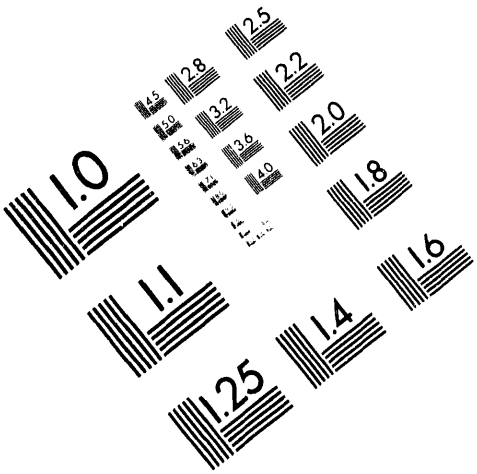

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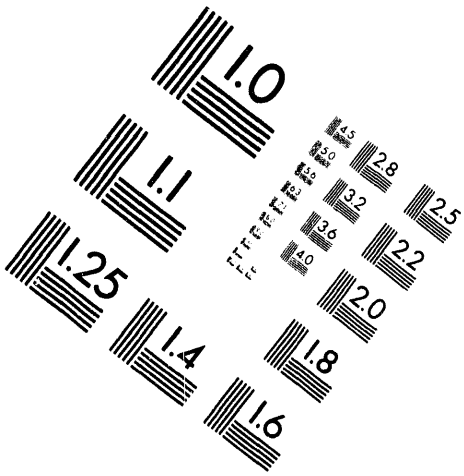

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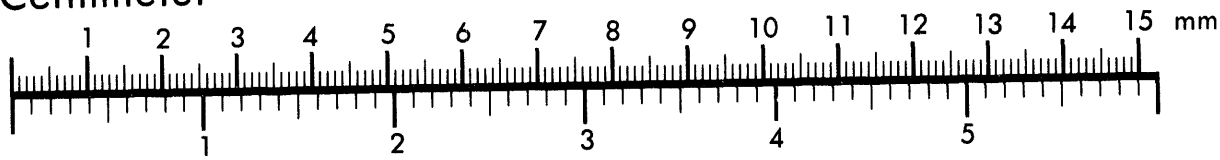

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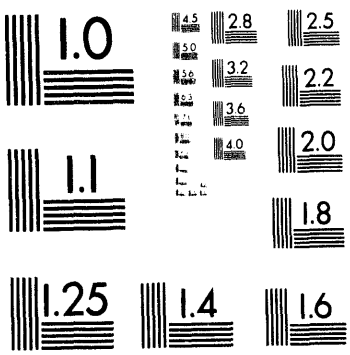

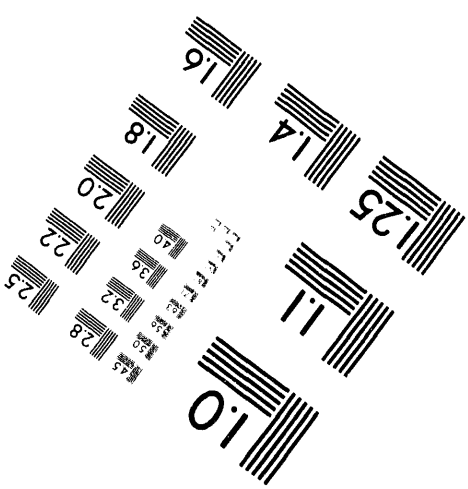

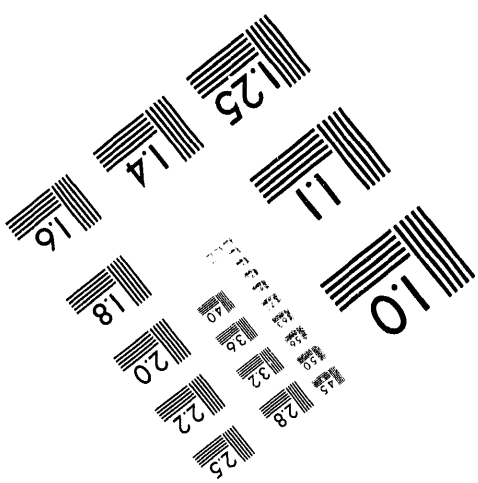

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FINAL REPORT ON PROGRAM

FOR USING X-8001 ALUMINUM ALLOY CLADDING MATERIAL

FOR HANFORD FUEL ELEMENTS

PT IP-43-A-84-MT, IP-80-A-91 FP and IP-2-I-99 FP

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Engineer, Process Engineering Operation

Fuels Preparation Department

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FINAL REPORT ON PROGRAM FOR USING X-8001 ALUMINUM ALLOY CLADDING MATERIAL FOR HANFORD FUEL ELEMENTS

PT-IP-43-A-84-MT, IP-80-A-91-FP and IP-2-I-99-FP

INTRODUCTION

Development of the technology for the use of X-8001 aluminum alloy as a fuel element cladding material for the Hanford reactors was initiated because of the superior resistance (based on laboratory studies) of this alloy to intergranular corrosion as compared to the C-64 alloy. Solid and I & E natural uranium fuel element irradiation performance has continued to indicate planned increases in reactor power will be limited by side "hot spot" failures. Localized areas of increased corroding surface temperatures associated with fuel element misalignment, distortion, or poor heat transfer properties have long been suspected as factors contributing to "hot spot" failures. Since the intergranular attack of C-64 alloy is initiated at temperatures in the order of 200 C and in excess of 350 C on X-8001 alloy, it was expected that X-8001 alloy would significantly reduce the hot spot rupture rate. Preliminary tests indicated that indeed X-8001 alloy resisted intergranular attack. However, severe pitting attack observed intermittently on downstream fuel elements clad in X-8001 alloy, and recently associated with side-other ruptures in old reactors has caused concern about continued use of this alloy. The purpose of this report is to summarize the evaluation of X-8001 alloy fuel element cladding and serve as a final report for PTs 43-A-84-MT,[1] IP-80-A-91-FP,[2] and PITA-IP-2-I-99-FP.[3]

SUMMARY

The irradiation performance of X-8001 alloy clad fuel elements during the past year cast some doubt on the suitability of this alloy for future use as fuel element cladding material. Since 1957, approximately 1,720,000 X-8001 alloy clad elements have been irradiated in the production reactors.

1. HW-47221 D, "Supplement A to Production Test IP-43-A-84-MT, Evaluation of the Uniform Corrosion Resistance of M-388 Alloy Slug Jackets". F. W. Van Wormer. April 4, 1957. (Secret)
2. HW-50141 C, "Production Test IP-80-A-91-FP, Evaluation of M-388 Alloy Fuel Element Jackets in Semi-Production Quantities". F. W. Van Wormer. July 1, 1957. (Secret)
3. HW-56704 C, "Process Improvement Transition Authorization IP-2-I-99-FP, Irradiation of X-8001 Alloy Jacketed Fuel Elements in Production Quantities". R. R. Bloomstrand. July 10, 1958. (Secret)

These include 126,000 solid, 40,000 cored, and 1,554,000 I & E fuel elements. The irradiation performance has continued to demonstrate the resistance of X-8001 alloy to intergranular attack, as well as equivalence to C-64 alloy in uniform corrosion rates. However, X-8001 alloy is more susceptable to a localized pitting as shown in Fig. 1, which appears to be associated with certain flow and temperature conditions and/or with mechanical damage to the autoclave film. Internal ruptures early in 1959 in both C-64 and X-8001 alloy components which may have been associated with fabrication problems have essentially been eliminated. The means have been found to circumvent difficulty in extrusion, cleaning for canning, and wetting X-8001 alloy with Al-Si during canning. Processing of large quantities of X-8001 clad fuel elements has permitted improvements in all stages of fabrication of the components and fuel elements, thus insuring the quality of X-8001 clad fuel elements being equal in all respects to C-64 clad counterparts.

At present reactor operating conditions there appears to be no significant difference in uniform corrosion rates of X-8001 and C-64 alloy. Extrapolation of the corrosion data to future operating conditions has led to the hypothesis that X-8001 alloy will perform better at anticipated increases in reactor power and coolant outlet temperatures. There are limited data taken from a laboratory comparison of the intergranular corrosion of the two alloys to substantiate these conclusions. Although both laboratory and in-reactor experience indicate X-8001 alloy is more resistant than C-64 alloy to intergranular attack, X-8001 alloy is susceptible to at least two forms of accelerated attack -- one of which is characterized by "hot spots" (not intergranular) and the other by groove pitting. Both forms of attack are suspected of contributing to jacket corrosion ruptures. A comparison of failure rates does not reveal a significant difference in the performance of the two alloys. These data, therefore, do not support the argument for exclusive utilization of either alloy.

Since there exists a potential superiority of X-8001 alloy at higher reactor power levels and temperature and there appears to be no difference in rupture incidence of the two alloys, based on the engineering recommendation,[4] the decision has been made to convert completely to the use of the X-8001 alloy for fuel jacketing components. The quantities of fuel elements tested strongly indicate the use of either alloy would permit operation of HAPO reactors at present power levels without incurring serious rupture problems. X-8001, however, offers the greater potential for satisfactory operation under proposed increases in reactor power and bulk outlet temperatures.

Brief summaries of results from production tests IP-43-A-84-MT, IP-80-A-91-FP, and Process Improvement Transition Authorization IP-2-I-99-FP, are included in appendix to this report.

4. Undocumented, "Termination of Ordering of C-64 Alloy Components". R. W. Reid and J. H. Brown. April 5, 1960. (Confidential)

Fig. 1 X-8001 alloy clad fuel element surface showing local accelerated (groove) pitting. (Tube: 3678-D, Position No. 4 from downstream) 0.75X

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DISCUSSION

Technical Basis for Use of X-8001 Alloy

Early data on possible fuel element cladding materials indicated that for optimum corrosion resistance, neutron cross-section, strength, and other pertinent variables, the best jacketing material would be aluminum. Corrosion data at that time indicated the purest aluminum alloy attainable would be the most desirable material to use. From this eventually evolved the fuel jacketing alloy, 1245. First indications that the high purity alloy would not withstand high temperature corrosion were manifest in 1955, when power and exposure increases resulted in 40 of 164 ruptures sustained in that year being classified as having been caused by localized accelerated corrosion of the jacket wall. Further power and exposure increases resulted in 48 of 142 ruptures sustained in 1956 being classified as jacket side-wall failures (termed hot spots). Metallographic examination of fuel element jackets from these ruptures showed the cause to be rapid intergranular corrosion.[5] This type of attack has been reproduced in laboratory tests by exposure to water above 200 C,[6] or to steam at temperatures above 300 C.[5] Flow perturbances due to fuel element misalignment, worn tube ribs, etc., and are believed to have been the causes of the high local jacket temperature, necessary for the occurrence of intergranular corrosion.

The increased side hot spot failure rate, and the concommitant fuel jacket swelling which resulted in "stuck" failures, caused a severe loss of reactor operating efficiency. Programs were then instituted to: (a) prevent fuel misalignment, and (b) investigate more corrosion resistant aluminum alloys.

Comparisons of various aluminum alloys in de-ionized water in the temperature range of 100-363 C indicated X-8001 aluminum alloy (1.0 w/o Ni - 0.5 w/o Fe) offered a greatly improved resistance to intergranular attack.[7,8] Flow laboratory tests on X-8001 ~~alloy~~ alloy in reactor process water indicated its normal (uniform) corrosion behavior was similar to 1245 alloy can stock.[9,10,11] X-8001 alloy has a relatively small percentage of heavy

5. HW-38030, "Interim Report on the Examination of Low Exposure Failures". D. P. O'Keefe. July 20, 1955. (Secret)
6. 57GL129, "Temperature Dependence of Aluminum Corrosion". General Electric General Engineering Laboratory, Corrosion Symposium - 1956. R. L. Dillon. August 12, 1957. (Unclassified)
7. HW-37637, "High Temperature Aqueous Corrosion of Commercial Aluminum Alloys". R. L. Dillon, R. E. Wilson, and V. H. Troutner. January 11, 1956. (Unclassified)
8. ANL-5430, "Corrosion Resistant Aluminum Above 200 C". J. E. Draley and W. E. Ruther. July 15, 1955. (Unclassified)
9. HW-36692, "The Corrosion of Aluminum and Its Alloys". C. Groot and R. M. Peekema. May 13, 1955. (Undocumented)
10. HW-45054, "A Review of the Aluminum Development Program". N. R. Miller and R. J. Lobsinger. August 21, 1956. (Secret)
11. HW-49425, "Preliminary Evaluation of M-388 Aluminum Cladding". N. R. Miller. March 26, 1957. (Secret)

metal additions and thus a low cross-section to thermal neutrons. Since it could be readily fabricated into cladding components by the same techniques used for the 1245 alloy, it was selected as a possible candidate to replace 1245 alloy.

Subsequent experience during the evaluation of components supplied by a potential new vendor in 1957[12] demonstrated the consequences of low-iron concentration on the resistance of 1245 alloy to intergranular attack. Component specifications were revised for an alloy having a minimum iron content of 0.35 percent and designated as C-64. Comparison of the in-reactor performance of C-64 and X-8001 alloy-clad fuel elements has proceeded since 1957.

ACTUAL PERFORMANCE

Based on laboratory data, X-8001 alloy jacketing material appeared to be superior to C-64 alloy from the standpoint of improved intergranular corrosion resistance with essentially no difference in uniform corrosion. However, if a difference existed, the real proof must necessarily be based on in-reactor performance. Since the inception of the in-reactor test program, approximately 1,720,000 fuel element clad in X-8001 alloy jackets have been irradiated. Included were 126,000 solid, 40,000 cored and 1,554,000 I & E fuel elements. The initial, small-scale production tests on solid fuel elements indicated the uniform corrosion rates were not significantly different; however, X-8001 alloy was more susceptible to a localized accelerated attack characterized as "groove pitting". During the course of the pilot evaluation, an X-8001 alloy-clad solid hot spot failure occurred in D Reactor. Subsequent examination of this failure in the Radiometallurgy Laboratory[13] revealed evidence of melting of the jacket at the hot spot. Other evidences of high temperature operation included spheroidization of the Al-Si bond and a beta transformed zone in the core, under the hot spot. There was no evidence of intergranular corrosion of the aluminum. Based on this demonstrated resistance to intergranular attack, and the previous uniform corrosion data, all remaining cored fuel elements (40,000 pieces) were canned in X-8001 alloy BNTL[14] components and irradiated in KE Reactor. Since a majority of the earlier cored failures had been classified as hot spots, the combination of X-8001 alloy and BNTL contours was expected to eliminate cored fuel element failures and permit evaluation of the cored fuel element as a means of preventing core splits. In addition, 35,000 solid fuel elements jacketed in X-8001 alloy BNTL components, were irradiated in Dr Reactor. There were five hot spot ruptures (four cored and one solid) sustained

12. Undocumented, "Rupture Memorandum - September, 1957". J. F. Music. November 14, 1957. (Confidential)
13. HW-53254, "Examination of Hot Spot Failure of an M-388 Alloy Jacket Slug - (RM 197)". W. S. Kelly. November 16, 1957. (Secret)
14. HW-50152 D, "Final Report - Irradiation of Fuel Elements Having Blunt Nose Tru-Line End Contours - PT IP-81-A-92-FP". W. H. Hodgson. February 4, 1960. (Secret)

in the X-8001 alloy clad BNTL fuel elements. A comparison of the side failure rate of X-8001 alloy clad cored and solid BNTL with 1245 alloy clad solid irradiated simultaneously showed that the failure rate of the X-8001 alloy BNTL was 3.8 times that of the 1245 alloy in KE and DR Reactors at the 95 percent confidence level.[15] Subsequent performance of X-8001 and C-64 alloy clad I & E solid fuel elements is summarized in Table I.

Table I

RUPTURE FREQUENCY OF C-64 AND X-8001 ALLOY CLAD FUEL ELEMENTS

BY ALLOY

(Including Natural and Enriched Fuel Elements)

		Pieces Discharged		Number Ruptures		Rupture Frequency Ruptures/10^6 Pieces Discharged	
Year	Type	X-8001	C-64	X-8001	C-64	X-8001	C-64
1957	Solid	4,374	1,470,236	1	168	223.7	114.2
	I & E	0	17,236	0	1	0	58.0
1958	Solid	87,322	1,052,174	10	99	114.3	94.1
	I & E	87,800	336,564	5	33	50.1	98.0
1959	Solid	27,502	213,050	1	3	35.5	14.1
	I & E	931,372	567,544	40	16	43.3	28.2

For natural I & E fuel elements in 1959, the rupture frequency may be expressed: for C-64 alloy ($10^6/377,432$) x 14 = $37.7/10^6$ (1/27,000) and for X-8001 alloy ($10^6/872,602$) x 40 = $45.8/10^6$ (1/22,000).

In 1957, the bulk of the X-8001 alloy clad fuel elements were irradiated in small-scale production tests. Production scale loadings of X-8001 alloy clad fuel elements were initiated in 1958. Upon conversion of the reactors to I & E loadings, utilization of X-8001 alloy was further accelerated. Early in 1959, the central zones of all old reactors and KW Reactor were essentially loaded with X-8001 alloy clad fuel elements. Only the C and KE Reactors contained primarily C-64 alloy clad elements. During 1959, and attempt was made to balance the quantities of X-8001 and C-64 alloys in the C, F, and H Reactors. A comparison of the rupture rates is shown in Table II.

15. Undocumented, "Rupture Memorandum". J. F. Music. April 16, 1958. (Confidential)

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Table II

COMPARISON OF RUPTURE RATES BY REACTOR AND ALLOY (1959)

(Rates Based on Pieces Discharged)

	Pieces Discharged		Number Ruptures		Rupture Frequency Pcs./10^6		Ratio of Frequencies
Reactor	X-8001	C-64	X-8001	C-64	X-8001	C-64	X-8001/C-64
B	90,814	33,388	3	1	33.0	30.0	1.10
D	84,184	32,606	4	2	47.5	61.3	0.77
DR	81,634	34,340	6	1	73.5	29.1	2.52
F	84,966	39,338	3	2	35.3	50.8	0.70
H	104,002	27,268	8	0	76.2	0	0
C	45,254	95,846	2	6	44.2	62.6	0.71
KE	130,452	107,692	5	1	38.3	9.3	4.12
KW	250,306	6,954	9	1	36.0	143.8	0.25
Totals	872,602	377,432	40	14	45.8	37.1	1.23

From Table II it will be noted the only true balance in numbers of pieces discharged was in KE Reactor, where the rupture rate of X-8001 alloy clad fuel elements was over four times that of C-64 alloy clad elements.

If the quality of the fuel elements clad in the two alloys were the same, the higher rupture frequency of X-8001 alloy may be due to a larger proportion of X-8001 alloy clad fuel elements being exposed in higher flux zones of the reactors. A simple comparison of ratios of discharged pieces to average numbers of pieces undergoing irradiation denoted the discharge rate of fuel elements clad in C-64 alloy was higher in all reactors except C Reactor and KW Reactor. A comparison of this ratio (1.12) for November and December, 1959, indicates that the current trend is to expose the X-8001 in the high flux zones, whereas early in 1959 the converse was true.

Examination of X-8001 alloy clad "hot spot" fuel element failures in the Radiometallurgy Laboratory[13,16,17] has failed to reveal intergranular corrosion as a cause of failure. Hot spots on X-8001 alloy jackets had the characteristic flow pattern and Al-Si bond spheroidization, the latter indicating high local bond temperatures; however, intergranular corrosion was not observed.

16. HW-50157, "Examination of M-388 Rupture from IP-80-A (RM-224)". W. J. Gruber. June 16, 1959. (Confidential)
17. HW-55964, "Examination of Ruptured M-388 Clad BNTL Slug from IP-80-A". W. S. Kelly. May 6, 1958. (Secret)

In addition to the failed pieces, other incidence of hot spots have been reported. In the measured charges from PT-IP-81-A-92-FP,[14] seventeen of 192 X-8001 alloy BNTL solid pieces were reported to have hot spots. X-8001 alloy clad I & E fuel elements in more recently measured charges for various production tests have also exhibited hot spots. The frequency of hot spots on C-64 and X-8001 alloy clad fuel elements appears to be the same.

Utilization of self-supported fuel elements in ribless reactor process channels offers a means of eliminating the side hot spot failure mechanism. To date, approximately 34 self-supported I & E charges and nine self-supported solid charges have been irradiated to normal discharge goals without incidence of hot spots. To demonstrate the rupture potential of the self-supported design and simulate future operating conditions, four columns each of enriched (1.47 percent U-235) seven-inch, X-8001 alloy clad CIIIE self-supported I & E and OIIE I & E controls were charged for run-to-rupture in the B Reactor ribless tube facility. Two control charges failed at low exposures. A side hot-spot rupture occurred at 286 MWD/T and a side-other rupture was sustained in 353 MWD/T. The remaining controls were discharged immediately. Irradiation of the self-supported elements continued without incident until they were discharged without rupture at approximately 850 MWD/T, having demonstrated a 30-fold improvement over the controls at the 95 percent confidence level. The maximum tube power and specific power were in the ranges 1200 to 1310 KW and 90 to 140 KW/feet, respectively. Visual examination revealed no hot spots on the self-supported elements, whereas the controls averaged one for each seven pieces irradiated. Further examination of two of the controls in the Radiometallurgy Laboratory revealed evidence of intergranular attack of the X-8001 alloy jackets. The self-supported pieces were reported to have lost up to ten grams by uniform corrosion and downstream pieces exhibited severely corroded pieces.

Severe localized corrosion (not revealed by weight loss results) of several X-8001 alloy clad solid pieces and some C-64 alloy clad solid pieces was discovered during visual examination of early test fuel elements.[18] This local attack appeared as groups of smooth surfaced teardrop-shaped pits. In most of the groups, individual pits had grown together or overlapped to form long, straight grooves or large corroded areas. Visual examination of the cleaned pieces revealed the most severe attack occurred on the downstream pieces (one through 16) decreasing in severity as the pieces were displaced upstream. The most aggravated attack appeared opposite the rib marks. Because of the long deep pits noted in the initial testing, the phenomenon has been called groove pitting. Groove pitting was first observed in solid fuel elements which had the common characteristics of (a) high core temperature with resultant high jacket temperature (b) moderate coolant flow velocity (c) high coolant temperature and (d) low coolant vapor

18. HW-56523, "In-Reactor Corrosion of X-8001 and 1245 Aluminum-Analysis of Data from PT-IP-42-A". R. L. Dillon and R. B. Richman. June 25, 1958. (Secret)

pressure on downstream pieces. Subsequently, groove pitting was noted intermittently on solid pieces discharged from the old reactors until flow rates were increased under Project CG-558 and I & E elements replaced solid elements in the central zones of all old reactors. This phenomenon was not observed again until the fourth quarter of CY 1959, when a majority of the ruptures in the old reactors exhibited groove pitting. Five of the eight X-8001 alloy clad ruptures reported in the same quarter were in new tubes. Since then, groove pitting has been observed on measured PT pieces from all reactors except C Reactor.

Possible factors which alone, or in combination, might cause this type of attack include cavitation, mechanical abrasion (erosion), intergranular attack, electrolytic corrosion, and water turbulence (erosion). Certain surface conditions of the jacket may also be necessary for the groove pitting. These include segregation of alloying constituents in the cladding surface, formation of a brittle oxide (autoclave) film which may be mechanically damaged by flowing water[19] and mechanical damage to the autoclave film prior to irradiation resulting in sacrificial corrosion in the damaged area. These latter "grooves" have appeared as a result of scratches but may be caused by other mechanical damage to the film. An in-reactor test[20] to reproduce the groove phenomena was interrupted by a failure which necessitated discharge of the entire test at about 50 percent of goal exposure. Coincidental with the in-reactor test, arrangements were made with the component vendor for increased "scalping" of the bloom stock from which X-8001 alloy components were fabricated, to reduce observed nickel segregation. The apparent relief of the groove pitting problem, which coincided with increased use of the segregation-free components, resulted in a de-emphasis of testing programs to reproduce the groove pitting phenomenon. Subsequent experience has shown that in spite of the improvement in jacket surface fabrication, decrease in the incidence of groove pitting may have been the result of lower tube outlet temperatures and that once again it is a serious corrosion problem in the old reactors.

Cavitation has been considered as a possible cause for localization of the erosion-corrosion attack.[18] However, it is not a satisfactory explanation for two reasons. Cavitation leaves a characteristically rough blasted surface, in contrast to the clean-cut, smooth surface of the X-8001 alloy jacket surface pits. Cavitation is readily identified from micrographic cross-sections of affected areas which show heavy mechanical working of the surface grains. Mechanical working of the surface grains has not been observed on any of the micrographic sections of groove pits, to date.

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 without signifi-

19. F. H. Krenz, "Corrosion of Aluminum-Nickel Type Alloys in High Temperature Aqueous Service". Corrosion 13, 575t-81t (1957).
20. HW-54010, "Production Test IP-124-A, Investigation of Conditions Leading to the Severe Pitting of M-388 Alloy Slug Jackets". N. R. Miller. December 3, 1957. (Secret)

cant corrosion of the grains themselves. Intergranular corrosion has not been seen on micrographic section of aluminum adjacent to groove pits.

The general appearance of the affected pieces suggests the attack was partly mechanical. The typical teardrop-shaped pits from which the grooves or large corroded areas are derived are very unlikely purely chemical or electrochemical pitting. The smooth metal surfaces within the pits are not characteristic of electrolytic corrosion. Chemical inhomogeniety of the jacket material, manifest as striations apparently is not a cause. Evidence supporting the erosion-corrosion theory includes (a) attack is more prevalent in new tubes (b) high outlet coolant temperatures apparently increase the incidence and (c) mechanical damage to the oxide film serves as a seat of attack.

Thus, it may be concluded that the uniform corrosion of the two alloys is not significantly different. Recent weight loss data[21] from measured charges in which both X-8001 and C-64 alloys were alternately loaded in the same charges substantiate earlier data.[18] Extrapolation of uniform corrosion data to predict reactor power, exposure, and coolant temperature conditions indicate the uniform corrosion of C-64 alloy is expected to be prohibitive with thirty percent additional increase in tube power or additional increase in coolant outlet temperatures; whereas, X-8001 alloy uniform corrosion rates may increase rapidly with forty percent additional increase in coolant outlet temperatures.[22] The production test[23] in which enriched (1.47 percent U-235) self-supported CII size I & E jacketed in X-8001 alloy were irradiated to 850 MWD/T at high specific powers (90-140 KW/feet) without failure indicated the uniform corrosion rates to be low on X-8001 alloy jackets where the pieces are centered in the tube.

The actual causes of groove pitting are not known. It is known, on the basis of visual examination after discharge, that mechanical damage to the autoclave film under some conditions results in formation of grooves. Other pits form where there was no apparent damage. Since prevention of film damage during and following autoclaving is extremely difficult, it may be that groove pitting cannot be prevented. The possibility exists that X-8001 alloy oxide films are not as stable as C-64 alloy oxide films under certain conditions of temperature, flow and/or turbulence. Since no grooves were seen on the 1.47 percent enriched elements, it may be that a specific combination of temperature and flow conditions is required. Finally, although the possibility exists that under conditions of true alignment obtained by using self-supported fuel elements, C-64 alloy uniform corrosion rates will be tolerable and the prevention of misalignment may eliminate intergranular corrosion, it appears that uniform corrosion of C-64 may be prohibitive.

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21. Personal Communication - N. R. Miller. March 3, 1960.
22. HW-60350, "Elimination of TQA Corrosion Limits". S. M. Graves. May 12, 1959.
23. HW-59756 C, "Production Test IP-247-A-8-FP - Irradiation of 1.47% Enriched Self-Supported I & E Fuel Elements in Ribless Tubes". R. E. Hall. July 29, 1959. (Secret)

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OTHER CONSIDERATIONS

The mechanical properties of X-8001 alloy were determined by Johnson and Ellis.[24] They found that the forming of components from this alloy is made more difficult than C-64 alloy by its higher mechanical strength, necessitating more extensive lubrication during extrusion. The higher temperatures produced during extrusion essentially "bake on" the extrusion lubricant, making it difficult to remove during the cleaning process at HAPO. Apparently due to the second phase nickel, which is markedly cathodic to the aluminum matrix, the surface film is slightly less soluble in Al-Si than the surface film on C-64 alloy. The components are more difficult to wet with Al-Si.[25] Vibration of the can-sleeve assembly during canning improved the wetting of the X-8001 alloy jacket as well as decreasing the porosity in the outer braze layer.[26] Brittle bonding was more severe on X-8001 alloy clad fuel elements than on C-64 clad fuel elements. This may have been due to the higher mechanical strength of the X-8001 alloy. It was hypothesized[27] that when the canned fuel element is quenched, the jacket and bond layer are first chilled to form a solid shell around the still hot and expanded core. As the core cools and contracts, it exerts a tensile force radially inward with the contracting core, and the can metal must undergo plastic flow, becoming thicker and smaller in outside diameter to keep up with the shape of the core to which it is attached. If the jacket metal were comparatively soft and plastic (1245 or C-64 alloy), the deformation would take place without exceeding the adhesive strength of the compound layer in nearly all cases; however, if the jacket metal were stiffer and more resistant to plastic flow (X-8001 alloy), the adhesion between core and jacket must be proportionally stronger in order to resist fracture to the same extent as the C-64. With increased quantities of X-8001 in use, although the above mechanism may be operative, many of the problems associated with brittle or broken bonds have been solved.

During the canning of X-8001 alloy jacketed fuel elements, the concentration of Ni increases in the canning furnaces. Tests to measure the effect of the nickel concentration in the canning braze metal on fuel element quality revealed that a concentration of 0.5 to 1.2 percent nickel in the canning furnace caused operational difficulties[28] and reduced weld quality.[29] Because of the nickel content, the X-8001 alloy

24. HW-41859, "Preliminary Study of the Mechanical Properties of M-388". D. E. Johnson and W. H. Ellis. March 16, 1956.
25. HW-57662, "Canning Summary of Production Test 84-MT, (PWR-182) Using Type M-388 Alloy Components". E. F. Baroch. January 3, 1957. (Confidential)
26. C. A. Strand - Personal Communication.
27. HW-56598, "M-388 Alloy Cans, Brittle Bonds and In-reactor Failures". E. A. Smith. July 1, 1958. (Secret)
28. HW-63115, "Effect of Increased Nickel Content in Canning Baths". C. A. Strand. February 2, 1960. (Confidential)
29. HW-63138, "The Influence of Nickel Content of the Brazing Alloy on Fuel Element Weld Quality". G. R. Hanson. December 21, 1959. (Confidential)

aluminum scrap cannot be utilized for replenishing the braze metal, a step which was estimated to result in a material cost reduction of up to $76,000 per year. If the nickel content of the braze metal were allowed to exceed 1.2 percent by weight, mixing of the weld metal would be severely inhibited, making inspection more difficult and reducing the integrity of the weld as measured by incidence of pinholes and the increased difficulty of inspection. In addition, up to 80 percent increase in outer weld rejects could be sustained if the nickel content of the braze metal were allowed to exceed 1.2 percent.

Production scale utilization of components of two alloy types aggravates the material handling problems.[30] In order to maintain sufficient quantities of each component on hand, large on-site inventories are required and/or uneconomical small quantity buying is necessary.

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30. Undocumented, "Jacketing Alloys". H. E. Berg. March 17, 1959. (Confidential)

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13. Kelly, W. S., Examination of Hot Spot Failure of an M-388 Alloy Jacket Slug - (RM 197). HW-53254. November 16, 1957 (Secret).

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16. Gruber, W. J., Examination of M-388 Rupture From IP-80-A (RM-224). HW-50157. June 16, 1959 (Confidential)

17. Kelly, W. S., Examination of Ruptured M-388 Clad BNTL Slug From IP-80-A. HW-55964. May 6, 1958 (Secret)

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23. Hall, R. E., Production Test IP-247-A-8-FP, Irradiation of 1.47% Enriched Self-Supported I & E Fuel Elements in Ribless Tubes. HW-59756 C. July 29, 1959 (Secret).

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33. Van Wormer, F. W., Supplement A to PT-IP-80-A-91-FP, Evaluation of M-388 Alloy Fuel Element Jackets in Semi-Production Quantities. HW-50141 D. September 12, 1957 (Secret).

34. Hall, R. E., Supplement B to PT-IP-80-A-91-FP, Evaluation of M-388 Alloy Fuel Element Jackets in Semi-Production Quantities. HW-50141 E. February 11, 1958 (Secret).

35. Hall, R. E., PT-IP-297-A-FP, The Effect of Autoclave Film Damage on the Incidence of Groove Pitting on X-8001 Alloy Fuel Jackets. HW-63122 C. April 6, 1960 (Secret).

APPENDIX

Following is a brief summarization of test data from PT's IP-43-A-84-MT, IP-80-A-91-FP, and PITA IP-2-I-99-FP:

PT-IP-43-A-84-MT

Purpose

Compare the corrosion resistance, under process conditions, of X-8001 (~1 percent Ni) alloy fuel element jackets to that of the then conventional 1245 alloy jacket. It was expected that sufficient experience would be obtained by this test to permit an early decision regarding partial conversion of the process stream to fuel elements jacketed in X-8001 alloy.

Test Plan

Weighed and measured charges, consisting of alternated X-8001 alloy jacketed solid and regular 1245 alloy jacketed solid control fuel elements were loaded into reactor tubes having a range of power and coolant temperature conditions.

Conclusions

It was concluded, on the basis of the examination of the X-8001 alloy failure in D Reactor, that X-8001 alloy was superior to 1245 alloy in resistance to intergranular attack. Results of the corrosion from C Reactor tubes indicated that if temperatures were not severe enough to cause accelerated attack on 1245 alloy, the weight losses on X-8001 and 1245 alloy were not distinguishably different.[31] Where accelerated attack occurred on 1245 alloy in B Reactor, groove pitting penetrated the X-8001 alloy jackets to the same depth (to the Al-Si layer) resulting in essentially the same rupture potential for the two alloys.

Fuel Element Characteristics

Composition: Natural Uranium

Dimensions:	Cored	Solid
	8.325 inches long	8.325 inches long
	1.336 inches O.D.	1.336 inches O.D.
	0.515 inch I.D.	--

Component Fabrication: Extruded From Extruded Rod Blanks
Canning Method: Standard Lead Dip "F" Process

31. Miller, N. R., Personal Communication. June, 1960.

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Irradiation Conditions

Reactors: B, C, H, and KE
Number of Tubes, Temperature, Exposure and Tube Power:

No. Tubes	Reactor	Tube Outlet Temperature	Exposure	Tube Power
10	B	110 - 120 C	3 to 300, 4 to 500 MWD/T	To 950 KW
8	C	About 90 C	2 to 400, 2 to 500, 4 to 600 MWD/T	900-950 KW
8	KE	90 - 95 C	2 to 400, 2 to 500, 4 to 600 MWD/T	1200 KW
8	H	About 100 C	2 to 400, 2 to 500, 4 to 600 MWD/T	800 KW

To provide a portion of the experience necessary for consideration of process conversion, the following charges of X-8001 jacketed fuel elements were included for irradiation to normal goal in this test:

Reactor	Fuel Element	No. of Charges
B	1/2" Cored-Solid	25 & 20
C	1/2" Cored-Solid	25 & 20
H	Solid	20
KE	Solid	20

Charge Pattern: Standard downstream dummy pattern; B, C, and H - 32 pieces per tube of alternated X-8001 alloy and 1245 alloy jacketed fuel elements. KE - 38 pieces per tube of alternated X-8001 alloy and 1245 alloy jacketed fuel elements.

Results of Irradiation: Corrosion temperatures were highest in B Reactor by a factor of: B - 120 C; D - 100 C; C - 95 C; H - 90 C; and KE - 90 C. In D and B Reactors in the maximum corrosion positions (4-10 downstream) corrosion losses were higher for 1245 alloy; however, groove pitting down to the Al-Si was more severe on X-8001 alloy. No groove pitting was seen on pieces from C Reactor. In B Reactor, accelerated corrosion and the top of 1245 alloy resulted in areas of corrosion down to the Al-Si. Two side hot spot ruptures were sustained in measured charges: a 1245 alloy-clad piece in tube 2732 KE at 607 MWD/T exposure and 1135 KW tube power, and an X-8001 alloy clad piece in tube 3578 D at 295 MWD/T exposure and 940 KW tube power. The X-8001 failure was examined in the Radiometallurgy Laboratory[13] where it was found the core operated in the beta phase and that the X-8001 jacket melted at the hottest point. No evidence of intergranular corrosion was observed.

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IP-80-A-91-FP

Purpose

To authorize the use of X-8001 (~1 percent Ni) alloy jacketed fuel elements on a semi-production basis.

Test Plan

To irradiate approximately 200,000 fuel elements clad in X-8001 alloy jackets. The test was to be conducted in several reactors simultaneously until all of the original 200,000 components were used and relative rupture frequency of X-8001 and C-64 alloys analyzed.

Conclusions[32]

M-388 aluminum alloy cladding did in actuality increase fuel element resistance to intergranular corrosion attack; however, other process problems existed which made M-388 alloy unacceptable as a cladding material for solid fuel. Further irradiation testing of the alloy was justified as soon as these problems were isolated and resolved.

Fuel Element Characteristics

Composition: Natural Uranium

Dimensions:	Solid	Cored
	8.325 inches long	8.325 inches long
	1.336 inches O.D.	1.336 inches O.D.
	--	0.515 inch I.D.

Component Fabrication: Extruded from extruded rod blanks
Two designs were used: (1) standard solid can, and (2) blunt nose tru-line can.[14]

Canning Method: Standard lead dip "F" process

Irradiation Conditions

Reactors: KE,[33] C, DR, and F[34]

32. HW-50141 F, "Status Report - IP-80-A-91-FP, Evaluation of M-388 Alloy Fuel Elements in Semi-Production Quantities". R. E. Hall, W. A. Blanton. May 21, 1958. (Secret)
33. HW-50141 D, "Supplement A to PT-IP-80-A-91-FP, Evaluation of M-388 Alloy Fuel Element Jackets in Semi-Production Quantities". F. W. Van Wormer. September 12, 1957. (Secret)
34. HW-50141 E, "Supplement B to PT-IP-80-A-91-FP, Evaluation of M-388 Alloy Fuel Element Jackets in Semi-Production Quantities". R. E. Hall. February 11, 1958. (Secret)

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Number of Tons Per Month:

Reactor	Solid Uranium X-8001 Regular	Solid Uranium Tru-Line X-8001	Cored Uranium Tru-Line X-8001
KE	40 Tons	--	60 Tons
C	--	--	--
DR	--	25 Tons	--
F	30 Tons	--	--

Charge Pattern: Standard downstream dummy pattern and number of fuel elements currently being charged in normal uranium columns in the reactors authorized to receive this test material.

Exposure: Exposure was normal discharge goal for type of material being irradiated.

Irradiation Summary

During the semi-production scale testing of M-388 clad fuel elements, thirteen failures occurred. Nine of these failures were solid and four were cored natural uranium. All failures, with the exception of one cap failure, were of the hot-spot type. Only slight evidence of intergranular attack had been noted. A type of corrosion attack termed "groove-pitting" was observed on some fuel elements; however, in no case was this the direct cause of a jacket failure.

Evaluation of the rupture data indicated that the M-388 alloy does not perform as well from a gross rupture standpoint as 1245 alloy clad fuel elements. On this basis early discharge of all remaining cored and solid M-388 alloy was recommended. Since the exact cause of the failures was not as yet established, testing was suspended pending further examination of the problem.

Data obtained on the uniform corrosion rates of elements clad in the two alloys appeared very encouraging for the M-388 alloy. When elements clad in 1245 alloy were irradiated under sufficiently severe conditions of temperature and specific power, the "uniform" corrosion rate became greatly accelerated even in the absence of noticeable fuel misalignment. Actually this acceleration of rate noted may in fact be a manifestation of the initiation of intergranular attack on non-misaligned fuel elements. The practical effect of this acceleration of rate is that powers at C, K, and possibly old reactors must be limited in order to prevent excessive corrosion losses. If the cause of the hot spot failures of M-388 clad elements and the pitting of the cladding were determined and rectified, the use of M-388 cladding would result in significantly relaxed fuel jacket corrosion limits with correspondingly higher permissible reactor powers before jacket corrosion again became limiting.

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PITA-IP-2-I-99-FP

Purpose

Authorize large-scale irradiation of X-8001 alloy jacketed fuel elements in order to evaluate their suitability to the reactor process.

Test Plan

Irradiate sufficient quantities of X-8001 and C-64 to permit evaluation of the relative rupture performance of the two alloys.

Conclusions

Although the failure rate of X-8001 alloy clad fuel elements irradiated for this test was higher in 1959, the difference was not significant. Rupture experience in the first five months of 1960 indicates a trend in the opposite direction. The failure rates for the first four months of 1960 were: X-8001, $(10^6/542,905) \times 29 = 53.4/10^6$ and for C-64 alloy $(10^6/205,693) \times 30 = 145.9/10^6$.

It is concluded, based on overall rupture frequencies to date, that there is no significant difference between the irradiation performance of the two alloys.

Fuel Element Characteristics

Composition: Natural solid and natural and enriched (0.94 percent U-235) I & E

Dimensions: Standard solid, O, K, and C, I & E core sizes

Component Fabrication: Extruded from extruded rod blanks

Canning Method: Standard lead-dip "F" process

Irradiation Conditions

Reactors: All HAPO reactors
Number of tons per month: Quantities varied from about 40 percent of I & E clad in X-8001 alloy in late CY 1958 to the 87 percent of I & E currently undergoing irradiation being clad in X-8001 alloy.

Charge Pattern: The charge patterns are standard for the reactors in which the X-8001 alloy jacketed elements are being irradiated.

Exposure: Exposure goals are based on the normal variable goal curve.

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Irradiation Summary

Production scale loadings of X-8001 alloy clad fuel elements were initiated in 1958. Upon conversion of the reactors to I & E loadings, utilization of X-8001 alloy was further accelerated. Early in 1959, the central zones of all old reactors were essentially loaded with X-8001 alloy clad fuel elements. Only the C and KE Reactors contained primarily C-64 alloy clad elements. During 1959, an attempt was made to balance the quantities of X-8001 and C-64 alloys in the C, F, and H Reactors. A comparison of the rupture rates is shown in Table II.

Table II

COMPARISON OF RUPTURE RATES BY REACTOR AND ALLOY (1959)

(Rates Based on Pieces Discharged)

	Pieces Discharged		Number Ruptures		Rupture Frequency Pcs./10^6		Ratio of Frequencies
Reactor	X-8001	C-64	X-8001	C-64	X-8001	C-64	X-8001/C-64
B	90,814	33,388	3	1	33.0	30.0	1.10
D	84,184	32,606	4	2	47.5	61.3	0.77
DR	81,634	34,340	6	1	73.5	29.1	2.52
F	84,966	39,338	3	2	35.3	50.8	0.70
H	104,002	27,268	8	0	76.2	0	0
C	45,254	95,846	2	6	44.2	62.6	0.71
KE	130,452	107,692	5	1	38.3	9.3	4.12
KW	250,306	6,954	9	1	36.0	143.8	0.25
Totals	872,602	377,432	40	14	45.8	37.1	1.23

From Table II, it will be noted the only true balance in numbers of pieces discharged was in KE Reactor, where the rupture rate of X-8001 alloy clad fuel elements was over four times that of C-64 alloy clad elements.

Severe localized corrosion (not revealed by weight loss results) of X-8001 alloy clad solid pieces was discovered during the fourth quarter of CY 1959, when a majority of the ruptures in the old reactors exhibited groove pitting. Five of the eight X-8001 alloy clad ruptures reported in the same quarter were in new tubes. Since then groove pitting, as shown in Fig. 1, has been observed on measured PT pieces from all reactors except C Reactor.

During the period from the authorization of this test to May, 1960, there were 74 X-8001 alloy clad failures. Twenty-three of these were internal ruptures which were attributable to fabrication problems and which have

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been essentially eliminated. During the same period there were 56 C-64 alloy clad failures, eight of which were internal. The overall rupture rates for the two alloys were: $(10^6/958,675) \times 56 = 58/10^6$ for C-64 alloy clad I & E elements, and $(10^6/1,378,085) \times 74 = 54/10^6$ for X-8001 alloy clad I & E elements. These rates are not significantly different. The reduction in the number of internal ruptures which predominated in the X-8001 alloy indicates an improvement in bond and closure integrity during 1959.

Elimination or control of the conditions which cause groove pitting is the remaining problem in development of X-8001 alloy. A production test[35] has been prepared for irradiation in F Reactor to determine the contribution of scratched or non-uniform autoclave films in the generation of groove pits. Since there is also evidence that groove pitting is flow- and temperature-dependent, bracketing of ranges of these variables should complete the picture of the causes of groove pitting on X-8001 alloy fuel element jackets.

35. HW-63122 C, "PT-IP-297-A-FP, The Effect of Autoclave Film Damage on the Incidence of Groove Pitting on X-8001 Alloy Fuel Jackets". R. E. Hall. April 6, 1960. (Secret)

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