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APAE NO. 82

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**EVALUATION OF KANIGEN,
ELECTROLESS NICKEL PLATING
FOR
STEAM SIDE OF A SODIUM
COMPONENT STEAM GENERATOR**

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ALCO PRODUCTS, INC.

RESEARCH AND DEVELOPMENT DEPARTMENT
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COMPONENT STEAM GENERATOR

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ALCO PRODUCTS, INC.
Research and Development
Schenectady, New York

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**EVALUATION OF KANIGEN ELECTROLESS
NICKEL PLATING
FOR STEAM SIDE OF SODIUM
COMPONENT STEAM GENERATOR**

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INTRODUCTION

This is a final report on the evaluation of Kanigen ⁽¹⁾ electroless nickel plating for surfaces in contact with water and steam in a sodium heated AISI Type 316 stainless steel steam generator. The purpose of the coating was to afford protection from stress corrosion cracking originating on the water-steam side of the unit. It has been concluded that the Kanigen coating does not afford adequate protection for the service conditions intended.

This work was performed as part of the research and development program for the United States Atomic Energy Commission Sodium Components Design Project.

OBJECTIVE

The objective of this test program was to evaluate the overall suitability of Kanigen coating protection against stress corrosion cracking of AISI Type 316 stainless steel under intended service conditions. This necessitated determination of the following properties of the electroless nickel-phosphorus coating:

1. Integrity of the coating on AISI Type 316 stainless steel.
2. Feasibility of obtaining adequate plating coverage of a simulated steam generator test model.
3. Adhesion of the coating to AISI Type 316 stainless steel.
4. Resistance of the coating to chloride stress corrosion cracking.
5. Tendency for the coating to afford cathodic protection against stress corrosion cracking to exposed surface of AISI Type 316 stainless steel.
6. Condition of the coating after being subjected to thermal shock of the magnitude possible in the sodium heated steam generator.
7. Erosion resistance of the coating to wet steam and to superheated steam at temperatures to 1100⁰ F.
8. Corrosion resistance of the coating to 1050⁰ F superheated steam.

(1) "Kanigen is a resistered trade mark of General American Transportation Corporation.

CONCLUSIONS

The electroless nickel-phosphorus coating does not afford reliable protection against stress corrosion cracking of an AISI Type 316 stainless steel steam generator under the intended service conditions.

The following specific conclusions have been derived from the test program:

1. A continuous and pore-free Kanigen coating is attainable on test specimens.
2. The feasibility of attaining a continuous and pore-free coating on the steam generator is highly questionable. Internal tube surfaces do not plate properly due to process difficulties. It has not been demonstrated that a perfect coating can be obtained on the steam channels, although the Kanigen processor feels they can do better than the initial attempt on a test model.
3. Adhesion characteristics appear to be satisfactory for service conditions.
4. The Kanigen coating is resistant to chloride stress corrosion cracking.
5. The Kanigen coating does not afford cathodic protection against stress corrosion cracking to exposed AISI Type 316 stainless steel.
6. The Kanigen coating is subject to cracking, exposing bare stainless steel, when subjected to severe thermal shock.
7. Erosion resistance of the Kanigen is unsatisfactory in wet steam at 650⁰ F and highly questionable in superheated steam at intended service conditions.
8. The Kanigen coating has very good corrosion resistance to low oxygen superheated steam at 1050⁰ F.
9. The ferroxyl test appears to be reliable for indication of imperfections in the coating

DESCRIPTION OF TEST PROCEDURES

A. Integrity of the Coating

Unbent standard ASME guided bend specimens (AISI Type 316 stainless steel) were plated by the processor with 5.0 ± 0.5 -0 mils of Kanigen. The plated specimens were heat treated at 650° F for one hour in an atmosphere controlled furnace, and tested by the electrographic technique. Satisfactory plating was to be evidenced by no indication of basis metal on the electrograph prints of test specimen surfaces.

Plating of five full length tubes (31 feet, 3 inches) was to be attempted by the processor. Flow and temperature conditions were to be varied to attain the optimum plating conditions. The tubes were to be sectioned for evaluation of plating uniformity.

A heat exchanger test model, simulating the original superheater design, was to be plated under plating conditions for the full size unit. The model was to be dismantled, inspected, and tested after plating to determine adequacy of plating coverage. The tubesheet was to be subjected to thermal shock cycles after examination for porosity by the ferroxyl test.

B. Adhesion of Plating

Adhesion of plating was determined by bending three standard 3/8 inch ASME guided-bend specimens once through an angle of 180 degrees, using the specified mandrel and die. The quality of pretreatment and plating was judged by the following standards:

1. The plating on the bend area shall not show separation from the basis material at the interface, when examined at a magnification of 4X.
2. It shall not be possible to detach any appreciable areas of plating with a sharp instrument on the outside radius of the bent specimen.

C. Stress Corrosion Cracking

Twelve standard ASME 6 X 1/2 X 1/4 inch U-bend test specimens were prepared from stress relieved AISI Type 316 stainless steel. The

surface treatments were varied as follows:

1. Three specimens - No surface treatment.
2. Three specimens - Kanigen plate after preliminary bending.
3. Three specimens - Kanigen plate after bending, and bolting to 1-1/2 inch diameter bend.
4. Three specimens - Kanigen plate after bending and bolting to 1-1/2 inch diameter bend - plating removed from 1/4 inch wide section on outer section midway between apex and end of bent section.

All specimens were heat treated at 650⁰ F for one hour in a controlled-atmosphere furnace after bending and bolting. The specimens were then exposed to boiling 42 per cent magnesium chloride solution, and examined every twenty-four hours.

D. Thermal Shock Resistance

One of the Kanigen plated tubesheets from the test model heat exchanger was subjected to thermal shock. It was held at 1100⁰ F for twenty-four hours prior to initial shocking. It was then cooled by a tap water spray, and cycled from 1150⁰ to 400⁰ F for two hundred cycles, and examined. The tubesheet was then given eleven hundred additional cycles with plant steam condensate used for shock cooling. The cooling cycles were thirty seconds, and the heating cycles thirty minutes in duration.

Figure 1 is a photograph of the test stand used for thermal shocking, and a sketch of the furnace arrangement is presented in Figure 2.

Prior to final examination, the tubesheet was given six eight hour furnace cooling cycles. Ferroxy test solution was applied to the Kanigen surface for visual examination, and metallographic specimens were prepared for final examination.

E. Erosion Resistance

Two test sections of internally plated straight and 90 degree bend tubing were inserted in the wet steam outlet of the boyonet heater test loop. The tubing, 5/16 o.d. X .049 inch wall, was exposed to 650⁰ F, 2200 psi, wet steam at a maximum velocity of about one hundred feet per second, for approximately six hundred hours.

Figure 1 - Thermal Shock Test Stand

Figure 2 - Furnace Arrangement

A high temperature test loop was constructed for additional erosion testing. Plant steam was superheated in an electrical resistance heated length of stainless steel tubing. A 5/16 O. D. X .049 inch wall internally plated length of tubing was inserted in front of the superheater to determine erosion resistance to wet plant steam. Internally plated test sections, 1/2 O.D. X .083 inch wall tubing, 1/2 O.D. X 0.49 inch wall tubing, and 3/8 inch Schedule 40 pipe, were inserted immediately after the superheater to determine erosion resistance at varying velocities to superheated steam at approximately 1100° F. The steam then passed through a larger test section, where corrosion test coupons were inserted. Three additional erosion test sections, identical to the postsuperheater test sections, were inserted in front of the condenser to determine erosion resistance to the cooler steam. Steam flow rates were controlled by a needle valve at the condenser entrance. Erosion test sections were sectioned for visual and metallographic examination after two thousand hours of testing. A diagram of the test loop is shown in Figure 3.

F. Corrosion Resistance

Twelve AISI Type 316 stainless steel corrosion test coupons, 3/4 X 1-1/2 X .049 inch, were plated with five mils of electroless nickel-phosphorus coating. They were cleaned, weighed and inserted in the corrosion test section of the high temperature erosion test loop. Steam temperature in this section was approximately 1040° F. Some of the coupons were removed from the loop for evaluation at periodic intervals up to two thousand hours of exposure. Evaluation was by weight change and visual and metallographic examination.

PRESENTATION OF TEST RESULTS

A. Integrity of the Coating

1. Bend Specimens

Examination of unbent 3/8 inch ASME guided-bend specimens by the electrographic technique revealed that a continuous and porefree Kanigen coating was present.

2. Tube Plating

The Kanigen plating processor could not obtain a satisfactory coating on the inside surface of 1/2 inch stainless steel tubing. Plating of the steam generator tubing was no longer considered after this operation.

Figure 3 - Schematic Diagram of High Temperature Steam Test Loop

3. Test Model Plating

The tubesheets and channel ends of the steam generator test model were plated in hope of obtaining protection with Inconel inner clad bimetallic tubes, combined with Kanigen plated steam side tubesheets and channel ends.

Coating on one of the channel ends was mechanically damaged by shipment of the test model. Tubesheets were cut out of the test model and subjected to a ferroxyl test. Indications of iron exposure were evident at several imperfections in the coating on the tubesheet surfaces. The trepanned surface at the tube-to-tubesheet joints, which would appear to be the most difficult area to obtain a good coating, had relatively few defects. Photographs of the tubesheets with ferroxyl test solution applied are presented in Figure 4.

It was decided to proceed with testing of the coating quality on one of the tubesheets (tubesheet A in Figure 4), and to send the other tubesheet and channel back to the processor for stripping and replating before testing. The processor felt that a pore-free coating could be attained on the tubesheet and channel ends. When subsequent testing demonstrated that a good coating would not give reliable protection under service conditions, no further action was taken with the second tubesheet.

B. Adhesion of Plating

Cold 180 degree guided-bend tests on standard ASME specimens revealed that specimens which had been heat treated at 600, 800 and 1000⁰ F for three hours had less satisfactory adhesion than as-plated specimens. However, hot bending at 800⁰ F showed perfect adhesion. It was considered that adhesion was satisfactory for service conditions.

C. Stress Corrosion Testing

Results of the boiling 42 per cent magnesium chloride tests on U-bend specimens were as follows:

1. Three stainless steel specimens with no surface treatment:

- Specimen Number One - Failure within forty-eight hours.
- Specimen Number Two - Failure within seventy-two hours.
- Specimen Number Three - Failure within seventy-two hours.

894 017

Figure 4 - As Received Kanigen Plated Tubesheets with Ferroxyl Test Solution Applied. Note Stainless Steel Exposure to Solution at Circled Zone

2. Three specimens with Kanigen plate after preliminary bending:

Cracks were formed in the plating to expose stainless steel during final bending and bolting:

- Specimen Number One - Failure within seventy-two hours.
- Specimen Number Two - Failure within ninety-six hours.
- Specimen Number Three - Failure within ninety-six hours.

3. Three specimens with Kanigen plate after bending and bolting to 1-1/2 inch diameter bend:

- Specimen Number One - Failure by single crack within seven hundred eighty hours.
(The Kanigen plate appeared to be defective where the crack initiated.)
- Specimen Number Two - No cracking after fourteen hundred fifty hours in test.
- Specimen Number Three - The bolt snapped in an unplated area after three hundred twenty hours in test.

4. Three specimens with Kanigen plate after bending and bolting to a 1-1/2 inch diameter bend.

Plating was removed from a 1/2 inch wide section.

- Specimen Number One - Failure within ninety-six hours.
- Specimen Number Two - Failure within ninety-six hours.
- Specimen Number Three - Failure within ninety-six hours.

The above results indicate that the electroless nickel phosphorus coating is not susceptible to stress corrosion cracking. However, it does not offer cathodic protection to exposed stainless steel, although it slightly increased the time to failure. More convincing evidence of the inadequacy of the coating to afford cathodic protection under service conditions was discovered by the subsequently described thermal shock test results.

D. Thermal Shock Tests

Visual examination of the Kanigen plated tubesheet from the test model heat exchanger after two hundred thermal shock cycles revealed a pattern of very fine surface cracks on the tubesheet. Application of ferroxyl test solution gave indication of several defects where stainless steel was exposed. However, stainless steel did not appear to be exposed through most of the fine surface cracks.

After eleven hundred additional thermal cycles, considerably more stainless steel exposure through the coating was evident by ferroxyl test. Tubesheet A, Figure 4, is a photograph of the plated tubesheet in the as-received condition under ferroxyl test solution. Figure 5 is a photograph of the same tubesheet without test solution on it after completion of thermal shock testing.

Tap water was used for shock cooling of the plated tubesheet for the first two hundred cycles. Difficulty was encountered in removing oxides and salt deposits from the tubesheet surface to allow visual inspection. Plant steam condensate was used for subsequent shock cooling cycles. Metallographic examination after completion of testing revealed that cracks and pits were prevalent at the base of the trepanned risers for the tube-to-tubesheet joints. Stress corrosion cracks extended into the stainless steel at many zones where it was exposed to the coolant. Figure 7 is a photomicrograph of one of the areas where cracking occurred. Figure 8 is a photomicrograph of an etched specimen cut from the base of another trepanned riser. Note the predominantly transgranular nature of the cracking into the stainless steel. This is typical of chloride stress corrosion cracks and was probably caused by chlorides deposited during the initial two hundred shock cycles. These cracks indicate that the Kanigen coating is definitely not reliable for cathodic protection of the stainless steel under service conditions. This substantiates the results obtained on U-bend specimens in the more severe boiling magnesium chloride tests.

A section cut from a flat portion of the tested tubesheet, showing complete coating penetration of the fine surface cracks, is shown in the photomicrograph, Figure 9.

E. Erosion Resistance

Erosion test results were somewhat inconsistent. Interpretation of results was complicated by apparent damage to the internal coating of some specimens by forces applied to the external surface of the pipe or tubing. It was demonstrated that the internal coating of a

Figure 5 - Kanigen Plated Tubesheet After 1300 Thermal Shock Cycles.
Note Heat Check Pattern of Fine Surface Cracks.

Figure 6 - Kanigen Plated Tubesheet Under FerroxyI Test Solution After 1300 Thermal Shock Cycles. Major Zones of Stainless Steel Exposure are Circled.

694 022

Figure 7 - Stress Corrosion Cracks at Base of Tre-panned Risers After Thermal Shocking

Etchant: 5% Chromic-Electrolytic

100 X

Figure 8 - Transgranular Stress Corrosion Cracks in AISI Type 316 Stainless Steel with Electroless Nickel Coating.

As Polished

100 X

Figure 9 - Cross Section from Coated Flat Surface of Tube Sheet After 1300 Thermal Shock Cycles.

pipe specimen could be cracked by gripping it in a vise and twisting on the external surface with a wrench. The damage was on the coating adjacent to the point of application of the wrench. Bare spots were found on metallographic as-received samples of pipe specimens three and seven. It was not certain whether this was due to incomplete plating or mechanical damage before or during metallographic preparation. One of these stripped areas is shown in Figure 16, which is a photomicrograph of a section from a tested pipe specimen. Identical zones were on an untested portion of the specimen.

Test specimen six also appeared to have suffered mechanical damage. The defect appeared as a continuous spiral serration over the entire length of the coated specimen. This showed up as cracks penetrating the coating at uniform intervals around the internal circumference of any cross section from the tube. Figure 12 is a portion of such a cross section showing two of the cracks. This defect is believed to have been caused by excessive torque on the end fittings of the test specimen when inserting it into the test loop.

Mechanical defects were not apparent in any specimens other than those previously noted.

Table 1 is a summary of the test conditions and post test evaluation for all erosion test specimens. Photomicrographs of tested specimens are presented in Figures 10 through 19.

The only specimen on which stainless steel exposure definitely resulted from test operation was the ninety degree bend tubing specimen inserted at the steam outlet of a boyonet tube test boiler. Water purity for this test was not rigidly controlled, so that total solids and oxygen content of the steam were relatively high. Visual examination of the split tube after test revealed some salt deposits. The extremely poor condition of the Kanigen was undoubtedly due to a combination of corrosion and erosion, influenced by impurities in the steam.

Plant steam going to the high temperature test loop was of fairly good purity. Total solids content did not exceed 2 ppm when analyzed. An oxygen analysis was taken on the exit steam condensate at least once each week during operation. Oxygen content was usually less than .01 ppm, except after startups, when it was usually about .05 ppm. The plant steam line was blown down before starting up after weekend shutdowns, in order to minimize the oxygen contamination. Maximum oxygen content of any steam to which the samples were exposed was approximately 0.2 ppm.

Complete wearing away of the electroless nickel-phosphorus coating was not attributed to erosion on any specimens exposed in the high temperature steam loop. However, the coating was worn dangerously thin in spots and probably would have exposed stainless steel when subjected to a longer test period. Correlation between steam temperature and velocity as to effect on test results was not obvious.

F. Corrosion Resistance

Table 2 is a tabulation of weight change data on corrosion test coupons removed from the high temperature test loop. Average steam conditions were 1040° F at 161 psia. Steam continuously flowed parallel with the plated surface of the test coupons at a lineal velocity of approximately twenty feet per second. Steam purity is given in a footnote of Table 1.

A very thin, tightly adherent, olive green oxide film covered the electroless nickel-phosphorus surface of all coupons subjected to test. Three of the oxidized specimens were subjected to nitric- HF solution and exhibited amazing resistance to attack, as compared with a blank sample that did not have the protective film. Surface attack of the Kanigen in the steam environment was negligible, as can be seen in the photomicrograph Figures 20, 21, 23 and 24.

A change in composition of the Kanigen-stainless steel interface occurred at test temperatures. Diffusion bonding occurred, resulting in the formation of an intermediate boundary layer between the Kanigen and stainless steel. The Kanigen appeared to be depleted of some constituent, probably phosphorus, near the interface. The interface layer increased with time until about fifteen hundred hours at temperature, and then remained fairly constant to two thousand hours. This is evidenced by comparison of the interface width in Figures 21, 22, 23, and 24. The contrast at the boundary between an as-plated specimen and the same specimen after two thousand hours exposure to 1120° F superheated steam is shown in Figures 25 and 26. Temperature appeared to have a strong effect on the magnitude of interface growth. A micro hardness survey was run across the interface on samples which had been exposed for five hundred and two thousand hours. The interface layer was intermediate in hardness. Results are given in Table 3.

Coupons four, seven and nine were drilled on one side, so as to simulate pits. This allowed observation of the behavior of the Kanigen-stainless steel couple in the steam environment. There was no noteworthy effect at the drilled zone, except for apparently harmless penetration of steam at the interface for a short distance. However, drilling of coupons seven and nine resulted in cracks in the Kanigen coating on the adjacent face. Steam penetrated the interface in these more confined areas, and initiated intergranular corrosion of the stainless steel. Representative photomicrographs of this condition are presented in Figures 27 and 28.

TABLE 1
EROSION TESTS OF KANIGEN PLATED SPECIMENS

SPECIMEN NUMBER	SPECIMEN SIZE*	STEAM TEMP. °F	STEAM PRESS. PSIA	STEAM VELOCITY ft/sec	EXPOSURE TIME HRS	REMARKS ON		FIGURE REFERENCE
						VISUAL EXAMINATION	METALLOGRAPHIC EXAMINATION	
0	5/16 X .049" tubing (12" length)	369 (sat.)	170.7**	163.0	1266	Rusty colored film-ap- peared to be in fair con-	Excellent condition; no evidence of erosion or corrosion.	10 and 17
5	1/2 X .083" tubing (12" length)	1150 (super- heat)	161.6**	144.0	2003	Dark film on surface, film eroded in spots, otherwise good.	Surface erosion fairly deep at spots.	11
6	1/2 X .049" tubing (12" length)	1135 (super- heat)	161.4**	97.0	2003	Dark uniform film in good condition, except for spiral serrations clear across the tube, probably due to mechanical twisting.	Complete penetration of the spiral serrations at uniform intervals around the tube internal cir- cumference. Slight surface erosion.	12
7	3/8" Schdl. 40 NPS (10" length)	1120 (super- heat)	161.3**	63.5	2003	Dark surface film some- what eroded. Difficult to distinguish between erosion and mechanical defects.	Mechanically damaged bare spots were evident in asplated pipe. Very thin zones in tested sample are believed due to erosion.	13
1	1/2 X .083" tubing (12" length)	940 (super- heat)	156.6**	128.0	2003	Very black surface film; appeared to be in poor general condition without localized defects.	Surface appeared uniform, but coating was very thin, probably due to erosion.	14

TABLE 1 (CONT'D)

SPECIMEN NUMBER	SPECIMEN SIZE*	STEAM TEMP. °F	STEAM PRESS. PSIA	STEAM VELOCITY ft/sec	EXPOSURE TIME HRS	REMARKS ON		FIGURE REFERENCE
						VISUAL EXAMINATION	METALLOGRAPHIC EXAMINATION	
2	1/2 X .083" tubing (12" length)	930 (super- heat)	156.4**	87.0	2003	Adherent purple and bluish oxide film; ap- peared to be in good con- dition.	Slightly eroded surface. Generally good condition with little penetration.	15
3	3/8" Schdl. 40 NPS (10" length)	920 (super- heat)	156.3**	57.0	2003	Adherent purple, yellow, and bluish oxide film; good condition, except for mechanically caused defects.	Slight erosion, good condition, except for stripped zones also evident on as-received specimen.	16
Straight tubing length.	5/16 X .049" tubing	650 (sat.)	2200.0***	97.5	600	Very black surface film with salt deposits and pits evident.	Coating worn very thin in spots by erosion; no stainless steel exposed.	17 and 18
90° elbow at steam exit of boiler test rig.	5/16 X .049" tubing	650 (sat)	2200.0***	97.5	600	Very black surface film with salt deposits and pits evident.	Surface erosion and deep pits exposing the stainless steel.	17 and 19

* Before plating with 5 mils of Kanigen.

Steam Purity

** Plant Steam: Total solids: <2.0 ppm.
O₂ content: <0.01 ppm for most of operation;
0.05 ppm for start-up after week end shutdown;
0.20 ppm maximum for short periods.

*** Test Boiler: High total solids and oxygen content in boiler water.

As Polished

100 X

Figure 10 - Specimen #0. Electroless Nickel-Phosphorus Coating After 1266 Hours Exposure to Wet Steam (369°F Sat.) Flow of 163 Feet per Second.

As Polished

100 X

Figure 11 - Specimen #5. Electroless Nickel-Phosphorus Coating After 2003 Hours Exposure to 1150°F Superheated Steam Flow of 144 Feet per Second. Note the Eroded Surface

As Polished

100 X

Figure 12 - Specimen #6. Electroless Nickel-Phosphorus Coating After 2003 Hours Exposure to 1135°F Superheated Steam Flow of 97 Feet per Second. Penetration is at Uniform Intervals and Believed to be Due to Mechanical Damage.

Etchant: 4% Sulfuric-Electrolytic

100 X

Figure 13 - Specimen #7. Electroless Nickel-Phosphorus Coating After 2003 Hours Exposure to 1120°F Superheated Steam Flow of 63.5 Feet per Second. Thin Coating Zone May be Due to Erosion.

As Polished

100 X

Figure 14 - Specimen #1. Electroless Nickel-Phosphorus Coating After 2003 Hours Exposure to 940°F Superheated Steam Flow of 128 Feet per Second. Coating is Believed to Have Been Worn Thin by Erosion Although the Surface is Even.

As Polished

100 X

Figure 15 - Specimen #2. Electroless Nickel-Phosphorus Coating After 2003 Hours Exposure to 930°F Superheated Steam Flow of 87 Feet per Second.

As Polished

100 X

Figure 16 - Specimen #3. Electroless Nickel-Phosphorus Coating After 2003 Hours Exposure to 920°F Superheated Steam Flow of 57 Feet per Second. Stripped Zones Were Also Present on the As-Received Pipe and are Believed to be Due to Mechanical Damage.

As Polished

100 X

Figure 17 - As-Received Electroless Nickel-Phosphorus Coated Tubing Used For Erosion Test Specimens Shown in Figures 10, 18 and 19.

As Polished

100 X

Figure 18 - Electroless Nickel - Phosphorus Coating After 600 Hours Exposure to 650^o F Saturated Steam Flow of 97.5 Feet per Second. Note the Severe Surface Erosion.

As Polished

100 X

Figure 19 - Electroless Nickel - Phosphorus Coating After 600 Hours Exposure to 650^o F Saturated Steam Flow of 97.5 Feet per Second Near 90^o Change of Flow Direction. Note the Severe Damage to the Coating, Exposing Stainless Steel.

TABLE 2
CORROSION DATA ON
KANIGEN PLATED COUPONS IN 1040° F STEAM

<u>COUPON NUMBER</u>	<u>ORIGINAL WEIGHT (gms)</u>	<u>EXPOSURE TIME (hrs)</u>	<u>WEIGHT CHANGE (mg)</u>	<u>*DESCALED WEIGHT CHANGE (mg)</u>	<u>CORROSION** RATE (mg/cm²/mo)</u>
2	8.7504	507	+0.5	--	--
3	8.7967	507	+0.2	--	--
***4	8.7517	507	+0.3	--	--
5	8.6808	559	-0.1	-1.4	0.13
6	8.7050	559	-0.3	-1.5	0.13
***7	8.7526	990	+0.4	+0.1	--
8	8.7767	990	+0.4	-0.4	0.02
10	8.6736	990	+0.5	+0.1	--
***9	8.6920	1502	+0.3	-0.9	0.03
11	8.7168	1502	+0.2	-1.7	0.05
12	8.7802	2003	+0.3	-2.6	0.06

* After two minute scrubbing with soft brush and moist abrasive detergent. The weight of metal removed on scrubbing a blank sample, 1.4 mg, was added to the post scrubbing weight.

** Based on the descaled weight loss and an exposed area of 14.84 cm².

*** These specimens were purposely drilled to expose stainless steel, disturbing the Kanigen corrosion results based on weight change.

TABLE 3

MICRO HARDNESS SURVEY ACROSS INTERFACE
OF KANIGEN PLATED TYPE 316 STAINLESS STEEL

100 gm. Load, Tukon Microhardness Tester

Distance from Kanigen Surface inch	Filar Units		Knoop Hardness		Rockwell C Conversion	
	Sample*	Sample**	Sample*	Sample**	Sample*	Sample**
	No. 5	No. 12	No. 5	No. 12	No. 5	No. 12
.001	2.40	2.54	705	634	54.5	51.0
.002	2.32	2.50	755	657	56.5	52.0
.003	2.22	2.48	824	666	59.0	52.5
.004	2.20	2.29	842	776	60.0	57.5
.005***	3.37	4.01	358	253	29.0	14.0
.006	4.17	4.52	-	-	<11.0	<11.0
.007	-	4.18	-	-	-	<11.0
.008	4.26	4.18	-	-	<11.0	<11.0
.009	-	4.19	-	-	-	<11.0
.010	4.02	4.29	245	-	13.0	<11.0
.012	4.06	4.32	247	-	13.0	<11.0

* After 559 hours exposure to 1040 F steam.

** After 2003 hours exposure to 1040 F steam.

*** Interface between Kanigen and stainless steel.

As Polished

500 X

Figure 20 - Coupon #5. Electroless Nickel - Phosphorus Coating After 559 Hours Exposure to 1040°F Steam. Note the Composition Change at the Interface.

Etchant: 4% Sulfuric-Electrolytic

500 X

Figure 21 - Coupon #6. Electroless Nickel - Phosphorus Coating After 559 Hours Exposure to 1040°F Steam. Note Interface Thickness.

894 035

Etchant: 4% Sulfuric-Electrolytic

500 X

Figure 22 - Coupon # 10. Electroless Nickel-Phosphorus Coating After 990 Hours Exposure to 1040°F Steam. Note Interface Thickness Increase Over Figure 21.

Etchant: 4% Sulfuric-Electrolytic

500 X

Figure 23 - Coupon #9. Electroless Nickel-Phosphorus Coating After 1502 Hours Exposure to 1040°F Steam. Note Interface Thickness Increase Over Figure 22.

Etchant: 4% Sulfuric-Electrolytic

500 X

Figure 24 - Coupon #12. Electroless Nickel - Phosphorus Coating After 2003 Hours Exposure to 1040°F Steam. Note Interface Thickness, About the Same as Figure 23.

Etchant: 4% Sulfuric-Electrolytic

500 X

Figure 25 - Electroless Nickel - Phosphorus Coating Interface with Type 316 Stainless Steel in As-Received Condition.

Etchant: 4% Sulfuric-Electrolytic

500 X

Figure 26 - Electroless Nickel - Phosphorus Coating Interface with Type 316 Stainless Steel. Same Specimen as Figure 25 After 2003 Hours at 1025°F.

As Polished

100 X

Figure 27 - Coupon #7. Drill Hole Simulating Pit on One Kanigen Plated Side of Test Coupon. Note accidental Crack of Coating on the Opposite Side and Steam Penetration with Corrosion of the Stainless Steel After 990 Hours in 1040°F Steam.

As Polished

500 X

Figure 28 - Coupon #7 Intergranular Corrosion at Tip of Penetration Shown in Figure 27.

DISCUSSION AND RECOMMENDATIONS

The primary need for the Kanigen coating on the steam generator was to give reliable protection against stress corrosion cracking of the stainless steel. In order to give a justifiable degree of reliability, it was necessary that the coating should either give one hundred per cent effective coverage of the stainless steel, or exhibit a desirable degree of cathodic protection in any areas where the stainless steel might be exposed. The feasibility of reliable protection for this application does not appear satisfactory for the following reasons:

1. It has not been demonstrated that one hundred per cent plating coverage can be attained initially on the tubesheet and channel ends of the design configuration. If a perfect coating is attained, it does not appear that it can be maintained, because of susceptibility to: (a) mechanical damage, (b) erosion damage, and (c) cracking when subjected to thermal shock.
2. Although a moderate prolonging of time to cracking was noted on boiling magnesium chloride tests of U-bend specimens, no protection was evident under simulated service conditions. Stress corrosion cracks initiated in the model tubesheet during thermal shock testing are conclusive evidence of the inadequacy of protection.

It is recommended that no further consideration be given to Kanigen plating as a reliable deterrent to stress corrosion cracking in a sodium component steam generator. An Inconel-type weld overlay procedure is being developed as an alternative for the present application.