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INVESTIGATION OF THE FACTORS AFFECTING SENSITIZATION OF ARMY PACKAGE POWER REACTOR (APPR-1) FUEL ELEMENTS

R. J. Beaver
R. C. Waugh
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METALLURGY DIVISION

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R. J. Beaver R. C. Waugh C. F. Leitten, Jr. W. R. Burt, Jr.

SUMMARY

Results are presented of the investigation necessitated by the unexpected intergranular attack of the type 304L stainless steel cladding in the Army Package Power Reactor (APPR-1) fuel plates after a flatten-annealing heat treatment and subsequent cleaning in 15% HNO_3–5% HF aqueous solution.

This fuel plate consists of a powder-metallurgy-prepared core containing 26 wt % UO_2 and 0.14 wt % B_4C in a type 304B stainless steel matrix. After the core is fabricated into a composite fuel plate, it is 20 mils thick and is clad with 5 mils of type 304L stainless steel.

The data accumulated permit an evaluation of the material specified for APPR-1 fuel plates with relation to the effect of the manufacturing heat treatments on carburization and sensitization of the type 304L stainless steel cladding. The effect of the substitution of type 347 stainless steel is also described. It is concluded that carbon diffusion from the type 304B fuel-core matrix increases the carbon level of the type 304L stainless steel cladding during the manufacturing heat treatments. The cladding is then susceptible to sensitization during the heat treotments and is subject to intergranular attack in a reducing acid. It was further concluded that substitution of type 347 stainless steel as the matrix material in the fuel core and the cladding, or as the cladding material only, would permit the fuel plates to be fabricated in accordance with the established APPR-1 manufacturing procedures without resulting in sensitization of the plate cladding.

INTRODUCTION

During manufacture of the stainless steel fuel plates for the APPR-1, an acid cleaning procedure was introduced into the fabrication procedure to remove the thin oxide film remaining on fuel plates after the annealing treatment prior to brazing. The acid used was a 15% HNO_3–5% HF aqueous solution. These fuel plates are composite in nature and contain a powder-metallurgy-prepared fuel core consisting of 26 wt % uranium dioxide and 0.14 wt % boron carbide in a type 304B stainless steel matrix which is clad with type 304L stainless steel. The clad-core-clad dimensions are 5-20-5 mils, respectively. No appreciable attack was expected during the acid cleaning because of the low carbon content (0.03 wt % max) of the type 304L cladding. However, inspection of the flatten-annealed APPR-1 fuel plates after this cleaning treatment revealed that severe intergranular attack had occurred. Figures 1 to 3 illustrate the observed phenomenon.

An investigation was immediately initiated to determine the source of this unexpected failure. Fuel plates of the above-described materials combination were examined after each heat treatment specified for manufacturing the composite fuel plates and elements. Also evaluated was the effect of substituting type 347B for type 304B stainless steel as the core matrix and/or of substituting wrought type 347 for type 304L cladding material on the sensitization susceptibility of the fuel plate cladding.

PROCEDURE

Since the object of the study was to determine the source of the difficulty with the type 304L stainless steel specified for the APPR elements as well as to investigate substitute materials combinations which might be more suitable to the established APPR fabrication and heat-treatment procedures, the investigation was divided into two phases, as outlined in Tables 1 and 2. After the specified heat treatment, each materials combination was evaluated, by metallographic examination and intergranular failure in the Strauss Test, for

Table 1. Stages of Fabrication at Which UO_2-Containing Fuel Plates of Various Materials Combinations Were Examined for Sensitization – Phase I

Materials Combinations A, B, and C – Type 304L stainless steel frame and clad; type 304B stainless steel core
A – Core with no boron compound
B – Core with B_4C
C – Core with ZrB_2

Hot-Rolled	Removal of Hot-Rolled Scale		Cold-Rolled and Degreased	Annealing Cycle		Flatten-Annealing		Brazing
	Acid-Pickled	Mechanically Cleaned		One	Two	Al_2O_3*-H_2O**	Al_2O_3*– Nicrobraze Cement**	
X		X						
X	X							
X	X		X					
X		X	X	X		X		
X		X	X	X			X	
X		X	X		X	X		
X		X	X		X		X	
X		X	X	X		X		X
X		X	X	X			X	X
X		X	X		X	X		X
X		X	X		X		X	X

*Separating agent.
**Dispersing agent for Al_2O_3.

Table 2. Stages of Fabrication at Which UO_2-Containing Fuel Plates of Various Materials Combinations Were Examined for Sensitization – Phase II

Materials Combinations A and B – Type 304L stainless steel frame and clad; type 347B stainless steel core
A – Core with B_4C; B – Core with ZrB_2

Materials Combinations C and D – Type 347 stainless steel frame and clad; type 304B stainless steel core
C – Core with B_4C; D – Core with ZrB_2

Materials Combinations E and F – Type 347 stainless steel frame and clad; type 347B stainless steel core
E – Core with B_4C; F – Core with ZrB_2

Hot-Rolled	Removal of Hot-Rolled Scale by Acid Pickling	Cold-Rolled and Degreased	One Annealing Cycle	Flatten-Annealing Al_2O_3*-H_2O**	Brazing
X	X	X			
X	X	X	X	X	
X	X	X	X	X	X

*Separating agent.
**Dispersing agent for Al_2O_3.

evidence of carbon diffusion and carbide precipitation. A control specimen was available at each stage for comparative purposes. It is recognized that the appraisal of the various materials combinations proposed in Phase II does not include an evaluation of low-carbon elemental iron, nickel, and chromium powders as a substitute for the two prealloyed stainless steels used as the fuel core matrix. The limited time and the lack of the required materials made it impossible to include this combination in the investigation.

The various core compositions and particle sizes of powders selected are listed in Table 3. Zirconium diboride was chosen to determine the influence of a lower carbon boride on subsequent increased carbon in the clad. The ZrB_2 content was based on the boron equivalent of B_4C.

Full-size cores of each composition were prepared by the following standardized APPR powder-metallurgy procedures:

1. The powders were individually weighed and placed in a 4-oz jar and dry-blended for 2 hr on an oblique blender.
2. An atomizer was used for adding 0.1 g of dodecyl alcohol, and the powders were reblended for 1 hr.
3. The dispersion was pressed in a 1.8 × 2.4 in. die at 33 tsi.
4. The green compact was sintered for $1\frac{1}{4}$ hr at 1175°C in a dry hydrogen atmosphere.
5. After sintering, the core was coined twice at 33 tsi.

Miniature cores in the form of cylinders 0.268 in. in diameter and 0.276 in. in height were dry-machined from each of the full-size cores.

The outer dimensions of the frames and cover plates were identical to those of the stationary APPR fuel plate, that is, $4\frac{1}{2} \times 4\frac{7}{16} \times 0.278$ in. and $4\frac{1}{2} \times 4\frac{7}{16} \times 0.065$ in., respectively. Two 0.271-in.-dia holes were drilled in each frame. The frames and cover plates were degreased and wire-brushed, the billet was assembled, and the covers were attached to the frame by Heliarc welding, except at the corners of the billet.

The billets were preheated for 20 min at 1150°C in a hydrogen atmosphere and reduced to a nominal 0.040-in. thickness, with a 2-min reheating between passes. After each pass, the billet was rotated 180 deg about its longitudinal and transverse axes.

The hot-rolled plates were either descaled by pickling in a 15% HNO_3–5% HF aqueous solution or were mechanically cleaned with emery paper. The descaled plates were marked, sheared, and cold-rolled to a nominal thickness of 0.030 in., after which they were degreased in trichloroethylene vapor and again sheared. The miniature core length after cold-rolling was approximately $3\frac{1}{2}$ in.

The plates were flatten-annealed in a hydrogen atmosphere by slowly heating to 1125°C, holding for approximately $2\frac{1}{2}$ hr, and furnace-cooling. Brazing consisted in heating to 1133°C, shutting off the power, and furnace-cooling. The maximum temperature attained was 1138°C. No plates were cleaned in acid after either the flatten-annealing or brazing operations.

At each outlined stage of fabrication the double core plate was sheared into two individual plates, which represented APPR type of fuel plates on a miniature scale. The miniature control plate was

Table 3. Core Compositions and Particle Sizes for Phases I and II

Core Materials	Materials Combination			Particle Size of Powders (Mesh)
	UO_2–Stainless Steel–No Boron Compound	UO_2–Stainless Steel–B_4C*	UO_2–Stainless Steel–ZrB_2	
Depleted UO_2, g	35.02	35.02	35.02	−170 +325
B_4C, g		0.188		−325
ZrB_2, g			0.753**	−325
Stainless steel, g	99.86	99.86	99.86	−100
Total core weight, g	134.88	135.07	135.63	

* Typical APPR stationary fuel plate core composition.

** ZrB_2 content based on the boron equivalent of B_4C.

transversely sectioned into specimens for metallography and a modified bend test. The other miniature plate was immersed in a boiling $CuSO_4$-H_2SO_4 aqueous solution for 72 hr. The Strauss-Test solution consisted of 13 g of $CuSO_4 \cdot 5H_2O$, 47 ml of H_2SO_4 of specific gravity 1.84, and enough distilled water to make a 1-liter solution. After the test the specimen was sectioned transversely into specimens for metallography and a modified bend test.

Prior to being mounted for metallographic inspection, the Strauss-tested specimens were nickel-plated. The metallographic examination consisted in a search for evidence of intergranular attack which may have occurred during the Strauss Test and a determination of the extent and type of carbide precipitation which may have occurred during the heat treatments imposed. Data on intergranular attack were obtained from specimens examined in the as-polished condition. The samples were then electrolytically etched, by the application of 6 v for ~9 sec, in dilute chromic acid aqueous solution so that the effect of heat treatment on carbide precipitation could be observed.

The modified bend test consisted in bending the specimen around a 0.388-in.-dia bar and examining the surface under a binocular microscope at 30X for evidence of grain-boundary separation.

In conjunction with Phase II studies, full-size APPR plates were fabricated to provide stock for carbon analyses of the clad material after the specified stages of fabrication. The cladding was machined from one side of each plate while the plate was held in a vacuum chuck, and the chips were analyzed for carbon by direct combustion. Carbon analyses were also obtained on the as-received types 304L and 347 stainless steel, B_4C, ZrB_2, depleted UO_2, Nicrobraze cement, and alumina.

To evaluate the performance of a sensitized fuel element in service, a previously prepared, depleted, three-plate fuel element which had been tested in a dynamic water loop at the Westinghouse Atomic Power Division was examined. This fuel element contained essentially the same materials combination as the APPR-1 fuel elements and was fabricated in the same manner, except that the fuel plates were not cleaned in acid prior to assembling for brazing and were brazed in a graphite jig instead of in a stainless steel jig. The test conditions[1] were as follows:

Water purity	24 cc of hydrogen per kiloliter; 10 cc of nitrogen per kiloliter; oxygen undetected
Water velocity	38.2 fps
Temperature	260°C
Time in dynamic water	6245 hr

A fuel plate from the element was removed to permit carbon analysis of the clad material and to provide Strauss and control specimens. Material for carbon analyses was obtained in the manner described previously. Strauss-Test specimens were prepared on transverse sections sheared from the plate by leaching the UO_2 from the section edges and sealing the edges by Heliarc welding.

DISCUSSION OF RESULTS

Phase I

The results of Phase I studies are summarized in Table 4. The table is self-explanatory but the data are abbreviated to permit convenience in comparing and analyzing the results. The data on the degree of intergranular attack are for as-polished specimens after they had been Strauss-tested. Attack extending through to the core is complete intergranular attack. Partial intergranular attack means attack to a depth of 0.0005 in. or less, unless otherwise noted. In all cases, measurements on the depth of chromium carbide formation at grain boundaries were made from the core in the direction toward the clad surface and from the core in the direction toward the frame edge.

The procedure which was used to obtain samples of clad material for carbon analyses in Phase I and II investigations was found to be unreliable. The results obtained would be misleading, and hence the data have not been included in Tables 4 and 6.

The results reveal that diffusion of carbon occurred from the core into the clad and frame because of the carbon gradient initially existing

[1] S. C. Datsko and C. R. Breden, *Corrosion of Metals in High Temperature Water at 500°F and 600°F*, ANL-5354 (Oct. 6, 1954).

Table 4. Summary of Phase I Data

Materials Combinations A, B, and C – Type 304L stainless steel frame and clad; type 304B stainless steel core
A – Core with no boron compound
B – Core with B_4C
C – Core with ZrB_2

	Hot-Rolled Plate		Hot-Rolled, Pickled, and Cold-Rolled	First Flatten-Annealing		Second Flatten-Annealing		First Flatten-Annealing – Brazed		Second Flatten-Annealing – Brazed	
	Not Pickled	Pickled		With H_2O-Al_2O_3	With NBC*-Al_2O_3	With H_2O-Al_2O_3	With NBC*-Al_2O_3	With H_2O-Al_2O_3	With NBC*-Al_2O_3	With H_2O-Al_2O_3	With NBC*-Al_2O_3
Materials Combination A											
	Specimen No. 1	Specimen No. 9	Specimen No. 2	Specimen No. 3	Specimen No. 7	Specimen No. 6	Specimen No. 10	Specimen No. 4	Specimen No. 8	Specimen No. 5	Specimen No. 11
Degree of intergranular attack	None	None	None	Complete	Complete	Complete	Complete	Partial (0.001 in.)	Partial (0.002 in.)	Complete	Complete
Depth and type** of chromium carbide formation at grain boundary, in.											
In the clad	None	None	None	TC; CN	TC; CN	TC; CN	TC; CN	TC; DN	TC; DN	TC; DN	TC; CN
In the frame	0.017; DN	0.020; EN	0.012; EN	TF; DN	TF; DN	TF; DN	TF; DN	TF; DN	TF; DN	TF; DN	TF; DN
Grain-boundary separation											
Strauss control specimen	Not tested	Not tested	Not tested	No	Not tested	No	No	No	No	No	No
Strauss-tested specimen	No	No	No	Yes	Yes	Yes	Yes	Slight	Slight	Yes	Yes
Materials Combination B											
	Specimen No. 12	Specimen No. 13	Specimen No. 14	Specimen No. 19	Specimen No. 15	Specimen No. 21	Specimen No. 18	Specimen No. 20	Specimen No. 16	Specimen No. 22	Specimen No. 17
Degree of intergranular attack	None	None	None	Complete but erratic	Complete but erratic	Complete	Complete	Partial (0.002 in.)	Partial (0.002 in.)	Complete	Partial (0.002 in.).
Depth and type** of chromium carbide formation at grain boundary, in.											
In the clad	0.003; DN	0.004; CN	0.002; DN	TC; CN	TC; CN	TC; CN	TC; CN	TC; CN	TC; CN	TC; EN	TC; CN
In the frame	0.032; DN	0.021; DN	0.025; EN	TF; DN	TF; DN	TF; DN	TF; DN	TF; DN	TF; DN	TF; EN	TF; DN
Grain-boundary separation											
Strauss control specimen	Not tested	Not tested	Not tested	No	No	No	No	No	No	No	No
Strauss-tested specimen	No	No	No	Yes	Yes	Yes	Yes	Slight	Slight	Yes	Slight
Materials Combination C											
	Specimen No. 23	Specimen No. 24	Specimen No. 25	Specimen No. 26	Specimen No. 30	Specimen No. 29	Specimen No. 33	Specimen No. 27	Specimen No. 31	Specimen No. 28	Specimen No. 32
Degree of intergranular attack	None	None	None	Complete	Complete	Complete	Complete	Partial (0.002 in.)	Partial (0.002 in.)	Complete	Complete
Depth and type** of chromium carbide formation at grain boundary, in.											
In the clad	0.003; EN	0.003; DN	0.002; EN	TC; CN	TC; CN	TC; CN	TC; CN	TC; CN	TC; EN	TC; CN	TC; EN
In the frame	0.080; EN	0.073; DN	0.042; EN	TF; DN	TF; DN	TF; DN	TF; DN	TF; DN	TF; EN	TF; DN	TF; EN
Grain-boundary separation											
Strauss control specimen	Not tested	Not tested	Not tested	No	No	No	No	No	No	No	No
Strauss-tested specimen	No	No	No	Yes	Yes	Yes	Yes	Yes	Slight	Yes	Yes

*Nicrobraze cement.

**CN – continuous Cr_4C network; DN – discontinuous Cr_4C network; EN – erratic Cr_4C network; TC – through clad; TF – through frame.

between the type 304L stainless steel clad, which contained 0.03% carbon, and the type 304B stainless steel matrix, which contained 0.07% carbon. Carbon diffusion into the cladding and subsequent carbide formation occurred during the hot-rolling operation; however, the precipitated network only partially penetrated into the cladding. As anticipated, no intergranular attack during the Strauss Test occurred. It was evident that the greatest directional diffusion of carbon was into the frame rather than into the cladding.

Subsequent heat treatments through flatten-annealing and brazing were sufficient to cause extensive carbon diffusion and subsequent carbide formation completely through the cladding. Metallographic examination of the Strauss-tested specimens in the as-polished condition revealed that the intergranular attack was most severe over the core area of the composite specimen. In some instances the attack had completely penetrated the cladding, exposing the core material. The Strauss-tested specimens failed intergranularly when bent. Control samples that had been given the same heat treatment but had not been exposed to the Strauss solution showed no intergranular failure after the bend test.

Results from fabricated composites, which had been limited to one annealing treatment prior to brazing, revealed that partial intergranular attack to a depth of 0.002 in. had occurred during the Strauss Test. In most cases the cladding on specimens which had a history of two annealing treatments prior to brazing was completely intergranularly attacked during the Strauss Test.

The carbon and niobium analyses of the processing and component materials are given in Table 5. The elimination of the boron carbide in the core or the substitution of the comparatively low-carbon zirconium diboride for the boron carbide did not affect the degree of carburization and subsequent intergranular attack. There is no experimental evidence favoring the use of Nicrobraze cement and alumina over water and alumina or vice versa as the separating material during the flatten-annealing of fuel plates.

No direct experimental evidence of alumina as a carbon contributor was found. The low, 0.020%, carbon content of alumina indicates that its effect would be small. Since the Nicrobraze cement–Al_2O_3 combination is no more deleterious than the water-Al_2O_3 combination, it does not appear that Nicrobraze contributes appreciably to exterior carbon contamination. The carbon content of Nicrobraze cement decreases with increasing temperature in the range 80 to 150°C. Although analysis could not be made under actual fabrication conditions, it is assumed that the carbon contribution from this source is insignificant.

Table 5. Carbon and Niobium Analyses of Processing and Component Materials

Material	Carbon (%)	Niobium (%)
Wrought type 304L stainless steel	0.015–0.024	
Type 304B[a] stainless steel powder	0.07	
Wrought type 347[b] stainless steel	0.056–0.069	0.88–0.91
Type 347B[a,b] stainless steel powder	0.05	0.97
Depleted UO_2	0.0196	
Alumina	0.020	
B_4C	21.7	
ZrB_2	1.51	
Nicrobraze cement		
Dry in boat at 80°C	1.62	
Dry in boat at 150°C	1.13	

[a] 2.00–3.00 % silicon.

[b] Per cent niobium = 10 times the per cent of carbon, minimum.

The degree of chromium carbide precipitation resulting from each important heat treatment outlined and the effect of the heat treatment on the intergranular attack which occurred during the Strauss Test are illustrated in Figs. 4 through 10.

Phase II

Phase II results are presented in Table 6. Some bend tests of cold-rolled specimens exhibited a transgranular failure and therefore are noted as ruptures. This type of failure is not to be confused with grain-boundary separation, which is characteristic of intergranular attack.

In comparison with Phase I results, it is evident that each of the substitute materials combinations is an improvement over the present APPR-1 type 304L frame and clad–type 304B core combination. The substitution of type 347 stainless steel as frame and clad material in conjunction with either type 304B or 347B stainless steel core matrix appears to be the best of the materials combinations studied. It passed all testing criteria which were established for evaluating materials in this investigation. Erratic patches of chromium carbide appeared primarily at intersections of three grains and were predominantly in the frame and in the clad over the frame rather than over the core area. In no case did the metallographic examination reveal a sufficient amount of chromium carbide at or near the surface of the cladding to initiate intergranular attack. This result was confirmed by the Strauss-tested specimens in which no intergranular attack was found upon metallographic examination nor any grain-boundary separation observed after the bend test. The beneficial effects of type 347 stainless steel as clad and frame material result from its being stabilized with niobium.

Specimens prepared with type 347 stainless steel as the frame and cladding material and type 347B stainless steel as the core matrix are shown in Figs. 11 through 16. These photomicrographs illustrate the effect of the APPR-1 heat treatments imposed after each important stage in the manufacturing process.

The cladding of a fabricated and annealed plate, which consisted of a type 304L stainless steel frame and cladding containing a core with a type 347B stainless steel matrix, was partially intergranularly attacked during the Strauss Test. No intergranular attack occurred in the cladding of a plate with the same materials which had been annealed and simulated-brazed. The Strauss specimen passed the bend test, although a discontinuous chromium carbide network was observed throughout the cladding.

The carbon content of the clad material of a plate sectioned from the element tested at WAPD analyzed 0.076%. This result indicates that the APPR-1 fabrication procedure involves sufficient heat treatment in flatten-annealing and brazing for the type 304L (0.03% carbon, maximum) clad material to become a 304-type stainless steel due to diffusion of carbon from the core into the clad. This increase in carbon content is sufficient for chromium carbide precipitation to occur at grain boundaries and subsequent susceptibility to intergranular attack in a reducing acid.

Strauss-tested specimens from this plate showed severe intergranular attack and grain-boundary separation upon bending. The control specimen did not fail the bend test.

Metallographic examination of the as-polished control section showed that no significant corrosion had occurred after 6245 hr of testing in the pressurized 260°C water loop at WAPD. These results support previous ANL data[2] that sensitized type 304 stainless steel has satisfactory corrosion resistance in pressurized 260°C water. This investigation indicates the inadequacy of the Strauss Test as a corrosion evaluation criterion under these conditions.

Metallographic examination of the brazed Coast Metals NP alloy joint in the test element revealed that no appreciable corrosion had occurred during the 6245-hr test. Photomicrographs of sections from the WAPD element are shown in Figs. 17 through 21.

CONCLUSIONS

The annealing and brazing heat treatments required in APPR-1 fuel element manufacture cause sufficient diffusion of carbon from the fuel core into the type 304L stainless steel cladding to transform the cladding material to a type 304 stainless steel, which, in the sensitized condition, is susceptible to intergranular attack in a reducing acid or failure in a Strauss Test.

The type 304B stainless-steel-powder core-matrix material, with its 0.07% carbon content, is

[2]Personal communication from J. Thielacker, WAPD, to R. J. Beaver, ORNL, dated June 29, 1956.

the major contributor to the increased carbon content of the cladding after the specified heat treatments.

Sensitized type 304 stainless steel has sufficient corrosion resistance in 500°F pressurized water to be a suitable material for fuel elements operating in this environment. However, fuel plates clad with this material cannot be cleaned in a reducing acid after the annealing and brazing treatments specified for APPR-1 fuel plates and fuel elements.

The substitution of type 347 stainless steel as the frame and cladding material results in a composite plate which, after the specified APPR-1

Table 6. Summary of Phase II Data

Materials Combination A – Type 304L stainless steel frame and clad; type 347B stainless steel core
Materials Combination B – Type 347 stainless steel frame and clad; type 304B stainless steel core
Materials Combination C – Type 347 stainless steel frame and clad; type 347B stainless steel core

	Combination A		Combination B		Combination C	
	With B_4C	With ZrB_2	With B_4C	With ZrB_2	With B_4C	With ZrB_2
Fabrication Operation: Cold-Rolled						
	Specimen No. 46	**Specimen No. 49**	**Specimen No. 37**	**Specimen No. 43**	**Specimen No. 52**	**Specimen No. 55**
Degree of intergranular attack	None	Partial	None	None	None	None
Depth and type* of chromium carbide formation at grain boundary, in.						
In the clad	0.0045; DN	0.0045; DN	None	None	None	None
In the frame	0.041; DN	0.026; DN	None	None	None	None
Grain-boundary separation						
Strauss control specimen	No	Ruptured	Not tested	Not tested	Ruptured	Ruptured
Strauss-tested specimen	No	Ruptured	No	No	Ruptured	Ruptured
Fabrication Operation: Single Anneal with H_2O-Al_2O_3						
	Specimen No. 47	**Specimen No. 50**	**Specimen No. 38**	**Specimen No. 44**	**Specimen No. 53**	**Specimen No. 56**
Degree of intergranular attack	Partial	Partial (0.002 in.)	None	None	None	None
Depth and type* of chromium carbide formation at grain boundary, in.						
In the clad	TC; DN	TC; DN	TC; EN	TC; EN	TC; EN	TC; EN
In the frame	TF; DN	TF; DN	TF; EN	TF; EN	TF; EN	TF; EN
Grain-boundary separation						
Strauss control specimen	No	No	No	No	No	No
Strauss-tested specimen	No	Slight	No	No	No	No
Fabrication Operation: Single Anneal and Simulated-Brazed						
	Specimen No. 48	**Specimen No. 51**	**Specimen No. 39**	**Specimen No. 45**	**Specimen No. 54**	**Specimen No. 57**
Degree of intergranular attack	None	None	None	None	None	None
Depth and type* of chromium carbide formation at grain boundary, in.						
In the clad	TC; DN	TC; DN	TC; EN	TC; EN	TC; EN	TC; EN
In the frame	TF; EN	TF; DN	TF; EN	TF; EN	TF; EN	TF; EN
Grain-boundary separation						
Strauss control specimen	No	No	No	No	No	No
Strauss-tested specimen	No	No	No	No	No	No

*CN – continuous Cr_4C network; DN – discontinuous Cr_4C network; EN – erratic Cr_4C network; TC – through clad; TF – through frame.

manufacturing heat treatments, passes the Strauss Test and is not subject to intergranular attack in a reducing acid.

Of the materials combinations studied, optimum selection for the APPR-1 fuel plate manufacturing specifications is type 347 stainless steel frame and cladding with either type 347B or 304B as the fuel core matrix and boron carbide as the burnable poison.

ACKNOWLEDGMENT

The authors wish to acknowledge the assistance of J. L. Gregg, Cornell University, and J. E. Cunningham, ORNL, in the general guidance of this investigation; of ORNL personnel J. W. Geer, C. Hamby, and E. R. Turnbill in processing the miniature fuel plates, J. L. English (REED) in performing the Strauss Tests, and R. J. Gray and group members in preparing the metallography specimens.

Fig. 1. As-Polished Section from APPR-1 Fuel Plate Which Had Been Subjected to Two Annealing Cycles at 1125°C and Pickled in 15% HNO_3–5% HF Aqueous Solution. Note intergranular type attack at clad surface. 500X.

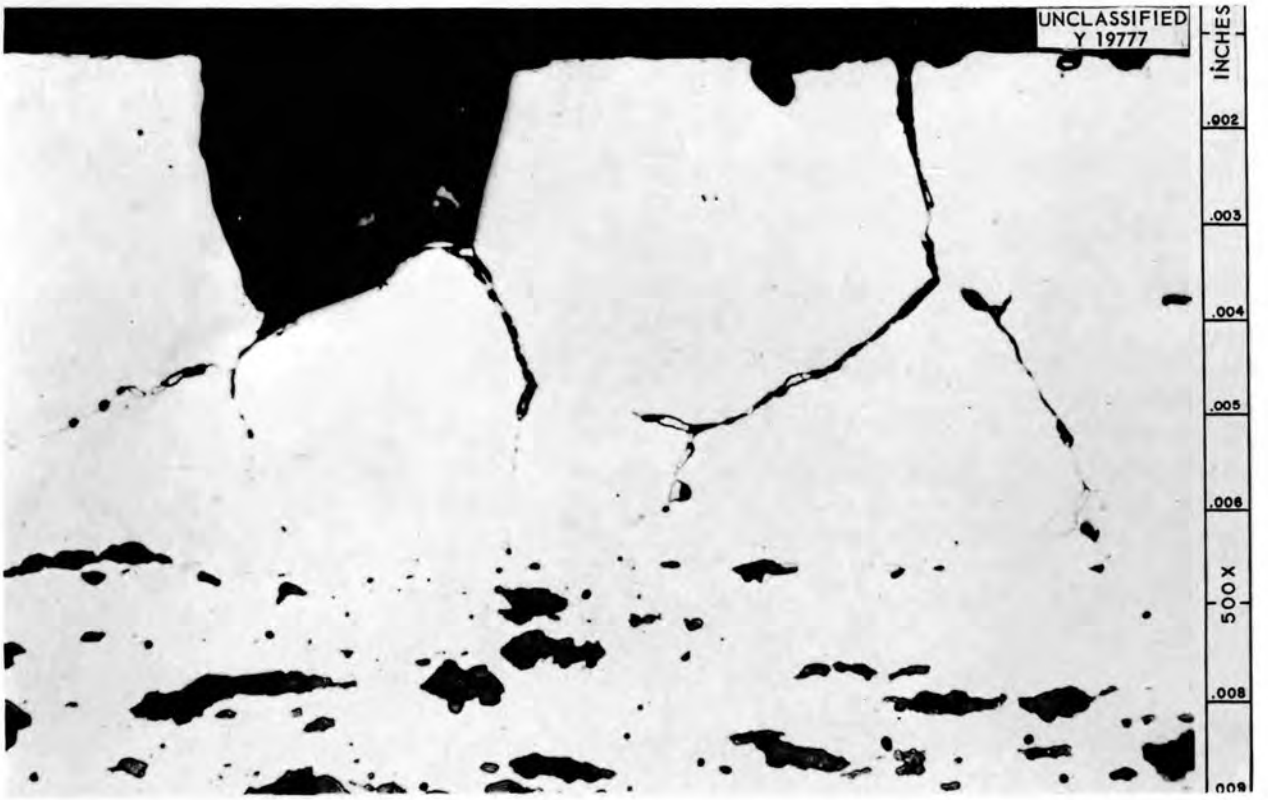

Fig. 2. As-Polished Section from APPR-1 Fuel Plate Which Had Been Subjected to Three Annealing Cycles at 1125°C and Pickled in 15% HNO_3–5% HF Aqueous Solution. Note complete removal of grain and heavy intergranular attack in cladding. 500X.

Fig. 3. As-Polished Section from APPR-1 Fuel Plate Which Had Been Annealed at 1125°C, Pickled in 15% HNO_3–5% HF Aqueous Solution, and Brazed at 1135°C. Note intergranular attack in cladding. 500X.

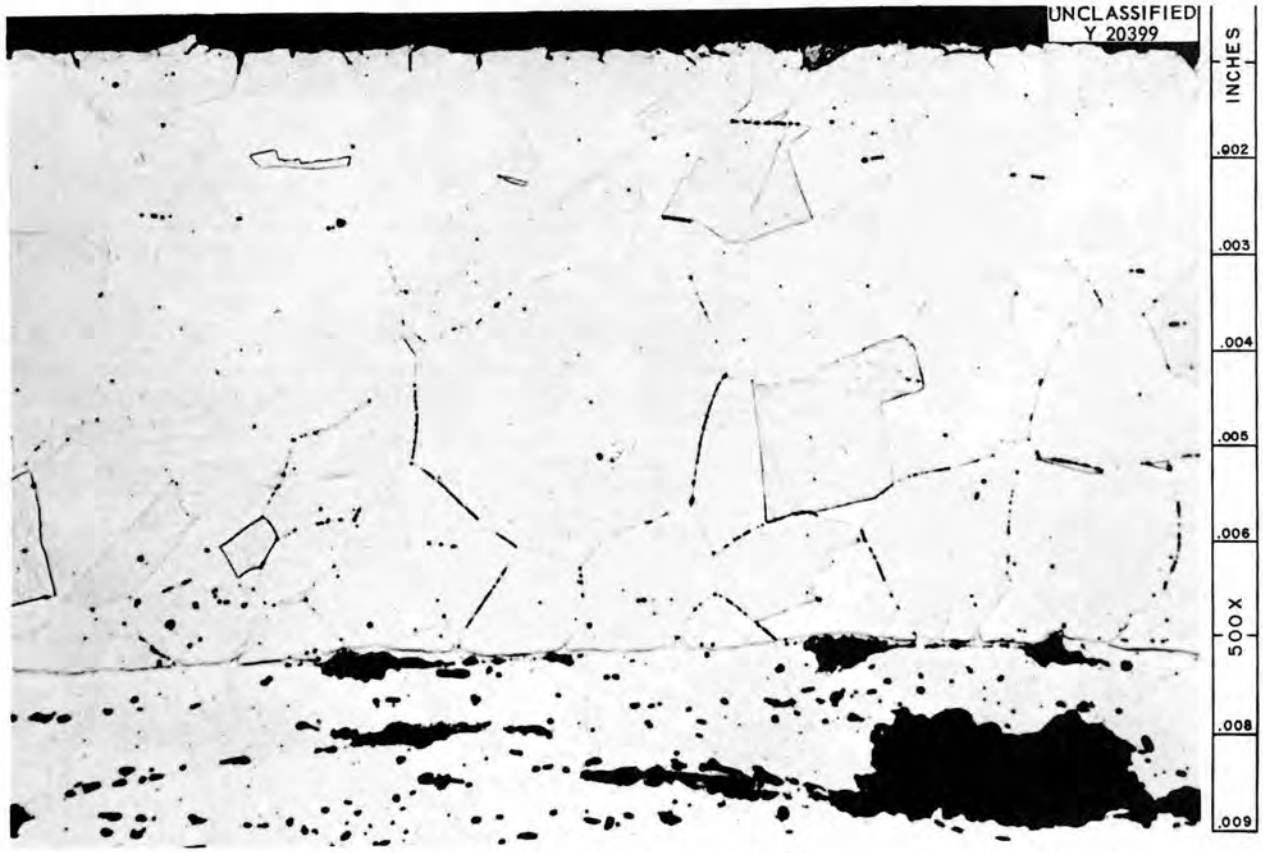

Fig. 4. Specimen No. 13, Which Had Been Electrolytically Etched with 5% Chromic Acid Solution. Section from a miniature APPR-1 plate which had been hot-rolled at 1150°C, pickled in 15% HNO_3–5% HF aqueous solution, and Strauss-tested. Note only partial chromium carbide precipitation at grain boundaries in the vicinity of the core. 500X.

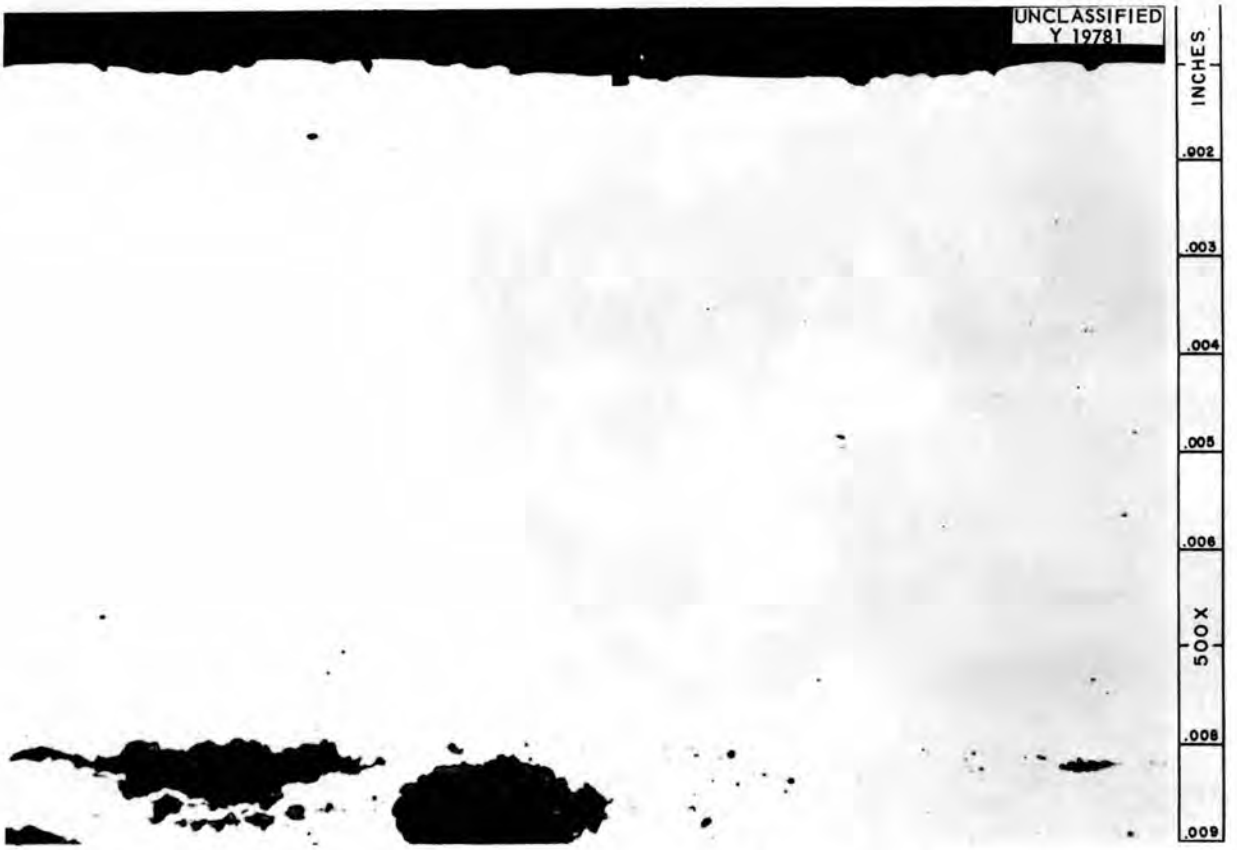

Fig. 5. As-Polished Specimen No. 13. Same as miniature plate shown in Fig. 4, after Strauss testing. No evidence of attack can be seen in the cladding. 500X.

Fig. 6. Specimen No. 19, Which Had Been Electrolytically Etched with 5% Chromic Acid Solution. Section from a miniature APPR-1 plate which had been annealed at 1125°C. Note the continuous network of chromium carbide precipitation at the grain boundaries. 500X.

Fig. 7. As-Polished Specimen No. 19. Section from a miniature APPR-1 plate which had been subjected to one annealing cycle at 1125°C and Strauss-tested. Note complete intergranular penetration of cladding. 500X.

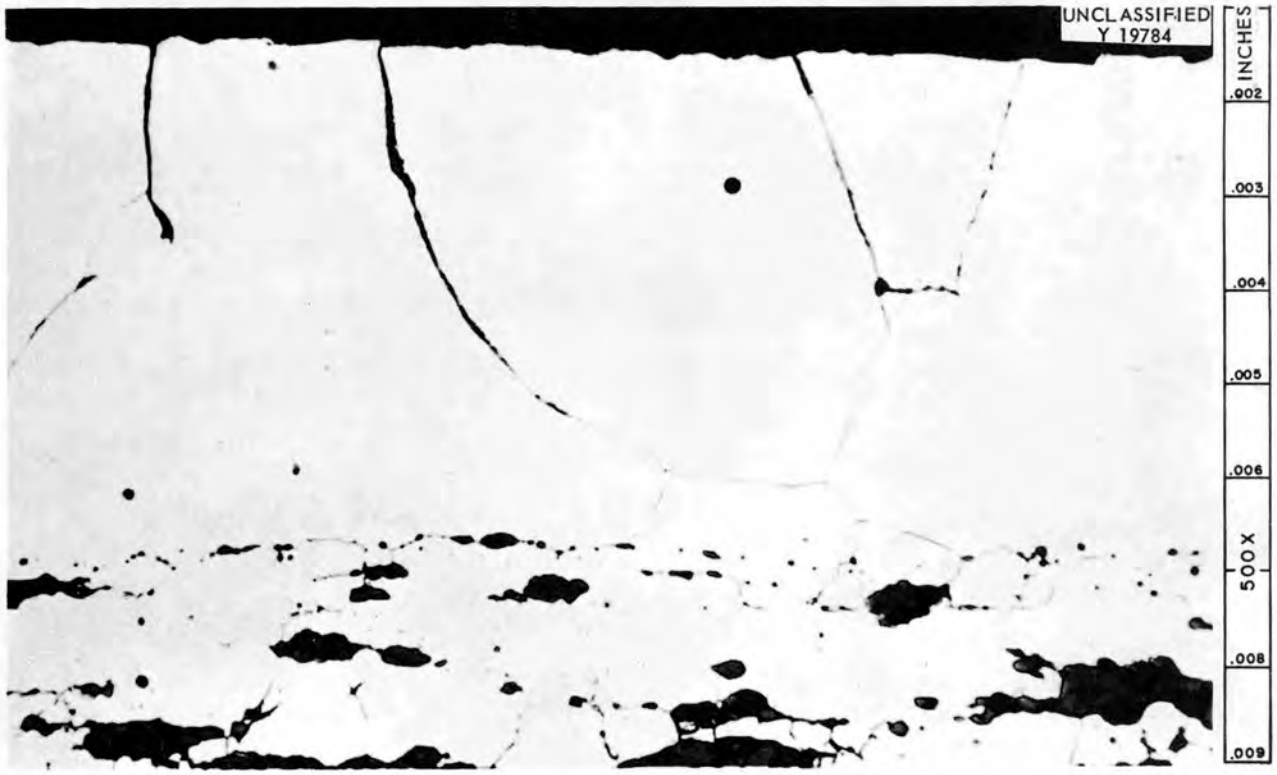

Fig. 8. As-Polished Specimen No. 21. Section from a miniature APPR-1 plate which had been subjected to two annealing cycles at 1125°C and Strauss-tested. Note heavy intergranular attack in the cladding. 500X.

Fig. 9. As-Polished Specimen No. 20. Section from a miniature APPR-1 plate which had been annealed at 1125°C, simulated-brazed at 1135°C, and Strauss-tested. Note partial penetration in from clad surface. 500X.

Fig. 10. As-Polished Specimen No. 22. Section from a miniature APPR-1 plate which had been subjected to two annealing cycles at 1125°C, simulated-brazed at 1135°C, and Strauss-tested. Note intergranular type attack in the cladding. 500X.

Fig. 11. Specimen No. 52, Which Had Been Electrolytically Etched with 5% Chromic Acid Solution. Section from a miniature type 347–347B stainless steel plate which had been processed through the cold-rolling operation. Note fine niobium carbide precipitation in clad. 500X.

Fig. 12. As-Polished Specimen No. 52. Section from a miniature type 347–347B stainless steel plate which had been processed through the cold-rolling operation and Strauss-tested. No evidence of attack can be observed at clad surface. 500X.

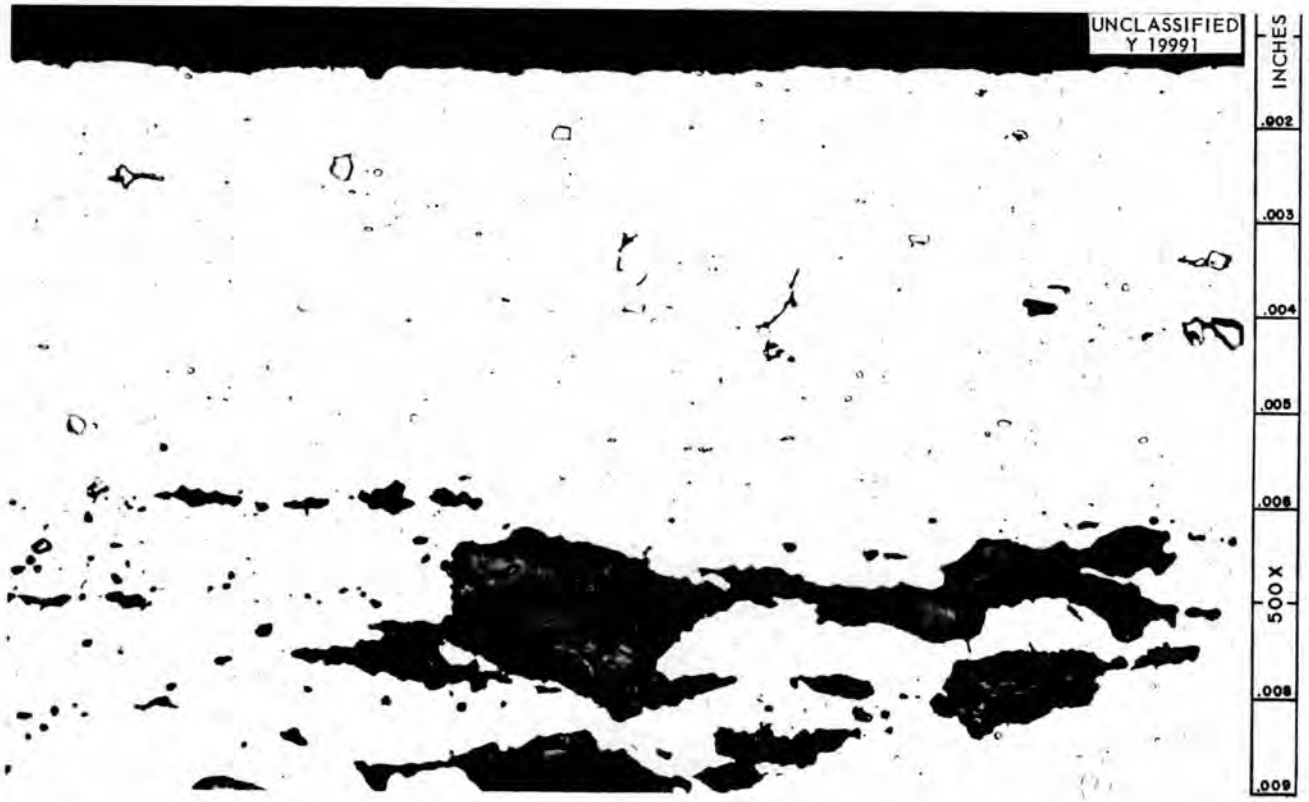

Fig. 13. Specimen No. 53, Which Had Been Electrolytically Etched with 5% Chromic Acid Solution. Section from a miniature type 347–347B stainless steel plate which had been processed through one annealing cycle at 1125°C. Note fine niobium carbide precipitation in clad. 500X.

Fig. 14. As-Polished Specimen No. 53. Same as miniature plate shown in Fig. 13, after having been Strauss-tested. No evidence of attack can be seen in the cladding. 500X.

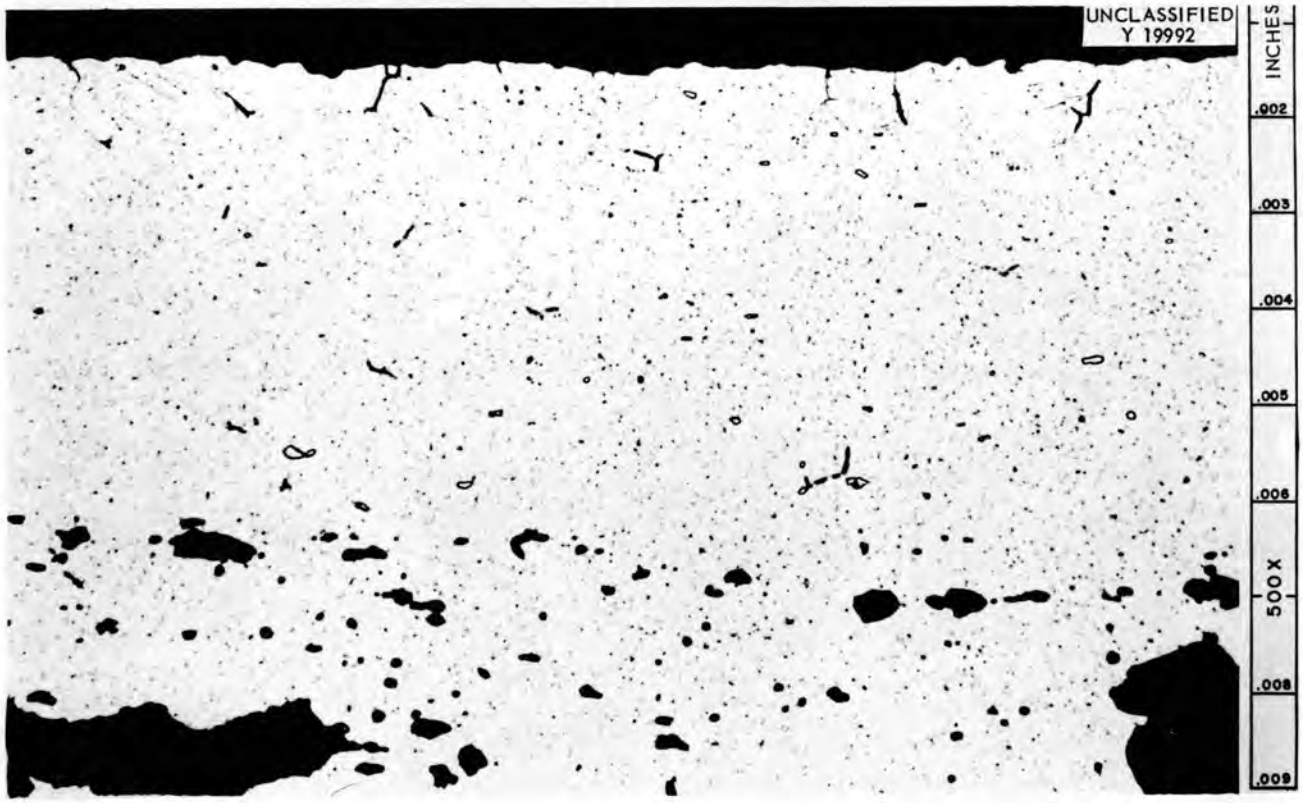

Fig. 15. Specimen No. 54, Which Had Been Electrolytically Etched with 5% Chromic Acid Solution. Section from miniature type 347–347B stainless steel plate which had been annealed at 1125°C and simulated-brazed at 1135°C. Note erratic chromium carbide precipitation in clad. 500X.

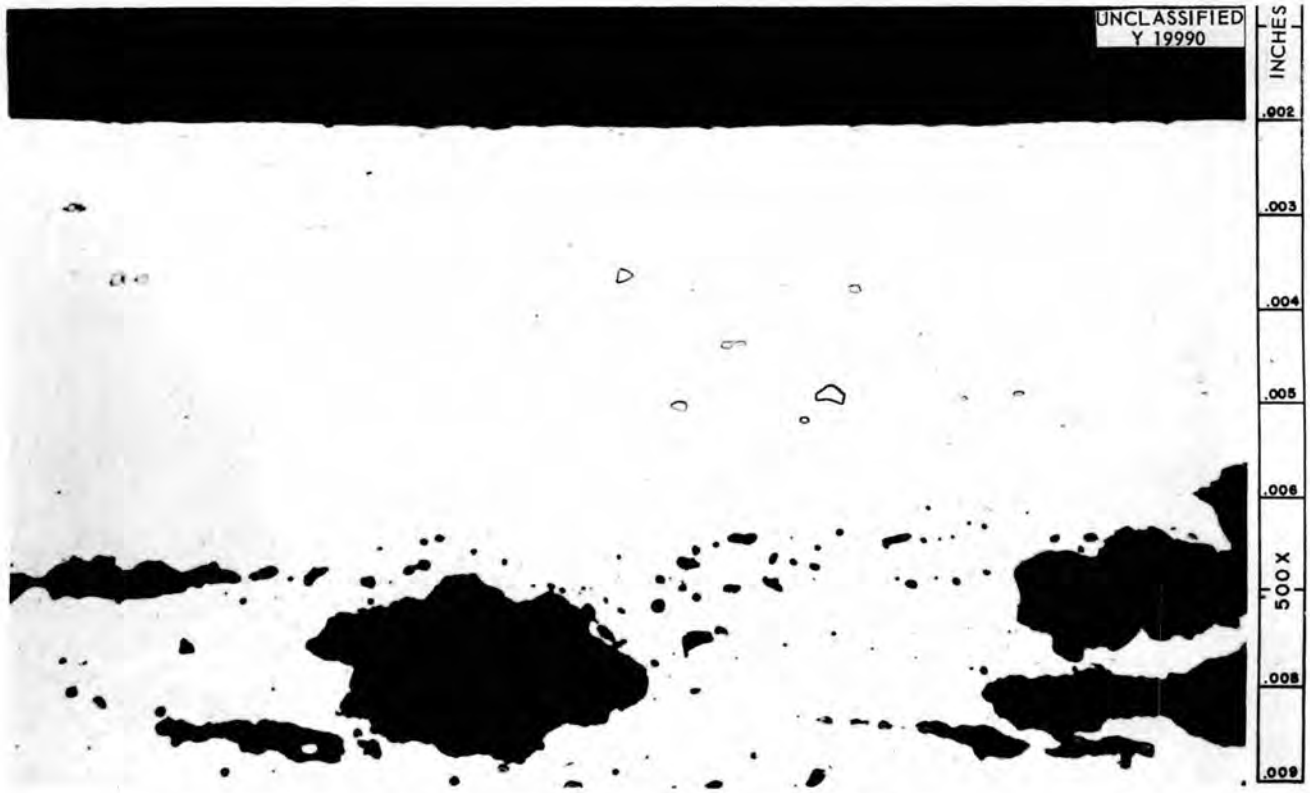

Fig. 16. As-Polished Specimen No. 54. Same as miniature plate shown in Fig. 15, after having been Strauss-tested. No evidence of attack can be seen in the cladding. 500X.

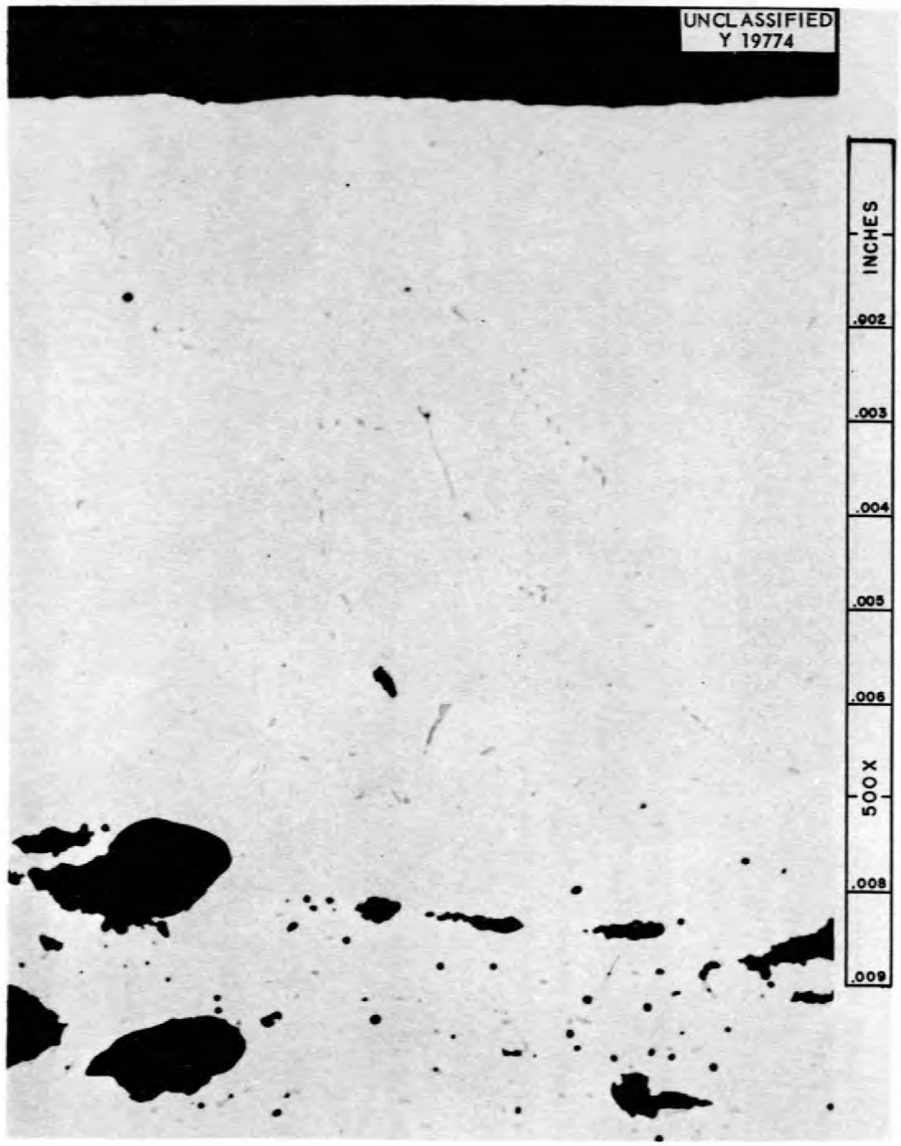

Fig. 17. As-Polished Section from APPR-1-Type Plate Which Had Been Machined from the WAPD Test Element After Being Corrosion-Tested for 6245 hr in 260°C-Pressurized Water. No evidence of attack can be seen in plate cladding. 500X.

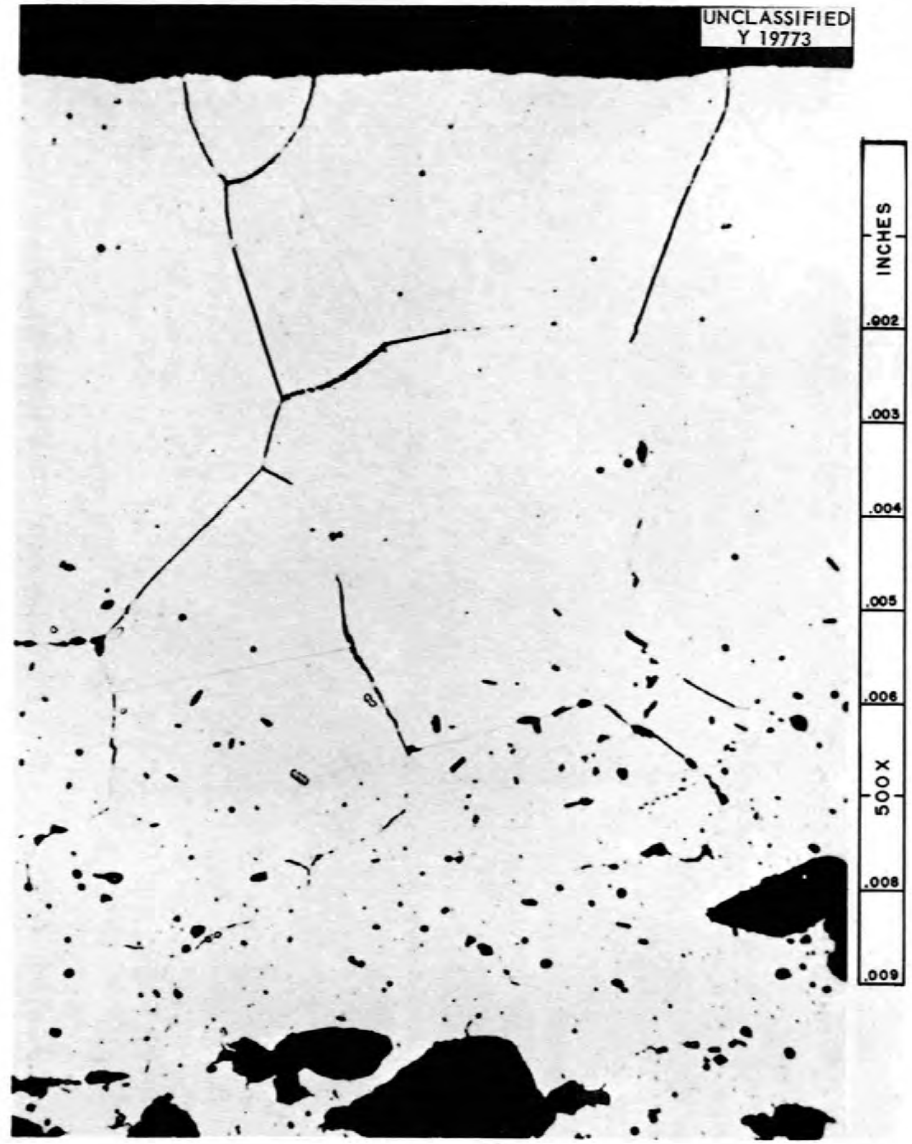

Fig. 18. Section Shown in Fig. 17, After Being Electrolytically Etched with 5% Chromic Acid Solution. Note sensitized condition of plate cladding. 500X.

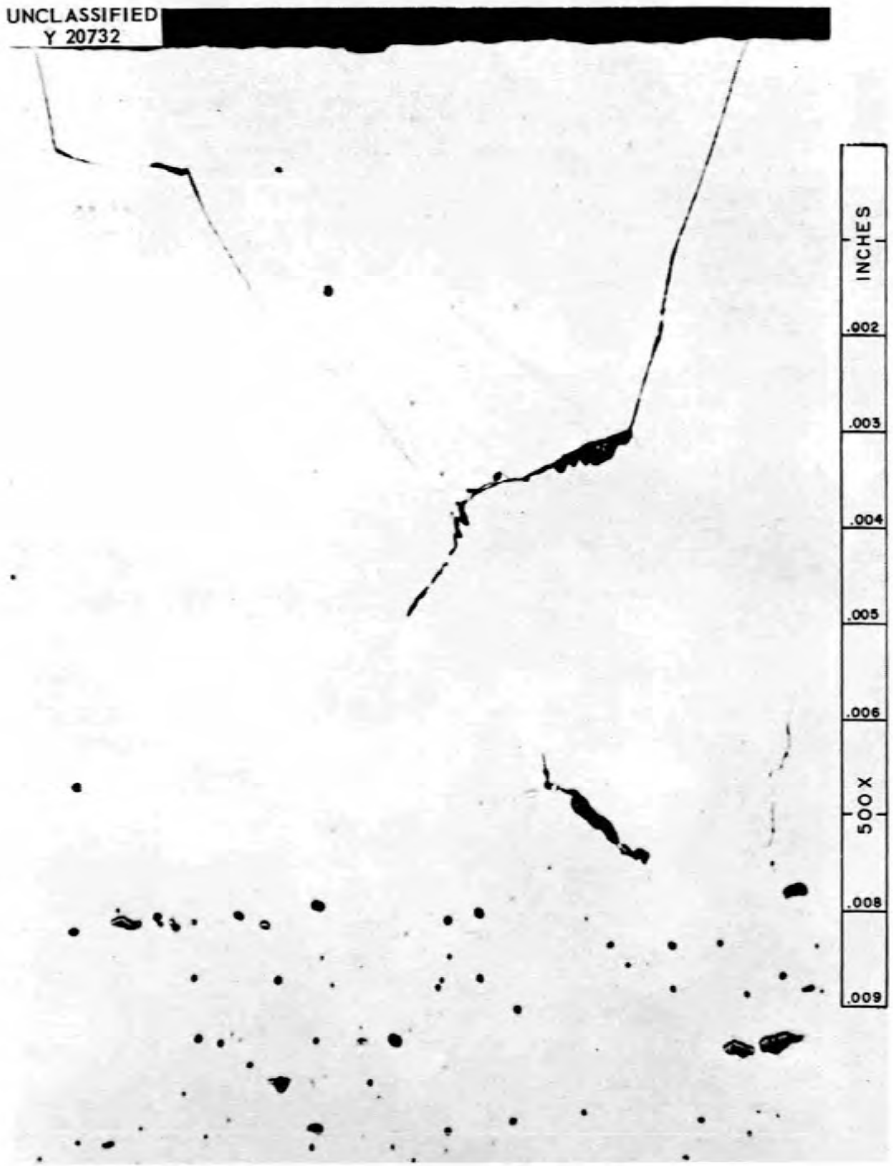

Fig. 19. As-Polished Specimen Shown in Fig. 17, After Having Been Strauss-Tested. Note intergranular type attack in plate cladding. 500X.

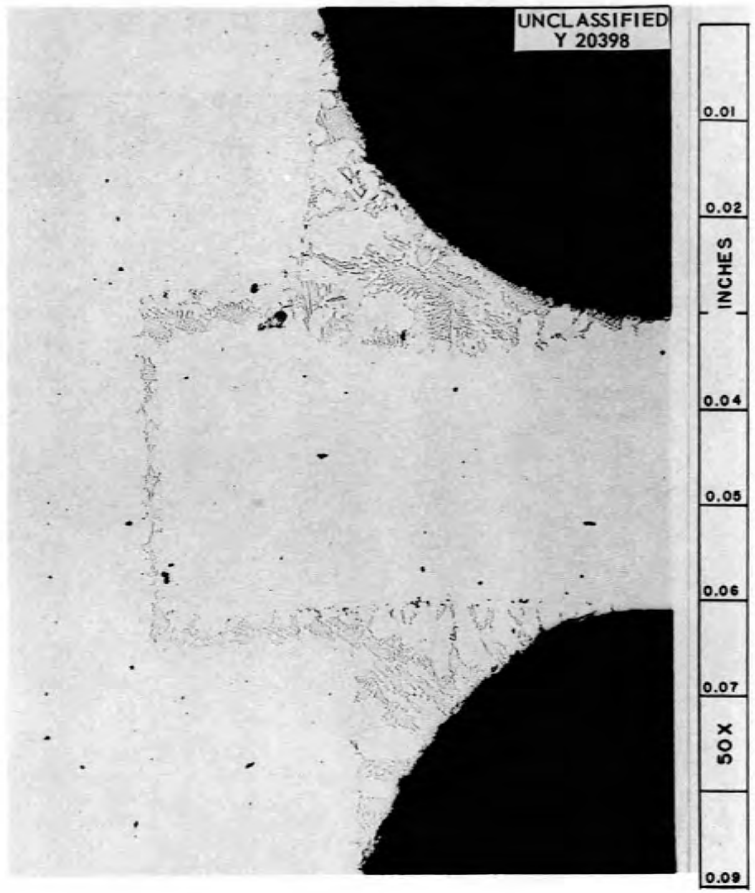

Fig. 20. Over-All View of a Typical Brazed Joint from the WAPD Test Element, After the 6245-hr Corrosion Test; As-Polished Condition. 50X.

Fig. 21. Magnified View of Upper Fillet Shown in Fig. 20. Note slight inequality of fillet surface. 150X.