

$$\Delta W_S (50-52) = \Delta W_G (0-52) - \Delta W_G (0-50) - \Delta W_B (HE)$$

where a) $\Delta W_G (0-52)$ is the gross weight loss (corrected for missing hot end or cold end pieces) measured at R-MAD, b) $\Delta W_G (0-50)$ is the gross weight loss for the increment 0-50 inches as measured by MULE, and c) $\Delta W_B (HE)$ is bore loss from MULE data at station 50 extrapolated for 50-52 inches, i.e., $\Delta W_B (HE) = (\Delta IW_{49-50}) (1.8)$.*

4.5 GROSS WEIGHT LOSS CORRECTIONS (U)

(CRD) The data studies described in sections 4.2, 4.3, and 4.4 were utilized to obtain the bore corrosion and surface losses for each WANL element. These data are tabulated in Appendix Tables A-5 to A-10 for the three axial regions 0-25, 25-50, and 50-52 inches.

(CRD) The averaged gross, surface, and bore losses on a 5-inch incremental "basis" for each WANL coating batch is given in Table 4-12. No blow-down loss corrections have been made for all GED-X elements and are included in the bore loss values only.

(CRD) The averaged surface losses per element in the two axial regions of significance (0-25 and 50-52 inches) are tabulated by WANL bore coating batch in Table 4-13.

(CRD) The mean incremental bore weight losses and calculated standard deviations (1σ) for the three principal regions of corrosion weight loss are tabulated for each WANL supplied bore coating batch in Table 4-14. Similar bore loss data for the whole elements (0-52 inches) are compared with the gross whole element weight losses as measured at R-MAD in Table 4-15. A general decrease in the standard deviation values for the bore losses is evident, indicating that the various corrections are producing a normalizing effect within batches, an expected performance characteristic assuming core location difference do not influence bore corrosion losses.

* Assume that rate of bore corrosion loss in the transition graphite is equal to that in the fueled section and that the rate in the composite section is only 1/2 that in the fueled section.

↑
16

57089

↑
19

↑
16

57304

↑
19

- A. WHOLE ELEMENT RADIOGRAPHS OF 15-20 INCH AXIAL REGION OF AN R-GEM (TOP) AND AN S-GEM (BOTTOM) WANL PW-1 ELEMENT.

- B. SURFACE OF ELEMENT 57304 (SEE FIGURE 4-1A) SHOWING HOLES AND PINHOLES IN REGION OF RADIOGRAPH.

Figure 4-1. (CRD) Whole Element Radiograph and Surface Pinhole Relationship. (U)

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Figure 4-2. (CRD) Comparison of A. Incremental Gross Weight Losses and B. Incremental Electrical Resistances Observed on WANL Element 525-57176, Core Position 330F4, Batch C398. (U)

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<u>Position</u>	<u>S/N</u>	<u>Core Position</u>	<u>Type</u>
1	50232	030D4	LSGEMGEDX
2	57216	090E1	WSGEDXM136
3	57239	030E5	WSGEDXC396
4	57041	270G6	WRGEDXL313
5	57079	090C2	WRGEMB218
6	57298	090E3	WSGEMB224
7	50228	090D2	LSGEMGEDX

Figure 4-3. (CRD) Surface Corrosion of Varying Severity on C Faces of PW-1 Elements in Midband Region. Elements (From Top to Bottom) Are as Shown in Table Above. (U)

Figure 4-4. (CRD) Severe Surface Corrosion, Pinholing, and Coolant Channel Exposure
Occurring in the Midband Region of WANL Element 269-58250, Core Position
270L5, Batch B219 (U)

Figure 4-5. (CRD) Surface Corrosion of Varying Severity on A Faces in the Hot End Tip Region of PW-1 Elements Previously Shown in Figure 4-3. Note That Corrosion Occurs On the Graphite Transition Section on WANL Elements (Positions 4, 5, and 6) and on the Fuel Side of the Fuel-Composite Joint in the LASL Elements (Position 7). (U)

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Figure 4-6. (CRD) Example of Moderate Hot End Tip Damage and Hole Formation in the Transition Graphite Side of Graphite-Composite Joint for WANL
PEWEE-1 Element 525-57041, Core Position 270G6, R GED-X, Batch L313 (U)

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Figure 4-7. (CRD) Severe Corrosion and Channel Exposure in Graphite Transition Section of Hot End on WANL PEWEE-1 Element 525-57077, Core Position 150C1, RGEM Batch B218 (U)

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Figure 4-8. (CRD) Incremental Gross Weight Loss Profiles for Some LASL and WANL PEWEE-1 Fuel Elements (U)

Figure 4-9. (CRD) ASP Film View of a WANL Additive GEM Coated Element, 269-58253 (Second from Top), Core Position 150L7, Showing Heavy Streak Corrosion and Pinhole Formation on B Face. The Incremental Weight Loss Profile for This Element Was Shown in Figure 4-8. (U)

Figure 4-10. (CRD) Axial Pinhole Distribution in WANL PEWEE-1
GEM Coated Fuel Elements (U)

Figure 4-11. (CRD) Midband Pinholing in WANL PEWEE-1 GEM Elements
Versus Core Radius (U)

Figure 4-12. (CRD) Gross Weight Loss Versus Core Radius for PEWEE-1 Fuel Elements (Excluding Data for Elements With Cold End or Hot End Corrections) (U)

Figure 4-13. (CRD) Incremental Gross Weight Loss Profiles Typical of Y-12
NbC GEM Coated and LASL ZrC GEM/ZrC GED Coated PEWEE-1 Fuel Elements (U)

Figure 4-14. (CRD) Typical Surface and Channel Condition of Hot End Tip
for Y-12 Standard GEM Coated Elements. Element 269-58467, Core
Position 330L8, Batch 8561 (U)

Figure 4-15. (CRD) Midband Surface Condition of a WANL Y-12 Standard GEM Coat (269-58482, 210L8, Third from Top) Compared With WANL Standard GEM (525-57308, 150E4, B224, Fourth From Top) and WANL Standard GED-X (525-57067, 150F4, C396, Fifth From Top) (U)

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Figure 4-16. (CRD) Fracture Surface at Station 22 on 269-58231, Core Position 210L7, Add. GEM, Batch B219. "A" Face Between Fingers, Channel 12 Toward Large Corrosion Pocket on "E" Surface. Corrosion Pocket Encompasses Channels 4, 5, 6, 7, 9, 10, 11 and 12. Fresh Uncorroded Fracture Surface Estimated 29 Percent (U)

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Figure 4-17. (CRD) Fracture Surface at Station 12.5 on 525-57300, Std. GEM, Batch B224, Core Position 270E5. Scallop of Surface by Streak Corrosion Prominently Displayed with Bores in Good Condition. Fresh, Uncorroded Fracture Surface Estimated 90 Percent. (U)

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Figure 4-18. (CRD) Mechanical Break at 9.5 Inches in WANL
Element 477-58612, Batch M138 (U)

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Figure 4-19. (CRD) Evidence of Interelement Bonding in PEWEE-1. "A" Face of 477-58612, Core Position 270G2, With NbC OD Coating from an Adjacent Element Adhering to It. The Adherence Is in the Streak Pattern Normally Observed for Soot-Pyrocarbon Deposition in This Axial Region (U)

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STA. 10-15 INCHES
PEAK $\Delta IW = 0.50$ GRAM/INCH

STA. 20-25 INCHES
PEAK $\Delta IW = 0.25$ GRAM/INCH

STA. 40-45 INCHES
PEAK $\Delta IW = 0.45$ GRAM/INCH

477-58628
ADD. GEDX, BATCH M139
CORE POSITION 090H4
GROSS $\Delta W(0-52) = 21.3$ GRAMS

STA. 10-15 INCHES
PEAK $\Delta IW = 0.30$ GRAM/INCH

STA. 20-25 INCHES
PEAK $\Delta IW = 0.07$ GRAM/INCH

STA. 40-45 INCHES
PEAK $\Delta IW = 0.45$ GRAM/INCH

269-58477
STND Y12 GEM, BATCH 8562
CORE POSITION
GROSS $\Delta W(0-52) = 10.12$ GRAMS

STA. 10-15 INCHES
PEAK $\Delta IW = 1.00 - 2.75$ GRAM/INCH

STA. 20-25 INCHES
PEAK $\Delta IW = 0.9 - 1.00$ GRAM/INCH

STA. 40-45 INCHES
PEAK $\Delta IW = 0.37 - 0.50$ GRAM/INCH

269-58253
ADD. GEM, BATCH B219
CORE POSITION 150L7
GROSS $\Delta W(0-52) = 45.7$ GRAMS

Figure 4-20. (CRD)
Condition of Coolant Channels in Axial Split
WANL PEWEE - 1 Fuel Elements (U)

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STA. 10-15 INCHES
PEAK $\Delta IW = 0.65$ GRAM/INCH

STA. 20-25 INCHES
PEAK $\Delta IW = 0.15$ GRAM/INCH

STA. 40-45 INCHES
PEAK $\Delta IW = 0.35$ GRAM/INCH

269-58283
ADD.GEM, BATCH B220
CORE POSITION 090L7
GROSS $\Delta W(0-52) = 21.3$ GRAMS

STA. 10-15 INCHES
PEAK $\Delta IW = 1.60$ GRAM/INCH

STA. 20-25 INCHES
PEAK $\Delta IW = 0.40$ GRAM/INCH

STA. 40-45 INCHES
PEAK $\Delta IW = 0.45$ GRAM/INCH

525-57080
STND. GEDX, BATCH G396
CORE POSITION 210G6
GROSS $\Delta W(0-52) = 24.9$ GRAMS

STA. 10-15 INCHES
PEAK $\Delta IW = 0.43$ GRAM/INCH

STA. 20-25 INCHES
PEAK $\Delta IW = 0.25$ GRAM/INCH

STA. 40-45 INCHES
PEAK $\Delta IW = 0.45$ GRAM/INCH

525-57071
RES. GEDX, BATCH L313
CORE POSITION 150F2
GROSS $\Delta W(0-52) = 16.2$ GRAMS

Figure 4-21. (CRD)
Condition of Coolant Channels in Axial Split
WANL PEWEE-1 Fuel Elements (U)

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Figure 4-22. (CRD) Photomicrograph of Transverse Section From 525-57172, Core Position 210F6, RGEDX, C398 at Sta. 14 Showing Cross-Sectional Relationship of OD Corrosion and Coolant Channel Corrosion (U)

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↙ OD CORROSION

CORROSION POCKET IN WEBBING AT STA. 14 BETWEEN CHANNEL 8 and OD SURFACE OF 269-58252, CORE POSITION 210L6, ADD GEM, B219 (50X)

OD CORROSION AND FLAKED OD COATING AT STA. 14 BETWEEN CHANNELS 2 & 3 OF 525-57249, CORE POSITION 270C1, STD. GEDX, C396 (50X)

BINDER CORROSION UNDERNEATH OD COATING AT STA. 19-20 OF 525-57034, CORE POSITION 330F2, STD. GEDX, L314 (250X)

Figure 4-23. (CRD) Photomicrographs of Midband Corrosion Typical of PW-1 Elements (U)

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Figure 4-24. (CRD) Center Channel Corrosion in 525-57034, Std. GED, Batch L314
at Station 17 Inches (U)

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A

A. 9-1/2 INCHES 0.25 GM/INCH

B. 10 INCHES 0.35 GM/INCH

C. 12 INCHES 1.0 GM/INCH

D. 13 INCHES 1.4 GM/INCH

(Face Orientation on all Samples as in (A))

Figure 4-25. (CRD) End Photographs of Transverse Section From 269-58268, Core Position 030L7, Batch B220. ASP Record of Surface Damage for Faces D, E, F Only in Region 10-12 Inches (U)

A. 10-1/2 INCHES, 0.35 GM/INCH

B. 12-1/2 INCHES, 1.0 GM/INCH

C. 13 INCHES 1.8 GM/INCH

D. 15 INCHES 0.9 GM/INCH

(Face Orientation on All Samples as in (A))

Figure 4-26. (CRD) End Photographs of Transverse Sections From 525-57217, Core Position 330E3, Batch M136. ASP Record of Surface Damage on All Faces in Region 12-14 Inches (U)

A. 10-1/2 INCHES, 0.40 GM/INCH

B. 12-1/2 INCHES, 0.60 GM/INCH

C. 14-1/2 INCHES 0.50 GM/INCH

D. 15-1/2 INCHES 0.40 GM/INCH

(Face Orientation on All Samples as in (A))

Figure 4-27. (CRD) End Photographs of Transverse Sections from 477-58635. Core Position 330H8, Batch M139. ASP Record of Light Edge Corrosion on B Face Only From 13-15 Inches (U)

A. ELEMENT NO. 50371, STATION 10, G-END VIEW,
0.5 GM/INCH

B. ELEMENT NO. 50371, STATION 13, G-END VIEW,
1.2 GM/INCH

Figure 4-28. (CRD) Cross-Sectional Photographs of LASL Element with Midband
Surface Corrosion Occurring Under OD Coatings. (U)

A. ELEMENT NO. 50544, STATION 46, G-END VIEW, 0.65 GM/INCH

B. ELEMENT NO. 50544, STATION 47, G-END VIEW, 0.5 GM/INCH

Figure 4-29. (CRD) Cross-Sectional Photographs of LASL Element with Hot
End Region Surface Corrosion Occurring Under OD Coatings. (U)

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Figure 4-30. (CRD) Center Channel Corrosion at Station 34 in Element 525-57034, Batch L314. (U)

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COMPOSITE
END

- CHANNEL 3

"A" FACE

- CHANNEL 1

4-31A. OD SURFACE AT 50-52 INCHES

- CHANNEL 17

- CHANNEL 14

- CHANNEL 10

- CHANNEL 6

- CHANNEL 3

4-31B. COOLANT CHANNELS AT 50-52 INCHES

Figure 4-31. (CRD) Hot End Tip Condition in Element 525-57034, Core Position 330F2, Batch L314. (U)

COMPOSITE END

- CHANNEL 3

"A" FACE

- CHANNEL 1

4-32A. OD SURFACE AT 50-52 INCHES

COMPOSITE END

- CHANNEL 17

- CHANNEL 14

- CHANNEL 10

- CHANNEL 6

- CHANNEL 3

4-32B. COOLANT CHANNELS AT 50-52 INCHES

Figure 4-32. (CRD)
Hot End Tip Condition in Element 269-58466, 412 GEM, Batch 8561. (U)

COMPOSITE
END

- CHANNEL 1

"B" FACE

- CHANNEL 8

4-33A. OD SURFACE AT 50-52 INCHES

COMPOSITE
END

- CHANNEL 12

- CHANNEL 11

- CHANNEL 10

- CHANNEL 9

- CHANNEL 8

4-33B. COOLANT CHANNELS AT 50-52 INCHES

Figure 4-33. (CRD) Hot End Tip Condition in Element 269-58238, Core Position 090L5, Batch M137. (U)

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- CHANNEL 3

- CHANNEL 1

4-34A. OD SURFACE AT 51-52 INCHES

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- CHANNEL 19
- CHANNEL 15
- CHANNEL 10
- CHANNEL 5
- CHANNEL 1

4-34B. COOLANT CHANNELS AT 50-52 INCHES

Figure 4-34. (CRD) Hot End Tip Condition in Element 525-57089, Batch B218.
Broken at 51 Inches During Hot Cell Examination. (U)

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FIGURE 4-35A. MODEST CORROSION POCKET UNDER CRACK IN NbC BORE COAT AT INTERSECTION OF CHANNEL 19 AND FUEL-TO-TRANSITION JOINT (250X).

FIGURE 4-35B. MODEST CORROSION POCKET AT NbC BORE COATING CRACK, SLIGHTLY UPSTREAM OF JOINT POSITION SHOWN IN A (250X).

FIGURE 4-35C. INTERSECTION OF FUEL-TO-TRANSITION JOINT WITH OD SURFACE AT CHANNEL 19 WEB. JOINT AND FUEL BEADS IN GOOD CONDITION (250X).

Figure 4.35. Fuel-Transition Joint Conditions in WANL PW-1 Elements
As Typified by Photo-micrograph of Element 525-57235, Batch C396.

Figure 4-36. (CRD) Photomicrographic Montage Of Outer Web Corrosion Typical in Transition Graphite Region of Hot End as Typified by Element 525-57252, Batch F387. (250X) (U)

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- F - E FACES APEX
(CHANNEL EXPOSURE)
- COOLANT CHANNEL NO. 12
- COOLANT CHANNEL NO. 7
- COOLANT CHANNEL NO. 3
- F - A FACES APEX (LIGHT CORROSION)

↑
STATION 52
(COMPOSITE CARBIDE TIP)

↑
COMPOSITE - TO -
TRANSITION GRAPHITE
JOINT

Figure 4-37. (CRD) Photomicrograph of 80-Mil Deep Tip Grind on the F Face of Element 525-57237, Batch L314. Visual Examination of Region Shows Heavy Corrosion and Channel Exposure on E Face and Light Corrosion of Graphite Surface on A Face in Transition Region (50X). (U)

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TABLE 4-1 (CRD)

POST OPERATIONAL DISPOSITION SUMMARY FOR WANL
SUPPLIED FUEL ELEMENTS FROM PEWEE-1 (U)

		Number of Elements To:									
Matrix ⁽¹⁾ NbC Coat Batch	Coat- Batch	Weigh	ASP	10 Point ⁽²⁾ Gamma	PDE ⁽³⁾	WER ⁽⁴⁾	MULE ⁽⁵⁾	Axial Split	Micro-RAD ⁽⁶⁾	Radio- Chem	Metallography
RGEM	B218	5	5	6	2	6	5	2	2	1	2
NGEM	B219	4	4	7	0	8	4	2	2	1	2
	B220	5	5	5	0	5	5	2	2	0	2
	B223	2	2	5	1	6	2	1	1	0	0
SGEM	B224	4	4	6	2	6	4	2	2	0	2
SGEDX	C396	12	12	12	0	12	11	3	3	2	2
	F387	2	2	2	0	2	2	1	1	0	1
	L314	14	13	14	1	14	9	3	3	0	3
	M136	7	7	7	1	7	7	2	2	0	2
RGEDX	C398	9	9	9	1	9	7	2	2	0	2
	L313	8	8	8	1	8	7	2	2	1	1
NGEDX	C397	0	0	0	1	0	8	2	2	0	0
	M137	7	7	7	0	7	7	2	2	0	1
	M138	10	10	12	1	12	9	2	2	0	2
	M139	12	12	12	1	12	11	3	3	0	2
SGEM	8561	4	4	4	1	4	4	2	2	0	1
	8562	2	2	2	1	2	2	1	1	0	1
Totals		116	115	127	14	129		34	34	5	26

(1) R-Nb Resinate; N-2.5 v/o NbC additive; S-standard

(2) Gamma Ray spectrometer measurement of fission products Ru-103, Zr-95, Ta 182 and Ba-La-140 in 5.25 inch long axial increments, performed at J-11.

(3) PDE - potential drop examination, 1-inch incremental electrical resistance profiles

(4) WER - whole element radiography

(5) MULE - mass per unit length, 1-inch incremental weight changes.

(6) Micro-RAD - microradiography of 15 mil thick transverse slices, performed at GMX-1.

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TABLE 4-2 (CRD)

PINHOLING IN WANL ELEMENTS FROM PEWEE-1 (U)

Loading Matrix	Coat Batch	Core Radius Range, Inches	Number of Elements		0-25 Inches *		25-51 Inches *	
			Examined	Pinholed	No. FE Ph'd.	No. Ph.	No. FE Ph'd.	No. Ph.
525 Nb Resinate	B218	1.99-2.26	5	5	5	59	3	11
269 NbC Add.	B219	7.18	4	4	4	244	4	82
269 NbC Add.	B220	7.18	5	5	5	161	4	7
477 NbC Add.	B223	4.94-5.27	2	2	2	175	2	29
525 Std.	B224	1.99-3.28	4	4	4	105	4	31
525 Nb Resinate	C398	2.26-4.20	9	7	6	23	3	11
525 Nb Resinate	L313	3.91-4.94	8	4	3	5	3	10
525 Std.	C396	1.99-4.70	12	10	7	27	6	15
525 Std.	F387	3.28-4.70	2	1	1	3	0	0
525 Std.	L314	1.99-4.70	13	12	10	28	5	7
525 Std.	M136	3.28-3.76	7	6	6	10	1	1
269 NbC Add.	C397	7.42	9	3	0	0	3	6
269 NbC Add.	M137	7.26-7.42	7	3	1	2	3	6
269 NbC Add.	M138	4.94-5.27	10	2	2	2	1	1
269 NbC Add.	M139	5.27-5.69	12	5	3	5	4	9
269 Std.	8561	7.26	4	3	2	8	3	7
269 Std.	8562	7.26	2	0	0	0	0	0

* Ph = pinhole

TABLE 4-3 (CRD)

COMPARISON OF PINHOLING IN WANL PEWEE-1 REACTOR-TESTED ELEMENTS
AND IN WANL STORED, ELECTRICAL HYDROGEN CORROSION TESTED ELEMENTS * (U)

Batch	Matrix, Loading	Average Number, Pinholes/Element	
		Reactor	Corrosion Test
GED			
C396	Standard, 525	2.2	4.0
C397	2.5 v/o NbC, 269	0.3	0.0
C398	Nb Resinate, 525	2.6	-
F387	Standard, 525	1.5	2.0
L313	Nb Resinate, 525	0.7	-
L314	Standard, 525	2.1	-
M136	Standard, 525	1.4	-
M137	2.5 v/o NbC, 269	0.3	1.0
M138	2.5 v/o NbC, 477	0.2	-
M139	2.5 v/o NbC, 277	0.4	-
GEM			
B218	Nb Resinate, 525	13.0	-
B219	2.5 v/o NbC, 269	78.1	88.0
B220	2.5 v/o NbC, 269	32.4	139.3
B223	2.5 v/o NbC, 477	90.0	377.0
B224	Standard, 525	30.0	-
8561	Standard, 269	2.0	-
8562	Standard, 269	0.0	5.0

* Elements air-stored in WNCO or Waltz Mill vaults for approximately 9 months before corrosion test.

** For axial region between Stations 10-30 inches.

TABLE 4-4 (CRD)

WHOLE ELEMENT RADIOGRAPHY RESULTS FOR
CORROSION POCKET OCCURRENCES IN WANL ELEMENTS (U)

Loading- Matrix (*) -Coat- Coat Batch	Average No. Corrosion Pockets Indicated Per Range (Avg. Ph Density **)			
	0-25 Inches		25-50 Inches	
525 RGEM B218	45.2	(11.8)	5.7	(3.7)
269 NGEM B219	89.9	(61.0)	26.8	(21.0)
269 NGEM B220	48.8	(32.2)	1.2	(1.8)
477 NGEM B223	103.6	(87.5)	29.4	(14.5)
525 SGEM B224	49.7	(26.3)	10.7	(7.8)
269 YSGEM 8561	0.0	(2.0)	0.0	(2.3)
269 YSGEM 8562	0.5	(0.0)	0.0	(0.0)
525 RGEDX C398	0.2	(3.8)	0.0	(3.7)
525 RGEDX L313	0.6	(1.6)	0.5	(3.3)
269 NGEDX C397	0.0	(0.0)	0.0	(2.0)
269 NGEDX M137	0.0	(2.0)	0.0	(2.0)
477 NGEDX M138	11.2	(1.0)	5.0	(1.0)
477 NGEDX M139	0.0	(1.6)	0.0	(2.3)
525 SGEDX C396	0.6	(3.9)	0.2	(2.5)
525 SGEDX F387	0.0	(3.0)	3.5	(0.0)
525 SGEDX L314	0.7	(2.8)	0.5	(1.4)
525 SGEDX M136	0.2	(1.7)	0.2	(1.0)

* Matrix Designations
R - Nb Resinate Impregnated
N - 2.5 v/o NbC Additive
S - Standard

** () Average number of pinholes per pinholed element in range indicated, by ASP visual.

TABLE 4-5 (CRD)

GROSS WEIGHT LOSSES OF ALL COATING-MATRIX TYPES IN PEWEE-1. DATA FOR ELEMENTS NEEDING COLD END OR HOT END CORRECTIONS NOT INCLUDED (U)

Supplier	Matrix - Coat	Type	No.	Ave ΔW	Standard Deviation	Min. ΔW	Max. ΔW
LASL	STND Y12 GEM	10016	4	11.26	1.60	9.51	12.81
	STND NbC (GEM + GED) + X	10019	139	18.74	5.97	10.37	43.19
	STND ZrC (GEM + GED) + X	10021	6	9.65	1.40	7.96	11.43
	STND NbC (GEM) ZrC (GED) + X	10022	1	19.57	.00	19.57	19.57
	STND Thick GEM + X	10023	1	25.57	.00	25.57	25.57
	HTB NbC (GEM + GED) + X	10051	2	29.70	8.00	24.05	35.36
	HTB NbC (GEM + GED)	10052	4	25.02	11.92	14.93	41.63
	STND NbC (GEM + GED)	10054	2	19.09	.62	18.65	19.53
	STND ZrC (GEM + GED)	10058	5	9.69	1.42	7.94	11.13
	STND NbC (GEM + GED) + X	10119	15	23.80	8.84	16.79	53.02
	STND NbC (GEM ZrC (GED) + X	10122	2	13.72	1.23	12.85	14.59
	STND Thick GEM + X	10123	4	26.31	3.46	23.24	29.47
	STND NbC (GEM + GED) + X	10219	3	27.61	11.05	20.11	40.30
	STND NbC (GEM) ZrC (GED) + X	10222	4	18.72	3.50	15.36	23.62
	STND Thick GEM + X	10223	6	28.09	4.51	22.11	33.52
	12 hole NbC (GEM + GED) + X	10321	2	11.60	.85	11.00	12.20
		12019	6	17.31	1.19	15.89	18.96
WANL	STND WNCO GED-X	41027	26	18.60	2.28	15.75	24.95
	STND WEFF GEM	41028	3	32.45	11.05	22.83	44.51
	RES. WEFF GEM	41031	5	18.03	2.96	13.79	21.68
	RES. WNCO GED-X	41033	15	15.94	1.27	13.78	18.16
	ADD. WNCO GED-X	42039	20	18.64	2.44	15.24	22.60
	ADD. WEFF GEM	42040	1	31.76	.00	31.76	31.76
	ADD. WEFF GEM	43037	9	27.42	11.63	16.34	45.67
	ADD. WNCO GED-X	43039	16	16.90	.85	15.84	18.51
	STND Y12 GEM	44026	6	10.64	.77	9.85	12.05

TABLE 4-6 (CRD)

WANL SUPPLIED PEWEE-1 FUEL ELEMENTS
WITH MISSING HOT END TIPS AT CORE DISASSEMBLY (U)

<u>Loading Serial No.</u>	<u>Core Position</u>	<u>Matrix Coating Coating Batch</u>	<u>Condition From ASP^(*)</u>
477-58652	330H4	NGEM B223	1 Inch Gone, 3/4 Inch Corrosion Tapered
525-57306	270C2	SGEM B224	1 Inch Gone, 1 Inch Corrosion Tapered
525-57063	330F6	RGEDX L313	1 Inch Gone, Mechanical Break
525-57236	030F2	SGEDX L314	1 Inch Gone, 1 Inch Corrosion Tapered

(*) In all cases, the "tip" (51-52 inches) was missing. The term "corrosion tapered" indicates the length of fuel affected by corrosion in the region 50-51 inches. In the case of element 57063, there was very little corrosion on the surfaces at the fuel end and the "break" at the fuel-to-transition piece joint was "fresh". Corrections to the R-MAD measured weight losses for these elements were made on the basis of the tip weight, i.e., for element 269-58652 the as-assembled coated tip weight was 16.48 grams, the measured weight loss 81.00 grams, and the corrected (0-52 inches) loss due to corrosion was therefore 64.52 grams.

TABLE 4-7 (CRD)

WANL SUPPLIED PEWEE-1 FUEL ELEMENTS
WITH MISSING COLD END PIECES AT CORE DISASSEMBLY* (U)

<u>Loading Serial No.</u>	<u>Core Position</u>	<u>Matrix Coating Coating Batch</u>	<u>Correction To ΔW^{**}</u>	<u>Cold End Missing Material Condition From ASP**</u>
525-57249	270C1	SGEDX C396	1.54	2 Orifices Missing + 2" Chan. Exposure
525-57173	270F6	RGEDX C398	2.44	4 Orifices Missing + 3" Chan. Exposure
525-57041	270G6	RGEDX L313	2.44	4 Orifices Missing + 3" Chan. Exposure
525-57045	030G7	RGEDX L313	1.35	3 Orifices Missing + 1.5" Chan. Exposure
525-57064	030F4	RGEDX L313	13.67	19 Orifices + 7/8" Fuel Gone
525-57026	270F4	SGEDX L314	15.17	19 Orifices + 1" Fuel Gone
525-57034	330F2	SGEDX L314	3.83	5 Orifices Missing + 5" Chan. Exposure
525-57036	090F2	SGEDX L314	15.17	19 Orifices + 1" Fuel Gone
525-57066	150E3	SGEDX L314	13.57	19 Orifices + 7/8" Fuel Gone
525-57115	150E1	SGEDX L314	11.09	19 Orifices + 5/8" Fuel Gone + 1" Chan. Exposure
525-57189	150E2	SGEDX L314	15.17	19 Orifices + 1" Fuel Gone
525-57190	090F4	SGEDX L314	15.17	19 Orifices + 1" Fuel Gone
525-57216	090E1	SGEDX L314	1.16	4 Orifices Missing + 1" Chan. Exposure
477-58605	210G2	NGEDX M138	1.36	3 Orifices Missing + 1.5" Chan. Exposure
477-58633	330G1	NGEDX M139	15.47	19 Orifices + 1" Fuel Gone

* Cold end piece broken off during unglueing operation.

** For these elements, estimated correction to R-MAD measured weight losses were made as follows:

Approximate orifice weight, gram per orifice = 0.13

Approximate coated fuel weight, gram per inch, 525 S, 0-1 inch = 12.70
525 R, 0-1 inch = 12.80
477 N, 0-1 inch = 13.00

TABLE 4-8 (CRD)

WANL SUPPLIED PEEWEE-1 FUEL ELEMENTS
WITH FRACTURES AT CORE DISASSEMBLY (U)

<u>Loading- Serial No.</u>	<u>Core Position</u>	<u>Matrix-Coating- Coating Batch</u>	<u>Fracture Station</u>	<u>Condition From Hot Cell Examination *</u>
525-57077	150C1	R GEM B218	18.5	Some Pockets (45%)
269-58231	210L7	N GEM B219	22	Corrosion Pockets (29%)
			34	Some Pockets (50%)
269-58245	270L7	N GEM B219	22, 23	Corrosion Pockets (18%, 16%)
269-58249	030L5	N GEM B219	12	Surface Corrosion, Pockets (70%)
			16, 19, 22.5	Corrosion Pockets (30%, 35%, 40%)
269-58250	270L5	N GEM B219	21, 29	Corrosion Pockets (20%, 70%)
			36	Surface Corrosion (25%)
477-58653	030G1	N GEM B223	18	Surface + Pockets (10%)
477-58662	030H4	N GEM B223	20	Surface + Pockets (15%)
477-58663	210G7	N GEM B223	29.5	Surface + Pockets (30%)
477-58664	030H6	N GEM B223	20	Surface + Pockets (20%)
525-57295	030E4	S GEM B224	14	Surface + Some Pockets (30%)
			25.5	Pockets (40%)
525-57300	270E5	S GEM B224	12.5	Surface Corrosion (90%)
			16	Corrosion Pockets (70%)
269-58232	330L5	N GEDX M137	38	Clean, Small Pocket (85%)
477-58604	090G1	N GEDX M138	13	Surface Corrosion (90%)
			35.5	Clean Break (99%)
477-58612	270G2	N GEDX M138	9.5	Clean Break (99%)

* Percent indicates amount of fresh, uncorroded fracture surface observed at respective fracture station.

TABLE 4-9 (CRD)

PERFORMANCE RATING, MID-BAND SURFACE DAMAGE (0-25), WANL PW-1 FUEL ELEMENTS (U)

Mid-band surface corrosion of each flat of each element (0-25) was appraised and assigned numerical values as follows:

Value	Corresponding Surface Condition From ASP Visual
0	Good
1	Light Corrosion
3	Medium Corrosion
5	Heavy Corrosion
7	Channel Exposure

PR, performance rating of each element = (value x length of corrosion x width factor) summed for all flats where width factor = 1 for streaking and edge corrosion
= 2 for corrosion covering entire flat.

Average performance rating (PR) for different indicated grouping is given below:

Coating Type	Avg. PR	Loading mg/cc	Avg. PR	Matrix Type	Avg. PR	Coating Batch	No. of Elements Evaluated In Coating Batch	Avg. PR
GED		525		Std.		C396	12	50
GED		525		Std.		F387	2	38
GED		525		Std.		L314	13	55
GED		525		Std.	48	M136	7	37
GED		525		Resinate		C398	9	7+
GED		525	41	Resinate	5	L313	8	1+
GED		477		2.5 v/o NbC		M138	10	7+
GED		477	6	2.5 v/o NbC		M139	11	4
GED		269		2.5 v/o NbC		C397	9	<1
GED	21+	269	1	2.5 v/o NbC	3+	M137	7	2
GEM		525		Std.	181	B224	4	181
GEM		525	84	Resinate	6	B218	5	6
GEM		477	17	2.5 v/o NbC		B223	2	17
GEM		269		2.5 v/o NbC		B219	4	182
GEM	84	269	99	2.5 v/o NbC	84	B220	5	33

TABLE 4-10 (CRD)
SUMMARY RESULTS OF CHANNEL
EXAMINATIONS ON WANL PEWEE-1 FUEL ELEMENTS (U)

Bore Coating Batches	Typical Corrosion Condition Per Axial Region	
	0-25 Inches	25-51 Inches
B218, B220 B224	Corrosion pockets primarily in 15-20 inch region; no significant coolant channel corrosion detected; good NbC bore coat adherence.	1-2 corrosion pockets per element: Light corrosion through coating cracks in 40-50 inch region (heaviest in B224). Fairly good coating adherence. No significant diffusion corrosion detected at bore coat-matrix interface.
B219, B223	Highest density of corrosion pockets of WEFF GEM elements; most pockets occur in 12-25 inch region. No significant coolant channel corrosion detected; good NbC bore coat adherence.	Several corrosion pockets per element still occurring in 25-40 inch region. Very light corrosion through coating cracks in 40-51 inch region, good coating adherence. No significant diffusion corrosion detected at bore coat-matrix interface.
L314, C396 M136, F387	No significant coolant channel corrosion at 10-15 inches, center channel corrosion of varying severity from approximately 17 to 25 inches. Heaviest center corrosion in C396 and L314 elements.	Center channel corrosion extends to 35 inches. Light to moderate diffusion corrosion and crack corrosion general in all channels in regions 40-51 inches.
C397, C398, M137, M138, M139, 8561, 8562	No significant coolant channel corrosion detected, good NbC bore coat adherence.	Diffusion corrosion and corrosion through coating cracks of varying severity is fairly general in 35-51 inch region; mildest corrosion in elements from C398, M138, 8561, and 8562.

TABLE 4-11 (CRD)

PERFORMANCE RATINGS, HOT END DAMAGE, FOR WANL PEWEE-1 FUEL ELEMENTS (U)

1. Hot end flats of each element were appraised and assigned numerical values as follows:

<u>Value</u>	<u>Corresponding Condition of Hot End Per ASP Visuals</u>
1	Good
3	Limited Damage, Moderate
5	Excessive Damage - Channel Exposure

2. The performance rating (PR) reported is the average value for elements of the groups indicated.

<u>Coating Type</u>	<u>Avg. PR</u>	<u>Loading (mg/cc)</u>	<u>Avg. PR</u>	<u>Matrix Type</u>	<u>Avg. PR</u>	<u>Coating Batch</u>	<u>No. of Elements Evaluated In Coating Batch</u>	<u>Avg. PR</u>
GED		525		Std.		C396	12	2.27
GED		525		Std.		F387	2	1.67
GED		525		Std.		L314	13	2.11
GED		525		Std.	2.01	M136	7	1.05
GED		525		Resinate		C398	9	2.22
GED		525	2.14	Resinate	2.56	L313	8	2.29
GED		477		2.5 v/o NbC		M138	10	3.15
GED		477	3.27	2.5 v/o NbC		M139	11	3.40
GED		269		2.5 v/o NbC		C397	9	2.45
GED	2.47	269	2.38	2.5 v/o NbC	2.89	M137	7	2.29
GEM		525		Std.	3.42	B224	4	3.42
GEM		525	4.11	Resinate	4.67	B218	5	4.67
GEM		477	4.50	2.5 v/o NbC		B223	2	4.50
GEM		269		2.5 v/o NbC		B219	4	4.92
GEM	4.40	269	4.67	2.5 v/o NbC	4.64	B220	5	4.47
						8561, 62	6	<1.0

TABLE 4-12 (CRD)

5-INCH INCREMENTAL GROSS, SURFACE, AND BORE LOSSES FOR
WANL-SUPPLIED COATING BATCH, LOADING, AND MATERIAL TYPES IN PEWEE-1 (U)

Matrix Load	Coating Batch	Loss* Type	Ave. Loss in Grams Per 5-Inch Increment**										Loss 50-52
			1	2	3	4	5	6	7	8	9	10	
ADD, 269	C397	G	0.08	0.50	1.33	0.91	1.12	1.52	2.03	2.33	2.45	2.41	2.57
		S	----	----	0.09	0.05	----	----	----	----	0.15	0.23	1.50
		B	0.06	0.31	0.74	0.35	0.62	1.26	1.85	2.15	2.12	2.00	1.07
ADD, 269	M137	G	0.09	0.41	1.04	0.67	1.07	1.62	2.06	2.34	2.29	2.34	2.67
		S	----	----	0.14	0.05	----	----	----	----	----	----	1.77
		B	0.02	0.26	0.50	0.22	0.67	1.46	1.90	2.19	2.14	2.19	0.90
ADD, 477	M138	G	0.11	0.67	2.06	1.21	1.05	1.43	1.80	1.96	1.97	1.94	3.58
		S	----	0.01	0.09	0.07	----	----	0.01	0.01	----	----	2.88
		B	0.07	0.36	1.28	0.79	0.70	1.26	1.62	1.78	1.79	1.77	0.70
ADD, 477	M139	G	0.09	0.54	2.10	1.36	1.23	1.60	2.14	2.37	2.34	2.36	3.20
		S	----	0.01	0.09	0.01	----	----	0.12	0.14	----	----	2.30
		B	0.01	0.35	1.56	0.90	0.78	1.43	1.84	2.06	2.16	2.19	0.90
RES, 525	C398	G	0.06	0.36	1.78	1.30	0.90	1.27	1.72	1.88	1.91	1.76	1.85
		S	----	----	0.17	0.20	----	----	----	----	----	----	1.21
		B	0.00	0.18	1.12	0.59	0.41	1.09	1.54	1.71	1.73	1.58	0.64
RES, 525	L313	G	0.15	0.26	1.31	1.25	1.24	1.63	2.16	2.25	2.13	1.95	2.21
		S	----	----	0.02	0.03	0.01	----	0.07	0.10	----	----	1.58
		B	0.05	0.08	0.80	0.72	0.74	1.45	1.91	1.97	1.95	1.77	0.63
STND, 525	C396	G	0.08	0.34	3.00	1.98	1.53	1.98	2.31	2.24	2.09	1.86	1.73
		S	----	----	1.90	0.77	0.13	0.06	0.03	0.03	0.01	0.20	1.17
		B	0.00	0.17	0.65	0.74	0.95	1.75	2.11	2.04	1.92	1.50	0.56
STND, 525	F387	G	0.10	0.30	3.68	1.94	1.35	1.70	2.26	2.32	2.13	1.90	0.91
		S	----	----	1.19	0.57	----	----	----	----	----	----	0.34
		B	0.02	0.13	2.00	0.88	0.87	1.53	2.09	2.15	1.96	1.73	0.57
STND, 525	L314	G	0.05	0.34	3.39	2.15	1.16	1.83	2.42	2.39	2.05	1.85	2.12
		S	----	0.05	1.71	0.81	0.06	----	----	0.01	----	----	1.59
		B	0.00	0.13	1.28	0.93	0.70	1.68	2.27	2.23	1.90	1.70	0.53
STND, 525	M136	G	0.08	0.24	2.33	2.25	1.33	1.70	1.93	2.13	2.10	1.72	0.90
		S	----	----	1.02	1.01	0.07	0.01	----	----	----	----	0.28
		B	0.00	0.08	0.86	0.78	0.81	1.53	1.77	1.96	1.93	1.56	0.62
RES, 525	B218	G	0.13	0.17	2.53	2.37	1.44	1.21	1.28	1.58	1.86	1.65	3.79
		S	----	----	0.37	----	----	----	----	0.07	----	----	3.29
		B	0.13	0.17	2.16	2.37	1.44	1.21	1.28	1.58	1.79	1.65	0.50
ADD, 269	B219	G	0.07	1.27	8.99	8.21	6.74	2.47	2.19	2.06	1.86	1.63	4.38
		S	----	0.54	5.18	0.46	0.35	----	0.20	0.17	----	----	3.85
		B	0.07	0.73	3.81	7.75	6.39	2.47	1.99	1.89	1.86	1.63	0.53
ADD, 269	B220	G	0.09	0.28	3.67	1.87	0.93	0.80	1.09	1.47	1.69	1.68	4.51
		S	----	----	0.86	----	0.10	----	----	----	----	----	3.93
		B	0.09	0.28	2.81	1.87	0.83	0.80	1.09	1.47	1.69	1.68	0.58
ADD, 277	B223	G	0.09	0.29	6.41	8.02	3.73	1.02	1.10	1.47	1.50	1.64	6.48
		S	----	----	0.70	----	----	----	----	----	----	----	5.94
		B	0.09	0.29	5.71	8.02	3.73	1.02	1.10	1.47	1.50	1.64	0.54
STND, 525	B224	G	0.10	0.32	10.72	7.53	4.60	1.58	1.40	1.72	1.69	1.44	1.36
		S	----	0.11	7.44	3.85	0.11	----	----	----	----	----	0.75
		B	0.10	0.21	3.28	3.68	4.49	1.58	1.40	1.72	1.69	1.44	0.61
STND, 269	8561	G	.03	0.12	1.01	0.92	0.35	0.64	1.29	1.86	1.81	1.65	1.11
		S	----	----	0.02	----	----	----	----	----	----	----	0.45
		B	.03	0.12	0.99	0.92	0.35	0.64	1.29	1.86	1.81	1.65	0.66
STND, 269	8562	G	0.07	0.17	1.23	0.65	0.52	0.81	1.37	2.06	2.10	1.97	1.01
		S	----	----	----	----	----	----	----	----	----	----	0.18
		B	0.07	0.17	1.23	0.65	0.52	0.81	1.37	2.06	2.10	1.97	0.33

* G is gross weight loss as measured by MULE, corrected for cold end or hot end losses.
S is surface loss estimated from ASP surface visuals.
B is bore loss after all corrections including molybdenum blowdown loss (if applicable).

** 1 is 0-5 inches, 10 is 45-50 inches, etc.

TABLE 4-13 (CRD)

WANL PEWEE-1 FUEL ELEMENT SURFACE LOSSES (U)

Bore Coating Batch	Load- Matrix- Coating	Average Surface Loss, Δ WS, Grams Grams Per Element Per Batch *	
		0-25 Inches	50-52 Inches
B218	525 RES. GEM	0.37 (0.5)	3.29 (0.4)
B219	269 ADD. GEM	7.10 (0.2)	3.85 (0.3)
B220	269 ADD. GEM	0.96 (0.4)	3.92 (0.35)
B223	477 ADD. GEM	2.63 (0.25)	5.94 (0.30)
B224	525 STND. GEM	11.80 (0.3)	0.75 (0.5)
8561(Y12)	269 STND. GEM	0.02 (0.65)	0.45 (1.4)
8562(Y12)	269 STND. GEM	0.00 (0.65)	0.18 (1.9)
C396	525 STND. GEDX	2.80 (0.6)	1.17 (0.6)
L314	525 STND. GEDX	2.50 (0.55)	1.59 (0.55)
M136	525 STND. GEDX	1.96 (0.55)	0.28 (0.6)
F387	525 STND. GEDX	1.76 (0.6)	0.34 (0.6)
C398	525 RES. GEDX	0.57 (0.6)	1.21 (0.6)
L313	525 RES. GEDX	0.05 (0.7)	1.58 (0.7)
C397	269 ADD. GEDX	0.14 (0.5)	1.50 (0.6)
M137	269 ADD. GEDX	0.19 (0.5)	1.77 (0.5)
M138	477 ADD. GEDX	0.18 (0.5)	2.88 (0.5)
M139	477 ADD. GEDX	0.27 (0.5)	2.30 (0.5)

* Values in parenthesis are batch average NbC O.D. thicknesses at Stations 13.5 (0-25") and 49.5 (50-52"). Y12 data for 50-52" taken from β -backscatter at station 51.

TABLE 4-14 (CRD)

MEAN INCREMENTAL BORE WEIGHT LOSSES AND
STANDARD DEVIATIONS FOR WANL SUPPLIED
COATING BATCHES IN PEWEE-1 * (U)

Batch	No. FE	0-25 ΔW , Grams		Incremental Data, Bore Loss 25-50 ΔW , Grams		50-52 ΔW , Grams	
		Mean	Sigma	Mean	Sigma	Mean	Sigma
B218	5	6.28	2.60	7.51	.44	.47	.07
B219	3	19.08	2.97	9.98	.57	.53	.03
B220	5	5.88	.89	6.74	.50	.57	.05
B223	1	17.84	.00	6.73	.00	.54	.00
B224	3	11.86	4.12	7.89	.59	.58	.06
C396	12	2.49	.75	9.55	.65	.57	.05
C397	7	1.99	.34	9.57	.58	1.03	.15
C398	7	2.17	.50	7.62	.55	.64	.07
F387	2	3.86	.07	9.43	.49	.57	.07
L313	7	2.38	.59	9.08	.67	.64	.11
L314	9	3.35	1.06	9.91	1.20	.53	.07
M136	7	2.89	.58	8.88	.34	.61	.15
M137	7	1.58	.58	9.87	1.28	.90	.17
M138	9	3.09	.34	8.22	.94	.69	.18
M139	11	3.59	.45	9.75	1.00	.89	.06
8561	4	2.07	.31	7.16	.26	.66	.02
8562	2	2.42	.35	8.07	.10	.82	.07

* For those with MULE data only.

TABLE 4-15 (CRD)

WANL PEWEE-1 WHOLE ELEMENT GROSS AND
BORE WEIGHT LOSSES COMPARISONS (U)

Bore Coating Batch	Matrix- Coating	Weight Losses, 0-52"			
		<u>ΔWG</u>	<u>σ</u>	<u>ΔWB *</u>	<u>σ</u>
B218	RES. W GEM	18.03	2.96	14.26	2.81
B219	ADD. W GEM	39.07	5.42	29.59	2.49
B220	ADD. W GEM	18.09	1.99	13.20	1.07
B223	ADD. W GEM	31.76	-0-	25.11	-0-
B224	STND. W GEM	32.45	11.05	20.15	4.42
8561	STND. Y GEM	10.29	0.41	9.83	0.40
8562	STND. Y GEM	11.33	1.01	11.15	0.53
C396	STND. GEDX	19.33	2.72	12.61	0.87
L314	STND. GEDX	18.96	0.64	13.79	1.32
M136	STND. GEDX	17.13	2.06	12.38	0.58
F387	STND. GEDX	18.60	2.61	13.86	0.50
C398	RES. GEDX	15.25	1.04	10.56	0.54
L313	RES. GEDX	16.99	0.78	12.10	0.87
C397	ADD. GEDX	17.22	0.87	12.62	0.87
M137	ADD. GEDX	16.50	0.68	12.34	1.48
M138	ADD. GEDX	17.78	2.88	12.01	1.04
M139	ADD. GEDX	19.34	1.85	14.21	1.32

* For those elements with MULE data only.

5.0 WANL FUEL ELEMENT PERFORMANCE SUMMARY (U)

(CRD) The PEWEE-1 post-operational data suggest that a significant contribution to the gross weight losses of most of the WANL supplied fuel elements came from effects such as surface corrosion losses in the 0-25 inch and 51-52 inch axial regions, pinhole and corrosion pocket formation in the 0-25 inch region, molybdenum overcoat blowdown losses, mechanical losses of fuel material at the cold ends and losses of the hot end tips. The range of weight loss contributions (corrections) and the frequency of the effects for the examined WANL fuel elements were found to be approximately as follows:

<u>Effect</u>	<u>Range of Loss Correction, Grams Per Element</u>	<u>Percent of WANL Elements Involved</u>
Surface Loss, 0-25 Inch	<0.1 - 18.8	70.4
Surface Loss, 51-52 Inch	<0.1 - 9.0	96.5
Mo blowdown, 0-51 Inch	2.3 - 2.8	78.3
Cold End Loss, 0-1 Inch	1.2 - 15.5	13.0
Hot End Tip Loss, 51-52 Inch	16.2 - 17.2	3.5

(CRD) Significantly, it was evident that the estimated corrections for the 0-25 inch surface corrosion losses were too low since an undetermined amount of surface corrosion was found to be occurring under intact OD surface coatings. There was also conclusive evidence that some surface losses had also occurred under OD coatings in the 25-50 inch axial region which were not accounted for during surface visual examination.

(CRD) An effect which contributed significantly to bore corrosion performance, and could not be quantitatively corrected for, was that of pinholing and the accompanying bore corrosion pocket formation. The WEFF-GEM coated elements were found to be very susceptible to fuel bead hydrolysis which resulted in very high pinhole densities and some gross corrosion pocket formation in the mid-band region. The resultant increment weight losses for these elements in this axial region were high and extremely variable although the "bore corrosion" at the coolant channels-matrix interface was typically mild.

(CRD) This section summarizes the corrosion performance of the WANL supplied PEWEE-1 fuel elements after corrections were made on a best effort basis to the gross weight loss data. The surface corrosion performance in the two identified "problem" regions (0-25 inches and 50-52 inches) and the bore and pinhole performance are discussed.

5.1 SURFACE CORROSION PERFORMANCE IN 0-25 INCH (MID-BAND) REGION. (U)

(CRD) Eighty-one (81) of the 115 WANL-supplied PEWEE-1 fuel elements which were examined post-operationally had surface corrosion visible in the 0-25 inch axial region. The losses for the region ranged from 0.02 to 18.75 grams per element and averaged about 1.60 grams per element overall. Typically, the maximum mid-band surface losses occurred in the 10-15 inch axial region as depicted in Figure 5-1 and were approximately four (4) times greater in the WEFF-GEM coated elements than in the WNCO-GED coated elements. With respect to uranium loading-matrix combinations, the trends in the 10-15 inch region surface losses were as follows:

<u>Loading-Matrix-Coating</u>	<u>10-15 Inch Surface Loss, Grams</u>
525-STANDARD-GEM	7.4
269-ADDITIVE-GEM	2.4
525-STANDARD-GED	1.6
525-RESINATE-GEM	0.4
477-ADDITIVE-GED	0.1
525-RESINATE-GED	< 0.1
269-ADDITIVE-GEM	< 0.1
269-STANDARD-Y12 GEM	< < 0.1

(CRD) The averaged mid-band surface losses for the various WANL-supplied bore coating batches are plotted as a function of OD coating thicknesses for the 10-15 inch region in Figure 5-2. There appears to be a definite trend toward decreasing surface losses with increasing NbC OD coating thickness considering the data in both Figures 5-1 and 5-2. While loading-matrix data comparisons are limited, there also appears to be a tendency for surface losses to be somewhat higher in the elements having the highest uranium loadings.

Considering the overall surface corrosion performance, it is evident that an OD coating thickness of 0.7 mil or greater is required to minimize surface losses in more highly loaded fuel elements when operated in a reactor test environment such as PEWEE-1.

5.2 SURFACE CORROSION PERFORMANCE IN 50-52 INCH REGION (CRD)

(CRD) Only four (4) of the 115 WANL elements examined on ASP film had no discernible damage in any face in the transition graphite tip region. The estimated hot end surface losses in this region on the other 111 elements ranged from 0.02 to 9.04 grams per element, averaging 1.82 grams per element. For the WEFF-GEM, Y12 GEM and WNCO-GED coated elements, the average hot end tip surface losses were 2.6, 0.5, and 1.6 grams per element, respectively.

(CRD) Metallographic, split element and surface visual studies indicate that the hot end tip surface corrosion was initiated in the 51.6 to 51.7 inch region at the graphite side of the transition-to-composite joint. The microstructural and coolant channel visual studies in particular strongly suggest that the surface attack was not the result of interior joint leakage or of massive failure of either joint by corrosion but instead was due to the poor adherence and lack of surface protection afforded by the thinner NbC OD coatings in the region.

(CRD) The estimated surface losses for the hot end tip region averaged for the various WANL bore coating batches are plotted as a function of the NbC OD coating thicknesses in Figure 5-3. While the available beta backscatter OD thickness data is not at the specific axial station of interest, there is a general trend of increasing hot end loss with decreasing OD thickness. It is apparent that the WANL fuel elements tested in the PEWEE-1 environment needed tip region NbC OD coat thicknesses greater than 0.7 mil in order to minimize the surface corrosion effect over the graphite transition section.

5.3 BORE CORROSION PERFORMANCE (U)

(CRD) As result of the various corrections to the gross weight losses, typical "best estimate" increment bore corrosion loss profiles were determined for the various types of WANL PEWEE-1 fuel elements. These profiles are compared with those typically obtained on sister elements during PEWEE-1 qualification corrosion testing in Figure 5-4. While variations existed for individual elements, the general bore corrosion performances of the various WANL types have been evaluated in the following paragraphs.

(CRD) The mid-band increment performance of the Y12 standard matrix GEM coated elements and of the WNCO GEDX coated elements are very similar with peak losses of about 1.0 gram in the 10-15 inch axial increment. On the other hand, the mid-band bore losses of the WEFF-GEM coated element average about 4 times higher. The variation of bore losses in the 10-15 inch region did not show any significant trends with NbC bore coat thicknesses except in the case of the WEFF-GEM elements; the generalized variations were as follows:

<u>10-15" Bore Loss, Grams</u>	<u>NbC Bore Thickness, Sta. 13.5, Mils</u>	<u>Bore Coating Batches Involved</u>
1.0 - 5.7	0.7 - 0.9	WEFF-GEM
0.5 - 2.0	0.8 - 0.9	STND. GEDX plus L313, M137 and M139
0.7 - 1.3	1.2 - 1.6	C398, C397, M138
0.9 - 1.2	1.9 - 2.7	Y12 GEM

(CRD) While the bore losses are apparently much higher in the WEFF-GEM coated elements with the thinner bore coats, the coolant channel examination and metallographic data for these elements indicate that the higher losses were due to the formation of pinholes and corrosion pockets and not to the usual mid-band channel corrosion mechanisms, i. e., binder attack and corrosion ring formation through coating cracks (a further discussion of WEFF-GEM element hydrolysis, pinholing, and bore coating defects is given in section 5.4).

(CRD) The hot end region bore performances of the Y12 Standard GEM elements and of the WNCO GEDX additive and resinate elements are similar; the peak losses in the 40-45 inch region are about 2.0 grams. The highest peak and integrated bore losses in this region occurred in the WNCO GEDX standard matrix elements; the reason for the higher losses in these latter elements was attributable to the greater amount of center channel corrosion occurring in the 20-40 inch axial region. The lowest hot end region bore losses were achieved in the WEFF GEM coated elements. The lower losses in these elements may have been due both to the somewhat thicker NbC bore coatings (lower diffusion losses) and a "saturation" of the coolant with hydrocarbons from the mid-band pinholing phenomenon. The bore weight loss and NbC bore coating thickness data plotted in Figure 5-5 indicate a trend of decreasing hot end region losses with increasing station 40-45 bore coating thickness.

(CRD) The estimated bore mid-band weight losses in both GEM and GEDX coated WANL elements tested in PEWEE-1 exceed those observed in sister elements tested for 60 minutes under the qualifying A6.04 electrical hydrogen corrosion condition. However, there are two items of post-mortem information which strongly suggest that this difference does not truly report differences in mid-band bore performance between the two test environments. These items are:

- a) There is definite evidence that the surface corrosion loss corrections are too low in the mid-band region for the reactor tested elements; and
- b) The mid-band bore corrosion patterns observed in most of the reactor tested elements were qualitatively the same as in the corrosion tested elements.

(CRD) Comparisons of the mid-band coolant channel corrosion characteristics for WEFF-GEM and WNCO GEDX elements tested in PEWEE-1 and in the A6.04 corrosion test are shown in Figures 5-6 and 5-7. The GEM elements tested in the reactor have a higher number of large-sized corrosion pockets but similar corrosion patterns at the bore coating - matrix interface compared to the corrosion tested elements. The bore corrosion patterns in both the reactor-tested and corrosion-tested GEDX elements were with some exceptions typically the same, the mid-band center channel corrosion tendencies being somewhat magnified in the reactor test in the case of the standard matrix elements. In general, the visual data and loss estimates indicate that the general mid-band bore performance of all WANL supplied fuel elements in PEWEE-1 was semi-quantitatively the same as predicted by the qualification corrosion test results.

(CRD) It was difficult to compare the hot end region bore performances of reactor-tested and corrosion-tested PEWEE-1 elements since the corrosion-tested elements characteristically had fuel bead migration due to the higher hot end region matrix temperatures. However, coolant channel and metallographic studies definitely indicated that corrosion through bore coating cracks was generally more severe in the hot end region in the reactor tested elements. This was particularly true for the GEDX coated elements.

5.4 PINHOLE PERFORMANCE OF WEFF GEM ELEMENTS (U)

(CRD) As was shown in previous sections, pinholing and pocket corrosion contributed significantly to the 0-25 inch region bore losses in the WEFF-GEM coated elements. The post-operational data and corrosion test data pointed up the fact that the corrosion in this region occurred through areas where the coating had flaked away as a result of hydrolysis of fuel beads at the coating graphite interface.

(CRD) During the course of these studies an interesting relationship was found between the bore coating crack resistance, R_c , and pinholing in these elements (R_c represents the difference between the measured electrical resistance value for the as-coated element and the value calculated for an element with a flaw-free NbC bore coating; the difference roughly representing the quantity of coating defects present in the coating. For a GEM coated element the major defects are coating cracks.). The data showed that when the average crack resistance value for any five-inch increment of any WANL PEWEE-1 GEM coated element was lower than 2.5 milliohms/inch (corresponding to about 25 cracks per inch as measured at 200 magnifications) the increment did not pinhole. Above 3.5 milliohms/inch (corresponding to greater than 35 cracks per inch) pinholing always occurred. The significance of this relationship arises from the fact that the hydrolysis susceptibility of GEM coated elements should be directly proportional to the number of "coating-induced" matrix cracks, which in turn should be proportional to the number of bore coating cracks. Since the number of cracks in the GEM coatings is generally found to be inversely proportional to the coating thickness, the thicker the bore coating the less probability there should be for a fuel bead to be damaged by the crack propagation mechanism. (Coating microstructure also influences the number of coating cracks.) It was noted that for the WEFF-GEM coated elements tested in PEWEE-1 the pinhole frequencies, Ph , definitely varied with the bore coating thickness in the region 15-20 inches:

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<u>Bore Coating Batch</u>	<u>Avg. Bore Coat Thickness, Mils, Station 19.5</u>	<u>Ph, 15-20 Station</u>
B219	1.01	30.5
B223	1.03	37.5
B224	1.15	13.3
B218	1.22	4.8
B220	1.30	5.4
8561	3.00	0.3

(CRD) Very few pinholes were observed in any WANL GEM's when bore coating thicknesses exceeded 1.8 mils. This explains the lack of pinholing in the Y-12 GEM coated elements and in the hot end region of most of the WEFF-GEM coated elements.

(CRD) The WEFF-GEM coated elements with the NbC additives showed the largest number of pinholes and internal corrosion pockets. Similar results were obtained in electrical corrosion tests on the hydrolysis back-up FOX elements (see Table 4-3). The additive GEM elements in particular showed significant variability in the number of pinholes from one element to another within a batch. This variability in turn was reflected in the variation of bore weight losses (see standard deviation data shown in Table 4-14). The best performing additive GEM elements with respect to pinholing and mid-band bore losses were those from coating batch B220, the thicker bore coatings (and OD coatings, see Table 4-13) in these elements apparently contributing significantly to their improved mid-band region performance.

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Figure 5-1. (CRD) Axial Distribution of Surface Corrosion Losses
Estimated for WANL PEWEE-1 Fuel Elements. (U)

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Figure 5-2. (CRD) Midband Surface Corrosion Losses Versus OD NbC Coating Thickness for WANL PEWEE-1 Fuel Elements. (U)

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Figure 5-3. (CRD)

Hot End Tip Surface Corrosion Losses Versus NbC OD Coating Thickness for WANL Coating Types in PEWEE-1. (U)

Figure 5-4. (CRD) Typical Incremental Bore Weight Loss Profiles for WANL-Supplied Fuel Elements Tested in PEWEE-1 and Electrical Corrosion Test. (U)

Figure 5-5. (CRD)

Station 40-45 Bore Weight Loss as a Function of Coating Thickness for WANL-Supplied PEWEE-1 Fuel Elements. (U)

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- A. STATION 15-20, ELEMENT 269-58242, BATCH B219, A6.04 CORROSION TESTED FOR 30 + 30 MINUTES, WEIGHT LOSS - 0.40 GRAM PER 5 INCHES.

- B. STATION 15-20, ELEMENT 269-58285, BATCH B219, TESTED IN PEWEE-1, WEIGHT LOSS = 7.54 GRAMS PER 5 INCH GROSS, PEAK INCREMENTAL GROSS WEIGHT LOSS = 2.0 GRAMS PER INCH (BOTH HALVES OF SPLIT ELEMENT SHOWN).

Figure 5-6. (CRD) Comparison of Bore Corrosion Characteristics in WEFF GEM Coated Elements Tested in PEWEE-1 and in Electrical Hydrogen Corrosion Test. (U)

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- A. STATION 10-15 (BORE COATING SCRAPED OUT), ELEMENT 525-57093, BATCH C396, A6.04 CORROSION TESTED FOR 30 + 30 MINUTES, WEIGHT LOSS = 0.05 GRAM PER 5 INCHES.

- B. STATION 10-15, ELEMENT 525-57067, BATCH C396, TESTED IN PEWEE-1, GROSS WEIGHT LOSS = 4.05 GRAMS PER 5 INCHES, PEAK INCREMENTAL GROSS WEIGHT LOSS = 1.4 GRAMS PER INCH. (BOTH HALVES OF SPLIT ELEMENT SHOWN.)

Figure 5-7. (CRD) Comparison of Bore Corrosion Characteristics in WNCO GEDX Coated Elements Tested in PEWEE-1 and in Electrical Hydrogen Corrosion Test. (U)

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APPENDIX A

TABLE A-1. (CRD)

PLANIMETER METHOD FOR DETERMINING MISSING SURFACE MATRIX MATERIAL IN
PEWEE-1 FUEL ELEMENT CROSS SECTIONS. (U)

I. GENERAL METHOD

Negative prints of end photographs of cross-sectional slices were blown up to 10X on Richardson film viewer and traced (see Figures A-1 and A-2 for examples). A Lasico polar planimeter was used per II, III, and IV below to determine missing area, A_c , and loss for axial station and type of surface corrosion involved. Losses were averaged to obtain surface loss factors for the type of corrosion recorded from ASP visuals of PW-1 elements (see Table A-2).

II. DEFINITION OF AREAS

A_o = Original area of element cross section bounded by six flats.
Area includes bores.

A_1 = Standard area, i. e., area remains constant during corrosion, assuming element does not expand or shrink significantly. Area is bounded by six sides which are determined by a line drawn between the geometric centers of the outer bores. This area is used to convert planimeter measurements to inches².

$\equiv A_o$ $\equiv A_1$ $\equiv A_c$

III. AREA CALCULATIONS

$$A_o = 6 \times 1/2 \times b \times h + 6 \times 1/2 \times 0.435 \times 0.377 = 0.492 \text{ in.}^2$$

$$A_1 = 6 \times 1/2 \times b \times h + 6 \times 1/2 \times 0.345 \times 0.298 = 0.308 \text{ in.}^2$$

Figure A-1. (CRD) Cross-Section Trace of Element 525-57217 at Station 12.5.
 (ASP Visual Data and Calculated Surface Matrix Loss Given for Each Face). (U)

Figure A-2. (CRD) Cross-Section Trace of Element 525-57217 at Station 13.5.
 (ASP Visual Data and Calculated Surface Matrix Loss Given for Each Face). (U)

TABLE A-1 (CONTINUED) (CRD)

IV. CALCULATIONS

A) Conversion constant, K.

$$K = \frac{0.308 \text{ in}^2 \text{ (standard area, } A_1\text{)}}{\text{standard area measured on planimeter}} = \text{in.}^2/\text{division}$$

B) Conversion from planimeter measurement to weight loss in grams per inch of element.

X = Planimeter measurement of area, A_c

ρ = Density (g/cm^3)

$$X \times K \times 1" \text{ length} \times 16.387 \frac{\text{cm}^3}{\text{in}^3} \times \rho (\text{g/cm}^3) = \text{grams weight loss for 1" increment.}$$

ρ for 525 standard and Nb resinate = 2.38 gm/cm^3

TABLE A-2 (CRD)

SURFACE CORROSION LOSS FACTORS (U)

<u>Type of[*]</u> <u>Surface Corrosion</u>	<u>Loss Factor, Grams Per Inch^{**}</u>
Streak, Heavy	0.35
Streak, Moderate	0.15
Streak, Light	0.05
Edge, Heavy	0.15
Edge, Moderate	0.10
Edge, Light	0.02
Face, Heavy	0.40
Face, Moderate	0.25

* As recorded during ASP surface visual examination of PEWEE-1 fuel elements.

** Values given are for Code 525 Standard and Nb resinate impregnated matrices having densities of about 2.38 grams per cubic centimeter; factors for 477 NbC additive and 269 NbC additive elements based on densities of approximately 2.49 and 2.30 grams per cubic centimeter, respectively.

TABLE A-3 (CRD)
5-INCH INCREMENTAL DISTRIBUTION OF PINHOLES AND PINHOLING FREQUENCY
IN PEWEE-1 WEFF AND Y12 GEM COATED FUEL ELEMENTS (U)

Bore Batch	Number Elements Examined	No. Pinholes / No. Elements Pinholed /						Ph per 5-Inch Increment			
		2	3	4	5	6	7	8	9	10	11
B218	5	0	20	24	14	6	4	1	1	0	0
		0	5	5	5	3	3	1	1	0	0
		0	4.0	4.8	2.8	1.2	0.8	0.2	0.2	0	0
B219	4	0	43	122	81	40	27	11	4	1	0
		0	4	4	4	4	4	2	3	1	0
		0	10.8	30.5	20.3	10.0	6.8	2.8	1.0	0.3	0
B220	5	0	111	27	23	1	3	2	1	0	0
		0	5	5	5	1	3	2	1	0	0
		0	22.2	5.4	4.6	0.2	0.6	0.4	0.2	0	0
B223	2	0	49	75	51	20	7	1	1	0	0
		0	2	2	2	2	2	1	1	0	0
		0	24.5	37.5	25.5	10.0	3.5	0.5	0.5	0	0
B224	4	0	14	53	39	18	6	4	2	0	0
		0	4	4	4	4	4	3	2	0	0
		0	3.5	13.3	9.8	4.5	1.5	1.0	0.5	0	0
8561	4	0	4	1	3	0	0	0	0	0	7
		0	2	1	1	0	0	0	0	0	3
		0	1.0	0.3	0.8	0	0	0	0	0	1.8
8562	2	0	0	0	0	0	0	0	0	0	0
		0	0	0	0	0	0	0	0	0	0
		0	0	0	0	0	0	0	0	0	0

(*) Ph is pinhole frequency or average number of pinholes per axial increment per element examined. 2 = increment 5-10 inches, 3 = 10-15 inches, etc, 11 = 50-51 inches.

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TABLE A-4 (CRD)
5-INCH INCREMENTAL DISTRIBUTION
OF PINHOLES AND PINHOLING FREQUENCY (U)

Bore Batch	Number Elements Examined	* No. Pinholes / No. Elements Pinholed / Ph per 5-inch Increment									
		2	3	4	5	6	7	8	9	10	11
C397	9	0	0	0	0	0	0	1	0	5	0
		0	0	0	0	0	0	1	0	3	0
		0	0	0	0	0	0	0.1	0	0.6	0
M137	7	0	0	0	1	4	1	1	0	2	0
		0	0	0	1	2	1	1	0	2	0
		0	0	0	0.2	0.6	0.2	0.2	0	0.3	0
M138	10	0	1	1	0	0	1	0	0	0	0
		0	1	1	0	0	1	0	0	0	0
		0	0.1	0.1	0	0	0.1	0	0	0	0
M139	12	0	5	0	0	1	0	0	4	3	0
		0	3	0	0	1	0	0	2	1	0
		0	0.4	0	0	0.1	0	0	0.4	0.3	0
C398	9	1	13	8	2	4	3	3	1	0	0
		1	4	5	2	1	2	2	1	0	0
		0.1	1.4	0.9	0.2	0.4	0.3	0.3	0.1	0	0
L313	8	0	3	1	0	2	4	2	1	2	0
		0	2	1	0	2	2	1	1	1	0
		0	0.4	0.1	0	0.3	0.5	0.3	0.1	0.3	0
C396	12	0	19	8	0	3	3	6	1	2	0
		0	5	5	0	2	2	3	1	1	0
		0	1.6	0.7	0	0.2	0.2	0.4	<0.1	<0.1	0

(*) See footnote to Table A-3.

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TABLE A-4 (CONTINUED) (CRD)

Bore Batch	Number Elements Examined	No. Pinholes		* /No. Elements Pinholed / Ph per 5-inch Increment							
		2	3	4	5	6	7	8	9	10	11
F387	2	0	2	0	1	0	0	0	0	0	0
		0	1	0	1	0	0	0	0	0	0
		0	1.0	0	0.5	0	0	0	0	0	0
L314	13	0	10	14	4	3	1	1	1	0	1
		0	6	7	2	1	1	1	1	0	1
		0	0.8	1.1	0.4	0.3	0.1	0.1	0.1	0	0.1
M136	7	0	6	3	1	0	1	0	0	0	0
		0	5	3	1	0	1	0	0	0	0
		0	0.9	0.4	0.2	0	0.2	0	0	0	0

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TABLE A-5. (CRD)
BORE AND SURFACE CORROSION WEIGHT LOSSES CALCULATED FOR WNCO GEDX,
STND. MATRIX, PW-1 ELEMENTS. (U)

Bore Batch	Load- Serial Number	Bore Loss/Surface Loss, Grams Per Axial Region				Core Radius Inches	NbC Thickness Bore	
		0-25	25-50	50-52	0-52		13.5"	43.5"
F387	525-57252	3.79/2.76	9.92/0.00	0.65/0.65	14.36/3.41	4.70	0.9	2.1
	525-57261	3.93/0.76	8.93/0.00	0.50/0.02	13.36/0.78	3.30	0.9	2.1
C396	525-57067	1.61/4.56	8.96/0.70	0.60/1.21	11.17/6.47	3.91	0.8	2.3
	525-57080	3.03/7.51	10.40/0.00	0.48/1.10	13.91/8.61	4.70	0.8	2.1
	525-57084	1.88/1.95	10.60/0.60	0.65/0.87	13.13/3.42	4.19	0.8	2.2
	525-57118	2.08/3.71	10.37/0.00	0.61/1.37	13.16/5.08	3.28	0.8	2.3
	525-57120	1.98/5.35	10.06/0.00	0.57/0.30	12.61/5.65	3.28	0.8	2.2
	525-57145	2.22/0.46	8.75/0.02	0.54/2.10	11.51/2.58	3.91	0.9	2.3
	525-57235	1.59/2.65	9.82/0.00	0.55/0.36	11.96/3.01	3.28	0.9	2.3
	525-57238	3.89/2.80	9.25/0.00	0.54/0.69	13.68/3.49	3.28	0.9	2.2
	525-57239	2.96/1.11	9.53/0.00	0.57/0.30	13.06/1.41	3.45	0.9	2.3
	525-57240	2.22/0.95	9.89/0.00	0.51/2.04	11.62/2.99	1.99	0.9	2.2
	525-57242	2.67/0.41	8.88/0.00	0.63/1.31	12.18/1.72	3.45	0.9	2.3
	525-57249	3.77/2.10	9.08/0.10	0.55/2.34	13.40/4.54	2.26	0.9	2.2
L314	525-57034	2.46/0.70	12.70/0.00	0.58/0.67	15.74/1.37	4.19	0.8	1.9
	525-57036	3.89/2.80	9.63/0.00	0.50/0.55	14.00/3.35	4.19	0.8	2.0
	525-57050	3.44/0.50	10.56/0.00	0.62/1.39	14.62/1.89	4.70	0.8	1.9
	525-57115	1.39/4.60	8.82/0.00	0.39/0.32	10.60/4.92	3.76	0.8	1.9
	525-57189	5.47/0.70	8.27/0.00	0.51/0.68	14.25/1.38	3.45	0.9	2.2
	525-57228	3.74/1.88	10.14/0.00	0.60/0.35	14.48/2.23	3.45	0.9	2.0
	525-57236	2.74/6.84	10.30/0.00	0.58/9.31	13.63/16.15	4.19	0.8	2.0
	525-57237	3.72/2.07	9.31/0.06	0.44/0.92	13.47/3.05	3.76	0.8	1.9
	525-57257	3.32/2.76	9.47/0.00	0.57/0.08	13.36/2.84	3.28	0.8	2.2
	525-57014	----NO MULE-----15.00/2.86 ⁽¹⁾				3.28	0.9	2.1
	525-57026	----NO MULE-----12.25/5.33 ⁽²⁾				3.91	0.8	2.1
	525-57066	----NO MULE-----14.22/3.06 ⁽³⁾				3.28	0.9	2.0
	525-57190	----NO MULE-----14.51/2.01 ⁽⁴⁾				3.91	0.9	2.0
	525-57258	----NO MULE-----14.32/1.84 ⁽⁵⁾				1.99	0.9	2.2
M136	525-57206	3.43/0.26	9.15/0.00	0.74/0.11	13.31/0.37	3.45	0.8	2.2
	525-57209	2.87/1.05	8.65/0.00	0.53/0.58	12.05/1.63	3.76	0.8	2.3
	525-57210	1.94/3.00	8.75/0.00	0.82/0.17	11.52/3.17	3.45	0.9	2.3
	525-57211	2.24/2.24	9.24/0.00	0.32/0.00	11.80/2.24	3.76	0.9	2.3
	525-57213	3.70/0.22	8.20/0.00	0.61/0.55	12.51/0.77	3.45	0.9	2.2
	525-57216	2.94/1.15	9.01/0.00	0.62/0.00	12.57/1.15	3.76	0.8	2.2
	525-57217	3.11/5.70	9.15/0.00	0.63/0.60	12.89/6.30	3.28	0.9	2.3

(1) 0.31 gm. in. 50-52", 2.55 gm. in. 0-25"

(2) 0.79 gm. in. 50-52", 4.54 gm. in. 0-25"

(3) 0.10 gm. in. 50-52", 2.96 gm. in. 0-25"

(4) 1.24 gm. in. 50-52", 0.77 gm. in. 0-25"

(5) 0.38 gm. in. 50-52", 1.46 gm. in. 0-25"

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TABLE A-6. (CRD)
 BORE AND SURFACE CORROSION WEIGHT LOSSES CALCULATED FOR WNCO GEDX,
 RESINATE MATRIX, PW-1 ELEMENTS (U)

Bore Batch	Load- Serial Number	Bore Loss/Surface Loss, Grams Per Axial Region				Core Radius Inches	NbC Thickness Bore	
		0-25	25-50	50-52	0-52		13.5"	43.5"
C398	525-57029	1.91/0.00	8.18/0.00	0.60/2.00	10.69/2.00	3.45	1.4	2.4
	525-57117	1.52/1.15	7.59/0.00	0.70/0.98	9.81/2.13	3.45	1.4	2.3
	525-57172	1.51/0.80	8.23/0.00	0.70/1.42	10.34/2.22	4.19	1.7	2.4
	525-57173	2.43/0.32	7.97/0.00	0.70/0.31	11.09/0.63	4.19	1.6	2.4
	525-57176	2.36/0.02	7.75/0.00	0.70/0.82	10.81/0.89	3.91	1.7	2.3
	525-57194	2.90/0.44	6.93/0.00	0.50/2.02	11.33/2.46	3.45	1.5	2.4
	525-57205	2.57/0.25	6.71/0.00	0.60/0.89	9.88/1.44	2.25	1.5	2.4
	525-57107	-----NO MULE-----			10.83/1.53 ⁽¹⁾	4.19	1.6	2.4
	525-57128	-----NO MULE-----			12.82/2.19 ⁽²⁾	4.70	1.7	2.5
L313	525-57041	2.83/0.04	9.78/1.05	0.40/0.34	13.01/1.43	4.70	1.0	2.1
	525-57045	1.53/0.00	8.60/0.00	0.69/2.53	10.82/2.53	4.94	0.9	2.1
	525-57051	1.79/0.06	10.33/0.00	0.79/1.09	12.91/1.15	4.70	0.9	2.0
	525-57053	1.93/0.00	8.44/0.00	0.68/3.76	11.11/3.76	4.19	0.9	2.2
	525-57063	2.61/0.00	8.46/0.00	0.57/1.22	11.64/1.22	4.19	0.9	2.0
	525-57064	2.73/0.00	8.70/0.00	0.48/1.38	12.11/1.38	4.19	0.9	2.0
	525-57071	3.25/0.24	9.22/0.00	0.65/0.72	13.12/0.96	3.91	0.9	7.9
	525-57062	-----NO MULE-----			13.07/0.30 ⁽³⁾	4.19	0.9	2.1

(1) All in 50-52 inch

(2) 2.09 gms. in 50-52" 0.1 gm. in 0-25".

(3) All in 50-52".

TABLE A-7. (CRD)
 BORE AND SURFACE CORROSION WEIGHT LOSSES CALCULATED FOR WNCO GEDX,
 NbC ADDITIVE (269 LOAD) PW-1 ELEMENTS. (U)

Bore Batch	Load- Serial Number	Bore Loss/Surface Loss, Grams Per Axial Region				Core Radius Inches	NbC Thickness Bore	
		0-25	25-50	50-52	0-52		13.5"	43.5"
C-397	269-58262	1.45/0.96	9.67/0.00	0.99/1.19	12.31/2.15	7.42	1.2	2.5
	269-58264	1.99/0.00	9.04/0.60	0.81/1.74	11.84/2.34	7.42	1.2	2.5
	269-58282	1.97/0.00	9.24/0.00	0.99/2.20	12.20/2.20	7.42	1.3	2.6
	269-58295	2.19/0.16	10.58/0.00	1.05/1.63	13.84/1.79	7.42	1.2	2.4
	269-58298	2.62/0.00	10.26/0.60	1.23/0.99	14.11/1.59	7.42	1.1	2.3
	269-58202	1.69/0.00	8.97/1.20	1.23/1.72	11.89/2.92	7.42	1.2	2.4
	269-58303	2.04/0.00	9.20/0.00	0.90/0.97	12.14/0.97	7.42	1.2	2.4
	269-58304	1.95/0.00	8.35/0.60	/1.48	11.74/2.08	7.42	1.2	2.4
	269-58266	----- NO MULE -----				12.95/1.05 ⁽¹⁾	7.42	1.2
M137	269-58229	1.75/0.00	8.27/0.00	0.69/3.23	10.71/3.23	7.26	0.9	2.3
	269-58236	2.74/0.00	8.96/0.00	0.90/1.41	12.60/1.41	7.42	1.0	2.2
	269-58238	1.22/0.40	10.81/0.00	0.85/0.58	12.87/0.98	7.26	1.0	2.4
	269-58239	0.83/0.96	9.19/0.00	0.83/2.24	10.85/3.20	7.42	1.0	2.5
	269-58243	1.12/0.00	9.90/0.00	0.76/2.32	11.79/2.32	7.26	0.9	2.3
	269-58273	1.83/0.00	12.43/0.00	1.20/0.25	15.45/0.25	7.26	0.9	2.2
	269-58274	1.54/0.00	9.51/0.00	1.08/2.37	12.14/2.37	7.42	0.9	2.3
	269-58232	----- Broken From Core -----				7.26	0.9	2.3

(1) 0.55 gms. in 50-52", 0.50 gms. in 0-25".

TABLE A-8. (CRD)
 BORE AND SURFACE CORROSION WEIGHT LOSSES CALCULATED FOR WNCO GEDX,
 NbC ADDITIVE (477 LOAD), PW-1 ELEMENTS. (U)

Bore Batch	Load- Serial Number	Bore Loss/Surface Loss, Grams Per Axial Region				Core Radius Inches	NbC Thickness Bore		
		0-25	75-50	50-52	0-52		13.5"	93.5"	
M138	477-58605	3.14/0.10	7.15/0.00	0.81/1.20	11.10/1.30	4.94	1.3	2.4	
	477-58613	3.60/0.42	7.05/0.00	0.63/3.19	11.28/3.61	5.27	1.3	2.4	
	477-58617	3.46/0.10	8.78/0.00	0.25/0.29	12.49/0.39	4.94	1.3	2.4	
	477-58618	3.24/0.10	7.99/0.00	0.60/4.94	11.84/5.04	4.94	1.2	2.3	
	477-58619	3.09/0.00	8.59/0.00	0.81/6.66	12.51/6.66	5.27	1.2	2.3	
	477-58620	2.48/0.60	7.76/0.00	0.72/1.42	10.95/2.02	4.94	1.2	2.4	
	477-58623	2.82/0.00	8.82/0.00	0.81/1.12	12.45/1.12	5.27	1.2	2.3	
	477-58624	3.26/0.02	10.23/0.08	0.90/5.38	14.39/5.48	5.27	1.2	2.3	
	477-58625	2.72/0.10	7.63/0.00	0.72/1.74	11.07/1.84	5.27	1.2	2.3	
	477-58626	----- NO MULE -----				12.03/3.50 ⁽¹⁾	4.94	1.2	2.4
	477-58604	----- Broken From Core -----					5.27	1.2	2.4
	477-58612	----- Broken From Core -----					4.94	1.2	2.4
M139	477-58621	3.65/0.30	9.48/0.00	0.81/1.50	13.94/1.80	5.27	0.8	2.3	
	477-58628	3.80/0.00	9.76/0.00	0.97/4.23	14.53/4.23	5.27	0.8	2.3	
	477-58629	3.86/0.00	9.88/2.10	0.90/3.01	14.64/5.11	5.27	0.8	2.3	
	477-58630	3.65/0.22	9.41/.02	0.81/1.24	13.87/1.48	5.27	0.8	2.3	
	477-58632	3.12/0.00	10.27/0.00	0.90/2.08	14.29/2.08	5.27	0.8	2.3	
	477-58634	3.55/0.05	10.32/0.00	0.90/2.13	14.77/2.18	5.69	0.8	2.2	
	477-58635	4.77/0.26	11.31/0.00	0.90/0.74	16.98/1.00	5.69	0.8	2.4	
	477-58636	3.32/0.00	11.41/0.55	0.97/2.71	15.70/3.26	5.27	0.7	2.2	
	477-58637	3.01/0.00	8.79/0.00	0.90/3.64	12.70/3.64	5.69	0.8	2.4	
	477-58638	3.49/0.20	8.36/0.00	0.81/1.96	12.36/2.16	5.69	0.8	2.2	
	477-58640	3.30/0.00	8.28/0.00	0.97/1.97	12.54/1.97	5.69	0.8	2.3	
	477-58633	----- NO MULE -----				13.69/4.28 ⁽²⁾	5.27	0.8	2.3

(1) 3.12 gms. in 50-52", 0.38 gms. in 0-25".

(2) 2.03 gms. in 50-52", 2.25 gms. in 0-25".

TABLE A-9. (CRD)
BORE AND SURFACE CORROSION WEIGHT LOSSES CALCULATED FOR WEFF GEM
(Nb RESINATE AND STND. MATRIX) AND Y12 GEM (STND. MATRIX) PW-1 ELEMENTS. (U)

Bore Batch	Load- Serial Number	Bore Loss/Surface Loss, Grams Per Axial Region				Core Radius Inches	NbC Thickness Bore	
		0-25	25-50	50-52	0-52		13.5	43.5
B218	525-57076	5.76/0.14	7.69/0.36	0.36/5.22	13.81/5.72	1.99	0.8	2.6
	525-57079	3.19/1.40	7.21/0.00	0.54/1.45	10.94/2.85	1.99	1.0	2.9
	525-57089	4.85/0.00	7.74/0.00	0.56/5.19	13.15/5.19	2.26	1.0	2.8
	525-57126	6.67/0.00	6.84/0.00	0.45/2.86	13.96/2.86	2.26	0.8	2.7
	525-57127	10.94/0.30	8.09/0.00	0.43/1.92	19.46/1.92	1.99	0.8	2.7
	525-57077	----- Broken From Core -----				2.26	0.8	2.6
B224	525-57298	16.15/18.75	7.28/0.00	0.64/1.69	24.07/20.44	3.28	0.8	2.4
	525-57304	6.29/8.70	7.70/0.00	0.50/0.15	13.98/8.85	3.45	0.8	2.6
	525-57308	13.13/7.10	8.69/0.00	0.59/0.60	22.41/7.60	1.99	0.8	2.6
	525-57306	----- NO MULE -----			16.72/21.50 ⁽¹⁾	3.28	0.7	2.4
	525-57295	----- Broken From Core -----				3.28	0.8	2.4
	525-57300	----- Broken From Core -----				3.45	0.8	2.5
8561	269-58466	2.12/0.06	6.83/0.00	0.65/0.41	9.60/0.47	7.26	2.6	2.8
	269-58467	1.85/0.00	7.06/0.00	0.70/1.13	9.61/1.13	7.26	2.6	2.9
	269-58468	2.55/0.00	7.55/0.00	0.65/0.00	10.52/0.00	7.26	2.7	2.8
	269-58470	1.76/0.00	7.20/0.00	0.65/0.24	9.61/0.24	7.26	2.6	2.9
8562	269-58477	2.07/0.00	7.97/0.00	0.90/0.00	10.62/0.00	7.26	1.8	2.8
	269-58482	2.77/0.00	8.17/0.00	0.75/0.36	11.69/0.36	7.26	1.9	3.2

(1) 9.0 gms. in 50-52", 12.50 gms. in 0-25".

TABLE A-10. (CRD)
 BORE AND SURFACE CORROSION WEIGHT LOSSES CALCULATED FOR WEFF GEM,
 NbC ADDITIVE, PW-1 ELEMENTS. (U)

Bore Batch	Load- Serial Number	Bore Loss/ Surface Loss, Grams Per Axial Region				Core Radius Inches	NbC Thickness Bore	
		0-25	25-50	50-52	0-52		13.5"	43.5"
B219	269-58252	21.73/5.66	9.21/0.45	0.49/3.80	31.43/9.91	7.18	0.7	2.6
	269-58253	20.58/8.20	10.16/8.20	0.53/5.60	31.27/14.40	7.18	0.7	2.3
	269-58285	14.94/6.30	10.57/0.06	0.57/2.15	26.08/8.59	7.18	0.7	2.3
	269-58301	----- NO MULE -----			24.03/10.57 ⁽¹⁾	7.18	0.7	2.3
	269-58231	----- Broken From Core -----				7.18	0.7	2.4
	269-58245	----- Broken From Core -----				7.18	0.7	2.3
	269-58249	----- Broken From Core -----				7.26	0.7	2.5
	269-58250	----- Broken From Core -----				7.18	0.9	2.6
B220	269-58255	6.60/0.00	6.55/0.00	0.54/4.59	13.70/4.59	7.18	0.8	3.2
	269-58268	7.18/1.93	7.08/0.00	0.50/1.36	14.76/3.29	7.18	0.8	3.3
	269-58283	5.73/0.25	6.90/0.00	0.56/7.83	13.20/8.08	7.18	0.8	3.1
	269-58288	4.97/1.40	5.87/0.00	0.63/3.47	11.47/4.87	7.18	0.7	3.1
	269-58294	4.94/1.20	7.32/0.00	0.63/2.42	12.89/3.62	7.18	0.8	3.2
B223	477-58648	17.84/0.70	6.73/0.00	0.54/5.94	25.11/6.64	4.94	0.7	2.4
	477-58652	----- NO MULE -----			39.50/24.50 ⁽²⁾	5.27	0.8	2.5
	477-58653	----- Broken From Core -----				5.27	0.8	2.6
	477-58662	----- Broken From Core -----				5.27	0.7	2.4
	477-58663	----- Broken From Core -----				4.94	0.7	2.4
	477-58664	----- Broken From Core -----				5.27	0.7	2.4

(1) 2.27 gms. in 50-52", 8.30 gms. in 0-25".

(2) 9.04 gms. in 50-52", 4.55 gms. in 0-25", 10.91 gms. in 25-50".

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