

Materials Reliability Program: Potential for Mitigation of Primary Water Stress Corrosion Cracking in Ni-Based Alloys by Using the EPRI Stabilized Chrome Process (MRP-194)

1013518



Effective December 6, 2006, this report has been made publicly available in accordance with Section 734.3(b)(3) and published in accordance with Section 734.7 of the U.S. Export Administration Regulations. As a result of this publication, this report is subject to only copyright protection and does not require any license agreement from EPRI. This notice supersedes the export control restrictions and any proprietary licensed material notices embedded in the document prior to publication.

Materials Reliability Program: Potential for Mitigation of Primary Water Stress Corrosion Cracking in Ni-Based Alloys by Using the EPRI Stabilized Chromium Process (MRP-194)

1013518

Technical Update, June 2006

EPRI Project Managers
J. Hickling
K. Ahluwalia

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Electricité de France (EDF) Research and Development

Electric Power Research Institute (EPRI)

Modeling and Computing Services LLC

NOTICE: THIS REPORT CONTAINS PROPRIETARY INFORMATION THAT IS THE INTELLECTUAL PROPERTY OF EPRI, ACCORDINGLY, IT IS AVAILABLE ONLY UNDER LICENSE FROM EPRI AND MAY NOT BE REPRODUCED OR DISCLOSED, WHOLLY OR IN PART, BY ANY LICENSEE TO ANY OTHER PERSON OR ORGANIZATION.

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Electric Power Research Institute and EPRI are registered service marks of the Electric Power Research Institute, Inc.

Copyright © 2006 Electric Power Research Institute, Inc. All rights reserved

CITATIONS

This report was prepared by:

EDF R&D
Materials and Mechanics of Components Department
Chemistry – Corrosion Group
Site des Renardières
Avenue des renardières
Ecuelles
F-77818 Moret sur Loing
France

Principal Investigators:

T. Couvant
A. Bescond

Electric Power Research Institute (EPRI)
3412 Hillview Avenue
Palo Alto, CA 94304

Principal Investigator
J. Hickling

Modeling and Computing Services LLC
P.O. Box 18583
Boulder Colorado 80308-1583

Principal Investigator
E. Eason

This report describes research sponsored by the Electric Power Research Institute (EPRI).

The report is a corporate document that should be cited in the literature in the following manner:
Materials Reliability Program: Potential for Mitigation of Primary Water Stress Corrosion Cracking in Ni-Based Alloys by Using the EPRI Stabilized Chromium Process (MRP-194), EPRI, Palo Alto, CA, 2006. 1013518.

PRODUCT DESCRIPTION

EPRI's stabilized chromium pre-treatment process (SCrP) has been shown to reduce activity deposition in replacement components exposed in the primary systems of light water reactors by enriching a thin surface layer of the material in chromium (to >90 weight %). Since the chromium level plays a key role in determining the susceptibility of nickel-base alloys to primary water stress corrosion cracking (PWSCC), this study was carried out to evaluate the ability of SCrP-treatment to delay cracking in reverse U-bend specimens made from a susceptible heat of Alloy 600. The results allow a preliminary assessment of the general potential for mitigating this type of degradation in nickel-based alloys.

Results and Findings

The aim of this investigation was to compare the characteristic lives of reverse U-bend specimens exposed to the simulated PWR primary environment at 320°C in the as-received and SCrP-treated conditions. All of the 20 as-received specimens failed after 1250 h of cumulated exposure to PWR environment, versus 3970 h for all of the 20 SCrP-treated specimens. Weibull parameters were identified, indicating that the SCrP process significantly delayed PWSCC initiation (by a factor of 2.4 with regard to characteristic life),

Challenges and Objectives

Additional tests and examinations of the outer material layers are recommended in order to better understand the protective action of the SCrP treatment, further optimize the process and thus improve the degree of PWSCC protection that might be provided by pre-treating nickel-base alloy surfaces.

Applications, Values, and Use

Although the feasibility and benefit of in-situ treatment of existing Alloy 600 parts is unclear, routine use of SCrP could probably be recommended for replacement components (including Alloys 690/152/52) since application field history is good and radiation benefits also result.

EPRI Perspective

The work carried out in this small program is part of the Material Reliability Program (MRP) efforts to develop a range of techniques to mitigate the degradation of PWR components through primary water stress corrosion cracking. The laboratory work performed was successful in reaching the main test objective, namely demonstrating that chromium enrichment at the surface of a susceptible heat of Alloy 600 would affect cracking behavior, as was suspected on the basis of knowledge of the behavior of various nickel-base alloys with different bulk chromium

contents. By itself, the delay in PWSCC initiation observed, although statistically significant, is not sufficiently high to offer a viable mitigation technique, especially since the feasibility of in-situ application to existing systems is doubtful and Alloy 600 is no longer being used for new or replacement PWR components. Since the stabilized chromium pre-treatment process has been successfully applied for radiation protection to over 100 PWR diaphragms, pump parts and valves during the last few years, however, it merits further consideration as an additional measure to guarantee that parts made of more PWSCC-resistant alloys perform as expected throughout extended plant lifetimes.

Approach

Interrupted stress corrosion tests were conducted under open-circuit conditions. The simulated PWR primary water contained 2 ppm Li as LiOH and 1000 ppm B as H_3BO_3 , with a pH of 7.2 at 320°C. Examinations were performed each 250 h in the case of as-received specimens and each 500 h in the case of SCrP-treated specimens. Weibull analysis permitted characterization of the failure rate versus time by determination of the characteristic life, corresponding to the point at which 63.2% of specimens in a data set had initiated cracking. In addition, an independent Weibayes analysis confirmed the significance of the findings.

Keywords

Nickel-base alloys
Primary water stress corrosion cracking
Mitigation of material degradation
RUB specimens
Surface pre-treatment
Chromium enrichment

ABSTRACT

EPRI's stabilized chromium pre-treatment process (SCrP) has been shown to reduce activity deposition in replacement components exposed in the primary systems of light water reactors. Because Cr depletion plays a key role in the degradation of Alloy 600 by PWSCC, this study was carried out to evaluate the ability of SCrP-treatment to mitigate PWSCC in reverse U-bend specimens made from a susceptible heat of Alloy 600. Weibull parameters have been identified after 3970 h of cumulated exposure to PWR environment, indicating that primary water stress corrosion crack initiation is significantly delayed by the SCrP process. The characteristic life of SCrP-treated specimens was increased by a factor 2.4 with respect to as-received specimens. Furthermore, the SCrP treatment was not found to have a deleterious effect on stress corrosion cracking susceptibility in any case.

Additional tests or examinations of the Cr outer layer are recommended in order to better understand the protective mechanism of the SCrP process, further optimize the process and thus improve the protection that might be provided by pre-treating nickel-based alloy surfaces against PWSCC.

CONTENTS

1 INTRODUCTION	1-1
2 EXPERIMENTAL PROCEDURE.....	2-1
Stress Corrosion Tests.....	2-1
Weibull Analysis Approach	2-2
3 TEST RESULTS	3-1
4 CONCLUSIONS	4-1
A APPENDIX	A-1
EPRI Stabilized Chromium Process (SCrP) Description	A-1
Surface Preparation.....	A-1
Plating.....	A-1
Oxidizing.....	A-2
B APPENDIX INDEPENDENT VERIFICATION OF EDF STATISTICAL ANALYSIS	B-1

LIST OF FIGURES

Figure 2-1 RUB specimen.....	2-1
Figure 3-1 Initiation of stress corrosion cracking on RUB specimens.....	3-2
Figure 3-2 Observation of cracks at the surface of as-received specimen MC/EP/03-26 after 1000 h (left) and SCrP-treated specimen MC/EP/03-17 after 2000 h (right)	3-3
Figure 3-3 Cross-section of as-received specimen MC/EP/03-44 after 1250 h (left) and SCrP-treated specimen MC/EP/03-07 after 2480 h (right).....	3-3
Figure 3-4 Evolution of cracking vs. time for the evaluation of Bernard parameters.....	3-4
Figure A-1 Concentration of major elements after applying SCrP process to stainless steel.....	A-2
Figure B-1 Independeant Weibayes analysis of EDF data sets	B-1

LIST OF TABLES

Table 3-1 Results obtained on as-received specimens.	3-1
Table 3-2 Results obtained on SCrP-treated specimens.	3-2
Table 3-3 Weibull approach for results interpretation using Bernard's formula.	3-4
Table 3-4 Identification of Weibull parameters.....	3-5

1

INTRODUCTION

EPRI's stabilized chromium pre-treatment process (SCrP) has been shown to reduce activity deposition in replacement components exposed in the primary systems of light water reactors. SCrP is a three stage process that involves:

① electropolishing, ② deposition of a thin Cr layer, and ③ preoxidation in moist air.

Detailed surface chemistry characterization of SCrP-treated specimens shows there is a significant increase in the Cr content beginning at $\approx 300 \text{ \AA}$ below the surface. Because Cr depletion plays a key role in the degradation of Alloy 600 by primary water stress corrosion cracking (PWSCC), this study was carried out to evaluate the ability of SCrP-treatment to mitigate PWSCC in reverse U-bend specimens made from a susceptible heat of Alloy 600.

2

EXPERIMENTAL PROCEDURE

Stress Corrosion Tests

EPRI provided the PWSCC-susceptible (low-temperature, mill-annealed) heat of Alloy 600 tubing M71 (7/8" OD and 0.05" wall thickness). 40 reverse U-bend (RUB) specimens (Figure 2-1) were machined from this and 20 RUBs were then returned to EPRI for application of the SCrP treatment in the pre-loaded condition. Further details of the treatment process are given in Appendix A.



Figure 2-1
RUB specimen

After EDF received back the treated RUBs, these and the 20 control specimens were ultrasonically rinsed in ethanol and then in distilled water before being placed in the autoclave.

Tests were carried out in low flow-rate, refreshed stainless steel autoclave (316L). The internal volume of the autoclave was 7 liters. The water flow-rate was 7 l/h during the test, thus refreshing the autoclave once per hour. Specimens were insulated from the autoclave by oxidized Zircalloy to avoid galvanic coupling. Experiments were conducted under open circuit conditions. The simulated PWR primary water contained 2 ppm Li as LiOH and 1000 ppm B as H_3BO_3 , with a pH of 7.2 at 320°C (calculated with Multeq v 3.0). The solution was de-aerated ($DO < 1$ ppb) by injecting nitrogen, and finally a hydrogen overpressure was introduced (30–50 cc/kg). Hydrogen and oxygen contents were checked using an Orbisphere analyzer.

Experimental Procedure

Tests were interrupted after 250 or 500 h, as defined in the initial planning of experiments. At the end of each sequence, cracked specimens were removed while uncracked specimens were reintroduced into the autoclave for the following sequence.

At the end of the tests, the specimens were rinsed in distilled water and then microscopically examined in order to find any stress corrosion cracking, using an optical microscope. Some cracked specimens were then investigated using cross-sections. Each cut specimen was metallographically mounted and the surface was wet ground to 1200 grit finish using polishing papers and diamond pastes (3 μm and 1 μm). In order to improve observations at the edges of the specimens, the RUBs were nickel-plated before metallographic mounting by electrolysis between 100 and 120°C of the cut samples in a Watt electrolyte, using a nickel backing electrode. The applied current density was 5 A.dm⁻².

Weibull Analysis Approach

Weibull analysis permits characterization of the failure rate versus time, taking into account non-failures. The intent of the analysis was to find the Weibull slope and the characteristic life, corresponding to the time at which cracking had initiated in 63.2% of a population. The Weibull cumulative distribution function is defined as follows:

$$F(t) = 1 - \exp\left[\left(-\frac{t}{\eta}\right)^\beta\right] \quad \text{Equation 1}$$

where F(t) is the percentage of the population which has failed on or before time t (median rank). Equation 1 can be linearized as follows

$$\text{Ln}\left\{\text{Ln}\left[\frac{1}{1-F(t)}\right]\right\} = \beta \text{Ln}(t) - \beta \text{Ln}(\eta) \quad \text{Equation 2}$$

The F(t) estimate of the cumulative fraction failed at a particular time was produced using Bernard's formula, assuming that the last of any failures found at a particular inspection had occurred at the inspection time. To use Bernard's formula, specimens were first ordered in a test set from the first failure to the last, giving each failure a rank number i and an associated time t. Then, the median rank was estimated as follows:

$$F(t) = \frac{i - 0.3}{N + 0.4} \times 100\% \quad \text{Equation 3}$$

where N is the total number of specimens in the group.

3

TEST RESULTS

Results of stress corrosion tests obtained with as-received and SCrP-treated specimens are summarized in Table 3-1 and Table 3-2 respectively. First failures on as-received specimens were observed after 1000 h. Then, all of the remaining specimens failed after 1250 h. On the other hand, first failures on SCrP treated specimens were observed after 2000 h. All of the as-received RUB specimens (20/20) failed after 1250 h, while 5/20 SCrP treated specimens remained uncracked after 3470 h. No initiation of SCC occurred in SCrP treated specimens more rapidly than for as-received specimens. Thus, the first conclusion is that SCrP treatment should not have a deleterious effect on stress corrosion cracking (SCC) susceptibility in any case. The second conclusion is that initiation of SCC was clearly delayed by the SCrP treatment.

Table 3-1
Results obtained on as-received specimens.

Specimens	Surface treatment	Time to initiation (h)
MC/EP/03-25	As-received	1250
MC/EP/03-26	As-received	1000
MC/EP/03-27	As-received	1250
MC/EP/03-28	As-received	1250
MC/EP/03-29	As-received	1250
MC/EP/03-30	As-received	1250
MC/EP/03-31	As-received	1250
MC/EP/03-32	As-received	1250
MC/EP/03-33	As-received	1250
MC/EP/03-34	As-received	1250
MC/EP/03-35	As-received	1250
MC/EP/03-36	As-received	1250
MC/EP/03-37	As-received	1250
MC/EP/03-38	As-received	1000
MC/EP/03-39	As-received	1250
MC/EP/03-40	As-received	1250
MC/EP/03-41	As-received	1250
MC/EP/03-42	As-received	1250
MC/EP/03-43	As-received	1250
MC/EP/03-44	As-received	1250

Table 3-2
Results obtained on SCrP-treated specimens.

Specimens	Surface treatment	Time to initiation (h)
MC/EP/03-01	SCrP	2480
MC/EP/03-03	SCrP	3470
MC/EP/03-04	SCrP	2480
MC/EP/03-07	SCrP	2480
MC/EP/03-08	SCrP	2980
MC/EP/03-09	SCrP	2980
MC/EP/03-10	SCrP	2480
MC/EP/03-11	SCrP	2980
MC/EP/03-12	SCrP	2980
MC/EP/03-13	SCrP	2000
MC/EP/03-14	SCrP	2000
MC/EP/03-15	SCrP	2980
MC/EP/03-16	SCrP	2980
MC/EP/03-17	SCrP	2000
MC/EP/03-18	SCrP	2480
MC/EP/03-19	SCrP	2000
MC/EP/03-20	SCrP	2480
MC/EP/03-21	SCrP	2000
MC/EP/03-22	SCrP	2000
MC/EP/03-23	SCrP	2000

For both as-received and SCrP-treated specimens, the cracks observed were located on the “wings” (location ① in Figure 3-1) or at the apex of the RUBs (location ② in Figure 3-1). The essential of the cracks were nevertheless observed on the “wings”, where stresses are usually more important and where strain hardening is more complex.

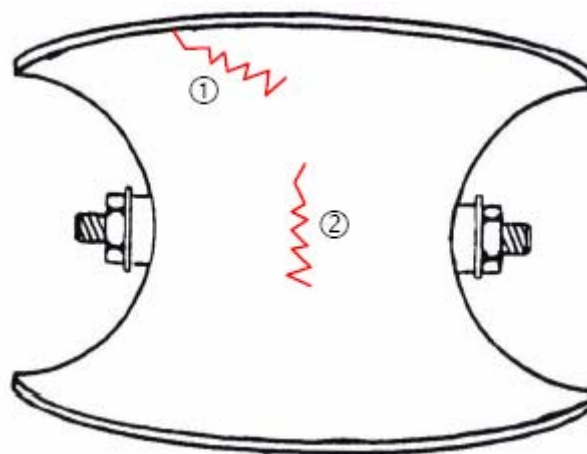


Figure 3-1
Initiation of stress corrosion cracking on RUB specimens

Figure 3-2 and Figure 3-3 illustrate details of the cracking observed at the apex of as-received and SCrP-treated specimens, respectively. As shown in the last cross-section, the crack depth can reach 80% of the specimen thickness, but cracking never led to the complete failure of any of the RUBs.

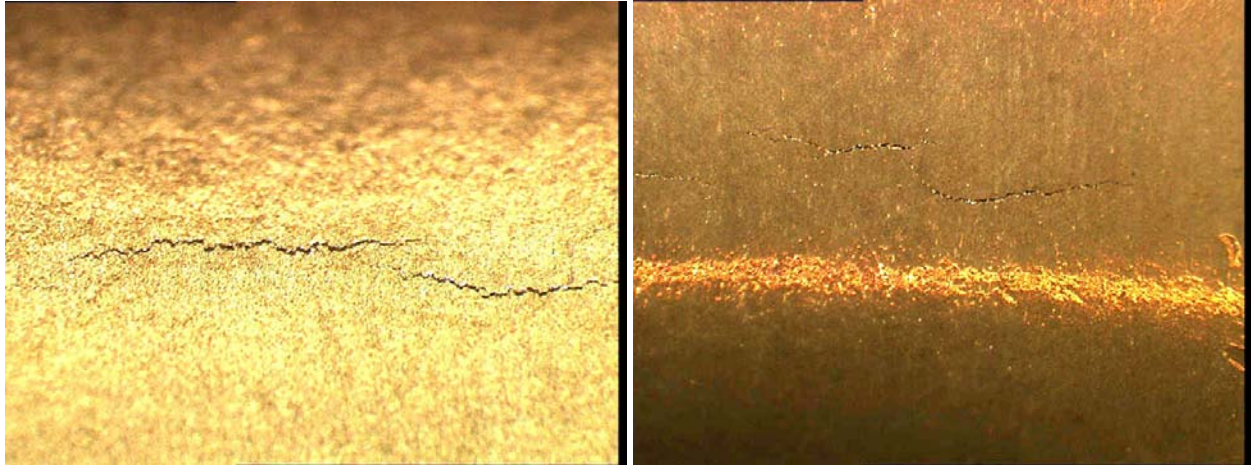


Figure 3-2
Observation of cracks at the surface of as-received specimen MC/EP/03-26 after 1000 h (left) and SCrP-treated specimen MC/EP/03-17 after 2000 h (right)

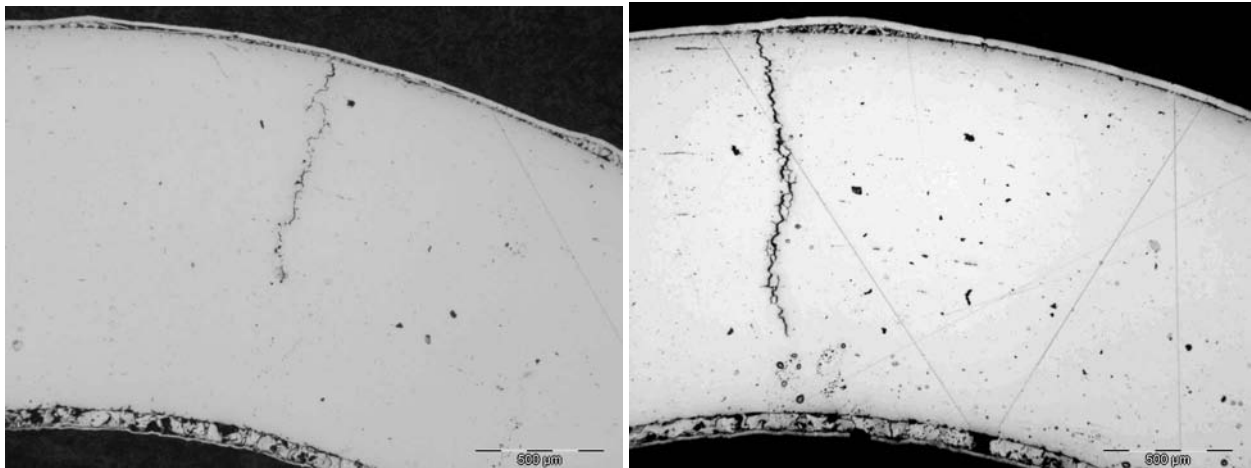


Figure 3-3
Cross-section of as-received specimen MC/EP/03-44 after 1250 h (left) and SCrP-treated specimen MC/EP/03-07 after 2480 h (right)

As described earlier, Weibull analysis of the data permit evaluation of the median rank $F(t)$ for each time to failure (Table 3-3). So, β and η parameters were computed by least squares fitting, as shown in Figure 3-4. The identified parameters are presented in Table 3-4.

Table 3-3
Weibull approach for results interpretation using Bernard's formula.

Surface state	Time to initiation (h)	Number of RUBs with initiation	Number of de RUBs without initiation	N	i	F(t)	Ln[Ln(1/(1-F))]	Ln(t)
As-received	250	0	20	20	-	-	-	-
As-received	500	0	20	20	-	-	-	-
As-received	750	0	20	20	-	-	-	-
As-received	1000	2	18	20	2	0.083	-2.442	6.908
As-received	1250	18	0	20	20	0.966	1.216	7.131
SCrP	500	0	20	20	-	-	-	-
SCrP	1000	0	20	20	-	-	-	-
SCrP	1500	0	20	20	-	-	-	-
SCrP	2000	7	13	20	7	0.328	-0.921	7.601
SCrP	2500	6	7	20	13	0.623	-0.026	7.824
SCrP	3000	1	6	20	14	0.672	0.107	8.006
SCrP	3470	1	5	20	15	0.721	0.243	8.152
SCrP	3970	5	0	20	20	0.966	1.216	8.287

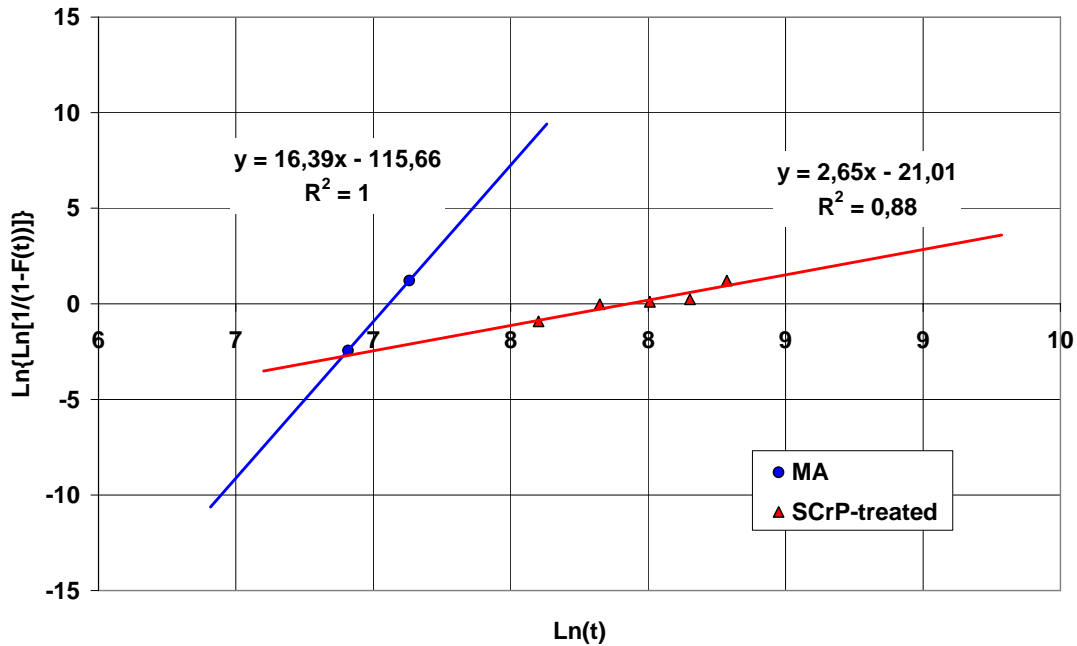


Figure 3-4
Evolution of cracking vs. time for the evaluation of Bernard parameters

Table 3-4
Identification of Weibull parameters

Surface state of RUBs	β	$\beta \text{Ln}(\eta)$	η (h)	R^2
As-received	16.39	115.66	1161	1.00
SCrP-treated	2.65	21.01	2770	0.88

Consequently, the Weibull cumulative distribution functions for as-received and SCrP surface states are expressed by:

- $F(t) = 1 - \exp\left[\left(-\frac{t}{1161}\right)^{16.39}\right]$ for as-received specimens.
- $F(t) = 1 - \exp\left[\left(-\frac{t}{2770}\right)^{2.65}\right]$ for SCrP-treated specimens.

As previously mentioned, the initiation of PWSCC is clearly delayed by SCrP: the characteristic life increases by a factor 2.4.

The dispersion of results, in term of time to failure, is significantly increased when specimens are SCrP-treated. 100% of the as-received specimens failed between 750 and 1250 h of exposure to the primary environment. In contrast, 60% of SCrP treated specimens failed between 1500 and 2500 h of exposure, whereafter the initiation rate strongly decreased. Finally, 5 specimens failed between 3470 h and 3970 h of exposure to the environment.

EPRI conducted an independent statistical review of the above data (see Appendix B) which confirmed that the effects of SCrP treatment are statistically significant using an alternative Weibull analysis.

It can be assumed that optimization of the SCrP process might allow the resistance to stress corrosion cracking to be improved even further. Additional tests or examinations are recommended to better understand the protective mechanism of SCrP treatment. For example, the structure of the deposit and the resistance of the interface between the deposit and the alloy 600 could be examined for cracked and uncracked specimens tested in the present work to understand the reason why the SCrP process led to different levels of protection.

4

CONCLUSIONS

All of the as-received reverse Alloy 600 U-bend specimens (20/20) failed after 1250 h, while all of the of the SCrP-treated specimens (20/20) cracked after 3970 h.

Using Bernard's formula, the Weibull parameters have been identified after 3970 h of cumulated exposure to PWR environment, indicating that primary water stress corrosion crack initiation is significantly delayed by the stabilized chromium process. The characteristic life of SCrP-treated specimens was increased by a factor 2.4 with respect to as-received specimens.

Furthermore, the SCrP treatment was not found to have a deleterious effect on stress corrosion cracking susceptibility in any case.

Additional tests or examinations of the Cr outer layer are recommended in order to better understand the protective mechanism of the SCrP treatment, further optimize the process and thus improve the protection that might be provided by pre-treating nickel-based alloy surfaces against PWSCC.

A

APPENDIX

EPRI Stabilized Chromium Process (SCrP) Description

The SCrP is a multiple step process involving surface finishing, application of the chromium layer and then oxidizing the entire unit to build a corrosion and deposition resistant film. The process details are as follows:

Surface Preparation

The first step is to ensure the surfaces to be treated are very clean and free from surface deformities and asperities. This can be done by mechanically polishing, with flapper type wheels, to physically remove these surface imperfections.

After mechanical preparation, the surfaces are electrochemically polished using typical electropolishing methods. This is accomplished by establishing an electrochemical cell with an electrolyte, such as phosphoric and/or sulfuric acid (for stainless alloys). The work piece is the anode of the cell and a geometrically conforming cathode is used to balance the cell. The cathode is typically made of highly conductive copper in a conforming geometric shape to the anode (work piece).

A current is applied to the cell for a given amount of time. During this time, material is first molecularly removed preferentially from the raised portions, or peaks of the surface. In this way, the surface is polished on a microscopic level. Note that if measured with a profiling type meter (typically using a stylus), the average roughness may not be significantly reduced as it can still be wavy. However, the advantage of the microscopically smooth surface is fully realized as well as the surface now being exceptionally clean of any foreign matter.

Plating

The next step is to apply a very thin layer of elemental chromium on the surface. This is done by electroplating hard chromium (+6) on the cleaned surface from the above step. The plating is done by simply reversing the above polarity (work piece is now the cathode) and changing the electrolyte to a chromic acid solution. The anode material is also changed from copper to stainless steel so as not to contaminate the work piece with elemental copper. Appropriate time, temperature and applied current levels are employed to provide a film thickness of from 3,000 to 10,000 Angstrom units.

Appendix

Oxidizing

The final step is to stabilize or oxidize the surface incorporating the plated chromium, thus producing a chromium-rich and stable oxide film. This step is accomplished by placing the component in an oxidizing environment, of heated air with and admixture of steam. The component is brought to the stabilizing temperature of 600°F for a period of about 100 hours. The heat-up and cool-down rates are controlled to prevent any thermal stress development in the alloy steel (i.e., 100°F per hour). The steam is injected to a level of about 2% by weight once the component is above 220°F. Similarly, the steam injection is terminated before reaching 212°F on cool-down.

The oxidation process will typically cause stainless steel to have a rather pleasing golden tint. However, with the chromium layer incorporated into the film, the surface will either be a dull, very slightly golden hew to a dull grayish finish, not particularly visually pleasing. In the present study, not much change in appearance was observed after final processing other than the dull to golden hew.

Figure A-1 shows an example of the distribution and depth of chromium enrichment that is typically achieved through carrying out this process as described above on stainless steel.

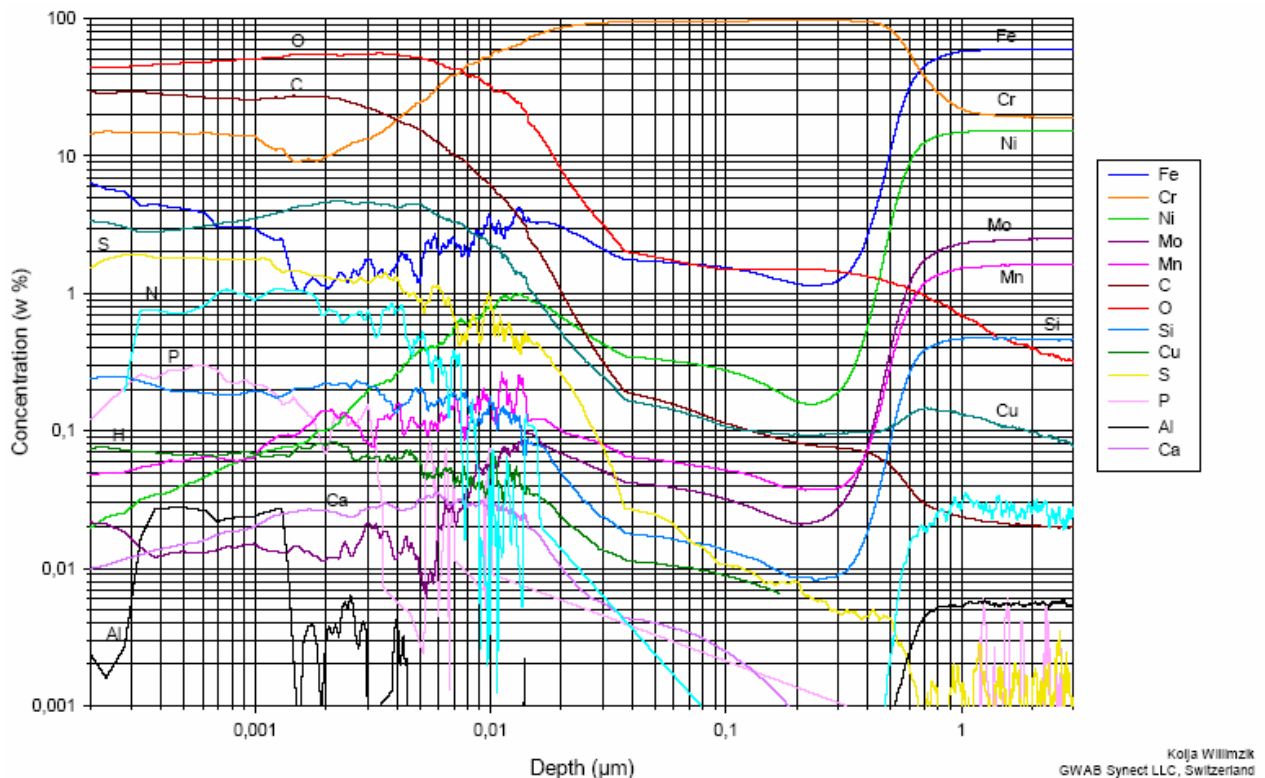


Figure A-1
Concentration of major elements after applying SCrP process to stainless steel

The strong effect of the chromium plating is clearly shown in this plot. Between 30nm and 400nm (log-scale!), the Cr concentration is well above 90%. In contrast to other elements, the concentrations of C, Cu, and S do not seem to drop accordingly throughout this Cr layer. Below 1 μ m the concentration of the elements approaches the base metal composition.

The top 10-20nm show comparably high amounts of C, Cu, S, N, and Ca, but, H appears to be relatively low.

B

APPENDIX INDEPENDENT VERIFICATION OF EDF STATISTICAL ANALYSIS

Modeling and Computing Services carried out a WeiBayes analysis, an alternative Weibull analysis which is recommended for small data sets and few failure times, by assuming the same β slope of 2.73 as in previous, extensive work (127 Weibull sets) on the PWSCC behavior exhibited by Alloy 600 RUB specimens [1]. The results are shown in Figure B-1. The assumed slope of 2.73 is very close to the result (2.65) from the EDF analysis, and the Weibull model line looks appropriate relative to the EDF data set for the SCrP-treated specimens (the blue Set 2 in Figure B-1). The assumed slope of 2.73 is also appropriate for the as-received specimen set (the red Set 1 in Figure B-1), because that set has only two closely-spaced times with data available (1000 hr and 1250 hr), thus leading to the uncertain, and probably unrealistically steep, apparent slope shown in Figure 3-4 of the present report. The slope of a Weibull is characteristic of the mode of failure, so the estimate from 127 other sets (and the SCrP set) failing in the same cracking mode in similar tests is probably more accurate than the estimate from those two closely-spaced times.

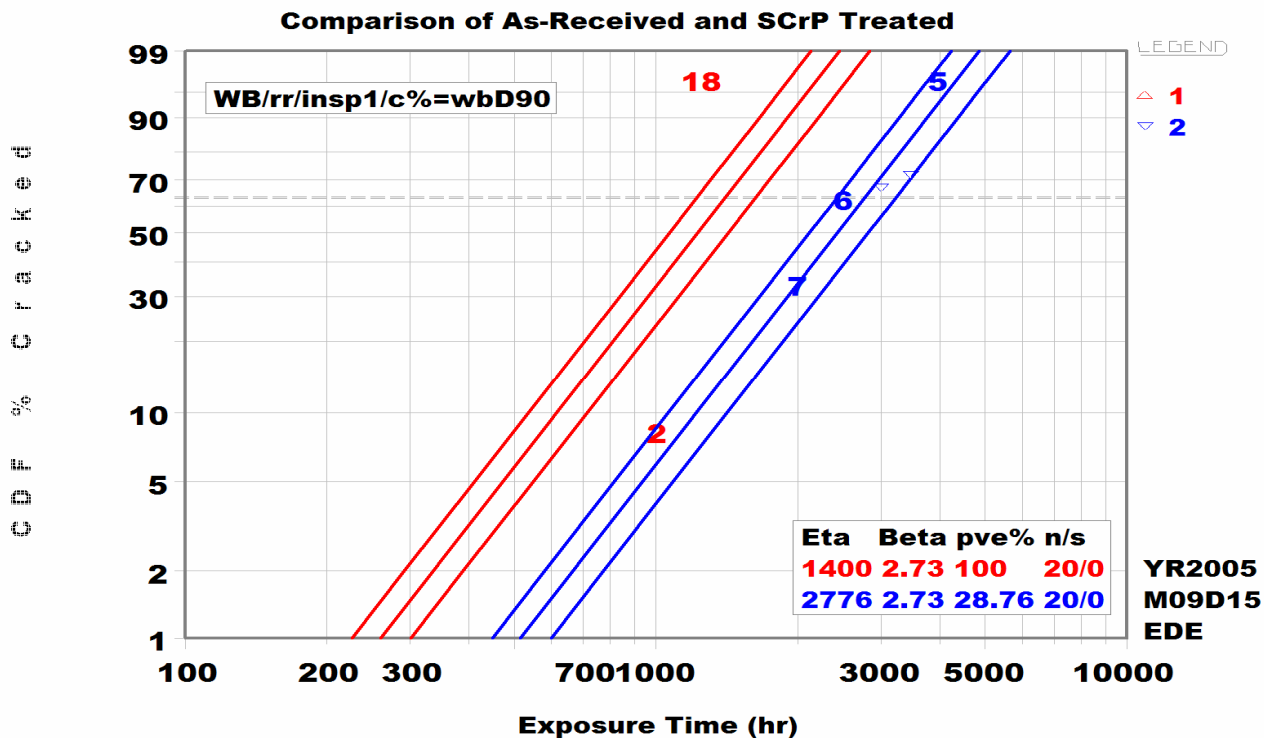


Figure B-1
Independent Weibayes analysis of EDF data sets from Table 3-1 and Table 3-2

Appendix Independent Verification of EDF Statistical Analysis

The proper interpretation of the plotted data points for the (red) Set 1 data (untreated specimens) is to think of the "18" for Set 1 as being plotted at the time and fraction failed corresponding to an "on or before" estimate. EDF found 2 specimens cracked at 1000 hr, which definitely occurred sometime on or before 1000 hr, and found 18 more cracked at 1250 hr, which probably occurred after 1000 hr and definitely on or before 1250 hr. It is not known when the 18 failed within that 250 hr interval, so the value "18" is plotted as high and far to the right as possible consistent with the observed facts. However, the trend line is expected to go through the estimated average time (about 1150 – 1200 hr) and fraction failed (about 45%) for that group of 18 specimens, and inspection of Figure B-1 shows that it does. Because of the large number failing, the bounds on characteristic life are relatively narrow for both sets.

The conclusion from the alternative analysis is that the results of the EDF analysis are confirmed. The bounds of the two data sets in Figure B-1 do not overlap, so the effect of SCrP treatment is statistically significant. The ratio of SCrP-treated to untreated life is about a factor of 2 in the alternative analysis, which agrees reasonably well with the factor of 2.4 improvement found in the EDF analysis.

- [1] *Effects of Hydrogen, pH, Lithium and Boron on Primary Water Stress Corrosion Crack Initiation in Alloy 600 for Temperatures in the Range 320 – 330 °C (MRP-147)*, EPRI, Palo Alto, CA: 2005. 1012145.

Export Control Restrictions


Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute (EPRI)

The Electric Power Research Institute (EPRI), with major locations in Palo Alto, California, and Charlotte, North Carolina, was established in 1973 as an independent, nonprofit center for public interest energy and environmental research. EPRI brings together members, participants, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of electricity generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States. International participation represents nearly 15% of EPRI's total research, development, and demonstration program.

Together...Shaping the Future of Electricity

© 2006 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute and EPRI are registered service marks of the Electric Power Research Institute, Inc.

 Printed on recycled paper in the United States of America

1013518

ELECTRIC POWER RESEARCH INSTITUTE

3420 Hillview Avenue, Palo Alto, California 94304-1395 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com