

AD-A062 500

AMERICAN UNIV WASHINGTON D C DEPT OF CHEMISTRY
CONTROL OF STRESS CORROSION CRACKING BY INHIBITORS (A REVIEW OF--ETC(U)
OCT 78 C S O'DELL, B F BROWN

F/G 11/6

N00014-75-C-0799

UNCLASSIFIED

TR-8

NL

| OF |
AD
A062500



END
DATE
FILMED
3--79
DDC

ADA062500

DDC FILE COPY

~~LEVEL II~~

12

**Control of Stress Corrosion Cracking by Inhibitors
(A Review of the Literature)**

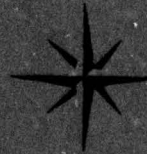
DDC
DEC 21 1978
B F

Technical Report No. 8

Department of Chemistry
The American University
Washington, D.C. 20016

By:
Charles S. O'Dell and B.F. Brown
Nov. 1978

To:
Office of Naval Research
Contract N00014-75-C-0799
NR 036-106



Distribution of this document is unlimited.
This work was sponsored by the Metallurgy Branch
of the Office of Naval Research.

78 12 20 001

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 147R- Technical Report No. 8	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Control of Stress Corrosion Cracking by Inhibitors (A Review of the Literature)	5. TYPE OF REPORT & PERIOD COVERED Technical Progress Report	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Charles S. O'Dell and B. F. Brown	8. CONTRACT OR GRANT NUMBER(s) N00014-75-C-0799 NR 036-106	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Chemistry Department The American University, Washington DC 20016	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS	
11. CONTROLLING OFFICE NAME AND ADDRESS Metallurgy Branch Office of Naval Research, Arlington, VA 22217	12. REPORT DATE October 1978	13. NUMBER OF PAGES 14
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 21p.	15. SECURITY CLASS. (of this report) Unclassified	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Distribution of this document is unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Inhibitors, stress corrosion cracking		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report is a copy of a manuscript to be presented at the "Discussion of Corrosion Control by Coatings" to be held at Lehigh University Nov 13 - 15, 1978, under the direction of Dr. H. Leidheiser, Jr., and under the sponsorship of ONR. This report summarizes the literature on inhibitors for stress cor- rosion cracking in all alloy systems for which published accounts have been found and is not restricted to inhibitors in coatings.		

DD FORM 1 JAN 73 1473

EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

387562

JB

CONTROL OF STRESS CORROSION CRACKING BY INHIBITORS

by Charles S. O'Dell and B. F. Brown
Department of Chemistry
The American University
Washington, D.C. 20016

ABSTRACT

Studies of inhibitors of stress corrosion cracking (SCC) are reviewed for austenitic stainless steels, brass, titanium, aluminum alloys, and carbon and low alloy steels. There are at least five combinations of alloy and environment for which inhibitors have provided engineering solutions for the control of SCC, and others are not improbable at an early date. In view of the complexity of the problem and the comparatively few sustained research programs in this special field, it is not surprising that the fundamentals of inhibition of SCC are incompletely understood.

OUTLINE

- I. INTRODUCTION
- II. AUSTENITIC STAINLESS STEELS
- III. BRASS
- IV. TITANIUM
- V. ALUMINUM
- VI. CARBON STEELS AND LOW ALLOY STEELS
- VII. DISCUSSION
- VIII. ACKNOWLEDGMENTS
- IX. REFERENCES

ACCESSION for	
NTIS	Write Section <input checked="" type="checkbox"/>
DDC	B. F. Section <input type="checkbox"/>
UNANNOUNCED	<input type="checkbox"/>
JUSTICE DIV	
BY	
DISTRIBUTION/ANNOUNCEMENT CODES	
Dist.	SPECIAL
A	-

I. INTRODUCTION

Stress corrosion cracking (SCC) is a process involving the nature of an alloy (metallurgy), stress (mechanics), and environment (chemistry or electrochemistry). All possible countermeasures to SCC may be assigned to these three categories, metallurgy, mechanics and electrochemistry (including temperature), and in engineering practice measures from any or all three categories may be employed. One may for example select cupronickel condenser tubing to replace admiralty metal tubing to avoid ammoniacal SCC, representing a metallurgical approach to the problem. Or one may employ a thorough stress-relieving anneal of an assembled admiralty metal heat exchanger, representing a mechanics approach. And one may elect to apply cathodic protection, as by spraying stainless steel with lead to prevent chloride SCC, representing an electrochemical approach.

Changing the composition of the environment can also be regarded as a chemical or electrochemical approach, usually pursued by identifying a contaminant species responsible for SCC (such as chloride in austenitic stainless steel systems) and lowering the concentration of this species below what is hopefully a safe threshold value.

Another possible approach to controlling SCC by controlling the environment is by the use of additives. These additives may act in three distinct ways: (1) They may destroy or prevent the formation of the cracking species, as by the use of soda ash or ammonia to prevent polythionic acids cracking of sensitized stainless steel. (2) They may move the potential of the alloy into a safe range. Or, (3) they may enter directly into blocking of one or more of the chemical reactions responsible for SCC. This present survey of these additives, or inhibitors, will summarize the work to date regardless of which of the three categories of mechanisms above is operative, partly because in many instances the mechanism is unknown or only suggested. Although the present conference is concerned largely with coatings which are not appropriate to heat exchanger technology, the inhibitor work on heat exchanger materials is included on the chance that some of the principles involved may be useful in formulating thoughts about inhibitors in coatings.

The material is organized according to alloy family.

II. AUSTENITIC STAINLESS STEELS

These alloys undergo SCC in warm or hot chloride solutions, in hot caustic solutions, in strong acids containing chloride at

room temperature, and (if sensitized) in polythionic acids at room temperature.

In hot chloride solutions Staehle, Beck and Fontana showed that reducing adventitious oxygen by reacting with hydrogen eliminated SCC (1), perhaps by depressing the potential into a protective range. Other studies, by Williams and Eckel (2), Rion (3), Edeleanu and Snowden (4), and Phillips and Singley (5) showed that deoxygenation by hydrazine was a countermeasure to SCC, again possibly by depressing the potential. Sulfite was found to be a somewhat less effective inhibitor (2, 4, 5). Although this deoxygenation approach is not considered to belong to the strictly inhibitor literature, it is noted here as it suggests that inhibitors may be sought for some alloys by consideration of the effects of additives on potential. Actually this approach (depressing the potential) was suggested by much earlier work by Mears, Brown and Dix who demonstrated the efficacy of cathodic protection against chloride SCC in stainless steel, with potential data (6). H. van Droffelaar has shown that sprayed coatings of metallic lead will prevent chloride SCC of stainless steel (7); O'Dell and Sarada have shown that this effect is due to cathodic protection and not to classic inhibition by lead species (8).

THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

Under various conditions, chromate may either be indicated to counter SCC (9, 10, 11, 12), or it may be counterindicated (4, 13). Perhaps this variability in response may reflect a competition between the beneficial effect of tending to stabilize a protective film versus the adverse effect of raising the potential into a hazardous range. Alkali phosphates have been reported to inhibit to various degrees chloride SCC of steel if unsensitized (2, 4, 10, 11, 12, 14), but perhaps the ratio of inhibitor to chloride is an important factor (11, 13).

Snowden found nitrite an effective inhibitor providing the molar ratio $\text{NaCl}/\text{NaNO}_2$ was 1/1, but not if the ratio was 2/1 (13), and Couper found it only slightly inhibiting at a much higher $\text{Cl}^-/\text{NO}_2^-$ ratio, in 42% MgCl_2 (12).

Couper (12) and Uhlig and Cook (15) reported prevention of SCC in boiling 42% MgCl_2 with 2% NaNO_3 . Fujii and Kumada reported work in 35% MgCl_2 showing that the inhibiting character of various polyoxyanions decreases as follows: $\text{NO}_3^- > \text{H}_2\text{PO}_4^- > \text{CrO}_4^{2-} = \text{WO}_4^{2-}$, from which they concluded that there is no relationship between oxidizing power and inhibition (16). Uhlig and Cook showed that the action of the nitrate is to shift the protection potential (or "critical cracking potential") with respect to the corrosion potential to put the corrosion potential in the protected range (15). The efficacy of nitrate is judged to be sufficient for it to be called out as a preventive measure in NACE Recommended Practice RP-01-70 (17). If the nitrate is not present in sufficient concentration, SCC will occur, as shown by

Uhlig and Cook (15) and as may be inferred from the work of Edeleanu and Snowden (4).

Uhlig and Cook also found iodide and benzoate to be inhibitive in 42% $MgCl_2$ (15).

THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

Holzworth and Symonds (18) found that dipping the steel in lithium silicate inhibited SCC in dilute acidified chloride solution at 90 C. Bergen found that sodium metasilicate somewhat inhibited SCC in $CaCl_2$ at 132 C, and burnishing the steel with silver inhibited SCC in short-time tests in that environment (19).

Overman used radioactive tracers to study inhibition of SCC in Type 304 stainless steel in boiling solutions of 10 - 100 ppm chloride plus the selected substances. One to 50 ppm silicate, phosphate, nickelous, iodide, bromide or chromate ions inhibited crack formation in the standard solution. The tracer studies revealed that corrosion and crack formation were inhibited by cations (complexes?) or anions that compete with the chloride ions for the available corrosion sites on the surface of the steel (20).

Podobaev and his associates studied the inhibition of SCC in $MgCl_2$ boiling at 153 C. KI acted as a partial inhibitor by itself; when combined with BA-12 (a condensation product of benzylamine and paraformaldehyde) there is a synergistic action to effect complete protection against SCC. Another inhibitor designated PB-5) (not further described) also protected completely against SCC (21). Katapin, a surface-active substance used as a pickling restrainer, retards the anodic process by forming a protective film, but it is incompletely effective in inhibiting SCC (22).

Podobaev showed that $SnCl_2$ added to boiling $MgCl_2$ (153 C) produced a large increase in survival time of stainless steel; there was some inhibition from additions of $SnCl_4$, $PbCl_2$, $SbCl_3$, and $BiCl_3$. The addition of $CdCl_2$ at 45 millimolar concentration produced a 5-fold increase in survival time. Podobaev explained the results on the basis of changing cathodic polarization characteristics (23). Beauchamp showed that if the chloride were present as 1705 ppm of $CdCl_2$ at 205 C, 18-8 stainless steel did not crack under a stress of 10 ksi in 8 hours, but if stressed at 26.5 ksi, SCC occurred in 17 hours (24). Leu and Helle found that the addition of $SnCl_2$, metallic magnesium or metallic zinc to boiling $MgCl_2$ prevented or spectacularly reduced SCC in type 304 stainless steel (25). O'Dell's study of sensitized type 304 stainless steel in 4 N NaCl with pH 2.3 at 100 C found that the additives NaI, $SnCl_2$, $SnCl_4$, $FeCl_3$, $SnSO_4$, $CdSO_4$, CdI and n-butylamine prevented SCC of U-bend specimens for 600 hours as compared with 24 hours required for SCC in the uninhibited system. All of these substances permitted pitting and/or general corrosion except for $CdSO_4$. Cd^{++} and SO_4^{--} were only moderately effective

when added separately; however, CdSO_4 produced a synergistic effect preventing all forms of corrosion. Polarization data showed that the inhibitor has a pronounced effect on the anodic reaction. EDAX analysis of the material within cracks initiated in uninhibited solution, to which CdSO_4 was then added, showed high concentration of the inhibitor. The inhibition was attributed to the synergistic effects of the cadmium polymerizing with the chloride combined with a desorbing action of the sulfate ion upon the chloride (26).

Although chloride is clearly a causative agent for SCC in stainless steel, the cation apparently has a significant role in the corrosion process. Varying the cation in chloride solutions can produce changes ranging from acceleration of SCC to blockage of the corrosion process (27, 28, 29). THIS PAGE IS BEST QUALITY PRACTICABLE FROM COPY FURNISHED TO DDG

Several groups have studied the aggressive behavior of metal chloride solutions with varying results (29-33). Perhaps the best order of ranking for four cations is as follows: Li^+ (most aggressive), Mg^{+2} , Ca^{+2} , Na^+ (34).

Zucchi and associates have reported on a series of researches on inhibition of SCC of austenitic stainless steels in strong acid chloride solutions at room temperature, using various organic inhibitors (35-40). Benzonitrile completely inhibited transgranular SCC in type 304 steel probably by interfering with the anodic reaction, and benzotriazole decreased SCC attack; the environment was 0.5 N NaCl acidified with H_2SO_4 (35). In 2 N HCl, phenyl thiourea completely blocked attack, again by blocking the anodic reaction; di-n-butyl thiourea also blocked all attack, as did the combination of KI + n-decylamine (36). In 2 N HCl, di-o-tolyl thiourea; benzoimidazole-2-thiol; N-N'-diphenyl thiourea; sulfadiazole-3-thiol; and benzothiazole-2-thiol completely blocked "fissuring" (cracking/) (37-39). Again in 2 N HCl but this time with type 316 steel the inhibition of SCC by benzimidazole-2-thiol; benzothiazole-2-thiol; sulfathiazole-3-thiol; and N-N'-diphenyl thiourea is due to blocking the anodic reaction. All the organic substances examined altered the hydrogen reaction, but only those substances which inhibited the anodic reaction prevented SCC. The proposed mechanism is one of rapid adsorption onto the metal exposed by stress to block the anodic reaction. There does not seem to be any correlation between inhibiting general corrosion and inhibiting fissuring (40).

Lafranconi et al. have studied SCC in austenitic stainless steel also in strongly acidic chloride media at room temperature, and they found inhibition by traces of Pb^{+2} . This inhibition they showed was due to effects on the cathodic reaction (hydrogen reduction), which they attributed to the effect of lead on hydrogen overvoltage (41). Perhaps the apparent discrepancy between this finding and that of O'Dell and Sarada (8) can be assigned to a difference in cracking mechanisms, as the latter were working with (only slightly acidic) MgCl_2 at 153 C.

One inhibitor of SCC in stainless steel in a strong acid--white fuming nitric acid--which found its way into engineering practice but not into the technical literature is 1% HF (42).

III. BRASS

Gisser found that continuous resin films such as phenol formaldehyde delayed attack on brass in ammonia (43). Whether there is any intrinsic inhibiting effect of substances in the film or whether only barrier properties are involved does not seem to be established. Rowlands protected aluminum brass (C68700) against SCC in sulfur-polluted seawater with sodium dimethyl-dithiocarbamate which forms a protective copper-chelate film on the brass surface (44). Poly-hexamethylphosphate and sodium chromate have also been found to prevent stress corrosion cracking of aluminum brass (C68700) in recirculating seawater but not in fresh water (45). Uhlig and his students found that with 63-37 brass exposed to ammoniacal and to tartrate solutions, delay in cracking occurred with the addition of bromide ions and also chloride ions. The delay was attributed to the shift of the protection potential (or critical cracking potential) in the positive direction with respect to the corrosion potential (46). Podobaev and his associates have worked on the problem of protecting cartridge brass against corrosion and SCC by protective coatings of greases and oils, with and without inhibitive additions. Though not perfectly protective, potassium ferrocyanide and dibutyl phthalate have inhibitive characteristics attributed to the formation of protective complex reaction products (47). Walston attributed the SCC of an admiralty heat exchanger exposed to ammonium chloride to ammonia released by reaction of the chloride with the brass, combined with the absence of hydrogen sulfide which would have acted as an inhibitor (48).

THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

IV. TITANIUM

Kiefer and Harple showed that in red fuming nitric acid 1% NaBr could inhibit SCC in commercially pure titanium (75A) at room temperature (49). Rittenhouse found that the addition of water to red fuming nitric acid would control SCC in pure titanium and in the Ti-8% Mn alloy (50). A Military Specification has been written calling for up to 14% NO₂ and 2.5% H₂O, balance HNO₃.

Haney and Wearmouth showed that additions of water inhibited SCC initiation in titanium in methanol (51). This inhibition is not effective in the presence of a crack or of chloride.

Pressurized fuel tanks of Ti-6%Al-4%V experience SCC if they contain N₂O₄ of sufficiently high purity, but the addition of NO inhibits the SCC (52). This inhibition is sufficiently practical as a solution to the SCC problem that a NASA Specification (PPD-2B) calling for 0.60 - 1 percent NO was written and has been successfully applied in the U. S. space program.

The addition of oxygen gas has been found to inhibit cracking of titanium tanks containing gaseous hydrogen (53).

The inhibition of SCC in titanium alloys is poorly understood, and little has been suggested concerning the mechanism(s).

V. ALUMINUM

THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDG

Protection of high strength aluminum alloys from SCC in moist atmospheres is promoted by a primer containing the inhibitor strontium chromate (MIL-P-23377), widely used in aerospace weapons systems. Zinc chromate primer confers some considerable protection for atmospheric service, and even more so when further covered by an epoxy paint system (54).

Galvanic coatings are practical solutions to the SCC problem for high strength aluminum alloys. Zinc-rich epoxy, zinc electroplate, and metallized 7072 coatings have been shown to greatly extend the life of 2014 and 7079 alloys (54). Magnesium pigment added to inorganic binders (55) or epoxy primer (56) has given good results.

A corrosion prevention compound has been developed by personnel of the Naval Air Development Center which contains two unidentified inhibitors (57). Although only corrosion tests, not stress corrosion tests, have been reported to date, the results of the corrosion tests are sufficiently impressive to suggest that tests of the compound as a countermeasure to SCC would be interesting. The compound, named AMLGUARD, is covered by military specification MIL-C-85054(AS).

VI. CARBON STEELS AND LOW ALLOY STEELS

Caustic cracking of boiler plate was once a serious problem for which inhibitor technology contributed many countermeasures. Straub lists phosphate, tannate, chromate, nitrate, acetate, and arsenic as inhibitors of this failure mode. He also showed that a ratio of sulfate to alkalinity of 2.1 would control cracking (58). Schroeder and Berk found that in high pressure boilers the addition of nitrates to 40% of the alkalinity inhibited

cracking, and sodium sulfate was also effective. Quebracho inhibited cracking by removing oxygen and by keeping the calcium phosphate and calcium carbonate dispersed. The addition of waste sulfite liquor to the water in locomotive boilers inhibited cracking (59). Several inhibitors of cracking in boiler plate were discussed in a symposium on caustic embrittlement. These additives included R_2O_3 (where $R=Fe$ and Al) (20), organic extracts (60), nitrate (61-63), phosphate (61), waste sulfite liquor (62) (for oxygen removal), quebracho (63), myrabalans (63), and combinations of sodium nitrate and lignin sulfonate (63) and of sodium nitrate and tannin (64). No mechanism of inhibition was proposed at this symposium. Extensive use has been made of coordinated phosphate and pH treatment to protect boilers against cracking (63).

THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

Ammonia storage tanks of mild steel can be protected against SCC by the addition of 0.2% water (65), and this procedure is in widespread use. It is required by the Department of Transportation for transport of ammonia in quenched and tempered steel tankages (66); the technical background is given in reference 67. But condensation of vapor on cold walls of the vapor space above water-inhibited ammonia can produce a film of insufficiently inhibited ammonia, leading to SCC; the practical solution to this sort of problem is to maintain the temperature of the liquid ammonia a few degrees cooler than the walls on which condensation would otherwise occur (68). The addition of ammonium chloride or oil will also retard SCC in liquid ammonia storage tanks (69). The addition of 0.05% refrigerator oil which coats the steel surface and prevents SCC is a patented procedure (70).

Ammonium chloride will also inhibit SCC of low carbon steel exposed to nitrate solutions (71).

Dunlop was able to show that SCC of ASTM A203 Grade E steel (a low strength nickel-bearing ferritic steel) in sulfide environments was an anodic process and not one of hydrogen embrittlement; morpholine was found to be an effective inhibitor (72).

Carbonate-bicarbonate solutions have been shown capable of producing SCC in line-pipe steel, and there is considerable incentive to develop an inhibitor effective against this attack and compatible with primer materials and with cathodic protection conditions. Berry and his associates have shown that in a standard carbonate-bicarbonate solution the following substances are effective inhibitors of SCC: Sodium chromate, potassium dichromate, and zinc chromate (0.1 wt. %, based on constant strain rate tests on smooth specimens); sodium monobasic phosphate, calcium monobasic phosphate, sodium tripolyphosphate, and potassium silicate (1.0 wt. %, based on constant load tests using edge-notched flat tensile constant load tests.) Phosphate inhibitors incorporated in asphalt-based primer and coal-tar based primer were shown to be effective countermeasures to SCC in laboratory tests (73).

Anthraquinone derivatives adsorbed on AISI 4340 steel (smooth specimens) retarded SCC presumably by acting as hydrogen acceptors (74) in a system in which SCC is probably a hydrogen-assisted cracking process. NaOH, Na₂CO₃, Na₃PO₄, Na₂SiO₃, or Na₂B₄O₇ when introduced with NaNO₂ produced a synergistic inhibition of SCC in AISI 4340 steel in 10% KNO₃ at 100 C (75). Several authors have found that organic amines, including aniline and hexamethylenetetramine can inhibit SCC in high strength steels by adsorbing on the metal surface and interfering with the transport processes (76-80). Using pre-cracked specimens, Parrish et al. showed that oxidizing inhibitors could increase K_{ISCC} for a high strength steel (D6ac), but that in the presence of chloride, dichromate is not a perfect inhibitor (81). C. T. Lynch et al., working with a variety of high strength steels, were able to reduce cracking rates in most of the steels with a multifunctional inhibitor such as borax-nitrate (82). Brown, using precracked specimens, showed that the addition of enough sodium acetate to prevent the crack tip from going acid, could inhibit SCC in high strength steel (83). Johnson found that the addition of a trace of oxygen was sufficient to inhibit the growth of cracks in high strength steel under stress in gaseous hydrogen at one atmosphere pressure (84).

THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

VII. DISCUSSION

Considering the small number of studies there have been on inhibiting SCC compared with the vast literature on SCC in general, it is somewhat surprising that there have been so many systems (combinations of alloy and environment) in which SCC is controlled in engineering applications by the use of inhibitors: water in ammonia in steel tankages, NO in N₂O₄ in titanium tankages, water in red fuming nitric acid in titanium tankages, HF in white fuming nitric acid in stainless steel tankages, and chromate against atmospheric moisture for high strength aluminum aerospace structures. The striking thing about the inhibitor approach is that when a good inhibitor is found, it is often the only measure needed for technological success. By contrast, when other control measures are applied, they are often partial measures and are often combined with partial measures, such as various combinations of altered alloy composition, reduced strength, changed microstructure, reduced stress, and modified environment and temperature.

Stress corrosion cracking is scientifically a complex process, and it is a nucleation-and-growth process. In very few of the studies reviewed here have nucleation and growth been differentiated.

Despite long years of work by brilliant and dedicated investigators, there is hardly a single SCC system for which a

mechanism of SCC has been proposed which has met with overwhelming acceptance by most of the workers in the field. It is therefore not surprising that our knowledge about the mechanisms of inhibition of SCC is so incomplete.

VIII. ACKNOWLEDGMENT

The support of the Office of Naval Research, under Contract N 00014-75-C-0799, NR 036-106, in the writing of this review is gratefully acknowledged. The final typescript was prepared by M. H. Wason. It is a pleasure to acknowledge the contributions of Dr. R. M. Hurd, who drew to the authors' attention several obscure and important references. Professor R. T. Foley kindly read the draft and made many helpful suggestions.

THIS PAGE IS BEST QUALITY PRACTICABLE

IX. REFERENCES FROM COPY FURNISHED TO DDC

1. R. W. Staehle, F. H. Beck and M. G. Fontana, *Corrosion* 15 373t (1959).
2. W. L. Williams and J. F. Eckel, *J. Am. Soc. Naval Engrs.* 68 93 (1956).
3. W. C. Rion, Jr., "Stainless Steel Information Manual for the Savannah River Plant," AEC Research and Development Rept. DP-860 (1964).
4. C. Edeleanu and P. P. Snowden, *JISI* 186 406 (1957).
5. J. H. Phillips and W. J. Singley, *Corrosion* 15 450t (1959).
6. R. B. Mears, R. H. Brown and E. H. Dix, *Symp. on Stress Corrosion Cracking of Metals*, ASTM, Philadelphia (1945), p. 337.
7. H. van Droffelaar, *CEBELCOR Rapports techniques* (Jan) 112 172 (1970).
8. C. S. O'Dell and T. Sarada, unpublished work, The American University, 1978.
9. J. J. Heger, *Metal Progress*, vol. 67, No. 3, p. 109 (March 1955).
10. L. R. Scharfstein and W. F. Brindley, *Corrosion* 14 588 (1958).

11. P. D. Neumann and J. C. Griess, *Corrosion* 19 345 (1963).
12. A. S. Couper, *Materials Prot.* 8 17 (1969).
13. P. P. Snowden, *Nucl. Eng.* 6 409 (1961).
14. W. Lee Williams, *Corrosion* 13 539t (1957).
15. H. H. Uhlig and E. W. Cook, Jr., *J. Electrochem. Soc.* 116 173 (1969).
16. Nasao Fujii and Makoto Kumada, *J. Japan Inst. Metals* 35 560 (1971).
17. Recommended practice RP-01-70, National Association of Corrosion Engineers, Huston, 1970.
18. M. L. Holzworth and A. E. Symonds, *Corrosion* 25 287 (1969).
19. C. R. Bergen, *Nuclear Applications* 1 484 (1965).
20. R. F. Overman, *Corrosion* 22 48 (1966).
21. S. A. Balezin and N. I. Podobaev, *J. Appl. Chem. USSR*, 33 1287 (1960).
22. N. I. Podobaev and S. A. Balezin, *J. Appl. Chem. USSR*, 33 2258 (1960).
23. N. I. Podobaev, *J. Appl. Chem. USSR* 36 341 (1963).
24. R. L. Beauchamp, M.S. thesis, Ohio State Univ. (1963), cited by R. M. Latanision and R. W. Staehle, *Proc. of a Conf. on Fundamental Aspects of Stress Corrosion Cracking*, R. W. Staehle, A. J. Forty and D. van Rooyen, Eds., NACE, Houston (1969), p. 229.
25. K. W. Leu and J. Helle, *Corrosion* 14 249t (1958).
26. C. S. O'Dell, Ph.D. Dissertation, The American University, 1978.
27. M. A. Scheil, O. Zmeskal, J. Waber and F. Stockhausen, *Welding J.* 22 499 (1943).
28. R. Franks, W. O. Binder and C. M. Brown, *Symposium on Stress Corrosion Cracking of Metals*, ASTM, Philadelphia (1945), pp. 411-420.
29. H. L. Logan and R. J. Sherman, Jr., *Welding J.* 35 389 (1956).
30. K. C. Thomas, H. M. Ferrari and R. J. Allio, *Corrosion* 20 89t (1964).

31. S. Brunet, H. Coriou, L. Grall, C. Mahieu and M. Pelras, Eur. Symp. Fresh Water Sea Preprints; cited in Chem. Abstr. 68:52431q.
32. P. R. Rhodes, Corrosion 25 462 (1969). THIS PAGE IS BEST QUALITY PRACTICABLE FROM COPY FURNISHED TO DDC
33. J. E. Truman, Corr. Sci. 17 737 (1977).
34. Stig Berg and Stue Henrikson, Jernkont. Ann. 144 392 (1960).
35. F. Zucchi, G. Trabanelli and A. Frignani, Atti della Accademia delle Scienze di Ferrara, 49 (1971-72).
36. F. Zucchi, G. Trabanelli and V. Sezione, Annali dell'Universita di Ferrara, Chimica Pura ed Applicata, Vol. III, No. 5, 62 (1973).
37. F. Zucchi, G. Trabanelli, A. Frignani and M. Zucchini, Ann. Univ. Ferrara Sez. 5, 4(1) p. 12 (1976).
38. G. Trabanelli, CEBELCOR Rapports techniques Vol. 129 94 (1976).
39. F. Zucchi, G. Trabanelli and A. Frignani, Extended Abstr. No. 3-14, 6th International Congress on Metallic Corrosion, Sydney, 1975.
40. F. Zucchi, G. Trabanelli, A. Frignani and M. Zucchini, Corr. Sci. 18 87 (1978).
41. G. Lafranconi, F. Mazza, E. Sivieri and S. Torchio, Corr. Sci. 18 617 (1978).
42. B. Cohen, personal communication to B. F. Brown, Dec. 21, 1977.
43. H. Gisser, Symposium on Stress-Corrosion Cracking of Metals, A.S.T.M., Philadelphia, 1945, pp. 199-209.
44. J. C. Rowlands, J. Appl. Chem. 15 57 (1965).
45. Shiro Sato and Tadashi Nasetani, Sumitomo Keidinzoku Giho 10 175 (1969). (Chem. Abstr. 72:15156R)
46. H. Uhlig, K. Gupta and W. Liang, J. Electrochem. Soc. 122 343 (1975).
47. N. I. Podobaev, S.A. Balezin and V. V. Romanov, J. Appl. Chem. USSR 33 1297 (1960).
48. K. R. Walston, Corrosion 17 492t (1961).
49. G. C. Kiefer and W. W. Harple, Metal Progress 63 74 (Feb. 1953).

THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

50. J. B. Rittenhouse, Trans. ASM 51 871 (1959).
51. E. G. Haney and W. R. Wearmouth, Corrosion 25 87 (1969).
52. R. M. Vance, Proc. 1st Joint Aerospace and Marine Corrosion Techn. Seminar, 1968. NACE, Houston, 1969, pp. 34-35. See also "Corrosion," Vol. 2, 18:15, L. L. Shreir, Ed., London, Newnes-Butterworsts, 1976.
53. D. P. Williams and H. G. Nelson, cited by T. R. Beck, "The Theory of Stress Corrosion Cracking in Alloys," J. C. Scully, Ed., NATO, Brussels, 1971, p. 18.
54. B. W. Lifka and D. O. Sprowls, "Shot Peening--A Stress Corrosion Cracking Preventative for High Strength Aluminum Alloys," paper presented at the 26th Annual Conference of the NACE, March 1970.
55. S. R. Brown and S. J. Ketcham, Evaluation of Sermatel 385 Coating for Protection of Aluminum Alloys Against Stress Corrosion Cracking, Rept. No. NADC-MA-6930, Naval Air Development Center, Oct. 24, 1969.
56. S. J. Ketcham, private communication to B. F. Brown, 1971.
57. W. E. Knight, "A M L G U A R D, A CORROSION PREVENTION COMPOUND FOR MILITARY APPLICATIONS," paper presented at the 1977 SAMPE Meeting.
58. F. G. Straub, Univ. of Ill. Eng. Expt. Sta. Bull. No. 216 (1930).
59. W. C. Schroeder and A. A. Berk, "Intercrystalline Cracking of Boiler Steel and Its Prevention," Bur. of Mines Bull. 443 (1944).
60. F. G. Straub, Trans. ASME 64 393 (1942).
61. T. E. Purcell and S. F. Whirl, Trans. ASME 64 397 (1942).
62. R. C. Bardwell and H. M. Laudermann, Trans. ASME 64 403 (1942).
63. P. G. Bird and E. G. Johnson, Trans. ASME 64 409 (1942).
64. E. P. Partridge, C. E. Kaufman and R. E. Hall, Trans. ASME 64 417 (1942).
65. A. W. Loginow and E. H. Phelps, Corrosion 18 299t (1962).
66. Department of Transportation, 49 CFR, part 173 (as revised, Federal Register 40 No. 113, June 11, 1975).

67. Fred F. Lyle, Jr., "A Study of Stress Corrosion Phenomena Resulting from Transportation of Anhydrous Ammonia in Quenched-and-Tempered Steel Cargo Tanks," Report No. DOT-FH-11-8568, Feb. 1976.
68. P. B. Ludwigsen and H. Arup, *Corrosion* 32 430 (1976).
69. Hiroshi Imagawa and Kouji Nakamura, *Nippon Kinzoku Gakkaishi*, 40 1250 (1976). Cited in Chem. Abstr. 86:58823n.
70. Hiroyuki Imakawa and Tashio Kano, Japan Patent 77 42,140 (CL C23Fa5100), 22 Oct. 1977. Cited in Chem. Abstr. 88:138341k.
71. K. Noninski, R. Raichev and P. Vodenicharov, *God. Vissh. Khim-Tekhnol. Inst., Sofia*, 22 127 (1977). Cited in Chem. Abstr. 88:67140f.
72. A. K. Dunlop, *Corrosion* 34 88 (1978).
73. W. E. Berry, T. J. Barlo, J. H. Payer, R. R. Fessler and B. L. McKinney, "Evaluation of Inhibitor-Containing Primers for the Control of SCC in Buried Pipelines," CORROSION/78 Paper Number 64.
74. A. Tirman, Paul Fugassi and E. G. Haney, *Corrosion* 25 434 (1969).
75. H. R. Baker and C. R. Singleterry, *Corrosion* 28 385 (1972).
76. F. F. Azhugin and Yu. K. Pavlov, *Zashch. Metal.* 2 533 (1966).
77. E. M. Gutman, L. N. Petrov and G. V. Karpenko, *Fiz.-Khim. Mekh, Mater.* 4 149 (1968).
78. V. P. Grigor'ev, *Fiz. Khim. Mekh. Mater.* 6 54 (1970).
79. A. G. Kanlarova, et al., *Korrozi. Zashch. Neftegazov Prom-sti*, 1977, cited in Chem. Abstr. 88:108893.
80. N. G. Eidel'man et al., *Fiz.-Khim. Mech. Mater.* 13 93 (1977).
81. P. A. Parrish, C. M. Chen and E. D. Verink, Jr., "Stress Corrosion--New Approaches," H. L. Craig, Jr., Ed., STP 610, ASTM, Philadelphia (1976), pp. 189-198.
82. C. T. Lynch, F. W. Vahldik, K. J. Bhansali and R. Summitt, Abstracts 1977 TMS-AIME Fall Meeting, to be published by AIME.
83. B. F. Brown, *The Theory of Stress Corrosion in Alloys*, NATO, Brussels, (1971), J. C. Scully, Ed., p. 186.
84. G. G. Hancock and H. H. Johnson, *Trans. AIME* 236 207 (1966).

(note added in proof)

Humphries and Parkins (85) showed that NaNO_3 and KMNO_4 inhibit the cracking of annealed mild steel in NaOH by moving the potential out of the cracking range; they also found that valonea and quebracho tannin with NaH_2PO_4 prevent SCC even in the SCC potential region. These substances may interfere with the formation of an Fe_3O_4 film which may play a vital role in crack propagation in caustic (86). Berry has found eleven inhibitors of SCC in line pipe steels in (1) $\text{Na}_2\text{CO}_3/\text{NaHCO}_3$, (2) 33% NaOH , and 20% NH_4NO_3 , as follows: CaH_2PO_4 , CaSO_4 , potassium chromate, NaH_2PO_4 , sodium orthosilicate (not effective in NaOH), sodium tetraphosphate, and tripolyphosphate (87).

85. M. J. Humphries and R. N. Parkins, *Corr. Sci.* 7 747 (1967).
86. J. Venczel and G. Wranglen, *Corr. Sci.* 4 137 (1964).
87. W. E. Berry, 5th Symposium on Line Pipe Research. American Gas Assoc., Cat. No. L30174, V-1 (1974).

BASIC DISTRIBUTION LIST

Technical and Summary Reports

April 1978

<u>Organization</u>	<u>Copies</u>	<u>Organization</u>	<u>Copies</u>
Defense Documentation Center Cameron Station Alexandria, VA 22314	12	Naval Air Propulsion Test Center Trenton, NJ 08628 ATTN: Library	1
Office of Naval Research Department of the Navy 800 N. Quincy Street Arlington, VA 22217		Naval Construction Battalion Civil Engineering Laboratory Port Hueneme, CA 93043 ATTN: Materials Division	1
ATTN: Code 471	1	Naval Electronics Laboratory	
Code 102	1	San Diego, CA 92152	
Code 470	1	ATTN: Electron Materials Sciences Division	1
Commanding Officer Office of Naval Research Branch Office Building 114, Section D 666 Summer Street Boston, MA 02210	1	Naval Missile Center Materials Consultant Code 3312-1 Point Mugu, CA 92041	1
Commanding Officer Office of Naval Research Branch Office 536 South Clark Street Chicago, IL 60605	1	Commanding Officer Naval Surface Weapons Center White Oak Laboratory Silver Spring, MD 20910 ATTN: Library	1
Office of Naval Research San Francisco Area Office 760 Market Street, Room 447 San Francisco, CA 94102	1	David W. Taylor Naval Ship Research and Development Center Materials Department Annapolis, MD 21402	
Naval Research Laboratory Washington, D.C. 20375		Naval Undersea Center San Diego, CA 92132 ATTN: Library	1
ATTN: Codes 6000	1	Naval Underwater System Center	
6100	1	Newport, RI 02840	
6300	1	ATTN: Library	1
6400	1	Naval Weapons Center	
2627	1	China Lake, CA 93555 ATTN: Library	1
Naval Air Development Center Code 302 Warminster, PA 18964 ATTN: Mr. F.S. Williams	1	Naval Postgraduate School Monterey, CA 93940 ATTN: Mechanical Engineering Department	1

BASIC DISTRIBUTION LIST (cont'd)

<u>Organization</u>	<u>Copies</u>	<u>Organization</u>	<u>Copies</u>
Naval Air Systems Command Washington, D.C. 20360 ATTN: Codes 52031 52032	1	NASA Headquarters Washington, D.C. 20546 ATTN: Code RRM	1
Naval Sea System Command Washington, D.C. 20362 ATTN: Code 035	1	NASA Lewis Research Center 21000 Brookpark Road Cleveland, OH 44135 ATTN: Library	
Naval Facilities Engineering Command Alexandria, VA 22331 ATTN: Code 03	1	National Bureau of Standards Washington, D.C. 20234 ATTN: Metallurgy Division Inorganic Materials Div.	1 1
Scientific Advisor Commandant of the Marine Corps Washington, D.C. 20380 ATTN: Code AX	1	Director Applied Physics Laboratory University of Washington 1013 Northeast Forthieth Street Seattle, WA 98105	1
Naval Ship Engineering Center Department of the Navy Washington, D.C. 20360 ATTN: Code 6101	1	Defense Metals and Ceramics Information Center Battelle Memorial Institute 505 King Avenue Columbus, OH 43201	1
Army Research Office P.O. Box 12211 Triangle Park, NC 27709 ATTN: Metallurgy & Ceramics Program	1	Metals and Ceramics Division Oak Ridge National Laboratory P.O. Box X Oak Ridge, TN 37380	1
Army Materials and Mechanics Research Center Watertown, MA 02172 ATTN: Research Programs Office	1	Los Alamos Scientific Laboratory P.O. Box 1663 Los Alamos, NM 87544 ATTN: Report Librarian	1
Air Force Office of Scientific Research Bldg. 410 Bolling Air Force Base Washington, D.C. 20332 ATTN: Chemical Science Directorate Electronics & Solid State Sciences Directorate	1 1	Argonne National Laboratory Metallurgy Division P.O. Box 229 Lemont, IL 60439	1
Air Force Materials Laboratory Wright-Patterson AFB Dayton, OH 45433	1	Brookhaven National Laboratory Technical Information Division Upton, Long Island New York 11973 ATTN: Research Library	1
Library Building 50, Rm 134 Lawrence Radiation Laboratory Berkeley, CA	1	Office of Naval Research Branch Office 1030 East Green Street Pasadena, CA 91106	1

SUPPLEMENTARY DISTRIBUTION LIST

Technical and Summary Reports

April 1978

Dr. T. R. Beck
Electrochemical Technology Corporation
10035 31st Avenue, NE
Seattle, Washington 98125

Professor I. M. Bernstein
Carnegie-Mellon University
Schenley Park
Pittsburgh, Pennsylvania 15213

Professor H. K. Birnbaum
University of Illinois
Department of Metallurgy
Urbana, Illinois 61801

Dr. Otto Buck
Rockwell International
1049 Camino Dos Rios
P. O. Box 1085
Thousand Oaks, California 91360

Dr. David L. Davidson
Southwest Research Institute
8500 Culebra Road
P.O. Drawer 28510
San Antonio, Texas 78284

Dr. D. J. Duquette
Department of Metallurgical Engineering
Rensselaer Polytechnic Institute
Troy, New York 12181

Professor R. T. Foley
The American University
Department of Chemistry
Washington, D.C. 20016

Mr. G. A. Gehring
Ocean City Research Corporation
Tennessee Avenue & Beach Thorofare
Ocean City, New Jersey 08226

Dr. J. A. S. Stern
Martin Marietta Corporation
1450 South Rolling Road
Baltimore, Maryland 21227

Professor R. H. Heidersbach
University of Rhode Island
Department of Ocean Engineering
Kingston, Rhode Island 02881

Professor H. Herman
State University of New York
Material Sciences Division
Stony Brook, New York 11794

Professor J. P. Hirth
Ohio State University
Metallurgical Engineering
Columbus, OHio 43210

Dr. D. W. Hoepfner
University of Missouri
College of Engineering
Columbia, Missouri 65201

Dr. E. W. Johnson
Westinghouse Electric Corporation
Research and Development Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235

Professor R. M. Latanision
Massachusetts Institute of Technology
77 Massachusetts Avenue
Room E19-702
Cambridge, Massachusetts 02139

Dr. F. Mansfeld
Rockwell International Science Center
1049 Camino Dos Rios
P.O. Box 1085
Thousand Oaks, California 91360

Professor A. E. Miller
University of Notre Dame
College of Engineering
Notre Dame, Indiana 46556

Dr. Jeff Perkins
Naval Postgraduate School
Monterey, California 93940

SUPPLEMENTARY DISTRIBUTION LIST (cont'd)

Professor H. W. Pickering
Pennsylvania State University
Department of Material Sciences
University Park, Pennsylvania 16802

Professor R. W. Staehle
Ohio State University
Department of Metallurgical Engineering
Columbus, Ohio 43210

Dr. E. A. Starke, Jr.
Georgia Institute of Technology
School of Chemical Engineering
Atlanta, Georgia 30332

Dr. Barry C. Syrett
Stanford Research Institute
333 Ravenswood Avenue
Menlo Park, California 94025

Dr. R. P. Wei
Lehigh University
Institute for Fracture and
Solid Mechanics
Bethlehem, Pennsylvania 18015

Professor H. G. F. Wilsdorf
University of Virginia
Department of Materials Science
Charlottesville, Virginia 22903



