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**IN-REACTOR CORROSION OF X-8001
AND 1245 ALUMINUM -
ANALYSIS OF DATA FROM PT IP-42A**

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JUNE 25, 1958

HANFORD LABORATORIES

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RICHLAND, WASHINGTON

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By

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IN-REACTOR CORROSION OF X-8001 AND 1245 ALUMINUM -
ANALYSIS OF DATA FROM PT IP-42A

INTRODUCTION

Failures of standard fuel element jackets (1245 aluminum alloy) after relatively short Hanford reactor exposures are occurring at high reactor power levels. ⁽¹⁾ Metallographic examination of fuel element jackets from short exposure ruptures shows the cause of failure to be rapid intergranular corrosion. ⁽²⁾ This type of attack has been reproduced in laboratory tests by exposure to water at temperatures above 200 C, ⁽³⁾ or to steam at temperatures higher than 300 C. ⁽²⁾ Flow disruptions due to misalignment of the fuel elements within the reactor process tube, worn tube ribs, etc., are believed to cause the high local jacket temperatures necessary for the occurrence of intergranular corrosion.

Recent comparisons of various aluminum alloys in deionized water in the temperature range 100-363 C have shown X-8001* aluminum alloy (nominal composition Al-1.0 w/o Ni-0.5 w/o Fe) to have greatly improved resistance to intergranular attack. ^(4,5) Flow laboratory tests of X-8001 alloy in reactor process water indicate that normal (uniform) corrosion behavior is similar to current 1245 alloy can stock. ^(6,7,8) X-8001 alloy has a relatively small percentage of heavy metal additions and thus a low cross section to thermal neutrons. Since it is readily fabricated into cans by the same techniques used for the current can stock, 1245 alloy, it has been selected as a possible candidate to replace 1245 alloy.

The low frequency of failure of short exposure jackets requires large scale in-reactor substitution of X-8001 for 1245 alloy to demonstrate the success of X-8001 in eliminating intergranular attack. Such a test might require charging half the tubes of a pile. Prudence suggests that the laboratory results be confirmed by in-reactor exposure of a small number

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* X-8001 is the alloy designation adopted by the Aluminum Association to replace the former designation M-388, used in previous reports.

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of X-8001 jacketed fuel elements prior to large scale substitution of X-8001 for 1245 alloy. This preliminary irradiation of X-8001 jacketed fuel elements was the purpose of this production test. (9, 10, 11)

SUMMARY

Natural uranium fuel elements canned in either X-8001 or 1245 aluminum alloy cans were irradiated for 3 to 5 months in 7.0 pH process water at average outlet temperatures of about 100 C. Tube outlet temperatures and flow rates were monitored throughout the exposure period. The fuel elements were weighed and inspected both before and after irradiation exposure.

Measured weight losses for the X-8001 and 1245 alloy jacketed fuel elements exposed during this test are comparable. There is indication that the rate of uniform corrosion of X-8001 alloy under the conditions of this test is slightly lower than the 1245 corrosion rate. Statistical analysis of weight loss data does not show, however, any significant difference between corrosion rates of the two alloys. The corroded surfaces of most of the X-8001 and 1245 jackets appear similar under visual examination.

While weight loss data was generally favorable to X-8001 alloy, serious local attack was observed on the X-8001 jackets of the downstream fuel elements of all four tubes in the H-Reactor tests. The attack consists of cleanly incised tear shaped pits which in a majority of cases elongate or coalesce into grooves. The causes of this local attack noted on the downstream fuel elements in the H-Reactor tests cannot be definitely established with current information. Many different mechanisms may have contributed to this severe local attack. The X-8001 jackets exposed in H-Reactor were apparently more susceptible to this type of attack than were the 1245 jackets.

Results from this production test clearly show that fuel element production should not be committed to majority use of X-8001 fuel element cans until the extent and severity of groove attack has been better defined and its effect on fuel element failure determined. Further in-reactor testing is being conducted on a larger scale than was done under this production test. (25, 26, 27, 28, 29, 30, 31, 32)

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Test Conditions

Seven charges of natural uranium fuel elements in aluminum cans were inserted into Hanford reactors C and H. Each charge consisted of X-8001 alloy jacketed elements alternated with 1245 alloy jacketed pieces. Six of the charges were irradiated to full exposures. The seventh charge was discharged after very short exposure due to failure of one of the 1245 alloy jackets. Exposure conditions for the tubes charged under this production test are summarized in Table I.

TABLE I
CONDITIONS OF EXPOSURE FOR TUBES
OF MIXED FUEL ELEMENTS IN C AND H REACTORS

Tube	MWD/T	Days Pile Operation	Avg. Outlet Temperature ° C	Avg. Inlet Temperature ° C	Process Water Flow Rate gpm	pH
2065-H	845	152	100.2	9.2	29.5	7.0
2086-H	792	152	100.0	9.2	27.7	7.0
2865-H	829	152	98.5	9.2	29.5	7.0
3376-H	829	152	98.5	9.2	29.5	7.0
0974-C	rupture 1245					
1074-C	568	92	107.3	7.7	29.8	7.0
2160-C	579	91	105.4	7.7	31.3	7.0

The exposure in H-Reactor is considerably greater than normal goal exposure (600 MWD/T). The tubes in C-Reactor run at higher than ordinary C-Reactor temperatures due to the use of BDF tubes⁽¹²⁾ which provide a smaller annulus for cooling water than do C-Reactor tubes. Complete data on each tube is listed in Appendix I, page 28.

RESULTS

The accuracy of the weight loss results from this test appears to be unusually good. Weight loss data obtained for these fuel elements show little over-all scatter. This is partly due to the long exposures and high temperatures which resulted in relatively large weight losses. Variations in measured weight loss caused by minor weight inaccuracies, temperature and flow fluctuations, etc., are thereby minimized.

Rates of uniform corrosion of X-8001 and 1245 aluminum fuel element jackets measured during this test are similar but not identical. Weight losses for pieces exposed under this test are plotted versus fuel element position for each tube charge in Figure 1 through 6. Weight losses plotted in this way reveal that some difference must exist between the two alloys in their sensitivity to the different factors which influence fuel element jacket corrosion. This difference is small, however, and can be determined quantitatively only by statistical analysis of the data. Without benefit of the statistical analysis, the data show that the resistance of X-8001 alloy to uniform corrosion in pH 7.0 process water is at least as good as, and probably better than the corrosion resistance of 1245 alloy.

Weight loss data from this test were analyzed by the Experimental Statistics Operation, HLO, to determine if the differences in corrosion behavior of X-8001 and 1245 alloy were statistically significant. The data were analyzed in terms of the corrosion expression obtained by Groot and Wilson from a previous analysis of Hanford fuel element corrosion data.⁽¹³⁾ This expression has the form:

$$\text{Log C. R.} = b_0 + b_1/T + b_2P + b_3 \text{ pH} \quad (1)$$

where C. R. = corrosion rate in mils/hrs

T = local water temperature in ° K

P = power in kw/8-inch fuel element

pH = inverse log of the hydrogen ion concentration

b_0, b_1, b_2, b_3 = constants

FIGURE 1

Experimental Data for Tube 1074-C

FIGURE 2

Experimental Data for Tube 2160-C

FIGURE 3

Experimental Data for Tube 2065-H

FIGURE 4

Experimental Data for Tube 2086-H

FIGURE 5

Experimental Data for Tube 2865-H

FIGURE 6

Experimental Data for Tube 3376-H

Application of this expression to the data was not satisfactory since the coefficient, b_2 , for the power term was found by a least squares analysis to be negative.

As an alternative, a corrosion expression was developed which differs from the Groot-Wilson equation in the manner in which the power term is treated. The assumption is made that power affects corrosion only by increasing the temperature controlling the corrosion process. Further it is assumed that the increase in the temperature governing the corrosion process is a linear function of the power. The corrosion expression * becomes

$$\text{Log C.R.} = k_0 + \frac{k_1}{T_c}, \quad (2)$$

$$\text{where } T_c = T + k_2 P$$

For equation (2), C.R., T and P have the same meaning as above, and k_0 , k_1 and k_2 are constants. For this test, water quality, specifically pH, was nominally constant. Therefore, no water quality parameter is included in the corrosion expression. The term T_c is the temperature actually experienced by the corroding fuel element surface.

A graphical method for calculating the constants, described before, ⁽¹⁴⁾ is used to calculate k_2 . In Figure 2A (tube 2160-C) a curve has been drawn to obtain a visual representation of the experimental corrosion data plotted against fuel element position. Horizontal lines are drawn at intervals connecting points of equal corrosion rates occurring within the tube. Equivalent corrosion is assumed to imply equal corrosion temperature. We can therefore write:

$$T_A + k_2 P_A = T_{A'} + k_2 P_{A'}$$

$$T_B + k_2 P_B = T_{B'} + k_2 P_{B'}$$

⋮

$$T_F + k_2 P_F = T_{F'} + k_2 P_{F'}$$

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*This expression is preferred to T_c calculations involving the Sieder-Tate relation for heat transfer. See Appendix III, page 37.

Appropriate values for T_A through T_F , $T_{A'}$ through $T_{F'}$, are obtained by dropping vertical lines from points A through F and A' through F' to intersect the plot of local water temperature versus piece position (Curve 2B). Similarly the values for P_A through P_F , $P_{A'}$ through $P_{F'}$, are obtained by extending the vertical lines to intersect the fuel element power curve 2C. For each of the tie lines a value of k_2 can now be calculated. In Table II the average value of k_2 for each of the six tubes is listed. Of the original seven tubes, tube 0974-C was discharged at very low exposure after a control piece ruptured. For tube 2086-H, estimated values for fuel element power were substituted for erratic data, pieces 18-32.

TABLE II
EQUIVALENCE BETWEEN FUEL ELEMENT POWER AND $T, ^\circ C$

<u>Tube</u>	<u>Operating Days</u>	<u>MWD/T</u>	<u>MWD/Tube</u>	<u>KW/Tube</u>	<u>k_2 $^\circ C/KW/Piece$</u>
1074-C	92	568	72.2	786	2.36
2160-C	91	579	80.9	810	1.77
2065-H	152	845	107.3	707	1.74
2086-H	152	792	100.9	663	1.21
2865-H	152	829	105.6	694	1.60
3376-H	152	829	105.6	694	1.69
Average k_2					1.73

The individual determinations of k_2 from which the averages were made are shown in Appendix II.

The temperature governing the corrosion process, T_c , is equal to the local water temperature, calculated from inlet and outlet temperatures and fuel element power, plus the product of k_2 and fuel element power:

$$T_c = T + k_2 P.$$

The quantities T and T_c (and also $1000/T_c$) are tabulated in Appendix I. In Figure 7 experimental log corrosion rates, in mils/month, are plotted as a function of reciprocal corrosion temperature. Included in Figure 7

FIGURE 7

Slug Corrosion in Mils/Month as a
 Function of Reciprocal Corrosion Temperature (Equation (3))

$\text{Log C. R.} = 8.21 - \frac{3240}{T_c^{\circ K}}$ is represented by the dotted line.
 Solid lines represent 95% confidence limits. Data from
 tube 2086-H (triangles) are not included in the analysis.

is one point from out-of-reactor testing of X-8001 alloy.⁽¹⁵⁾ The in-reactor data have been analyzed by the least squares method to determine the values of k_0 and k_1 , which best fit an equation of the form of (2). The constants k_0 and k_1 are calculated to be, respectively, 8.21 and -3,240. Inserting these values in equation (2) gives:

$$\text{Log C. R.} = 8.21 - \frac{3240}{T_c, ^\circ \text{K}} \quad (3)$$

A 95 per cent confidence prediction band has been calculated for the data from five of the charges irradiated during this test (1074-C, 2160-C, 2065-H, 2865-H, and 3376-H).^(16,17) This 95 per cent prediction band is shown on Figure 7 as the region between the dotted lines. Data points for charge 2086-H have been plotted separately on Figure 7, since they were not used in determining the prediction band. A curve fitted to the data from charge 2086-H was found visibly different from the curve fitting the other five charges. The least squares analysis has shown that curves calculated for X-8001 and 1245 alloys do not vary significantly from one another.⁽¹⁶⁾ The similarity of the two alloys is in agreement with most out-of-reactor comparisons in which no significant corrosion differences were found between the alloys. Determination of this point was the crux of the test design.

Localized Corrosion Attack of X-8001 Alloy

Description

Severe local corrosion (not revealed by the weight loss results) of several X-8001 pieces and some of the 1245 pieces was discovered during visual examination of the discharged fuel elements. This local attack appears as groups of smooth surfaced teardrop-shaped pits. In most of these groups the individual pits have grown together, or overlapped, to form long, straight grooves or large corroded areas. Visual examination of the cleaned pieces shows the attack to have been most severe on the downstream (No. 1) pieces. The same type of attack was noted on some

of the No. 2 pieces (1245 alloy controls) and on some of the No. 3 pieces (X-8001 alloy), both with much reduced severity. Photographs of a No. 1 and No. 2 piece (Figures 8 and 9) provide a basis for comparing severity of attack.

The most aggravated attack for all fuel elements occurred on the side opposite the rib marks and was fairly evenly distributed longitudinally over the fuel element length. The black area in the bottom of the severely corroded region near the right end of the No. 1 piece (Figure 8) is the aluminum-silicon braze layer which appears to have been an effective barrier to the groove type attack. Along the bottom of the piece are two grooves running half the length of the piece which probably result from extension or coalescence of pits. The grooves do not correspond to the rib marks although it is possible that abrasion during charging may have initiated the attack. Figure 9 is a photograph of a No. 2 control piece. The most prominent feature on this piece is the groove running the length of the fuel element. This groove is opposite the rib marks and is similar in appearance to the two grooves noted in Figure 8 for the X-8001 No. 1 piece. An extensively pitted region of the No. 2 control piece has been circled on Figure 9.

Possible Causes

Factors which alone, or in combination, might cause this type of local attack include cavitation, mechanical abrasion (erosion), intergranular attack, electrolytic corrosion, and water turbulence (erosion). There are several characteristics of this pitting corrosion and certain features of the exposure history from which an explanation for this attack might be sought:

- (1) The type of attack - clean cut, tear shaped pits and grooves.
- (2) Attack confined to downstream pieces; most severe on No. 1.
- (3) Top of piece pitted 90-180° away from rib marks.
- (4) Attack apparently resisted by AlSi.
- (5) No deformation of, or penetration between, Aluminum grains in attacked area (see micrograph of transverse section, Figure 10b). (18)

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FIGURE 8

Piece 1, Numbered from the Rear of Tube 2065-H,
X-8001 Aluminum Alloy Jacket Showing Severe Local Attack
Region of exposed Al-Si is circled.

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FIGURE 9

Piece 2, Numbered from Rear of Tube 3376-H,
1245 Aluminum Alloy Jacket

Region of moderate local attack is circled.

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- (6) Long exposure, 900 MWD/T; high temperature, 100 C outlet; pH 8.0 water.
- (7) Intermittent periods of high turbidity - one serious, one minor, filter break through.

Cavitation has been considered as a device to account for the localization of the erosion-corrosion attack. It is not a satisfactory explanation, for two reasons. Cavitation attack leaves a characteristically rough blasted surface, in contrast to the clean cut, smooth surface in the X-8001 pits. Cavitation is readily identified from micrographic cross sections of affected areas which show heavy mechanical working of the surface grains. Figure 10b is a cross section micrograph of a pitted area of the X-8001 clad piece shown in Figure 8. Figure 10a is a cross section of a sample of 6061 aluminum known to have undergone cavitation.⁽¹⁹⁾ The unworked aluminum at the pit in Figure 10b cannot have been subjected to significant cavitation.

Intergranular attack does not contribute to this local corrosion. Intergranular corrosion is characterized by deep penetration of attack along grain boundaries, thus creating spaces between the grains (and in severe cases, even loosening surface grains, which may actually fall out intact), without significant corrosion of the grains themselves. The integral grain structure found in the metal surrounding these X-8001 pits would not be present if intergranular attack were causing these pits. Compare Figure 10b with Figure 10c, which shows typical intergranular attack obtained during other testing.⁽²⁾

The general appearance of the affected pieces suggests that the attack was partly mechanical. The typical teardrop shaped pits, from which the various grooves and rippled corroded areas are plainly derived, are very unlike purely chemical or electrochemical pitting. The smooth metal surfaces within the pits are not characteristic of electrolytic corrosion. Chemical inhomogeneity of the can material could not be more than a contributing factor, reasoning from the distribution of attack along the fuel element charge. Finally, inspection of the corrosion rate curves, Figures 1-4, will show that the No. 1 piece is well away from the position of maximum chemical attack.

FIGURE 10

- (a) Cross Section of 6061 Aluminum Alloy Tubing Which Has Suffered Severe Cavitation Attack
- (b) Cross Section of X-8001 Aluminum Alloy Jacket from Fuel Element Shown in Figure 8
- (c) Cross Section of 1245 Aluminum Fuel Element Jacket Which Has Suffered Severe Intergranular Corrosion

There is, however, a qualitative resemblance to the teardrop patterns observed in "F" type pitting three or four years ago,⁽²⁰⁾ and to the corrosion attack produced during laboratory testing of the effects of reduced dichromate concentration on corrosion of aluminum in process water.⁽²¹⁾ In Figure 11a, a photograph of "F" type attack is shown next to a section (Figure 11b) of the piece shown in Figure 7. Since the "F" type attack was photographed under water it is difficult to say that the similarity of the teardrop pits is more than skin deep.

The accepted view of the cause of "F" type pitting states that, in the absence of sufficient dichromate, a protective oxide does not form sufficiently rapidly to repair the abrasive effects of process water;⁽²²⁾ it is, in effect, erosion-corrosion attack. This conclusion is supported by laboratory low dichromate testing, where deliberate addition of erosive material (diatomaceous earth purge material) to process water was found necessary to overcome the protective effects of dichromate concentrations as low as 0.1 parts per million.⁽²³⁾ Figure 11c is a photograph of a 1245 alloy fuel element jacket exposed in the laboratory in dichromate free process water with 1.8 ppm purge material concentration. Qualitative resemblance of this laboratory corrosion to the X-8001 pitting attack (Figure 11b) is more or less obvious, depending on the prejudices of the observer.

It has been indicated that two filter break-throughs occurred at H-Reactor during the exposure, producing periods of high turbidity, along with eight scheduled purges. The dichromate concentration at H-Reactor during the exposure was checked in the reactor log and found to be normal. Whether normal concentration (2 ppm) is sufficient during times of high turbidity is not known.

Additional support of erosion corrosion as the cause of the local attack may be found in the resemblance to impingement attack as described by H. R. Copson.⁽²⁴⁾ He writes in part: "Impingement attack is a form of erosion corrosion. It occurs when a turbulent aerated water stream impinges against a metal surface .... It is associated with continuous local breakdown

- (a) A 1245 Aluminum Alloy Jacketed Fuel Element Discharged from F Reactor in 1952.
Local attack popularly known as "F" type pitting.
- (b) Section of X-8001 Aluminum Alloy Jacketed Fuel Element Exposed under PT-IP-42A. (See Figure 8)
- (c) 1245 Aluminum Alloy Dummy Fuel Elements Exposed in Dichromate Free Process Water during Laboratory Testing.

FIGURE 11

and removal of protective films from the metal surface by impingement. . . . Typical impingement pits have a smooth rounded contour, and they are deeper and often undercut on the downstream side".

The special vulnerability of the No. 1 piece to the type of attack which can tentatively be called erosion corrosion, is not readily explained. The selectivity of the attack suggests that turbulence in the cooling water may have some effect on this pitting. The downstream piece is probably in a region of maximum turbulence. This arises from the fact that, although fuel element surface temperatures are less than maximum, the bulk effluent water temperature is at a maximum. The turbulence (Reynolds number), an inverse function of viscosity, increases with temperature and would be greatest at the downstream piece. The new tubes installed prior to the test would produce a somewhat reduced flow annulus at the top of the fuel element tending to raise surface temperature, favoring high turbulence at the point of greatest attack. It is recognized, however, that the localization of attack requires a sensitivity to apparently minor changes in flow characteristics. This point remains to be demonstrated in the laboratory.

While the erosion corrosion attack occurred in both X-8001 and 1245 alloy, the intensity of attack was far greater in the No. 1, X-8001 fuel element. Whether the intensity of attack was a function of alloy or position is not known.

The most plausible theory at the present time concerning the causes for this groove-pit attack is that a concentration of two ppm of dichromate is not quite sufficient to prevent erosion corrosion of aluminum by high purge or turbidity concentrations in 7.0 pH process water. Due either to metallurgical treatment during fabrication or canning or to inherent weakness in the metal, X-8001 alloy appears to be more susceptible to this type of attack than 1245 alloy.

CONCLUSIONS AND RECOMMENDATIONS

Two characteristics of X-8001 alloy were demonstrated by this production test:

1. Over-all uniform corrosion rates for X-8001 fuel element jackets are at least as good as the corrosion rates for 1245 alloy fuel element jackets.
2. The X-8001 alloy is more susceptible to a peculiar type of local attack than is 1245 alloy

Further tests are required to determine the significance of this local attack in terms of fuel element failure rates. Further tests might also result in better understanding of the causes of local attack and lead to practical control measures.

Variables related to localized X-8001 attack which are presently being studied, or should be studied in further testing include:

1. Purge concentrations
2. Dichromate concentrations
3. Low pressure and turbulent flow conditions
4. Minor alloy variations
5. Canning procedure variations
6. pH effects
7. Jet impingement

The effects of these variables should be measured during in-reactor testing wherever feasible. Substantial in-reactor testing of X-8001 alloy is being conducted. (25, 26, 27, 28, 29, 30, 31) This further testing includes some charges in which the No. 1 piece is 1245 alloy instead of X-8001. (25) Charges alternated in this manner may provide important information on the relative selectivity of this attack toward the different downstream pieces. Some out-of-reactor X-8001 testing has been conducted, and more is scheduled, to specifically study the effects of excess purge concentration and/or low dichromate concentration on X-8001 corrosion in regions of turbulent process water flow at high tube outlet temperatures. (15, 32)

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APPENDIX I

Tube Number	1074-C
Time of Operation, Days	92
Average Tube Power, kw	786
Exposure, MWD/T	568
Average Tube Outlet Temp., C	107.3
Average Tube Inlet Temp., C	7.7
Average Coolant Flow Rate, gpm	29.8
pH	7.0
Dichromate Concentration, ppm	2

No.	Wt. Loss gms/piece	Fuel Element Power (kw)	Local Water Temp. C	ΔT_c C*	T_c C	$\frac{1000}{T_c}$ °K	Corr. Rate, Mils/Mo.
1.	4.32	10.6	107.3	18.3	125.6	2.508	0.7
2.	9.89	14.6	105.9	25.3	131.2	2.472	1.6
3.	7.86	18.2	104.1	31.5	135.6	2.446	1.3
4.	14.60	21.7	101.8	37.5	139.3	2.424	2.4
5.	10.82	24.6	99.1	42.6	141.7	2.410	1.8
6.	17.27	27.4	96.1	47.4	143.5	2.399	2.9
7.	16.08	30.0	92.7	51.9	144.6	2.393	2.7
8.	15.89	32.2	88.8	55.7	144.5	2.394	2.6
9.	17.06	33.7	84.7	58.3	143.0	2.402	2.8
10.	13.16	34.8	80.4	60.2	140.6	2.416	2.2
11.	14.55	35.1	76.0	60.7	136.7	2.439	2.4
12.	11.19	35.0	71.5	60.6	132.1	2.467	1.9
13.	10.51	34.7	67.0	60.0	127.0	2.498	1.7
14.	6.65	34.2	62.7	59.2	121.9	2.531	1.1
15.	5.55	33.7	58.3	58.3	116.6	2.565	1.0
16.	4.31	32.9	53.9	56.9	110.8	2.604	0.7
17.	2.80	31.9	49.7	55.2	104.9	2.644	0.5

* Value of $k_2 = 1.73$ °C/kw/piece (average k_2) used in calculation of ΔT_c .

Tube Number	2160-C
Time of Operation, Days	91
Average Tube Power, kw	810
Exposure, MWD/T	579
Average Tube Outlet Temp., C	105.4
Average Tube Inlet Temp., C	7.7
Average Coolant Flow Rate, gpm	31.3
pH	7.0
Dichromate Concentration, ppm	2.0

No.	Wt. Loss gms/piece	Fuel Element Power (kw)	Local Water Temp. C	ΔT_c C*	T_c C	$\frac{1000}{T_c}$ °K	Corr. Rate, Mils/Mo.
1.	3.24	10.7	106.8	18.9	125.7	2.507	0.5
2.	12.20	13.1	105.5	23.2	128.7	2.488	2.0
3.	6.32	15.5	103.9	27.4	131.3	2.472	1.0
4.	11.96	18.1	101.9	32.0	133.9	2.456	2.1
5.	7.43	20.8	99.8	36.8	136.6	2.440	1.2
6.	12.72	23.5	97.4	41.6	139.0	2.426	2.1
7.	11.68	26.0	94.4	46.0	140.4	2.417	2.0
8.	12.39	28.4	91.3	50.3	141.6	2.411	2.1
9.	11.85	30.3	87.7	53.6	141.3	2.413	2.0
10.	10.17	31.9	83.9	56.5	140.4	2.418	1.7
11.	9.48	33.2	80.0	58.8	138.8	2.427	1.6
12.	8.26	34.4	76.0	60.9	136.9	2.438	1.4
13.	7.31	35.6	71.9	63.0	134.9	2.450	1.2
14.	5.90	36.4	67.7	64.4	132.1	2.467	1.0
15.	4.91	36.9	63.3	65.3	128.6	2.488	0.8
16.	3.91	36.9	58.7	65.3	124.0	2.517	0.7
17.	3.55	36.6	54.0	64.8	118.8	2.551	0.6

* Value of $k_2 = 1.77$ °C/kw/piece used in calculation of ΔT_c .

Tube Number 2065-H
 Time of Operation, Days 152
 Average Tube Power, kw 707
 Exposure, MWD/T 845
 Average Tube Outlet Temp., C 100.2
 Average Tube Inlet Temp., C 9.2
 Average Coolant Flow Rate, gpm 29.5
 pH 7.0
 Dichromate Concentration, ppm 2.0

No.	Wt. Loss gms/piece	Fuel Element Power (kw)	Local Water Temp. C	ΔT_c C*	T_c C	$\frac{1000}{T_c} ^\circ K$	Corr. Rate, Mils/Mo.
1.	5.3	9.5	99.0	16.5	115.5	2.573	0.6
2.	--	12.6	97.4	21.9	119.3	2.547	--
3.	16.8	15.4	95.4	26.8	122.2	2.529	1.9
4.	22.9	18.7	93.0	32.5	125.5	2.508	2.6
5.	19.3	21.2	90.2	36.9	127.1	2.498	2.2
6.	25.2	22.8	87.3	39.7	127.0	2.498	2.8
7.	18.7	24.3	84.2	42.3	126.5	2.501	2.1
8.	18.2	25.3	80.9	44.0	124.9	2.511	2.0
9.	14.0	26.1	77.6	45.4	123.0	2.524	1.6
10.	11.2	26.5	74.1	46.1	120.2	2.541	1.3
11.	9.7	27.0	70.6	47.0	117.6	2.558	1.1
12.	6.6	26.8	67.2	46.6	113.8	2.583	0.7
13.	5.8	26.5	63.7	46.1	109.8	2.610	0.6
14.	3.9	26.1	60.4	45.4	105.8	2.638	0.4
15.	3.3	25.5	57.1	44.4	101.5	2.668	0.4
16.	2.7	24.9	54.0	43.3	97.3	2.699	0.3
17.	2.1	24.5	50.7	42.6	93.3	2.728	0.2

* Value of $k_2 = 1.74 ^\circ C/kw/piece$ used in calculation of ΔT_c .

Tube Number	2086-H
Time of Operation, Days	152
Average Tube Power, kw	663
Exposure MWD/T	792
Average Tube Outlet Temp., C	100.0
Average Tube Inlet Temp., C	9.2
Average Coolant Flow Rate, gpm	27.7
pH	7.0
Dichromate Concentration, ppm	2.0

No.	Wt. Loss gms/piece	Fuel Element Power (kw)	Local Water Temp. C	ΔT_c C*	T_c C	$\frac{1000}{T_c} ^\circ K$	Corr. Rate, Mils/Mo.
1.	--	1.9	99.7	3.3	103.0	2.658	--
2.	8.9	3.1	99.3	6.6	105.9	2.637	1.0
3.	8.4	5.4	98.6	11.2	109.8	2.610	0.9
4.	10.9	8.4	97.5	17.6	115.1	2.575	1.2
5.	15.3	11.3	95.9	23.7	119.6	2.545	1.7
6.	15.3	14.4	93.9	30.1	124.0	2.517	1.7
7.	10.6	17.4	91.5	36.5	128.0	2.492	1.2
8.	21.3	20.6	88.7	43.1	131.8	2.469	2.4
9.	16.5	23.4	85.5	49.0	134.5	2.452	1.8
10.	14.3	25.3	82.0	52.9	134.9	2.450	1.6
11.	12.2	26.4	78.5	55.2	133.7	2.457	1.4
12.	10.8	27.2	74.7	56.9	131.6	2.470	1.2
13.	9.0	27.9	70.9	58.5	129.4	2.483	1.0
14.	6.0	28.5	67.0	59.7	126.7	2.501	0.7
15.	3.5	28.8	63.1	60.2	123.3	2.522	0.4
16.	5.2	28.9	58.8	60.6	119.4	2.547	0.6
17.	3.9	28.8	55.2	60.2	115.4	2.573	0.4

* Value of $k_2 = 1.73 ^\circ C/kw/piece$ (Average k_2) used in calculation of ΔT_c .

Tube Number	2865-H
Time of Operation, Days	152
Average Tube Power, kw	694
Exposure MWD/T	829
Average Tube Outlet Temp., C	98.5
Average Tube Inlet Temp., C	9.2
Average Coolant Flow Rate, gpm	29.5
pH	7.0
Dichromate Concentration, ppm	2.0

No.	Wt. Loss gms/piece	Fuel Element Power (kw)	Local Water Temp. C	ΔT_c C*	T_c C	$\frac{1000}{T_c} ^\circ K$	Corr. Rate, Mils/Mo.
1.	3.8	8.5	98.5	13.6	112.1	2.595	0.4
2.	10.9	12.0	97.5	19.2	116.7	2.564	1.1
3.	12.3	14.5	96.1	23.2	119.3	2.547	1.2
4.	16.1	16.8	94.4	26.9	121.3	2.534	1.6
5.	14.7	18.9	92.2	30.2	122.4	2.527	1.5
6.	14.7	20.5	89.8	32.8	122.6	2.526	1.5
7.	14.9	21.8	87.1	34.9	122.0	2.530	1.5
8.	12.9	23.2	84.4	37.1	121.5	2.533	1.3
9.	10.9	24.2	81.2	38.7	119.9	2.544	1.1
10.	8.9	25.1	78.3	40.2	118.5	2.552	0.9
11.	7.7	25.7	74.9	41.1	116.0	2.569	0.8
12.	6.5	26.1	71.7	41.8	113.5	2.585	0.6
13.	4.6	26.1	68.3	41.8	110.1	2.608	0.5
14.	3.7	25.1	64.9	40.2	105.1	2.643	0.4
15.	3.0	24.3	61.8	38.9	100.7	2.674	0.3
16.	1.8	23.8	58.6	38.1	96.7	2.703	0.2
17.	1.6	23.2	55.0	37.1	92.1	2.737	0.2

* Value of $k_2 = 1.60 ^\circ C/kw/piece$ used in calculation of ΔT_c .

Tube Number	3376-H
Time of Operation, Days	152
Average Tube Power, kw	694
Exposure MWD/T	829
Average Tube Outlet Temp., C	98.5
Average Tube Inlet Temp., C	9.2
Average Coolant Flow Rate, gpm	29.5
pH	7.0
Dichromate Concentration, ppm	2.0

No.	Wt. Loss gms/piece	Fuel Element Power (kw)	Local Water Temp. C	ΔT_c C*	T_c C	$\frac{1000}{T_c}$ °K	Corr. Rate, Mils/Mo.
1.	3.3	8.0	98.5	13.5	112.0	2.596	0.3
2.	4.7	12.0	97.4	20.3	117.7	2.558	0.5
3.	--	14.7	95.9	24.8	120.7	2.538	--
4.	17.3	17.7	94.1	29.9	124.0	2.517	1.7
5.	12.0	20.1	91.8	34.0	125.8	2.506	1.2
6.	24.5	22.5	89.0	38.0	127.0	2.498	2.5
7.	12.3	24.1	85.9	40.7	126.6	2.501	1.2
8.	18.0	25.3	82.9	42.8	125.7	2.506	1.8
9.	13.9	26.3	80.1	44.4	124.5	2.514	1.4
10.	10.1	27.1	76.7	45.3	122.0	2.530	1.0
11.	9.2	27.7	73.7	46.8	120.5	2.540	0.9
12.	7.9	27.9	70.1	47.2	117.3	2.560	0.8
13.	5.1	28.1	66.7	47.5	114.2	2.581	0.5
14.	3.6	27.9	63.2	47.2	110.4	2.606	0.4
15.	3.8	27.1	59.6	45.3	104.9	2.644	0.4
16.	2.8	26.1	56.3	44.1	100.4	2.676	0.3
17.	1.6	25.3	52.7	42.8	95.5	2.712	0.2
18.	2.4	24.3	49.3	41.1	90.4	2.750	0.2
19.	2.0	23.7	46.3	40.1	86.4	2.780	0.2
20.	2.4	23.5	43.2	39.7	82.9	2.808	0.2
21.	0.9	23.7	40.2	40.1	80.3	2.828	0.1
22.	0.9	24.5	37.1	41.4	78.5	2.843	0.1

* Value of $k_2 = 1.69$ °C/kw/piece used in calculation of ΔT_c .

APPENDIX II

CALCULATION OF k_2 FROM LOCAL WATER TEMPERATURE
AND FUEL ELEMENT POWER DATA

TUBE 1074-C

107 C	+	9.5 k_2	=	60.5 C	+	28.5 k_2
106 C	+	12.4 k_2	=	65.5 C	+	29.5 k_2
104 C	+	15.4 k_2	=	70.0 C	+	29.6 k_2
102 C	+	17.4 k_2	=	74.8 C	+	29.4 k_2
99.2 C	+	20.8 k_2	=	79.3 C	+	29.2 k_2
<u>96.5 C</u>	+	<u>23.3 k_2</u>	=	<u>84.7 C</u>	+	<u>28.7 k_2</u>
614.7 C	+	98.8 k_2		434.8 C		174.9 k_2

$$k_2 = 2.36$$

TUBE 2160-C

A 106.1 C	+	10.6 k_2	=	51.5 C	+	36.1 k_2
B 105.4 C	+	13.0 k_2	=	63.2 C	+	36.9 k_2
C 104.0 C	+	15.7 k_2	=	69.4 C	+	36.0 k_2
D 102.7 C	+	17.1 k_2	=	75.0 C	+	34.7 k_2
E 99.8 C	+	20.8 k_2	=	79.5 C	+	33.3 k_2
F <u>97.3 C</u>	+	<u>23.2 k_2</u>	=	<u>84.0 C</u>	+	<u>32.0 k_2</u>
615.3 C	+	100.4 k_2		422.6 C		209.0 k_2

$$k_2 = 1.77$$

TUBE 2065-H

99.0 C	+	9.5 k ₂	=	64.5 C	+	26.5 k ₂
98.5 C	+	11.0 k ₂	=	69.5 C	+	27.0 k ₂
98.0 C	+	11.8 k ₂	=	73.0 C	+	26.7 k ₂
97.5 C	+	13.0 k ₂	=	76.5 C	+	26.3 k ₂
96.5 C	+	14.2 k ₂	=	78.5 C	+	25.8 k ₂
<u>94.5 C</u>	+	<u>17.0 k₂</u>	=	<u>82.0 C</u>	+	<u>24.8 k₂</u>
584.0 C		76.5 k ₂		444.0 C	+	157.1 k ₂

$$k = 1.74$$

TUBE 2086-H

99.5 C	+	2.0 k ₂	=	59.0 C	+	28.9 k ₂
99.2 C	+	3.2 k ₂	=	67.0 C	+	28.5 k ₂
98.4 C	+	5.4 k ₂	=	72.5 C	+	27.7 k ₂
98.0 C	+	7.4 k ₂	=	77.0 C	+	26.7 k ₂
96.6 C	+	9.6 k ₂	=	80.8 C	+	25.7 k ₂
<u>94.2 C</u>	+	<u>13.8 k₂</u>	=	<u>84.3 C</u>	+	<u>24.0 k₂</u>
585.9 C		41.4 k ₂		440.6	+	161.5 k ₂

$$k_2 = 1.21$$

TUBE 2865-H

98.7 C	+	8.5 k ₂	=	66.0 C	+	25.5 k ₂
98.2 C	+	10.2 k ₂	=	71.3 C	+	26.1 k ₂
97.8 C	+	11.4 k ₂	=	76.3 C	+	25.6 k ₂
97.0 C	+	12.7 k ₂	=	80.0 C	+	24.6 k ₂
96.3 C	+	14.4 k ₂	=	83.3 C	+	23.5 k ₂
<u>94.4 C</u>	+	<u>16.0 k₂</u>	=	<u>86.0 C</u>	+	<u>22.4 k₂</u>
582.4 C	+	73.2 k ₂	=	462.9 C	+	147.7 k ₂

$$k_2 = 1.60$$

TUBE 3376-H

98.2 C	+	8.8 k ₂	=	64.0 C	+	25.5 k ₂
97.8 C	+	10.6 k ₂	=	68.0 C	+	26.8 k ₂
97.0 C	+	12.5 k ₂	=	71.0 C	+	27.1 k ₂
95.5 C	+	15.5 k ₂	=	77.0 C	+	28.0 k ₂
94.0 C	+	17.8 k ₂	=	80.0 C	+	28.1 k ₂
<u>92.0 C</u>	+	<u>20.4 k₂</u>	=	<u>83.0 C</u>	+	<u>27.9 k₂</u>
574.5 C		85.6 k ₂		443.0 C	+	163.4 k ₂

$$k_2 = 1.69$$

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APPENDIX III

COMPARISON OF GRAPHICAL METHOD WITH CORROSION RATE
CORRELATION USING THE SEIDER-TATE RELATION

Values for ΔT_c were originally calculated using heat transfer rates determined from the Seider-Tate relation plus an empirical film correction. For a description of the application of the Seider-Tate relation and the empirical correction most frequently used in connection with HAPO reactor data see HW-34196.* The ΔT_c 's calculated from the graphical method exceed by as much as a factor of three the ΔT 's deduced from the Seider-Tate relation. For the conditions encountered during this test, the Seider-Tate calculation also displaces the point of maximum predicted corrosion with respect to the observed maximum and does not properly predict the diminution of corrosion at the downstream end of the charge.

The method described in HW-34196 was developed from data obtained under different conditions of temperature and water quality than those of this report. These changes in corrosion environment are sufficient to make the use of the parameters of HW-34196 questionable under current reactor operating conditions.

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* deHalas, D. R., The Corrosion of Hanford Fuel Elements - Method for Treatment and Analysis of In-Pile Corrosion Data, HW-34196, December 21, 1954 (Secret).

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ABSTRACT

Six alternated charges of aluminum jacketed fuel elements, canned in either X-8001 or 1245 aluminum alloy, have been exposed in-reactor in Hanford process water. Data from this test show no significant difference in corrosion rates between these two aluminum alloys at outlet water temperatures up to 110 C. An unusual type of pitting attack occurred during this test on several downstream X-8001 jacketed elements, and to a less extent on some 1245 jacketed pieces. Causes of this unusual attack are not presently defined, but similarities to erosion corrosion observed in Hanford reactors and described in the corrosion literature have been noted.

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