CONFIDENTIAL
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Atomic Energy Act - 1954

Subcontract NP-1

WANL-TME-1858
DECEMBER 1968

Westinghouse Astronuclear Laboratory

FINAL REPORT
FUEL DEVELOPMENT TEST ON SPECIFICATION IV-3
" HI-EXPANSION GRAPHITE "

(TITLE UNCLASSIFIED)

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Westinghouse Astronuclear Laboratory

MASTER

WANL-TME-1858
DECEMBER 1968

FINAL REPORT

FUEL DEVELOPMENT TEST ON SPECIFICATION IV-3 "HI-EXPANSION GRAPHITE"

(TITLE UNCLASSIFIED)

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Astronuclear Laboratory

ABSTRACT

(CRD) The primary objective of this experiment was to test the effect of increased thermal expansion on the corrosion test performance of NERVA fuel elements. Fueled elements were manufactured using 25, 50, and 75 percent Robinson Coke mixed with Great Lakes flour as the graphite coke constituent. These elements were processed along with standards through coating and corrosion testing. The results of the corrosion testing were not conclusive for a number of reasons. However, it was found that the highest-expansion elements had far fewer coating cracks and better coating adherence than did the standard elements. Un-overcoated high-expansion elements outperformed un-overcoated standard elements, especially in the midband region, in corrosion testing. The high-expansion elements appeared to withstand cycling in the corrosion test better than the standard elements.

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1.0 INTRODUCTION (U)

1.1 PURPOSE AND OBJECTIVES (U)

(U) The purpose of this test was to increase the thermal expansion of fueled elements and investigate the resultant effect upon the quality of the element.

(U) The primary objective was to determine the effect of matrix thermal expansion (in increments of 20, 40, and 60 percent more than standard A-6 elements) upon the hydrogen corrosion resistance of coated, fueled elements. Secondary objectives were as follows:

1) Determine the physical and thermal characteristics of high-expansion elements made from Robinson Coke.

2) Determine machining characteristics of high-expansion elements.

3) Determine coating characteristics of elements which have a controlled thermal expansion range.

1.2 BACKGROUND (U)

(CRD) It is known that a poorly graphitized carbon will have a higher coefficient of thermal expansion than a well graphitized material. Development of a high-expansion matrix material has, until recently, centered around an air-blown petroleum coke produced by the Carbon Products Division of Union Carbide Corporation. This material is referred to as Robinson Coke. The secondary powder, milled from pitch-bonded stock that has been heat-treated to 2800°C, shows a relative degree of graphitization of about 50 percent, compared to a value of greater than 80 percent for the normal type "W" flour used in the fabrication of standard fueled elements. Non-fueled, 3/8-inch stock extruded from Robinson Coke has almost doubled the thermal expansion of similar stock with a Type "W" flour base. Mixtures of the two base cokes produce an expansion which is proportional to the amount of each coke used.

(CRD) In August of 1966 the decision was made to extrude several fueled batches of Robinson Coke based elements to study the effect of element coefficient of thermal expansion on element corrosion test performance. The batches were made up of combinations of Type "W" flour and Robinson Coke so that a range of coefficients of thermal expansion could be obtained. The results of this study are presented in this report.

2.0 PROCESSING (U)

2.1 EXTRUSION (U)

(CRD) Extrusion was accomplished at Y-12 in October 1966. All elements were loaded to A-6 Code 9 levels (432 mg U/cc). Four types of matrices were extruded: standards, 25, 50, and 75 flour w/o Robinson Coke. Since this was an experimental program, the matrix constituent combinations were not completely optimized, and metallography later revealed large longitudinal cracks, presumably due to an insufficient quantity of binder in the original formulation. Some extrusion cracking was noted, but this was considered a normal extrusion. The yield was as follows:

16	Standard Elements
27	75 w/o Robinson Elements
27	50 w/o Robinsom Elements
27	25 w/o Robinson Elements
98	Total

2.2 THERMAL PROCESSING (U)

(U) Curing, baking, and graphitizing were all accomplished at Y-12. Standard A-6 thermal cycles were used and no unusual occurrences were noted.

2.3 MACHINING (U)

(CRD) Machining was accomplished at Y-12. All elements were machined to standard A-6 tolerances and dimensions. The elements were not tipped. After machining, all elements were shipped to WNCO for leaching and coating.

2.4 LEACHING (U)

(CRD) Leaching was done at WNCO by the standard A-6 cycle. The elements and their respective leach weight losses are presented in Table 1. The gross average weight loss in leach for the experiment was 9.29 grams with a range of 8.2 to 10.3 grams. However, it appears that the amount of high-expansion flour in the mix affects the leach loss because a trend is observed (9.79 to 8.69 grams) as the high-expansion flour is removed.

2.5 COATING (U)

(CRD) Coating was accomplished at WNCO. The elements were NbC coated by the diffusion process, and approximately half of the elements received a molybdenum overcoat. The coated elements, coating runs, and coating combinations are presented in Table 2. A problem was encountered with several of the coating runs, necessitating a repair run on about thirty elements. Run F-320 was found to have the most acceptable parameters. Therefore, the repair run, S-59, was modeled after F-320, except that the repair run was of 3 hours duration. The coating runs and their respective conditions were as follows:

Run No.	Time Hours	Temperature °C Station At			Gas Flows (SLPME)				Wt. Gain (Grams)
		51	26	0	Argon	HCl	H_2	$NbCl_5$	
F-318	14.0	1730	1650	1650	0.87	0.43	0.068	0.057	57.8
F-320	14.0	1720	1660	1600	0.87	0.43	0.068	0.057	52.0
S-59	3.0	1718	1663	1608	0.87	0.43	0.68	0.057	3.7

(CRD) Molybdenum overcoating was accomplished in the WEFF Ceramic Fuel Laboratory. The coating runs were AA031, AA032, and AA039. The specific loadings in each of these runs are detailed in Table 2. The runs were accomplished by standard procedure and were considered normal.

2.6 CORROSION TESTING (U)

(CRD) Corrosion testing was accomplished under the A6-02 conditions of power and flow and for various lengths of time. Testing was complicated by the fact that the elements were not tipped. Initially, there was a problem with the elements breaking, but it was soon apparent that the thermal expansion of the elements was greater than allowed for and they tried to expand farther than the chucks would allow. This resulted in bowing or cracking and breakage. The problem was alleviated and testing became routine.

3.0 DATA AND RESULTS (U)

3.1 MACHINING (U)

(CRD) The IV-3 elements were reamed and diamond milled at Y-12. No unusual problems were noted in these machining operations. Similar elements were broached at WEFF. A pitting problem on the flats was noted in the broaching operation. This problem was eliminated with a slight adjustment of the broaching cutters. Reaming was accomplished with no reported problems.

3.2 LEAK RATE (U)

(U) Table 3 lists the as-leached leak rate for the Phase IV-3 elements. It is obvious that with few exceptions these elements were not of core quality. As explained in the extrusion section of this report (Section 2.1), very little optimization study was done to determine the binder requirements of Robinson Coke flour. At first glance, it would appear this is the cause of the high leak rates. However, the results for the standards are also high. Work at WNCO has indicated that the extrusion die has the largest effect on element permeability. These elements were all extruded using the LASL short pin die, which should yield elements with low permeabilities. Why the leak rate is so high on both the standard and the experimental elements cannot be explained at this time. However, the permeability of both standards and experimentals is equally high, and its effect is probably cancelled out when the elements in this specification are cross-compared.

3.3 INCREMENTAL RESISTANCE (U)

(CRD) Incremental resistance profiles were measured on all types of elements in the as-leached, as-NbC coated, the repair coated, and molybdenum coated conditions, where applicable. Typical curves for these elements are presented in Figures 1, 2, 3, and 4. Prior to coating, the resistance profiles of all of the elements are relatively flat, with the average values as follows:

(CRD)

Matrix Type	Average Resistance (ohms/in.)
Standard	0.00194
25 w/o Robinson	0.00217
50 w/o Robinson	0.00238
75 w/o Robinson	0.00263

(U) The high resistance of the Robinson Coke is interpreted as resulting from the poorly graphitic character of the high-expansion flour. These values are normal for the respective flours and combinations.

(U) After coating, the resistance profiles began to take on the characteristics of the coatings. This is to be expected because most of the current will go through the coating. However, the change in resistance from the as-leached condition to the as-NbC coated condition is much greater for the high w/o Robinson Coke flour elements than for the standard elements. This is interpreted as meaning that there are far fewer coating cracks on the high-expansion elements than the standards, and also that the cracks are finer in the high-expansion elements, i.e., less crack resistance.

(CRD) After molybdenum overcoating, the elements have similar resistance profiles with the midband having the lowest resistance. This result is expected because the molybdenum is basically deposited most thickly in this region of the elements. The standard elements still have the lowest resistance because of the more graphitic character of GL 1008 flour, the standard flour.

(CRD) It is important to note the higher resistance of the high-expansion elements. This higher resistance has a tendency to skew the power dissipation in the electrical corrosion test and distort the temperature profile during the test, thus coloring the test results. It is expected that with this resistance, the midband of the element would be shifted upstream toward the cold end. This effect has been observed on similar elements recently tested.

3.4 PHYSICAL PROPERTIES (U)

(CRD) Table 4 presents a summary of the physical properties measured for the Phase IV-3 elements. The high-expansion elements appear to be weaker in flexure than the standards. This may be explained by the low amount of binder used in the extrusion of the high-expansion elements (22 w/o). The compressive strength is higher for the high expansion elements, a trend which is found to hold for the IIG_a elements. The CTE of the high-expansion elements is, of course, notably higher than the standard. The other measured properties are about normal.

3.5 COATING (U)

(CRD) The NbC and molybdenum coating runs were discussed in Section 2.5. Table 2 lists the coating runs and the elements in the runs and Figure 5 presents the coating profiles of Runs F-318 and F-320. No profile was taken on the repair Run, S-59. The average weight gain for S-59 was 3.7 grams, with a range of 2.2 to 4.7 grams. The average molybdenum weight gains for the three overcoating runs were as follows:

(CRD)

	Weight Gain (g)		
Run Number	Average	Maximum	Minimum
AA031	3.29	4.10	1.53
AA032	1.90	2.06	1.60
AA039	3.62	5.50	2.41

(CRD) Crack counts as read from bore replicas at 100X were made on all NbC coating elements except the destruct elements. Typical crack profiles for the various types of elements are presented in Figures 6, 7 and 8. While replica readings are not the most accurate pieces of data (the readings tend to vary with the reader and the magnification at which the reading is made), certain important points stand out. First, the number of cracks in the coating decrease as the amount of high-expansion flour in the matrix increases, as expected. Also, there is some indication that there is a channel to channel variation in the number of cracks. Channel 10 appears to have the fewest cracks, the middle ring of channels the most cracks, and the peripheral cooling channels some intermediate number. It has not yet been proven if this is a true indication or a fluke in the data. In general, the high-expansion elements have fewer and much finer coating cracks than the low-expansion elements.

3.6 CORROSION TESTING (U)

(CRD) Corrosion test data for the Phase IV-3 elements is presented in Table 5. All corrosion tests were run under PB test conditions listed in Table 6. It should be noted that these elements were not high priority elements for corrosion tests. Due in part to this fact, the elements were subjected to testing on a time-available basis and to whatever tests were being run at the time. This helps to explain the wide variation in time cycles to which the elements were subjected. Also, the elements were tested without the benefit of non-fuel hot end tips and this helps to explain some of the large weight loss corrections.

(CRD) Due to the wide variation in time cycles, direct comparison of performance is difficult. An attempt was made to compare cyclic and continuous run performance, overcoated and non-overcoated bores, repair and non-repair coated elements, and the three combinations of high-expansion flours with the standard. It is felt that an insufficient sample was taken to compare all of these variables.

(CRD) A few statements of a general nature may be valid. Pinholing was not too extensive on any of the elements. The non-overcoated high expansion elements seem to hold up better than the non-overcoated standards, especially in the midband region. Also, there is some indication that the high expansion elements stand cycling better than do the standard elements. However, testing was insufficient to give definitive results on element performance.

4.0 DISCUSSION OF RESULTS (U)

(CRD) The results of the corrosion testing done in conjunction with this phase are somewhat inconclusive. It is unfortunate that the corrosion test priority for these elements was as low as it was at the time of testing. The A6 screening test, the test to which the elements were subjected, was not designed for multiple cycle studies. Later work has shown that the value of a high-expansion element is not really demonstrated until the element has seen several cycles. Time was simply not available to develop such a specialized test when testing on these elements was performed.

(CRD) However, some important trends stand out. The non-overcoated high-expansion elements appear to outperform the non-overcoated standard elements, especially in the mid-band region. The high-expansion elements seem to withstand cycling better than the standard elements. Performance seems to improve with an increase in matrix expansion coefficient. The coating adherence tended to improve with increasing expansion. Coating cracks diminished as expansion increased.

(CRD) The lack of a non-fuel tip caused several corrosion test difficulties. Many tests were aborted due to gross hot end corrosion. Due to this effect, few of the elements were tested to their limit.

(CRD) The data, while not conclusive, does leave favorable impressions concerning the potential of this type of element. The coating adherence of a high-expansion element is superior to the adherence on a standard element. Future work in this area should concentrate on optimization in initial formulation, special coatings designed to take advantage of the increased adherence, and a corrosion test designed for this type of element.

5.0 APPENDIX (U)

TABLE 1 (CRD)

LEACH WEIGHT LOSSES OF PHASE IV-3 ELEMENTS (U)

S/N	Matrix Type	Leach Run	Weight Loss (g)
99-79078	Standard	D489	8.5
99-79079	Standard	D488	8.2
99-79080	Standard	D489	8.9
99-79081	Standard	D489	8.6
99-79082	Standard	D488	9.8
99-79083	Standard	D489	8.6
99-79084	Standard	D489	8.6
99-79085	Standard	D489	8.6
99-79086	Standard	D488	8.5
99-79087	Standard	D488	8.9
99-79088	Standard	D488	8.9
99-79089	Standard	D488	8.2
99-79090	Standard	D488	8.7
99-79091	Standard	D489	9.1
99-79092	Standard	D488	8.9
99-79093	Standard	D488	8.8
		Avg. Loss	8.69
99-79114	75 w/o Robinson Coke	D486	9.6
99-79115	7/5 w/o Robinson Coke	D486	9.2

[redacted]

TABLE 1 (CONTINUED) (CRD)

S/N	Matrix Type	Leach Run	Weight Loss (g)
99-79116	75 w/o Robinson Coke	D486	9.3
99-79119	75 w/o Robinson Coke	D486	10.0
99-79120	75 w/o Robinson Coke	D486	9.6
99-79121	75 w/o Robinson Coke	D486	9.5
99-79122	75 w/o Robinson Coke	D486	9.7
99-79123	75 w/o Robinson Coke	D486	9.0
99-79124	75 w/o Robinson Coke	D486	9.9
99-79125	75 w/o Robinson Coke	D486	9.1
99-79126	75 w/o Robinson Coke	D486	9.8
99-79127	75 w/o Robinson Coke	D486	9.5
99-79128	75 w/o Robinson Coke	D486	10.1
99-79129	75 w/o Robinson Coke	D486	9.5
99-79130	75 w/o Robinson Coke	D486	9.9
99-79131	75 w/o Robinson Coke	D486	10.2
99-79132	75 w/o Robinson Coke	D486	10.2
99-79133	75 w/o Robinson Coke	D486	10.0
99-79134	75 w/o Robinson Coke	D486	10.1
99-79135	75 w/o Robinson Coke	D486	10.1
99-79136	75 w/o Robinson Coke	D486	9.8
99-79142	75 w/o Robinson Coke	D485	9.8

[redacted]

TABLE 1 (CONTINUED) (CRD)

S/N	Matrix Type	Leach Run	Weight Loss (g)
99-79143	75 w/o Robinson Coke	D485	10.3
99-79144	75 w/o Robinson Coke	D485	9.6
99-79145	75 w/o Robinson Coke	D485	10.0
99-79146	75 w/o Robinson Coke	D485	10.1
99-79147	75 w/o Robinson Coke	D485	10.4
		Avg. Loss	9.79
99-79148	50 w/o Robinson Coke	D485	9.2
99-79149	50 w/o Robinson Coke	D485	9.2
99-79150	50 w/o Robinson Coke	D485	9.5
99-79151	50 w/o Robinson Coke	D485	9.3
99-79152	50 w/o Robinson Coke	D485	9.8
99-79153	50 w/o Robinson Coke	D485	10.0
99-79154	50 w/o Robinson Coke	D485	9.3
99-79155	50 w/o Robinson Coke	D485	9.2
99-79156	50 w/o Robinson Coke	D485	9.4
99-79157	50 w/o Robinson Coke	D485	9.8
99-79158	50 w/o Robinson Coke	D485	9.1
99-79159	50 w/o Robinson Coke	D485	9.3
99-79160	50 w/o Robinson Coke	D485	9.1

TABLE 1 (CONTINUED) (CRD)

S/N	Matrix Type	Leach Run		Weight Loss (g)
99-79161	50 w/o Robinson Coke	D485		9.1
99-79162	50 w/o Robinson Coke	D485		9.9
99-79163	50 w/o Robinson Coke	D485		9.3
99-79166	50 w/o Robinson Coke	D485		9.2
99-79167	50 w/o Robinson Coke	D485		9.3
99-79168	50 w/o Robinson Coke	D485		9.4
99-79169	50 w/o Robinson Coke	D485		8.7
99-79170	50 w/o Robinson Coke	D485		9.3
99-79172	50 w/o Robinson Coke	D485		10.1
99-79173	50 w/o Robinson Coke	D485		9.6
99-79174	50 w/o Robinson Coke	D485		9.1
99-79175	50 w/o Robinson Coke	D485		9.2
99-79176	50 w/o Robinson Coke	D485		9.6
99-79177	50 w/o Robinson Coke	D485		9.6
			Avg. Loss	9.39
99-79178	25 w/o Robinson Coke	D484		9.1
99-79179	25 w/o Robinson Coke	D484		9.4
99-79180	25 w/o Robinson Coke	D484		8.8

TABLE 1 (CONTINUED) (CRD)

S/N	Matrix Type	Leach Run	Weight Loss (g)
99-79181	25 w/o Robinson Coke	D484	9.6
99-79182	25 w/o Robinson Coke	D484	9.2
99-79183	25 w/o Robinson Coke	D484	9.0
99-79184	25 w/o Robinson Coke	D484	9.1
99-79185	25 w/o Robinson Coke	D484	9.1
99-79186	25 w/o Robinson Coke	D484	9.2
99-79187	25 w/o Robinson Coke	D484	9.4
99-79188	25 w/o Robinson Coke	D484	9.1
99-79189	25 w/o Robinson Coke	D484	9.0
99-79190	25 w/o Robinson Coke	D484	9.0
99-79192	25 w/o Robinson Coke	D484	9.2
99-79193	25 w/o Robinson Coke	D484	9.0
99-79194	25 w/o Robinson Coke	D484	8.5
99-79195	25 w/o Robinson Coke	D484	9.1
99-79196	25 w/o Robinson Coke	D484	8.9
99-79197	25 w/o Robinson Coke	D484	8.8
99-79198	25 w/o Robinson Coke	D484	8.9
99-79199	25 w/o Robinson Coke	D484	8.6
99-79200	25 w/o Robinson Coke	D484	8.7
99-79201	25 w/o Robinson Coke	D484	9.0

TABLE 1 (CONTINUED) (CRD)

S/N	Matrix Type	Leach Run		Weight Loss (g)
99-79202	25 w/o Robinson Coke	D484		8.9
99-79203	25 w/o Robinson Coke	D484		9.1
99-79204	25 w/o Robinson Coke	D484		9.1
99-79206	25 w/o Robinson Coke	D484		9.9
			Avg. Loss	9.06

Gross Average Loss = 9.29 g

Maximum Loss = 10.3 g

Minimum Loss = 8.2 g

TABLE 2 (CRD)

COATING RUN SHEET FOR PHASE IV-3 ELEMENTS (U)

S/N	NbC Coating Run	Repair Run	X-Coat	Corrosion Test
99-79078	F-320	-	AA039	1.b-1.0857
99-79079	F-318	S-59	-	1.b-1.1105
99-79081	F-320	S-59	-	1.b-1.1106
99-79082	F-318	-	-	-
99-79083	F-320	S-59	AA031	1.b-1.0904
99-79084	F-320	-	-	1.b-1.0752
99-79085	F-320	S-59	-	-
99-79086	F-320	-	AA039	1.b-1.0858
99-79087	F-318	S-59	-	1.b-1.1706
99-79088	F-318	S-59	AA031	1.b-1.0902
99-79089	F-318	S-59	-	-
99-79091	F-320	-	AA039	-
99-79092	F-318	S-59	AA031	1.b-1.0903
99-79093	F-320	-	AA039	1.b-1.0882
99-79114	F-318	-	AA039	1.b-1.0898
99-79116	F-320	S-59	-	1.b-1.1084
99-79120	F-318	-	AA039	1.b-1.0899
99-79122	F-318	S-59	AA031	-
99-79125	F-320	-	-	1.b-1.0740
99-79126	F-320	-	-	1.b-1.0769
99-79127	F-318	-	AA039	1.b-1.0901
99-79128	F-320	-	AA039	1.b-1.0905
99-79129	F-318	-	-	1.b-1.1095
99-79131	F-320	-	AA039	1.b-1.0869

TABLE 2 (CONTINUED) (CRD)

S/N	NbC Coating Run	Repair Run	X-Coat	Corrosion Test
99-79133	F-318	-	-	-
99-79134	F-320	-	AA039	1.b-1.0870
99-79135	F-318	S-59	-	1.b-1.1085
99-79136	F-318	S-59	-	1.b-1.1104
99-79144	F-320	-	AA039	1.b-1.0906
99-79145	F-318	-	-	-
99-79146	F-320	-	AA039	-
99-79148	F-318	-	AA039	1.b-1.0883
99-79151	F-318	S-59	-	1.b-1.0964
99-79152	F-318	S-59	AA031	1.b-1.0772
99-79153	F-320	S-59	-	1.b-1.1083
99-79154	F-318	-	AA039	1.b-1.0889
99-79155	F-320	-	-	1.b-1.0700
99-79157	F-320	-	-	1.b-1.0768
99-79158	F-318	S-59	AA031	1.b-1.0878
99-79160	F-318	-	AA039	-
99-79161	F-320	S-59	AA031	1.b-1.0773
99-79166	F-318	S-59	-	1.b-1.1082
99-79167	F-320	-	-	-
99-79168	F-318	-	AA039	1.b-1.0900
99-79169	F-320	S-59	AA031	1.b-1.0877
99-79170	F-318	S-59	-	1.b-1.1102
99-79174	F-320	-	AA039	1.b-1.0844
99-79175	F-318	S-59	-	1.b-1.1103
99-79176	F-320	S-59	AA031	-

TABLE 2 (CONTINUED) (CRD)

S/N	NbC Coating Run	Repair Run	X-Coat	Corrosion Test
99-79178	F-318	S-59	AA031	1.b-1.0771
99-79179	F-320	S-59	-	1.b-1.0962
99-79182	F-318	S-59	AA031	1.b-1.0795
99-79183	F-320	-	-	1.b-1.0695
99-79184	F-318	-	AA032	1.b-1.0875
99-79187	F-320	-	-	-
99-79188	F-318	S-59	AA031	1.b-1.0837
99-79189	F-320	-	-	1.b-1.0766
99-79190	F-318	-	AA032	-
99-79193	F-320	-	-	1.b-1.1094
99-79195	F-318	S-59	-	1.b-1.0965
99-79196	F-320	-	AA032	1.b-1.0876
99-79197	F-318	S-59	-	-
99-79198	F-320	-	AA032	1.b-1.0838
99-79199	F-318	-	-	1.b-1.0767
99-79202	F-320	-	AA032	1.b-1.0796
99-79203	F-318	-	-	1.b-1.0753
99-79204	F-320	S-59	AA031	1.b-1.0770

[redacted]

TABLE 3 (CRD)

INCREMENTAL HELIUM AND WHOLE BODY AIR LEAK RATE FOR PHASE IV-3 ELEMENTS (U)

S/N	Matrix Type	Incremental Helium cc/min 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Whole Body Air cc/min
99-79078	Standard	48	50	45	40	38	42	41	40	37	36	39	43	48	48	48	49	53	350
99-79079	Standard	19	20	24	29	31	34	33	32	32	32	34	37	38	38	40	42	44	330
99-79080	Standard	22	29	31	33	35	32	33	34	32	33	34	34	36	36	37	37	42	270
99-79081	Standard	28	28	29	30	31	32	32	32	30	29	31	33	34	35	35	33	38	250
99-79082	Standard	19	21	25	27	32	34	36	41	41	37	38	44	45	43	42	42	44	340
99-79083	Standard	27	32	33	35	37	36	35	32	34	35	37	37	36	36	37	37	42	280
99-79084	Standard	21	25	26	29	32	30	30	30	29	29	29	29	32	32	32	36	38	230
99-79085	Standard	20	22	26	30	32	32	29	28	27	27	30	30	31	33	34	35	38	235
99-79086	Standard	25	31	35	39	42	42	37	33	33	34	34	35	38	38	39	40	43	300
99-79087	Standard	19	20	19	22	26	27	29	29	27	31	30	31	33	32	36	38	41	280
99-79088	Standard	18	20	21	22	25	26	26	23	23	24	26	26	24	25	25	26	29	210
99-79089	Standard	13	14	16	17	19	20	20	20	20	20	22	23	22	22	23	25	27	190
99-79090	Standard	14	13	16	17	18	20	21	22	23	22	24	25	26	29	27	29	35	200
99-79091	Standard	15	21	21	22	23	23	23	23	24	24	24	25	25	26	26	26	34	190
99-79092	Standard	14	14	16	17	18	18	17	18	17	18	18	19	20	20	20	22	20	180
99-79114	75 w/o Robinson Coke	12	19	21	25	28	28	29	33	33	28	28	36	31	31	29	34	42	260
99-79115	75 w/o Robinson Coke	8	9	10	10	11	13	18	19	19	21	18	20	22	23	24	24	41	170
99-79116	75 w/o Robinson Coke	7	2	4	15	12	11	12	12	12	11	12	14	14	15	16	20	17	115
99-79119	75 w/o Robinson Coke	12	24	20	25	32	33	35	37	34	36	39	40	41	41	43	44	49	340
99-79120	75 w/o Robinson Coke	16	20	26	33	36	37	41	42	43	43	47	45	48	53	55	59	81	430
99-79121	75 w/o Robinson Coke	45	48	49	48	47	47	48	48	52	54	62	63	62	-	-	66	57	-

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TABLE 3 (CONTINUED) (CRD)

S/N	Matrix Type	Incremental Helium cc/min 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Whole Body Air cc/min
99-79123	75 w/o Robinson Coke	25	31	32	32	35	35	34	34	37	38	38	42	43	43	42	42	37	320
99-79124	75 w/o Robinson Coke	18	24	26	32	33	32	35	37	40	38	39	41	43	42	43	40	34	310
99-79125	75 w/o Robinson Coke	20	24	26	31	36	38	37	36	39	40	40	42	43	42	41	38	25	320
99-79126	75 w/o Robinson Coke	19	22	26	29	32	33	34	34	37	38	39	40	41	42	42	42	37	300
99-79127	75 w/o Robinson Coke	26	31	32	34	40	41	41	43	43	47	48	48	49	48	44	42	36	370
99-79128	75 w/o Robinson Coke	22	28	32	34	39	40	41	40	42	41	41	43	43	43	44	43	37	340
99-79129	75 w/o Robinson Coke	24	38	45	48	50	49	48	48	47	48	50	54	55	50	49	48	45	490
99-79130	75 w/o Robinson Coke	21	28	31	30	31	31	30	31	31	31	32	32	35	40	40	40	39	280
99-79131	75 w/o Robinson Coke	14	16	18	20	21	22	19	19	20	20	23	22	25	24	24	26	24	170
99-79132	75 w/o Robinson Coke	12	16	18	21	24	27	27	30	32	32	34	37	34	37	36	33	31	240
99-79133	75 w/o Robinson Coke	20	21	22	24	25	27	28	29	30	33	35	35	35	34	33	33	31	250
99-79134	75 w/o Robinson Coke	17	21	21	86	31	29	28	29	34	32	33	35	34	35	36	35	32	310
99-79135	75 w/o Robinson Coke	18	20	22	24	27	29	31	31	31	31	31	32	34	32	33	33	30	240
99-79136	75 w/o Robinson Coke	14	19	20	24	29	32	35	33	35	35	34	35	39	40	40	39	34	270
99-79142	75 w/o Robinson Coke	31	26	40	72	270	180	52	20	180	45	31	34	40	47	32	36	41	125
99-79143	75 w/o Robinson Coke	11	10	10	10	11	11	12	11	11	12	13	14	17	17	15	13	13	105
99-79144	75 w/o Robinson Coke	9	10	10	12	10	11	11	11	12	12	12	13	16	12	13	13	12	105
99-79145	75 w/o Robinson Coke	29	50	66	56	120	57	120	48	36	150	180	120	135	62	61	81	37	115
99-79146	75 w/o Robinson Coke	25	29	43	61	71	73	48	48	48	54	49	46	46	37	44	38	32	330
99-79147	75 w/o Robinson Coke	81	270	120	530	345	480	385	660	345	240	64	100	120	150	180	345	180	320
99-79148	50 w/o Robinson Coke	63	67	66	66	75	81	70	55	43	56	63	48	43	43	42	40	42	420
99-79149	50 w/o Robinson Coke	22	22	23	26	29	43	43	43	44	52	47	48	37	34	36	38	40	220
99-79150	50 w/o Robinson Coke	16	19	20	20	22	23	24	24	26	25	25	26	27	29	29	30	40	210

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TABLE 3 (CONTINUED) (CRD)

S/N	Matrix Type	Incremental Helium Leak Rate (cc/min) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Whole Body Air cc/min
99-79151	50 w/o Robinson Coke	180	36	58	150	345	240	240	67	120	480	240	180	310	100	48	345	45	210
99-79152	50 w/o Robinson Coke	20	21	23	22	24	25	26	26	26	26	27	29	28	28	30	30	33	225
99-79153	50 w/o Robinson Coke	19	21	23	24	28	30	29	27	29	30	31	32	35	35	33	34	37	230
99-79154	50 w/o Robinson Coke	18	19	22	23	25	29	27	29	29	31	31	31	32	33	32	35	37	220
99-79155	50 w/o Robinson Coke	29	52	47	37	37	46	38	38	35	38	38	38	38	40	40	41	43	250
99-79156	50 w/o Robinson Coke	30	31	37	39	40	45	43	42	41	45	47	45	46	47	45	43	45	300
99-79157	50 w/o Robinson Coke	45	43	41	40	44	48	43	43	45	45	45	67	63	64	180	60	69	265
99-79158	50 w/o Robinson Coke	40	37	35	35	40	58	120	56	48	56	53	120	49	48	61	51	58	240
99-79159	50 w/o Robinson Coke	17	20	21	23	22	23	20	22	22	24	26	29	32	32	35	35	37	220
99-79160	50 w/o Robinson Coke	51	21	18	54	55	80	32	180	48	43	43	56	45	22	20	16	16	90
99-79161	50 w/o Robinson Coke	0	0	0	0	6	6	6	9	10	10	11	10	11	11	13	13	17	86
99-79162	50 w/o Robinson Coke	9	9	10	10	10	10	11	11	13	12	13	16	21	22	23	22	24	115
99-79163	50 w/o Robinson Coke	10	13	13	15	16	18	21	21	24	24	24	24	26	27	28	28	32	195
99-79166	50 w/o Robinson Coke	12	12	12	12	15	16	17	18	18	20	22	21	22	23	22	21	24	160
99-79167	50 w/o Robinson Coke	11	11	11	11	11	12	13	13	12	13	13	14	14	15	16	18	20	120
99-79168	50 w/o Robinson Coke	11	12	15	16	17	20	26	24	26	25	28	29	26	29	27	30	32	195
99-79169	50 w/o Robinson Coke	18	23	27	30	28	36	31	32	30	31	32	34	34	44	45	41	40	290
99-79170	50 w/o Robinson Coke	24	24	27	27	25	24	22	24	21	21	19	19	20	22	23	24	25	205
99-79172	50 w/o Robinson Coke	12	13	14	15	18	19	19	18	21	21	24	24	24	25	26	31	35	175
99-79173	50 w/o Robinson Coke	18	19	20	22	24	26	27	29	29	33	31	29	27	29	30	31	39	225
99-79174	50 w/o Robinson Coke	18	20	22	25	25	26	26	27	24	26	35	34	34	35	40	42	42	245
99-79175	50 w/o Robinson Coke	16	18	19	21	24	27	27	26	28	29	30	29	30	30	33	32	33	220
99-79176	50 w/o Robinson Coke	20	19	21	23	23	22	22	25	26	28	28	30	32	30	31	33	35	220
99-79177	50 w/o Robinson Coke	15	17	20	20	19	26	18	17	19	21	25	20	19	23	26	22	26	180

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TABLE 3 (CONTINUED) (CRD)

S/N	Matrix Type	Incremental Helium Leak Rate (cc/min) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Whole Body Air cc/min
99-79178	25 w/o Robinson Coke	16	16	17	19	26	27	26	27	29	31	31	29	30	32	32	34	34	200
99-79179	25 w/o Robinson Coke	13	12	14	15	22	23	24	26	27	27	28	29	30	30	31	32	34	210
99-79180	25 w/o Robinson Coke	10	16	18	19	19	20	31	31	24	25	24	26	26	26	27	28	29	180
99-79181	25 w/o Robinson Coke	18	21	24	26	26	28	27	29	29	29	31	31	31	31	33	32	Chip	-
99-79182	25 w/o Robinson Coke	19	19	20	22	26	29	31	34	37	40	43	40	45	46	86	45	45	400
99-79183	25 w/o Robinson Coke	21	21	24	27	28	29	31	31	31	24	26	32	35	35	37	38	39	260
99-79184	25 w/o Robinson Coke	21	22	21	24	24	26	24	24	24	25	26	28	28	29	29	31	32	180
99-79185	25 w/o Robinson Coke	14	16	19	22	22	23	25	28	27	27	26	28	27	28	29	31	32	200
99-79186	25 w/o Robinson Coke	14	16	18	18	20	20	21	22	24	25	25	25	28	28	26	26	27	190
99-79187	25 w/o Robinson Coke	13	14	18	18	19	19	19	22	23	26	26	26	25	26	28	27	28	190
99-79188	25 w/o Robinson Coke	14	16	17	20	20	22	22	24	26	27	26	27	28	30	30	34	35	200
99-79189	25 w/o Robinson Coke	15	16	16	17	20	22	23	25	26	25	26	28	29	31	31	32	38	210
99-79190	25 w/o Robinson Coke	26	36	40	35	37	38	35	24	26	29	29	27	33	31	31	31	33	270
99-79192	25 w/o Robinson Coke	18	21	23	27	30	30	31	30	30	30	30	29	30	33	33	26	19	240
99-79193	25 w/o Robinson Coke	18	22	29	31	34	38	38	36	37	36	38	40	37	37	35	31	22	265
99-79194	25 w/o Robinson Coke	29	34	35	37	38	38	37	35	35	37	37	38	41	35	32	29	23	275
99-79195	25 w/o Robinson Coke	18	25	32	34	36	35	36	37	38	35	35	35	35	34	29	26	20	260
99-79196	25 w/o Robinson Coke	16	20	22	26	29	32	32	35	34	35	32	32	32	34	31	26	20	240
99-79197	25 w/o Robinson Coke	21	26	34	38	38	40	40	37	37	38	41	38	35	33	30	26	25	290
99-79198	25 w/o Robinson Coke	22	33	38	42	44	43	42	42	42	40	38	38	36	34	32	30	22	300
99-79199	25 w/o Robinson Coke	36	44	48	56	65	58	50	49	47	46	43	43	41	38	35	32	25	370
99-79200	25 w/o Robinson Coke	24	32	34	35	35	35	35	35	35	36	34	35	31	30	30	30	27	280
99-79201	25 w/o Robinson Coke	16	21	22	25	26	26	26	28	30	31	29	28	27	26	25	25	22	240
99-79202	25 w/o Robinson Coke	17	20	25	29	31	32	32	31	31	31	29	29	25	22	19	16	15	210
99-79203	25 w/o Robinson Coke	18	22	29	35	35	40	41	44	43	42	42	41	39	34	29	24	20	300
99-79204	25 w/o Robinson Coke	19	25	36	39	36	35	30	22	17	17	17	17	21	18	16	13	12	200
99-79206	25 w/o Robinson Coke	10	11	12	16	17	17	18	20	21	21	21	21	20	20	18	16	15	140

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TABLE 4 (CRD)

PHYSICAL PROPERTIES OF PHASE IV-3 ELEMENTS (U)

Matrix Type	S/N	Flexural Strength (psi) Avg.	Max.	Min.	Compressive Strength Avg.	Max.	Min.	CTE % Expansion at 2000°C (long.)	Porosity % Avg.	Max.	Min.
Standard	99-79080										
	99-79090	4375	4990	3860	7473	8320	6380	0.610	15.00	15.27	14.69
			6 samples			6 samples					
25 w/o Robinson Coke	99-79181										
	99-79186	3910	4340	3650	9140	9400	8880	0.795	14.52	14.92	14.14
	99-79192		9 samples			9 samples				9 samples	
50 w/o Robinson Coke	99-79150										
	99-79159	3810	4360	3450	9210	11150	8420	0.910	14.20	15.93	13.76
	99-79193		12 samples			12 samples				12 samples	
	99-79163										
75 w/o Robinson Coke	99-79121										
	99-79132	3540	3780	3210	8490	9970	7800	1.190	13.81	14.31	13.34
	99-79143		12 samples			12 samples				12 samples	
	99-79124										

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TABLE 5 (CRD)

CORROSION TEST DATA FOR THE PHASE IV-3 ELEMENTS (U)

Coating Batch NbC	X	S/N	Test Time	Test ΔW	Test Corr. ΔW	Pinholes 0-35	Pinholes 35-48	Inc. ΔW 0-35	Inc. ΔW 35-52
Standards									
F-320	AA039	99-79078	30+20	21.0	10.6	1	0	0.50	8.40
F-318, S-59	-	99-79079	19.0	11.2	10.3	1	0		
F-320, S-59	-	99-79081	24.9	20.0	17.7	3	0	13.20	4.54
F-318, S-59	AA031	99-79083	30+20	18.1	10.4	0	0	0.84	9.53
F-320	-	99-79084	24.3	16.0	12.0	0	0	8.80	3.20
F-320	AA039	99-79086	30+30	35.5	15.4	0	0		
F-318, S-59	-	99-79087	21.2	13.85	12.11	0	0	9.95	2.16
F-318, S-59	AA031	99-79088	30+30	40.4	27.54	1	8	7.63	19.91
F-318, S-59	AA031	99-79092	11.4+18.6+12.8	20.2	8.30	0	0	1.60	6.70
F-320	AA039	99-79093	30+20	29.2	14.43	0	0	0.50	8.40
75 Flour w/o Robinson Coke									
F-318	AA039	99-79114	19.7	14.0	11.3	0	0	0.96	10.34
F-320, S-59	-	99-79116	13.1	7.3	6.25	0	0	3.06	3.19
F-318	AA039	99-79120	30+30	20.9	11.2	0	0	2.89	8.35
F-320	-	99-79125	30	15.0	10.8	4	0	4.66	6.13

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TABLE 5 (CONTINUED) (CRD)

Coating Batch				Time		Pinholes		Inc. ΔW	
NbC	X	S/N	Time	ΔW	Corr. ΔW	0-35	35-48	0-35	35-52
75 Flour w/o Robinson Coke - Continued									
F-320	-	99-79126	20	9.2	7.4	0	0	2.99	4.46
F-318	AA039	99-79127	30+30	15.8	12.4	0	0	2.00	10.38
F-320	AA039	99-79128	30+20	12.0	9.0	0	0	0.64	8.32
F-318	-	99-79129	25.1	16.1	11.13	0	0	5.44	5.69
F-320	AA039	99-79131	30+20	24.0	9.5	0	0	1.17	8.32
F-320	AA039	99-79134	30+30	17.6	9.3	0	0		
F-318, S-59	-	99-79135	26.3	14.9	13.5	3	0	10.97	2.52
F-318, S-59	-	99-79136	27.1	16.6	14.40	0	0	11.11	3.29
F-320	AA039	99-79144	30+30	14.0	11.3	0	0	0.96	10.34
50 Flour w/o Robinson Coke									
F-318	AA039	99-79148	30+20	21.5	15.7	0	0	3.78	11.32
F-318, S-59	-	99-79151	25.2	15.0	12.35	0	0	3.14	9.21
F-318, S-59	AA031	99-79152	30+20	15.5	11.3	0	0	1.44	9.90
F-320, S-59	-	99-79153	20.3	13.3	11.8	0	0	8.33	3.43
F-318	AA039	99-79154	30+30	23.0	12.45	0	0	2.64	9.81
F-320	-	99-79155	28.8	16.5	10.9	11	0	6.04	4.87

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TABLE 5 (CONTINUED) (CRD)

Coating Batch NbC	Coating Batch X	S/N	Test Time	Test ΔW	Test Corr. ΔW	Pinholes 0-35	Pinholes 35-48	Inc. ΔW 0-35	Inc. ΔW 35-52
50 Flour w/o Robinson Coke - Continued									
F-320	-	99-79157	20.0	10.0	8.92	0	0	3.80	5.12
F-318, S-59	AA031	99-79158	30+30	29.5	15.9	0	0	3.78	11.32
F-320, S-59	AA039	99-79161	30+20	15.1	11.4	0	0	1.84	9.52
F-318, S-59	-	99-79166	16.8	11.5	9.72	0	0	6.74	2.98
F-318	AA039	99-79168	7.9	10.2	3.1	0	0	0.83	2.23
F-320, S-59	AA031	99-79169	30+30	25.6	12.5	0	0	3.18	9.29
F-318, S-59	-	99-79170	17.0	16.0	14.98	0	0	11.39	3.59
F-320	AA039	99-79174	30+20	20.0	10.7	0	0	1.72	8.99
F-318, S-59	-	99-79175	19.5	15.8	15.50	0	0	13.48	2.02
25 Flour w/o Robinson Coke									
F-318, S-59	AA031	99-79178	30+20	21.5	15.5	0	0	5.17	10.32
F-320, S-59	-	99-79179	22	16.0	14.2	0	0	11.61	2.61
F-318, S-59	AA031	99-79182	30+20	25.3	14.9	0	0	5.35	9.69
F-320	-	99-79183	26.0	21.8	14.0	3	0	9.62	4.97
F-318	AA032	99-79184	30+30	17.5	11.3	0	0	2.23	9.10

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TABLE 5 (CONTINUED) (CRD)

Coating Batch			Test			Pinholes		Inc. ΔW	
NbC	X	S/N	Time	ΔW	Corr. ΔW	0-35	35-48	0-35	35-52
25 Flour w/o Robinson Coke - Continued									
F-318, S-59	AA031	99-79188	30+20	20.3	13.4	0	0	3.11	10.32
F-320	-	99-79189	20	8.9	8.9	0	0	5.00	3.90
F-320	-	99-79193	23.7	16.5	12.8	2	0	-	-
F-318, S-59	-	99-79195	19.6	18.0	16.80	0	0	15.77	1.03
F-320	AA032	99-79196	30+30	25.7	14.23	0	0	3.28	10.95
F-320	AA032	99-79198	30+20	16.3	10.8	0	0	1.64	9.20
F-318	-	99-79199	20	9.3	9.1	0	0	6.77	2.38
F-320	AA032	99-79202	30+20	20.0	11.2	0	0	1.74	9.48
F-318	-	99-79203	24.3	16.0	8.8	1	0	-	-
F-320, S-59	AA031	99-79204	30+20	18.2	11.1	0	0	1.57	9.59

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TABLE 6 (CRD)

HYDROGEN CORROSION TEST PARAMETERS PB CORROSION TEST (U)

Item	Test Parameter	Units	Value or Condition
1	Nominal element surface temperature[1]	°R (°C)	4700 (2338)
2	Duration at steady state	min.	294613-1 30 + 20 294613-2, -3, & -4 30 + 30
3	Duration of power startup	sec	45 - 60
4	Duration of power shutdown	sec	30 - 60
5	Inlet hydrogen temperature	---	Ambient
6	Startup hydrogen flow (at ambient temperature)		Full Flow
7	Steady state hydrogen flow	SCFM	
	a) Elements without extensive external NbC coating, i.e., <4 inches		592 ± 15
	b) Elements with extensive external NbC coating, i.e., >4 inches		592 ± 15
8	Cooldown hydrogen flow	---	Full Flow
9	Exit hydrogen pressure	psig	560
10	Inlet hydrogen pressure	---	Footnote 2
11	Excess of average element bore pressure at Δ psi station 20 over external helium pressure		30 ± 5
12	Helium flow	SCFM	Not to exceed 80
13	Test control temperature[3] (surface temperature at the sight port 14.4 inches from the hot end of the element)	°R (°C)	4100 ± 100 (2004 ± 56)
14	Power generation in element at steady state		
	a) Elements without extensive external NbC coating, i.e., <4 inches		900 ± 25
	b) Elements with extensive external NbC coating, i.e., >4 inches		893 ± 25

Footnotes on following page.

[redacted]

TABLE 6 (CONTINUED) (CRD)

[1] Defined as the hottest surface temperature of the fuel element as viewed through the optical pyrometer at the sight port nearest to the hot (nozzle) end of the element.

[2] Consistent with flow and outlet pressure.

[3] In the event that items 13 and 14 cannot be held simultaneously within their respective limits, item 14 (power) shall govern, and the test shall be evaluated by Materials and Quality Control.

[redacted]

Astronuclear Laboratory

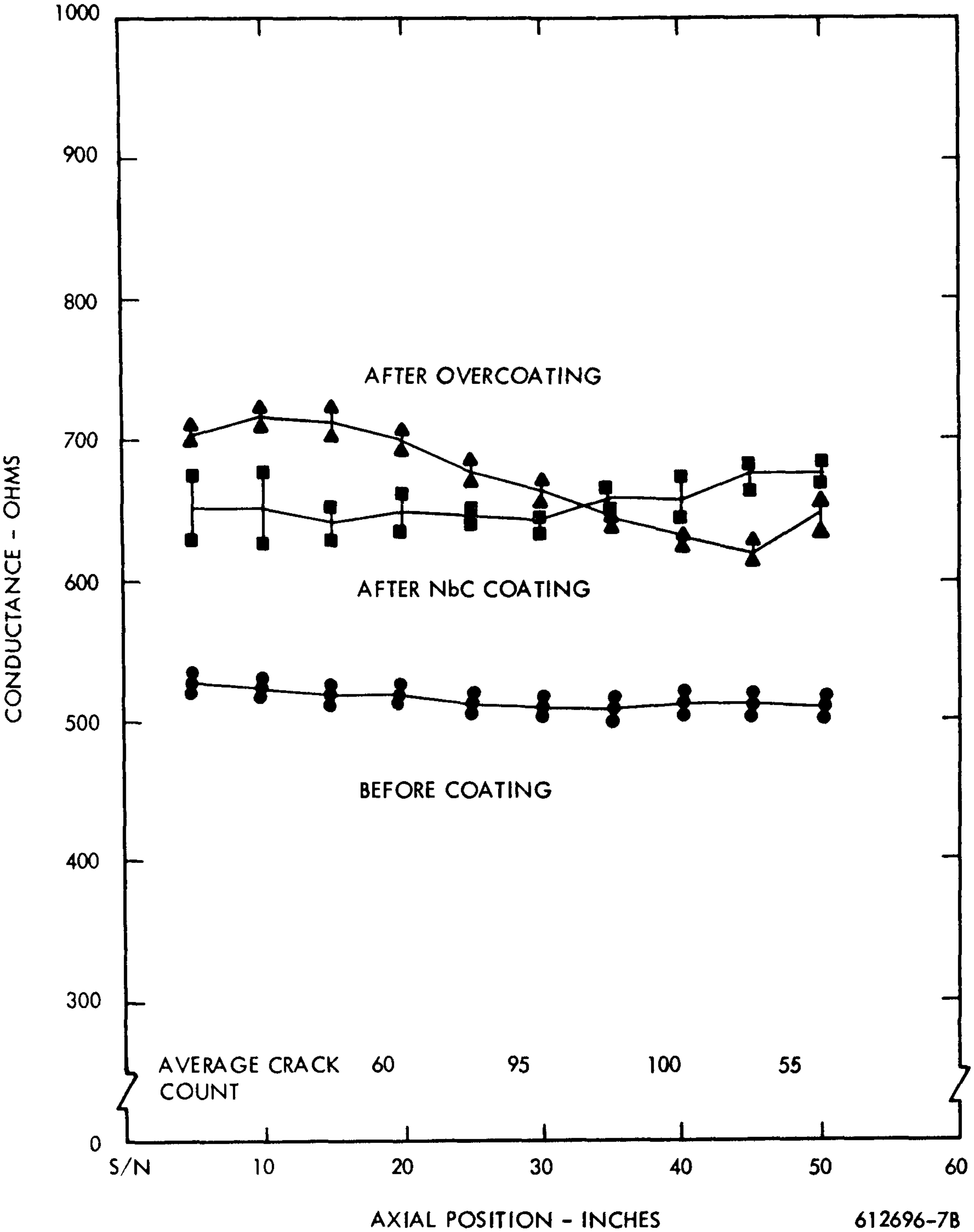

Figure 1. (CRD)Experimental Conductance Values of Standard Elements in Coating Batch F-318(U)

[redacted]

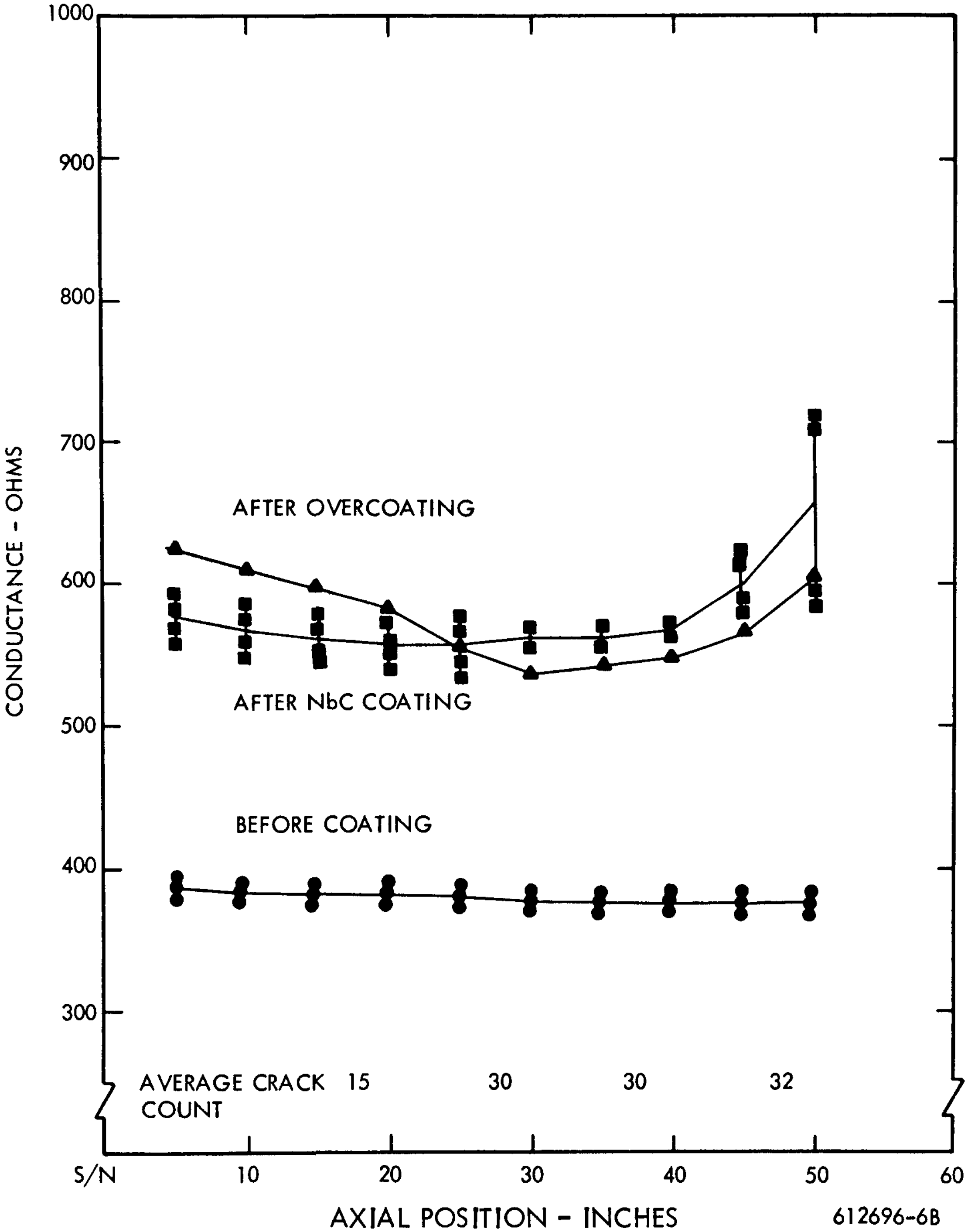

Figure 2. (CRD) Experimental Conductance Values of 75 Percent "High-Expansion" Elements in Coating Batch F-318 (U)

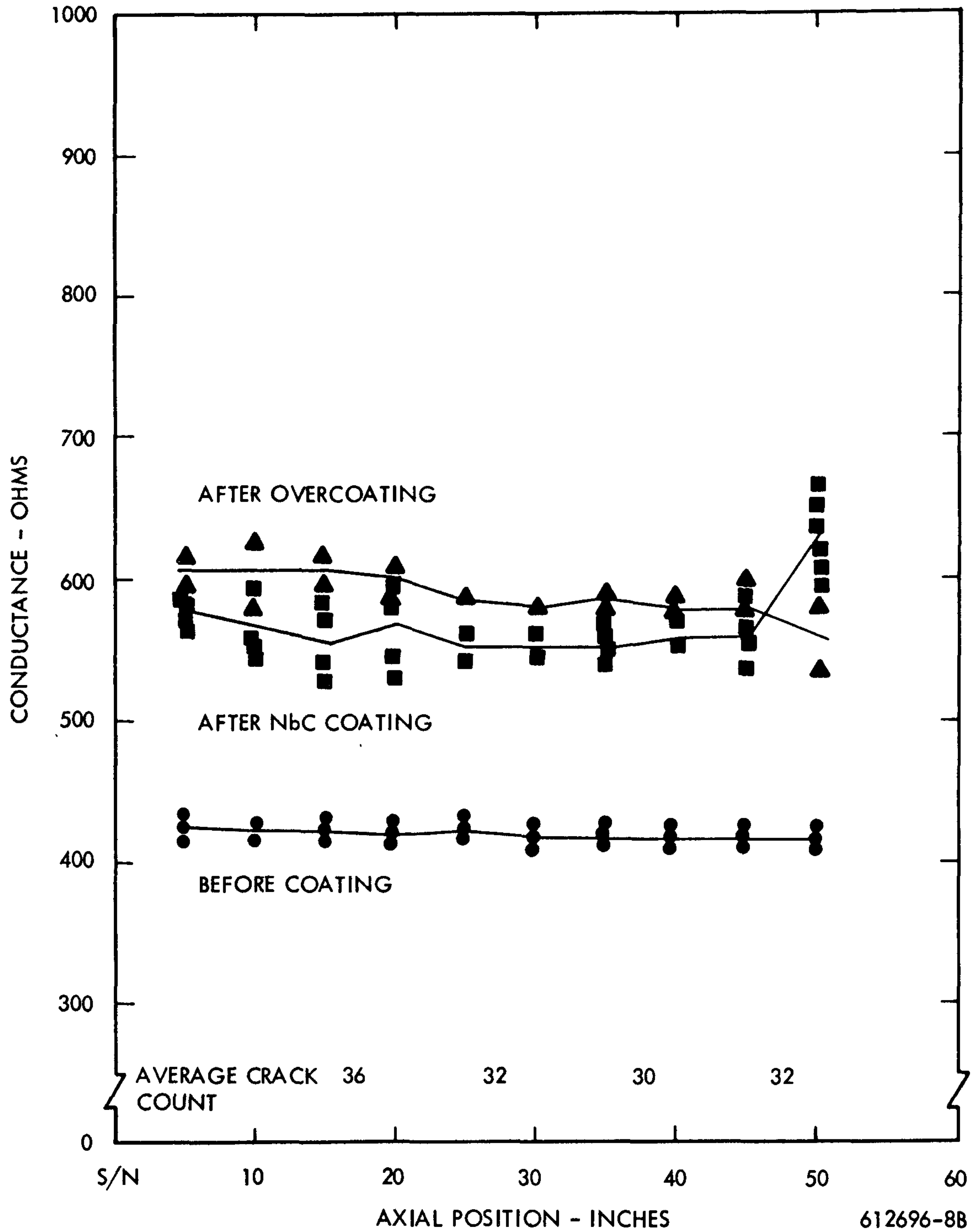

Figure 3. (CRD) Experimental Conductance Values of 50 Percent "High-Expansion" Elements in Coating Batch F-318 (U)

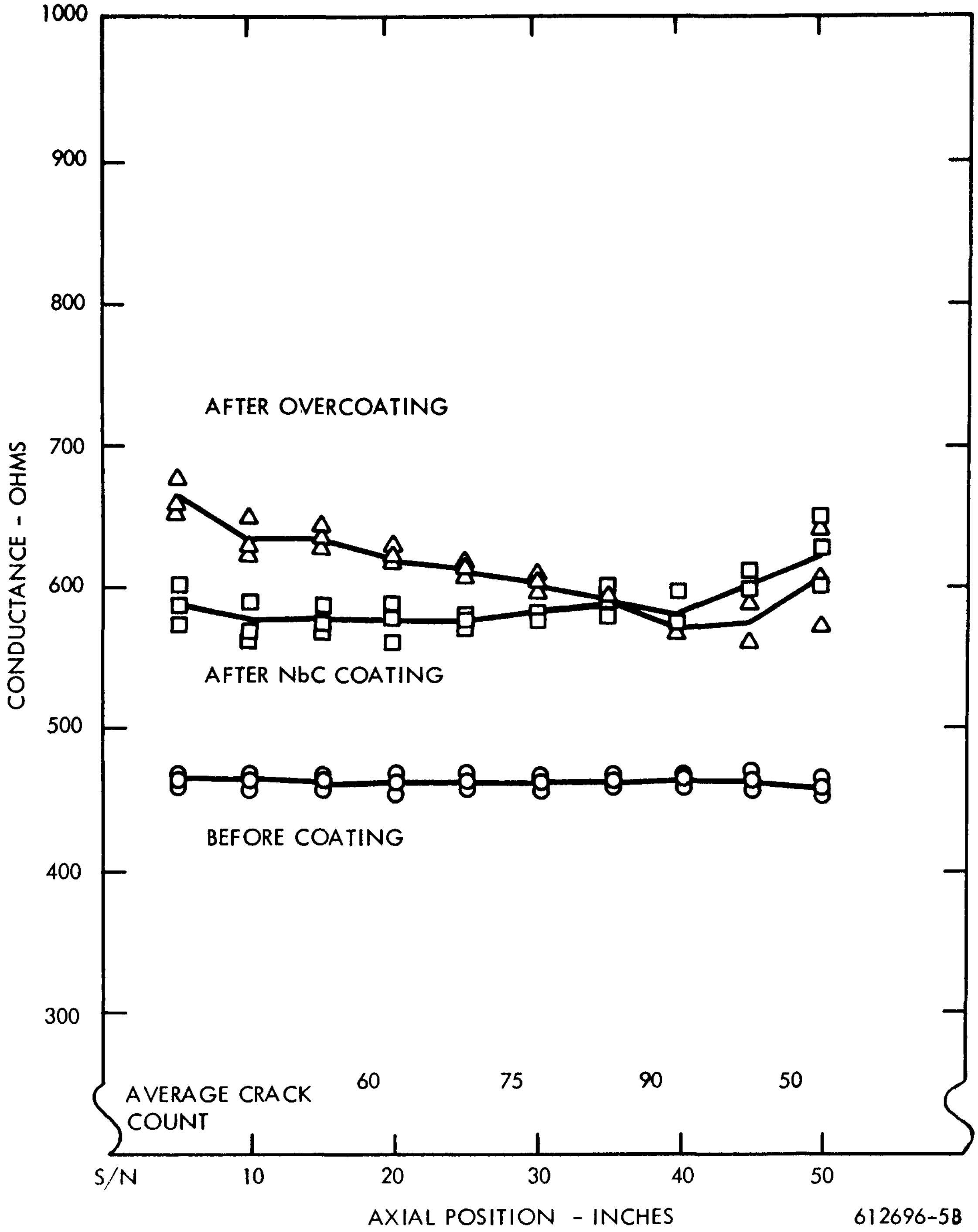

Figure 4. (CRD) Experimental Conductance Values of 25 Percent "High-Expansion" Elements in Coating Batch F-318 (U)

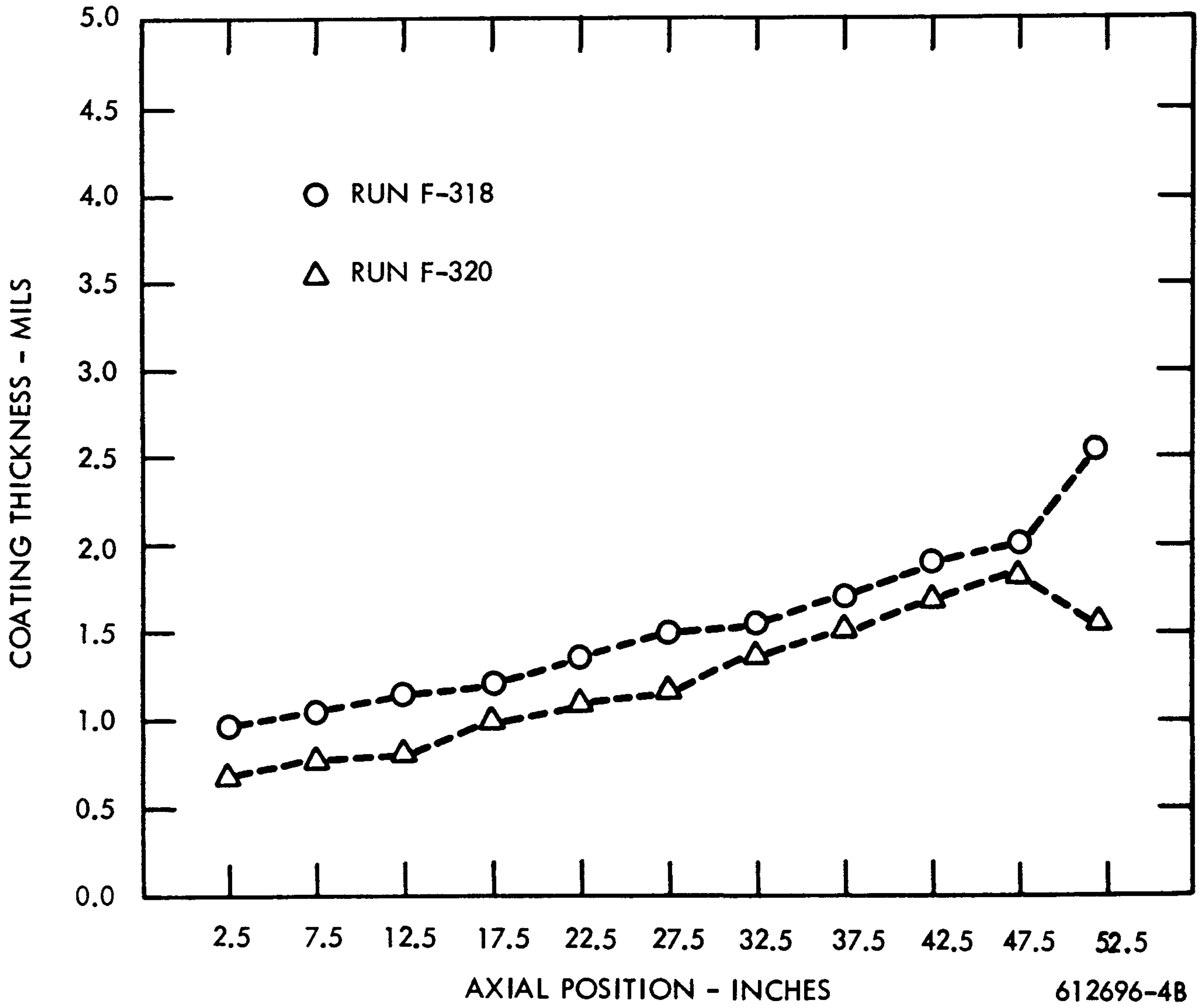

Figure 5. (CRD) Representative Coating Profiles of Phase IV-3 Elements (U)

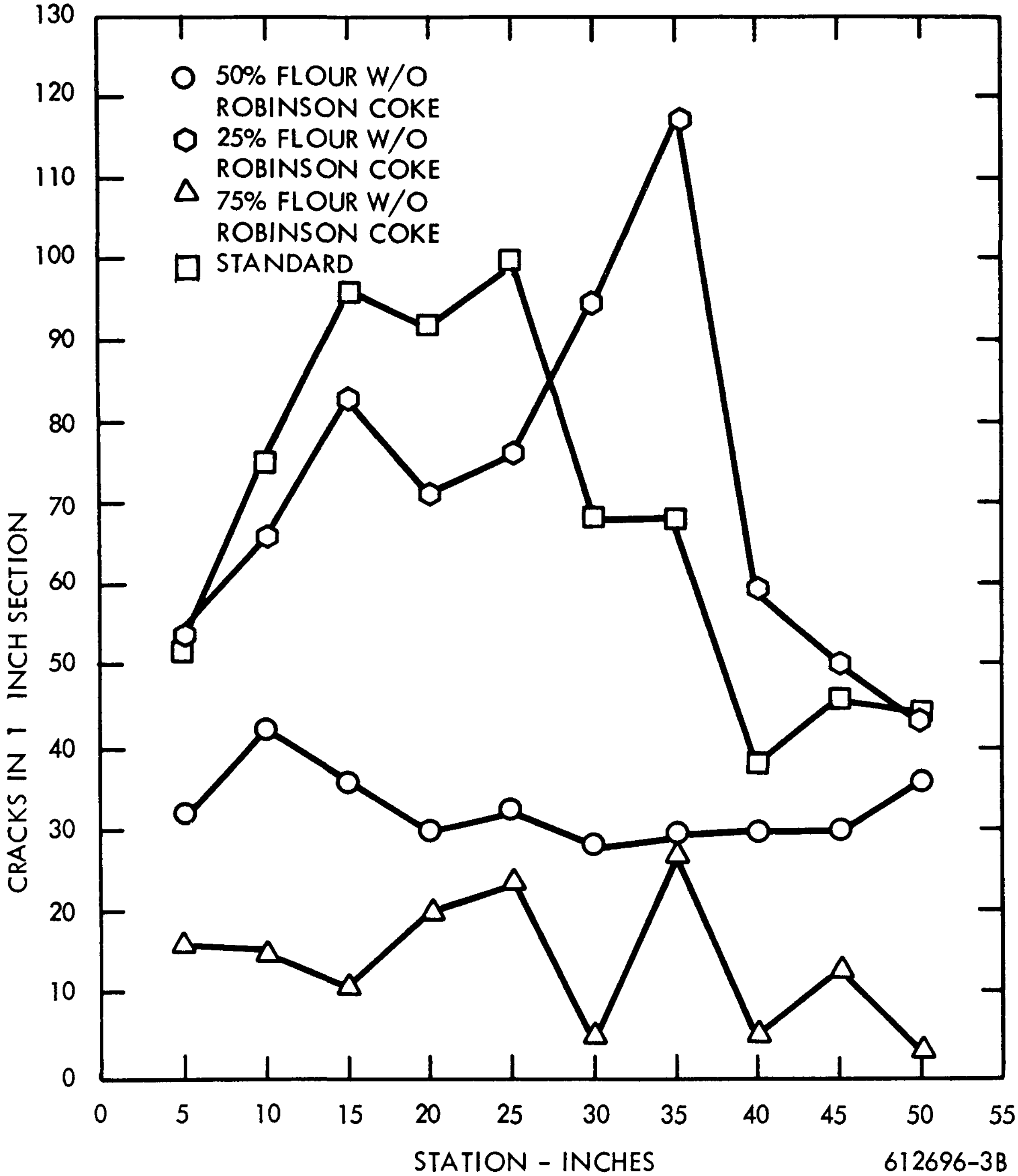

Figure 6. (CRD) Typical Crack Distributions for Elements in Coating Batch F-318 (U)

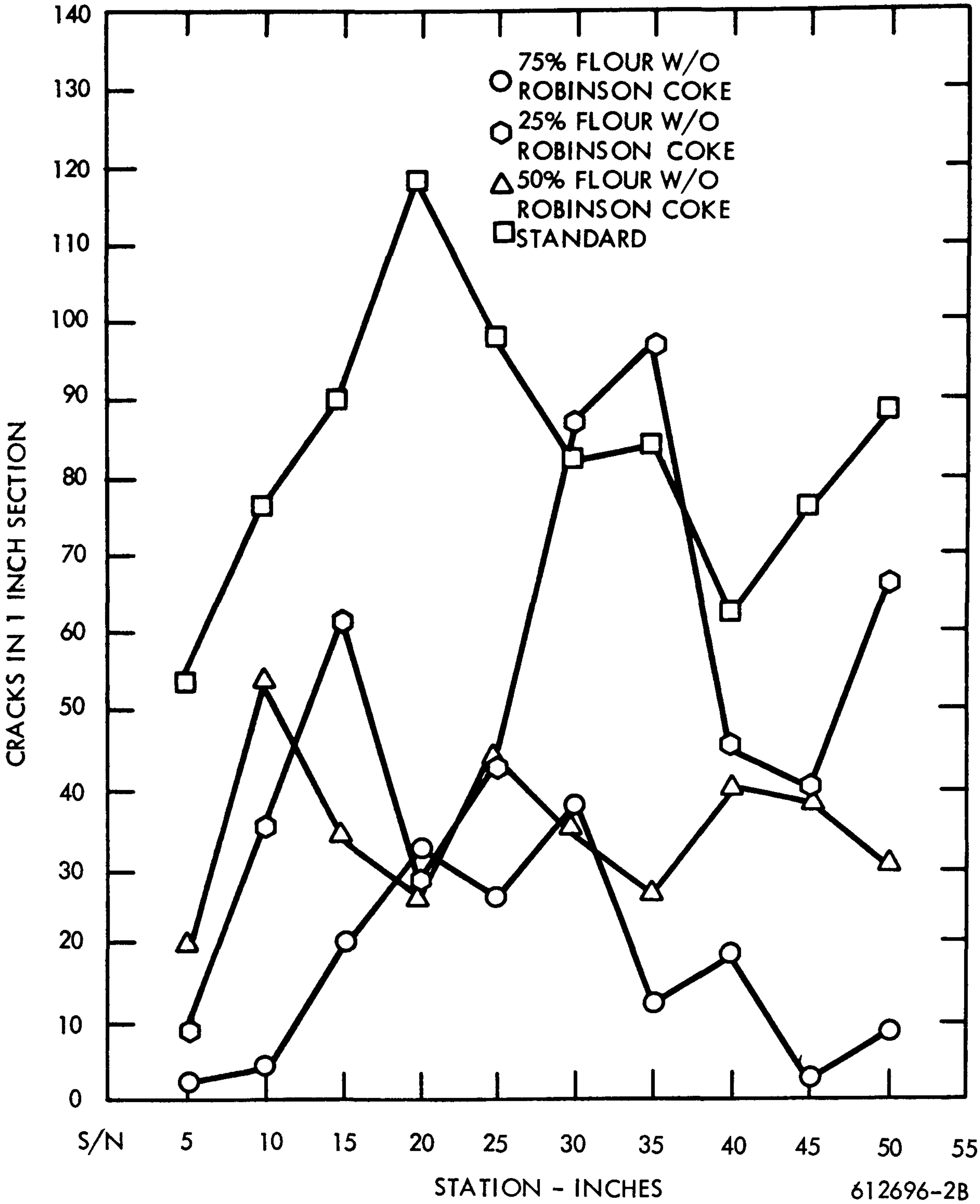

Figure 7. (CRD) Typical Crack Distributions for the Coating Run Combination F-318 and S-59 (U)

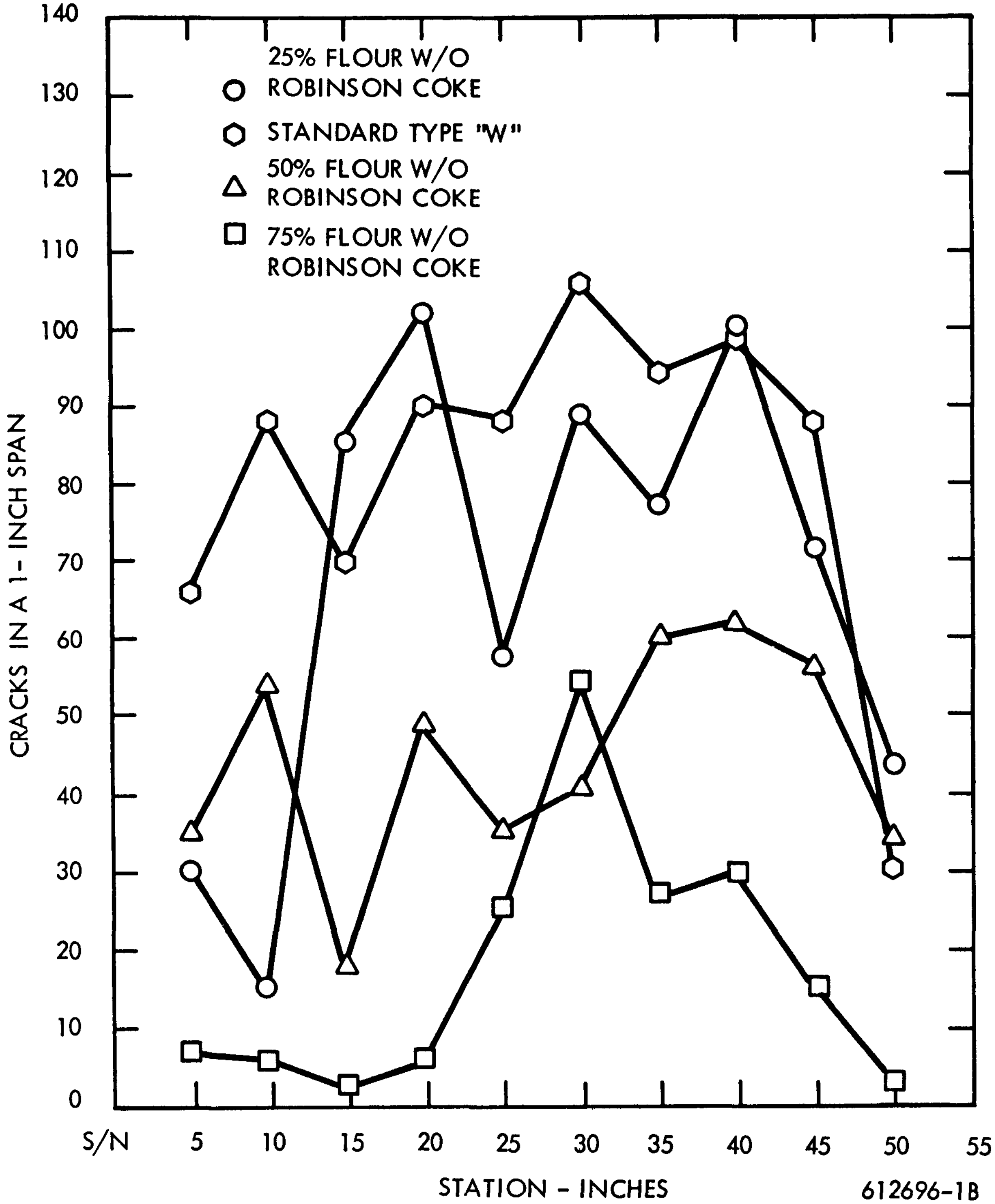

Figure 8. (CRD) Typical Crack Distributions for Coating Batch F-320 (U)