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OCT 19 1994

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1	1	Cog. Mgr. P.C. Ohi	<i>P.C. Ohi</i>	10/3/94	R1-30				
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7. Abstract This document is a collection of memos from M.A. Streicher which convey findings on corrosion in high-level underground waste tanks. The memos are related to his participation in the DOE Headquarter's Tank Structural Integrity Panel from 1991 through 1994.		
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Rev. 0

**M. A. STREICHER FINDINGS REGARDING HIGH-LEVEL
WASTE TANK CORROSION ISSUES**

September 1994

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**M.A. STREICHER FINDINGS REGARDING
HIGH-LEVEL WASTE TANK CORROSION ISSUES**

INTRODUCTION

Dr. Michael A. Streicher is a nationally recognized metallurgist and corrosion scientist. He has served on the Department of Energy, Headquarters Tank Structural Integrity Panel as the primary corrosion technical expert since the panel's inception in October 1991. Attachment 1 is Dr. Streicher's permission to publish these papers. Attachment 2 is his professional résumé. Attachments 3 through 13 are Dr. Streicher's correspondence and presentations to the panel between November 1991 and May 1994. This compilation addresses Dr. Streicher's findings on High-Level Waste tank corrosion issues such as:

- Corrosion mechanisms in carbon steels
- Hydrogen generation from waste tank corrosion
- Stress corrosion cracking in carbon steel tanks
- Water line attack in Hanford's single-shell tanks
- Stress corrosion cracking of austenitic stainless steels
- Materials selection for new Hanford waste tanks.

These papers discuss both generic and specific corrosion issues associated with waste tanks and transfer systems at Hanford, Savannah River, Idaho National Engineering Laboratory, and West Valley Demonstration Project.

ATTACHMENT 1

MICHAEL A. STREICHER
Corrosion Consultant

September 26, 1994

Westinghouse Hanford Company has my permission
to issue the attached compilation of memoranda
and presentation material I created as a participant
in DOE Headquarters' High-Level Waste Tank Structural
Integrity Panel.

Michael A. Streicher
Dr. Michael A. Streicher

Date 9/26/94

ATTACHMENT 2
PROFESSIONAL BIOGRAPHY
MICHAEL A. STREICHER

Date of Birth:

September 6, 1921

Education:

B.Ch.E., Rensselaer Polytechnic Inst., Troy, N.Y., Chem. Eng. (1943)

M.Ch.E., Syracuse University, Chem. Engg., (1945)

Ph.D., Lehigh University, Bethlehem, PA, Metallurgy (1947)

Post Doctoral Research Associate in Department of Metallurgy, Lehigh University, December 1947 to December 1948.

Employment:

E. I. du Pont de Nemours & Co., Inc., Engineering Department,
Wilmington, DE, 19898, at the Experimental Station in Engineering
Research

01/1/49 Research Engineer

03/1/53 Research Project Engineer

10/1/56 Research Associate

07/1/67 Research Fellow (Principal Consultant)

03/31/79 Retired from du Pont Company

04/1/79 Research Professor, University of Delaware
to Department of Mechanical Engineering
11/1/87 Newark, Delaware 19716

Organized Corrosion Research Laboratory with support from the National Science Foundation, the Department of Commerce, Electric Power Research Institute, Exxon Corporation, Haynes International, Inc., and Carpenter Technology Corp.

Consulting:

Chemical process, paper, petroleum and power companies, steel and stainless alloy procedures and processors, electrochemical instrument company, U. S. Department of Energy and Commerce, Nuclear Regulatory Commission and Legal Consultations.

Research Field: Chemical Metallurgy:

Research in chemical metallurgy consists of a study of factors in metals (composition and structure) and in the chemical environment which govern the interactions between them. More specifically, it includes metal dissolution, corrosion, oxidation, etching, catalysis and the formation of films and coatings on metals.

The following topics from this field have been the subject of Streicher's major laboratory investigations:

- The electrochemistry of corrosion of aluminum, carbon steels, stainless steels and nickel-base alloys
- Passivity of stainless alloys
- Pitting and crevice corrosion
- Intergranular corrosion
- Chloride stress corrosion cracking of stainless steels and nickel-base alloys
- Stress corrosion of carbon steels in N_2OH and in HCN solutions
- Corrosion inhibition by organic and inorganic inhibitors
- The relationship of composition, heat treatment, and microstructure to corrosion
- The formation of surface conversion coatings: phosphate and oxalate
- Corrosion by water
- Corrosion at temperatures above atmospheric boiling points (autoclave tests) in aqueous and polymeric solutions
- Development of new, corrosion resistant alloys
- Development of new corrosion test methods
- Corrosion in organic solvents
- Marine corrosion
- Electrochemical methods for detecting sensitization in stainless steels.

ATTACHMENT 3
MICHAEL A. STREICHER

Corrosion Consultant

November 25, 1991

MEMORANDUM

To: Dr. Kamal K. Bandyopadhyay

Comments on Corrosion and Other Problems in Carbon
Steel Tanks for Nuclear Waste

- References:
- 1) Report by G. L. Borsheim and N. W. Kirch, "Summary of Single-Shell Tank Waste Stability", March, 1991.
 - 2) Minutes of HWL Tank System Structural Integrity Panel Meeting by K. K. B. Meeting of October 31, 1991.
 - 3) Three items sent on November 18, 1991 by Howard Eckert: Daily Hanford Reports (9), Draft of Report by D. Wodrich, 11/15/91, Nine documents related to the corrosion-low pH issue.

The following comments are based on the study of the above items. Of these, #1 is the most comprehensive and detailed. The writer is only at the beginning of his acquaintance with this many-faceted subject. The comments below indicate areas for which he feels a need for further information. Some of this may already be available in other reports, e. g., the results of corrosion failure analyses, such as carried out for SR by Donald Warren. Other items may require further theoretical study, searches in the literature, and further plant and laboratory tests.

A) CORROSION

On page 4-28 of the G.L. Borsheim and N. W. Kirch Summary Report, it is stated, for Hanford, that "--the tanks should function at least 40 more years (i. e., equal to their present age) if there are no changes in operating conditions; more likely they will perform adequately for hundreds of years. Dramatic changes in operating limits (such as going to an acid waste form or large increases in soil loads) could, however, change this estimate."

(page 1 of 4 pages)

This important statement is not included in the SUMMARY of the report on page 1-3. According to the Minutes of the October 31, 1991, Panel Meeting, the objective of the Panel is " To assist tank farm operators in evaluating and maintaining structural integrity of tank systems."

On the basis of information available in the Borsheim-Kirch report and the other items listed above for this review, the writer is not able to agree with their conclusion on the conditions of the steel tanks and their ability to survive another 40 or hundreds of years.

- 1) At Hanford 66 single-shell tanks were declared "assumed leakers" (KKB Minutes). Why are they leaking (stress corrosion cracking, pitting) and for how long? Where has the liquid gone?
- 2) At the SRP " many of the type I and II tanks are cracked." (KKB minutes)

What kind of cracking is this, caustic and/or nitrate stress corrosion? How many have leaked and how were the leaks handled? Has there been any hydrogen cracking?
- 3) What kind of reports are available on failure analyses to determine the presence or absence of general corrosion, pitting attack and various forms of stress corrosion cracking. Hydrogen stress cracking can occur when the pH is neutral or is in the acid range and there is corrosion on the steel with evolution of hydrogen.

It is noted that on coupon corrosion tests in tanks corrosion is consistently more severe in the vapor space than in the liquid or slurry.

Has there been preferential attack of any kind on the various components of weldments, base plate, heat affected zone, mixed zone, and weld metal?

B) DECREASE in p H

What is the effect of decreases in pH from alkaline values to neutral and even acid values on corrosion of steel in the form of stress corrosion, pitting and general corrosion? What effect will caustic and nitrate stress corrosion cracks have on the

growth of hydrogen cracks which may appear when the pH is decreased to acid values? Hydrogen cracking will then be on "pre-cracked" steel.

How much pitting and general corrosion is there at lower pH, especially in the vapor space?

In the presence of corrosion at lower pH there may be deposition of certain metals present as dissolved salts on the surface of steel. Among these metals are Pb, Hg, Cu, Bi, Cd (Table 3-1 of Summary). Low-melting metals may diffuse into steel along grain boundaries at elevated temperatures over long periods of time and cause embrittlement of the metal?

C) REACTIONS WHICH CAN CAUSE EXPLOSIONS

Ferrocyanide-nitrate

Organic -nitrate

Ammonium-nitrate

Organic vapor and Hydrogen

(Tank Bumps)

- 1) A review is needed of the potential interactions which might occur. For example, can the shock from a small hydrogen explosion set off an ammonium nitrate explosion? Can there be a chain of events among the various types of explosions including tank bumps?
- 2) Simulated laboratory tests must approach actual conditions in the tanks, i. e., with all the same ingredients and with special attention to catalytic effects. Some of these items have been mentioned in the report (Borsheim-Kirch) but more extensive laboratory work of this highly simulated kind is needed.
- 3) In the review of the ammonium-nitrate problem, page 2-3 of the B-K report there is a list of items on this subject quoted from the Material Data Sheet on Ammonium Nitrate (GPC 1981). This is useful. However, a study should also be undertaken of the original literature on this subject which was published in connection with several large explosions of ammonium nitrate.
 - a) Oppau, Germany, September 21, 1921
561 fatalities
 - b) Oppau, Germany, July 28, 1948
207 fatalities
 - c) Texas City

(Memo to KKB cont.)

4.

- 4) What effect will even "minor" explosions of any kind have on tanks with pre-existing stress corrosion cracks? Numerous undetected cracks may be present and greatly reduce the rupture strength of steel tanks.
- 5) There seems to be a need for a detailed analysis of every possible reaction in the tanks as a function of a decrease in pH because the general assumption has been that the pH is 11 or more. A start on this problem has already been made, but a more detailed and extensive effort appears necessary.
- 6) More extensive corrosion tests in tanks and in the laboratory are needed: the effect of pH, solution composition on immersion and vapor-space tests, for general, pitting and various types of stress corrosion, on specimens including weldments.

D) Review OF OUTSIDE LITERATURE

As mentioned above for ammonium nitrate, as much help as possible should be obtained on metal failures and explosions from non-nuclear sources; e. g., on hydrogen cracking the relatively recent Union Oil absorber failure. Various NACE Technical Practices Committees monitor caustic, nitrate and hydrogen cracking failures in industry. It may be useful to attend their deliberations and information exchanges at the annual meetings. The next one is in Nashville, TN, April 27 to May 1, 1992.

Also, books and their authors, such as "Industrial Explosion Prevention and Protection" by F. T. Bodurtha, may be useful.

ATTACHMENT 4

MICHAEL A. STREICHER

Corrosion Consultant

February 12, 1992

MEMORANDUM

To: Dr. Kamal K. Bandyopadhyay, BNL

Corrosion Meeting at SRP (1-28-92) and Tours
of Tank Farm and Vitrification Plant (1-29-92)

A) Meeting on Corrosion of HLW Tanks at SRP

- 1) Procedures - The agenda for this meeting, provided by Howard Eckert, is attached. Minutes will be provided by Tom Temple, DOE-SRP. The attendance list is attached. Two speakers provided copies of their visuals. A page with a summary of the contents of each type of tank (copy attached) was provided, as well as a page showing the tanks in the H-Area Tank Farm, which some of us visited on 1-29-92.

All of the items in the agenda were covered in the meeting. However, the last item on the "Prediction of Useful Service Life of Tanks" requires further discussion in the light of questions raised at this meeting.

The following are some specific comments derived from this meeting and the two tours.

- 2) Corrosion Work at SRP - The work on corrosion problems in waste tanks at the SRP goes back to the sixties when there were leaks which were traced to stress corrosion cracks in the walls of Tank #16 and some others. This led to extensive observations on tank walls, especially at weldments, laboratory testing and the development of a successful method for inhibiting this type of failure, as well as pitting in the cooling coils. There has been continuity in effort and staff over decades. (It should be noted that the senior corrosion scientist on these problems, R. S. Ondrejcin, retired shortly after our visit.)

In contrast, at Hanford there has been much less work on corrosion and less continuity. It was assumed at Hanford that their many leaks (66 tanks) are also a result of nitrate stress corrosion cracking on the basis of the work at the SRP.

- 3) SRP-Hanford Exchanges - It is very encouraging that there have been joint meetings in recent years between SRP and Hanford personnel, as well as exchange visits. This should be especially useful to Hanford on corrosion problems.
- 4) Relative Humidity in Annular Spaces - The walls of the waste tanks are being photographed regularly in the annular space to detect new leaks which might occur at stress corrosion cracks, especially near weldments, and to monitor existing leaks by observing the size and shape of salt deposits at leaks. These deposits plug the leaks. This plugging action depends on immediate and continuous evaporation of waste liquid coming out of the stress corrosion cracks when they have completely penetrated the thickness, 5/8 in, of the wall.

Warmed air is circulated through the annular space. It not only evaporates the waste liquid as it emerges into the annular space and precipitates the salts which block further flow at the cracks, but it also prevents corrosion, rusting, of all of the steel surfaces making up the annular space, including the bottoms of the tanks. Rusting of steel ceases when the relative humidity is reduced to 30%.

Because of these important roles of the air circulating through the annular spaces, it appears useful to monitor not only the temperature of the warmed air, but also its relative humidity. Laboratory tests might be made to determine the rate of air flow, temperature and relative humidity which are required to keep the stress corrosion cracks plugged and to prevent rusting of the steel.

- 5) Exterior of Tank Bottoms - The photographic record now being made of the outside walls of the tanks in the annular space can not be extended to the bottoms of the tanks for technical reasons. Therefore, statements about the conditions of the inside and outside of the steel surfaces apply only to the walls and the roofs of the tanks. This qualification should be highlighted in summaries about the extent of corrosion damage and in predictions of useful service life of the tanks.

What differences, if any, are there in the conditions of the bottoms as compared with the accessible walls: number and size of the stress corrosion cracks, pits under solid wastes inside the tanks, corrosion of the exterior surface where in contact with the concrete supports? Does the effect of the weight of the waste in the tanks and its concentration at the supports increase the number and size of stress corrosion cracks on the inside surface of the bottoms and the incidence of pitting? Is it possible to develop devices which can be used to monitor the exterior surfaces of tank bottoms?

- 6) Pockets in Solid Wastes - When solids precipitate from waste solutions, enclosures or pockets may gradually be formed which limit flow of fluids and diffusion of dissolved species. Reactions, including the products of radiolysis and the consumption of nitrite and alkaline inhibitors at steel surfaces, e. g., tank bottoms, can drastically change the composition of the solutions in such pockets. There may be a loss of inhibitors and, perhaps, a drop in pH. Can further efforts be made to probe for the existence of such pockets? Is it possible to simulate the formation of pockets in laboratory experiments? Can changes in composition in pockets at the bottoms of tanks lead to pitting attack and to nitrate stress corrosion cracking or even hydrogen embrittlement and cracking, especially at weldments? As the wastes "age" there may be an increase in corrosiveness in localized areas such as pockets.
- 7) Predictions of Useful Service Life - If it is accepted that inhibitors, nitrite and caustic, have stopped the growth of stress corrosion cracks and have prevented the formation of new cracks in welded and non-stress relieved tanks, and also have eliminated pitting of cooling coils, then the predictions of useful service life can be simply based on the very low rate of general corrosion of steel in the various waste solutions. This procedure also assumes that the unobserved tank bottoms do not and will not suffer more severe forms of pitting and stress corrosion than the other steel surfaces. At the meeting it was predicted that on the basis of the very low rate of general corrosion the life of the tanks would be 7,000 to 12,000 years.

However, this prediction was based on the dissolution of the entire thickness of the steel plates in the tanks. These thicknesses are 1/2 in for tops and bottoms and 5/8 in for the walls. Of course, the structural capacity of the plates will be destroyed long before the entire thickness of the plates is dissolved. Probably no more than 10% of the thickness can be considered a "corrosion allowance". Thus, even for failure by general corrosion, the useful life is not more than about 700 years, if we assume there are no cracks or pits in the steel plates!

Some highly desirable data on the conditions of the steel plates in the tanks and also on the concrete structures are not available and, in some cases are unobtainable. Nevertheless, it appears important to list what kind of data might have a crucial bearing on estimates of service life even though they are not available so that uncertainties can be recognized and conclusions can be properly qualified where necessary.

It appears desirable to review the methodology to be used for the preparation of the predictions of useful service life.

- 8) Analysis of Possible Modes of Failure - It may be helpful to make a theoretical analysis of the sequence of events which would be initiated and which would proceed from a total cessation of tank maintenance to obtain a comprehensive understanding of the problems inherent in the care of the waste tanks and, perhaps also of predictions of useful service life. What would be the result if there were no water circulation in the cooling coils, no replenishment of inhibitors and no forced circulation of air in the annular space? (Note also the temperature requirement for the steel to prevent embrittlement as mentioned in item #9.) Such an analysis for each type of tank configuration and corrosion history and for each type of waste ~~content~~ may provide an enhanced understanding of the interrelationships of each of the various controls in use to extend service life and guarantee safety.
- 9) Laboratory Tests, the J. A. Donovan Compilation, DP-1476, 1977 -
- a) To minimize the probability of brittle failure in the steels of the waste tanks the temperature must be maintained above 21 C (69.8 F), see page 8 of the report. This requirement should be reviewed in connection with item #8 above.
 - b) The time factor in laboratory stress corrosion tests on welded and stress relieved specimens, pages 27-29, was explored up to 167 days (4,008 hr) in 50% sodium nitrate solution at 90-95 C, Table 8. What effect does a longer testing time and simulation of external field stresses have, i. e., the effect of the weight of waste at concrete supports of tank bottoms? It seems that it may be desirable to supplement the available laboratory data with long-time additional tests.
 - b) It may be useful to discuss previous and future laboratory electrochemical tests, especially the applicability of the results for assessing and predicting corrosion in the waste tanks at a special meeting with interested personnel.

B) Tour of H-Area Tank Farm

A group from the visitors toured this area with Mario Ceravolo, who was very helpful in providing information on the operation and history of the tanks. There is a considerable variety of tank designs, histories of use and steels, with and without stress relief. This complex combination of factors must be taken into account when estimates are made of useful service life, when laboratory and tank corrosion tests are planned, and when analyses of potential failure modes are made in connection with the proposal of item #8 above.

C) Tour of Vitrification Plant

This new plant, which is nearing completion, was seen on the afternoon of 1-29-92. Waste in the form of molten glass is to be poured into Type 304L stainless steel canisters. These are to be shipped to the storage site and individually sealed at the site into carbon steel containers for underground storage (Yucca Mountain, Nevada?).

Type 304L austenitic stainless steel is highly susceptible to chloride stress corrosion cracking.

Chlorides in ground water will be highly concentrated when water is evaporated at the hot surface of the carbon steel outer container. Attack on the carbon steel may be intensified if the chloride solution also contains acid species resulting from radiolysis of water and air, nitric acid, various oxides of nitrogen and ozone.

If the carbon steel container is breached by the above acid environment created by long-time exposure of the hot surface to ground water, the acid chloride solution can reach the hot surface of the Type 304L stainless steel container. There may then be rapid stress corrosion cracking of the canister and penetration of the hot acidified chloride solution to the waste glass.

The result may be attack on the borosilicate glass and dispersal of radioactive waste into the environment, volcanic tuff.

Concentrated sodium chloride solutions are known to attack borosilicate laboratory flasks when used for long-time tests in boiling 26% (saturated) sodium chloride solutions. In about 1000 hr one half of the thickness of laboratory flasks is dissolved or etched away. See page 16 of DOE Report ANL/EES-TM 339, October, 1987, copy attached.

Therefore, the life of the carbon steel container and the Type 304L stainless steel canister may be directly dependent on the presence or absence of water in the (volcanic tuff) environment.

M. A. Streicher

United States Government

Department of Energy

memorandum

DATE: January 13, 1992
REPLY TO:
ATTN OF: EM-35:Eckert:FTS 233-7173
SUBJECT: Meeting on Corrosion of SRS HLW Tanks

TO: T. Temple

As we have previously discussed, the purpose of this meeting is to provide a means for DOE-HQ staff and their corrosion consultants to quickly learn more about corrosion of the SRS High-Level Waste tanks. Topics of interest are:

- Chemistry of the waste in the SRS tanks (e.g., source and type of waste, pH)
- SRS experience with corrosion of the tanks (e.g., known corrosion problems, stress corrosion cracking, pitting)
- SRS program to control corrosion (e.g., chemistry control, cathodic protection)
- SRS plans for dealing with corrosion (e.g., inspection programs, monitoring, coupon testing)
- Knowledge and plans for dealing with potential corrosion of the rebar within the concrete vaults
- Prediction of useful service life of the tanks (e.g., does localized corrosion control life?)

Attendees from HQ will be:

Howard J. Eckert, EM-35
Charles S. O'Dell, EM-35
Richard A. Wullaert, SAIC
John R. Weeks, BNL
Michael A. Streicher, BNL

HLW Tank Task Force (Tank Integrity Subcommittee)

Attendance Roster

Name	Phone	Business
Tom Temple	FTS 237-8248	DOE-SR
CHARLES ODELL	FTS 233-7192	DOE-EM36
WILL MULLERT	(911) 501-5017	WHIC
TOM ELLERMAN	(919) 515-3600	NCSU
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Michael Streicher	(302) 478-7725	BNL
FRED G. McNATT	571-8351	WSRC
David Hobbs	725-2838	WSRC-SRL
Brenda Lewis	557-8720	WSRC-WMT
Philip Zapp	FTS 239 725 2567	WSRC - SRL Materials Tech Section
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ROBERT ANDREJCIN	803-725-3567	WSRC-SRL MATLS. TECH.
Howard Eckert	301-913-7173	DOE-EM36
Gos K. Gorgutan	803-557-6822	WSRC-WMT Waste Mgmt Tech

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DOCUMENT PROCESSING

WASTE TANK LEVELS

MHC-SD-WM-TA-157
Rev. 0

TANK 1F
INACTIVE

TANK 2F
INACTIVE

TANK 3F
INACTIVE

TANK 4F
INACTIVE

TANK 5F
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TANK 6F
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TANK 9H
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TANK 10H
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TANK 11H
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TANK 12H
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TANK 13H
STANDBY

TANK 14H
INACTIVE

TANK 15H
INACTIVE

TANK 16H
OUT OF SERVICE

TANK 17F
INACTIVE

TANK 18F
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TANK 19F
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TANK 20F
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TANK 44F
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TANK 45F
ACTIVE

TANK 46
EMERGENCY SPARE

TANK 47F
ACTIVE

TANK 48H
ACTIVE

TANK 49H
ACTIVE

TANK 50H
ACTIVE

TANK 51H
ACTIVE

LEGEND

SUPERNATE
SALT
SLUDGE
* TANK HAS CRACKS

H-Area Tank Farm

ARGONNE NATIONAL LABORATORY
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ANL/EES-TM-339

CONTAINER MATERIALS FOR ISOLATION
OF RADIOACTIVE WASTE IN SALT

Proceedings of Workshop Held at
Columbus, Ohio,
September 25-26, 1986

edited by

M.A. Streicher* and A. Andrews

Energy and Environmental Systems Division
Engineering Geosciences Group

Published October 1987

work sponsored by

U.S. DEPARTMENT OF ENERGY
Office of Civilian Radioactive Waste Management
Salt Repository Project Office

*Wilmington, Delaware.

5 EFFECT OF CONTAINER FAILURE ON THE CANISTER AND ADJACENT CONTAINERS

If containers are breached, either by corrosion or by mechanical failure, brine may come into contact with the canisters. If the canisters are made of Type 304L stainless steel, they will very probably be subject to rapid stress-corrosion cracking. The brine might then penetrate to the waste forms. Borosilicate glass, one of the anticipated waste forms, is readily attacked by high-temperature salt solutions.* Thus, radioactive species may reach nearby containers. The result might be an increase in the corrosiveness of the salt environment, resulting from generation of HCl, O₂, Cl₂, and other species. The consequences of container failure on adjacent containers should be studied.

*The attack of glass laboratory flasks by boiling chloride solutions has been observed repeatedly in long-term (1000-2400-hr) stress-corrosion tests. In boiling 26%-NaCl (107°C) and 45%-MgCl₂ (155°C) solutions, about one-half of the thickness of the glass flask is dissolved in 1000 hr (information from Michael A. Streicher).

ATTACHMENT 5
MICHAEL A. STREICHER
Corrosion Consultant

February 27, 1992

MEMORANDUM

To: Dr. Kamal K. Bandyopadhyay, BNL

Meetings and Tour at Hanford Plant, February 18-20, 1992,
on High-Level Waste Tank Systems, Structural Integrity Workshop

Previous reports on Waste Tank Problems by author:

November 25, 1991, on meeting of October 31, 1991 at Rockville.

December 16, 1991, on meeting at Hanford on Low p-H Briefing
on December 9, 1991.

February 12, 1992, on meetings and tour at Savannah River
Plant on January 28-29, 1992.

Introduction

The six-member Workshop Panel met at the Hanford House in Richland, WA for a two-day program with speakers from the Hanford Plant and a total attendance of 58. Most of these were from Hanford, but there were also representatives from Savannah River, Oak Ridge, Stone and Webster, West Valley, NY, and Idaho Falls. Visuals were provided for all presentations, and ample opportunities for questions and discussion were a part of the program. F. R. LaSalle effectively presided over the proceedings. At the end of each day the panel met alone to discuss a draft of their conclusions.

1) Objectives

This two-day meeting provided an effective forum for:

- a) Educating Panel members on waste and tank history, operations and problems.
- b) The tour of some tank farms gave some of the Panel members an opportunity to get a closer view of the tank operations and personnel on February 18, 1992.
- c) Interaction among the large number of personnel from various sites while they were brought up-to-date on the work at Hanford.
- d) Gaining information on ways in which the members of the Panel might be of assistance on problems at various sites.

Another of the objectives of the Panel's effort is to review the basis and methodology to be used for "Predicting

Useful Service Life of High-Level Waste Storage Tanks". For these predictions it will be necessary to use available data on the corrosion of steel in the tanks and on the deterioration of the steel-reinforced concrete. Where technically feasible, it may be desirable to obtain additional data on these subjects to supplement the available information. Furthermore, it will be essential to list the kinds of data which would be highly desirable, if not vital, to have for a confident prediction of service life, but which can not be obtained because of technical or economical limitations. This second list is needed to provide realistic qualifications and limits for "Predictions of Useful Service Life". The writer stressed this point in comments during the last discussion period of the meeting.

2) Some Specific Items

a) Hanford personnel have developed cameras for examining surfaces in the annulus of DSTs. All these tanks are to be monitored for signs of leaks on the walls of the primary tanks and for corrosion on the walls of the primary and secondary steel surfaces. This procedure is already being followed at the SRP, where there are DSTs with leaks which have been plugged with dry waste salt. (Question: Did Hanford personnel benefit from the development work on cameras at the SRP?)

It is important to note that these cameras can not be used to examine the bottoms of the DSTs because the primary tank rests on cement pads. This is also the case for the steel exposed in the drainage/aeration channels in these pads because the cameras can not be run into these channels.

Thus, neither the inside nor the outside of the tank bottoms is accessible for inspection. There is a possibility that these upper and under sides of the tank bottoms may be more severely corroded than the inside and outside surfaces of the vertical walls or of the steel domes.

b) We were shown an impressive video film of the "burping" action, which occurs regularly every 90 to 100 days. Hydrogen is released, proving that there are chemical reactions taking place in the waste. There are also significant differences in temperature between various layers (140 F at the bottom and 105 F at the top) as well as differences in specific gravity (1.0 at the top and 1.7 at the bottom). Thus, there well may be "pockets" in this "burping" tank, as well as others, in which there are considerable differences in composition, pH and temperature from the values determined in bulk samplings.

c) The cameras used to observe "bumping" in the tanks could also be used to monitor the interior surfaces of the steel domes of the DSTs. The vapors over the waste solutions may be more corrosive than the solution in the tanks.

d) A similar camera system might also be developed to examine the concrete surface on the inside of the dome (roof) of single shell tanks. The results can then be correlated with the history of each tank. These observations may provide the best estimate of the resistance of the concrete to waste tank environments throughout the entire tank farm system.

3) Unknowns Which May Affect Predictions of Useful Service Life

"Useful Service Life" was defined as time to "collapse" of the tank. Should this definition be expanded to include time to unacceptable leaks and the appearance of an unacceptable degree of pitting and/ or stress corrosion cracking and of general corrosion?

a) So far, 66 tanks have been designated as "leakers" because of the large loss of liquid. However, there is a great possibility that all of the other SSTs also have stress corrosion cracks at which there may have been leaks. Therefore, all of the SSTs may have seriously impaired resistance to mechanical failure, e. g., during seismic events.

None of the SSTs have had additions of inhibitors to prevent stress corrosion cracking. Weldments in the bottom plates of relatively dry tanks may be especially susceptible to stress corrosion cracking, which may involve a continuous process of crack growth with time.

b) There are 149 individual tank (SS) histories and "final" chemical compositions. Because of radiolysis and non-homogeneous distribution of the chemical species, especially if pockets are formed, the "final" composition may still be changing in a largely unknown manner and degree. Some tanks were used to let high activity wastes boil and others contain ferrocyanide and are kept wet. Thus, the sampling program now scheduled should be detailed within each tank and should involve every tank, at least as a first approach and until the first results permit some contraction of the sampling program.

c) It was pointed out by Bryan Mather that ammonium nitrate and elevated temperatures degrade concrete. Thus, assessment of the condition of concrete should include the thermal history of the tanks, the amount and composition of leaked solution, the condition of the inside of the concrete dome, and the condition of the interface between the steel liner and the concrete shell. How much corrosion has there been on the outside of the steel liner by moisture and waste solution at leaks?

4) Comments on Recommendations

a) Corrosion Testing Program - Include tests in ferrocyanide solutions and in solutions having the compositions of tanks with "bumping".

Carry out corrosion tests in sludge, in addition to tests in liquid and vapor, at various levels down to the bottom of the tanks, with flat specimens for general and pitting corrosion,

and U-bend specimens for stress corrosion.

c) For tests on 304L stainless steel, for the new tank, "dope" the chemicals with chlorides, and, if appropriate, bromides, and check for pitting, general corrosion and stress corrosion cracking in vapor space, the liquid and in the sludge.

5) Suggestions

a) Exchange reports and selected, reciprocal visits with members of other Panels dealing with waste tank problems, such as, safety, explosion and seismic. Can our Panel have briefings by personnel from these Panels?

b) Set up a special meeting for corrosion personnel from our Panel with the corrosion groups from Hanford and SRP on future corrosion monitoring and testing in waste tanks and for the design of laboratory tests, and for qualification tests for the use of Type 304L stainless steel for the new tank at Hanford.

c) Assist Idaho personnel with acceptance (evaluation) testing of various stainless steels.

d) On the DSTs increase the measurements of relative humidity and temperature of the air being circulated through the annulus because these values can be a clue to the first appearance of leaks. They may indicate whether or not there is enough drying to form salt plugs at the leaks, and whether or not the values are low enough to prevent the steel surfaces from corroding by humid air.

e) Replace the term "out of service" to describe the current status of the 149 SSTs. Some are actually still in "service", the ferrocyanide tanks, and they are all still performing a "service" which requires extensive monitoring and adjustments. The term "out of service" creates a very different picture from this condition, more like "mothballing".

Michael A. Streicher

Michael A. Streicher

cc Howard Eckert, DOE
Dr. John R. Weeks, BNL

ATTACHMENT 6
MICHAEL A. STREICHER
Corrosion Consultant

cc: Howard Eckert
DOE

May 22, 1992

MEMORANDUM

To: Dr. Kamal K. Bandyopadhyay, BNL

SUBJECT: Calculation of Corrosion Rates in a Waste Tank

Problem: A carbon steel tank has generated 3,000 cu ft of hydrogen gas in 100 days while exposed to an alkaline environment. What was the corrosion rate on the steel tank, which was 75 ft in diameter and the liquid was 30 ft deep?

Solution: 3.63 mil/year

Calculations:

Assumptions

- a) In very alkaline environments, such as concentrated sodium hydroxide, the following reaction can be assumed:

For every equivalent weight of hydrogen generated one equivalent weight of iron was dissolved.

- b) Corrosion was uniform over all steel surfaces, bottom of the tank and walls.
- c) Standard conditions of pressure and temperature for the hydrogen gas.
- d) The following physical constants were used:
- density of iron (steel) = 0.284 lb/cu₃in
or 7.87 g/cm³
 - one pound molecular weight of hydrogen = 359 cu ft
(a gram mol wt = 22.4 liter)
 - molecular weight of iron = 55.85
 - therefore, on a pound basis: 55.85 lb Fe
generate 2 lb or 359 cu ft of hydrogen;
molecular weight of H₂ is 2 lb.

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Calculations, continued

When 3,000 cu ft of hydrogen were generated, this represented
3,000 cu ft / 359 cu ft per mole = 8.36 lb molecular
weights of hydrogen and an equal number of
molecular or atomic lb weight of iron consumed;
therefore $8.36 \times 55.85 = \underline{466.68 \text{ lb of steel dissolved}}$
over the entire surface in 100 days.

Total surface area exposed to alkaline solution:

$$\begin{aligned}\text{bottom, 75 ft diam. area} &= (D/2)^2 \times \pi \\ &= (37.5)^2 \times 3.14 \\ \underline{\text{bottom}} &= \underline{4,417.86 \text{ sq ft}}\end{aligned}$$

$$\begin{aligned}\text{walls: 30 ft high, area} &= D \times \pi \times 30 \\ &= 75 \text{ ft} \times 3.14 \times 30 \\ \underline{\text{area of walls}} &= \underline{7,068.58 \text{ sq ft}}\end{aligned}$$

$$\underline{\text{Total Area: } 7,068.58 \text{ plus } 4,417.86 = 11,486.44 \text{ sq ft}}$$

$$\begin{aligned}\text{lb of steel dissolved per sq ft in 100 days} &= 466.68 \text{ lb} / 11,486.44 \text{ sq ft} \\ &= 0.0407 \text{ lb/sq ft} \\ &\quad \text{in 100 days} \\ \text{or } 0.0407/144 &= \underline{0.0002825 \text{ lb/sq in}}\end{aligned}$$

with a density of 0.284 lb/cu in for iron:

$$\begin{aligned}0.0002825 \text{ lb/sq in} / 0.284 \text{ lb/cu in} &= \\ 0.0009947 \text{ in in 100 days or} & \\ 0.0009947 \times 365/100 &= 0.0036 \text{ in/year}\end{aligned}$$

$$\text{CORROSION RATE OF STEEL TANK} = \underline{\underline{3.63 \text{ mil/year}}}$$

Rule of thumb : For each 1,000 cu ft of hydrogen evolved
in 100 days the corrosion rate in round numbers
is 1 mil per year.

However, if corrosion was essentially on the bottom of the tank:

$$\begin{aligned}\text{then its rate of corrosion would have been } &11,486/4,417 \times 3.63 \\ \text{or } 9.4 \text{ m/year or about } &3 \text{ m/y per 1,000 cu ft} \\ &\text{of hydrogen in 100 days.}\end{aligned}$$

ATTACHMENT 7

SST Interim Stabilization Technical Issues Program Review
Thursday October 15, 1992
Richland Public Library

Breakout Session # 1: Single Shell Tank Corrosion

Attendees:	Phil Ohl	EM-36 (WHC)
	Dick Wullaert	EM-36 (SAIC)
	Ed Escalante	NIST
	Bill Carlos	WHC
	Mo. Anantatmula	WHC
	Keith Scott	WHC
	Bill Brehm	WHC
*	Harry Harmon	WHC
	Mike Streicher	Consultant (University of Delaware)
	John Marra	WSRC
	Bob Ondrecjin	Consultant (WSRC Retired)
	Claude Goodlett	Consultant (WSRC Retired)
*	Howard Eckert	EM-36
*	Cherrie Defigh-Price	WHC
*	Bob Vandercook	WHC
*	Harold Sullivan	LANL
	Gene Senat	DOE-RL
*	Guy Bishop	DOE-RL
*	Kamal Bandyopadhyay	BNL
*	Rick Raymond	WHC

* Denotes partial attendance

NOTE: Attendance was not recorded during session. This list was generated after the fact.

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ATTACHMENT 8
MICHAEL A. STREICHER
Corrosion Consultant

October 19, 1992

MEMORANDUM

To: Mr. Dick Wullaert, SAIC
Dr. Kamal K. Bandyopadhyay, BNL

SST Interim Stabilization Technical Issues Program Review

Richmond, WA, October 15, 1992

Summary of Some Comments on SS Tank Corrosion at
Breakout Session #1

The following is in response to a request by the Chairman of Breakout Session #1, Dick Wullaert, for a report of my comments at the end of this meeting. Attendance varied somewhat, but consisted of about 14 people. A list of names is being supplied by Dick Wullaert.

To summarize the presentations and discussions on SS tank corrosion, the following findings and conclusions were presented to the group for review. The entire group was in complete agreement with all of the following items.

FINDINGS

- 1) Stress corrosion cracking and leaks occurred at the Savannah River Plant on tanks which had not been stress-relieved. These were DS tanks.
- 2) Introduction at the SRP of the nitrite inhibitor program stopped further cracking and leaks.
- 3) Stress-relieving of new DD tanks, together with addition of nitrite inhibitor, has prevented all cracking of new DS tanks at the SRP.

(The above observations are based on examination of exterior tank walls in the annular space of DS tanks. The bottoms of the tanks are inaccessible for observation at this time.)

- 4) None of the welded steel liners of the SS tanks at Hanford were stress-relieved. In some early tanks the design of the welds was inferior and resulted in severe buckling of bottom plates.

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A8-1

- 5) None of the solutions in the SS tanks at Hanford have been inhibited with the SRP nitrite program.
- 6) The concrete walls of the Hanford SS tanks simply rest on concrete pads to permit some movement. No attempt was made to seal this joint.

CONCLUSIONS

It can be assumed that:

- A) all the SS tanks at Hanford have (nitrate) stress corrosion cracks at or near the welds and that there have been leaks at these cracks;
- B) the number and size of these stress corrosion cracks will increase with time and that, therefore leaks will increase with time;
- C) leakage to ground has and will continue to occur when the solution goes through the stress corrosion cracks and the open joint between the concrete wall and the concrete bottom;

(The exception to this process is the case of more concentrated liquid waste seeping through the cracks slowly enough to permit evaporation of the liquid and consequent precipitation of the salts which then plug the cracks.)

- D) addition of nitrite inhibitor to the SS tanks at Hanford will probably not be effective in suppressing leaks or preventing new stress corrosion cracks because of the difficulty of mixing inhibitor solution with the aged sludge, slurries and liquids in the old tanks;
- E) chemical reactions and radiolysis are changing the compositions in the Hanford SS tanks with time in as-yet undetermined ways;
- F) even in inhibited tanks, such as the DS tanks at the SRP, condensate running down the steel walls in the vapor space does not contain nitrite inhibitor and will, therefore, dilute the inhibitor in the liquid waste where the condensate enters the waste and may make the steel surface at the vapor-liquid interface vulnerable to stress corrosion cracking;

G) pumping liquid from a leaking tank will:

- a) reduce the hydrostatic head on leaks which are below the new, lower liquid level,
- b) stop leaks on cracks which are above the new, lower liquid level,
- c) probably not affect the incidence of stress corrosion cracking or other forms of corrosion, such as pitting and general corrosion.

(Additional Note: During sluicing of slurries and solids there may be new leakage if the sluicing action dissolves the salt deposits which now are plugging stress corrosion cracks, and, perhaps, pits.)

M. J. Streicher

Charts Used for Presentation at Panel
Meeting in Augusta, GA, December 8, 1992

Factors Affecting Chloride and Caustic Stress Corrosion
Cracking of Stainless Alloys

Michael A. Streicher

Abstract

Stainless steel is to be used for new, double shell waste storage tanks at Hanford. The waste solutions vary in pH from 5 to 14, and contain significant amounts of chlorides. The most commonly used stainless steel, Type 304 (L), contains 8 to 12% Ni, which makes it highly susceptible to both chloride and caustic stress corrosion cracking.

Information is provided on the effect of nickel concentration in stainless alloys on their resistance to both kinds of stress corrosion cracking, on the design of laboratory test methods for detecting susceptibility to cracking in liquid, vapor and condensate, and on the design of stress corrosion specimens.

Available data show that about 45% Ni are required for superior resistance to cracking in chloride solutions, but that an even higher nickel content may be required to resist cracking in caustic solutions, e. g., 63 or 77% Ni, as in Inconel 625 and Inconel 600 alloys.

3/5/93

Chart I Effect of nickel content on stress corrosion of stainless steels in boiling magnesium chloride.

Stress corrosion cracking is a function of the nickel content of the alloy. The most susceptible alloy is the Type 304 stainless steel with about 10% Ni.

It is shown below that resistance to caustic cracking is also a function of the nickel content. In both cases 40 to 70% Ni are needed to resist cracking under the most severe conditions. Table 5 illustrates the effect of nickel on chloride stress corrosion.

Chart II Nominal compositions of stainless alloys.

Chart III Four different designs for condensers used in stress corrosion tests.

The amount of oxygen in the condensate decreases from left to right. In tests for detecting susceptibility of stainless alloys to stress corrosion in chloride solutions, the susceptibility to cracking decreases when the oxygen content of the solution is decreased. With the modified Allihn condenser the condensate slides down the wall of the flask in a thin film and is preheated before it gets into the solution. Oxygen from the air in the flask is absorbed by the condensate when it is cold and is expelled during the heating while the film of condensate slides down the walls of the flask. See Chart V for solubility of oxygen as a function of temperature.

Chart IV Details of some stress corrosion tests.

Flask used for tests in boiling solution of magnesium chloride, with U-bend and bent-beam specimens. The U-bend specimen provides a severe state of stress, as well as some plastic deformation. The bent-beam specimen provides a highly controlled state of elastic stress, which is uniform between the two cylindrical supports.

For details on the effect of condenser design on stress corrosion testing see Y-L. Chiang and M. A. Streicher, CORROSION 85, Paper Number 353, March 1985.

Chart V Solubility of oxygen in water as a function of temperature.

Chart VI Further details on U-bend and bent-beam specimens.

Welds in U-bends should be of two kinds: as shown and lengthwise.

Slow strain rate stress corrosion tests are illustrated in Fig.8.

A slow tensile test is made while the specimen is immersed in the chloride test solution. The resulting stress-strain curve is then compared with a similar test in air, i. e. without the chloride solution.

Chart VII Two other stress corrosion test specimens (ASTM).

The stresses are provided by the residual stresses resulting from welding of relatively thick specimens.

Chart VIII The Effect of condenser design on time to stress corrosion cracking in magnesium chloride solutions.

Removing oxygen from the condensate by preheating it increases the time to cracking. This factor must be kept in mind when designing laboratory tests which simulate plant conditions.

Chart IX Stress corrosion tests in sodium chloride solutions.

These solutions are less severe than magnesium chloride solutions, but the effect of nickel in the alloys is the same as shown in Chart I. The NaCl curve falls inside the one shown in this Chart.

1) Condenser design controls cracking in NaCl solutions. It is important to know what the concentration of oxygen is in the waste solution and in the condensate from the vapor generated by the waste.

2) The data on Carpenter 20 Cb-3 alloy clearly shows the effect of increasing the nickel content from 10% (Type 304) to 34% (Carpenter 20 Cb-3).

Chart X Design of test corrosion flasks for stress corrosion tests in liquid, vapor and condensate. See J. J. Demo, Corrosion, Vol. 24, No. 5, pp. 139-49, (1969).

Chart XI Stress corrosion cracking of Type 304 Stainless Steel in sodium hydroxide solutions.

This alloy fails by stress corrosion in caustic solutions, with the highest susceptibility at about 40% NaOH.

The role of nickel in stress corrosion in NaOH solutions is similar to that in chloride solutions. Figure 12, in this Chart shows that the Type 304 cracks readily in an autoclave test at 200 C in 50% NaOH, but that a stainless steel without nickel or with only 2% resists cracking in this test.

Chart XII Stress corrosion in 50% NaOH at 300 C, U-bend tests up to 981 hr. The effect of nickel.

Increasing nickel content from 20% to 77% increases the resistance to stress corrosion in this severe test. Note that 67% Ni was not enough to provide immunity to cracking up to 981hr.

Previous reports dealing with potential corrosion problems in the new stainless steel tanks at Hanford:

M. A. Streicher, Memorandum to K. K. Bandyopadhyay, dated May 12, 1992.

M. A. Streicher, Memorandum to K. K. Bandyopadhyay, dated January 12, 1993, on Augusta Panel meeting of December 7-8, 1992.

Chart I

Fig. 1 — Effect of nickel on stress corrosion cracking of stainless steel with 13 to 20% Cr in $MgCl_2$ boiling at 154 C (310 F). (After Copson, Ref 9.)

Table I — Some Alloys With Improved Resistance to Chloride Stress Corrosion

Alloy (UNS No.)	Composition, wt%				
	Cr	Ni	Mo	Cu	Other
Nickel-Rich					
Carpenter 20Cb-3 (N08020)	20	33	2.5	3.5	0.5 Cb
AL-6X (N08366)	20	25	6.5	—	—
904L (N08904)	20	25	4.7	1.6	—
Hastelloy G (N06007)	22	47	6.0	1.8	2 Cb
Incoloy 825 (N08825)	22	44	2.7	1.7	0.7 Ti
Duplex					
Ferrallium 255 (S32550)	26	6	3.2	1.8	0.2 N
Sandvik 3PE60 (S31500)	19	5	2.7	—	1.7 Si
SAF 2205 (S31803)	22	6	3.0	—	0.14 N

Table V — Stress Corrosion Cracking in 45% $MgCl_2$ and Various NaCl Tests

Alloy (UNS No.)	Stress Corrosion Cracking		
	$MgCl_2$ at 155 C (310 F)	NaCl Wick Test at 100 C (212 F)	Autoclave Test (26% NaCl) at 200 C (390 F)
Type 304 (S30400)	Yes	Yes	Yes
Carpenter 20Cb-3 (N08020)	Yes	No	No
26Cr-1Mo-Cb (S44627)	No	No	—
27.5Cr-3.4Mo-1.7 Ni-Ti (S44660)	Yes	No	—
29Cr-4Mo (S44700)	No	No	No
29Cr-4Mo with 210 ppm C (S44735)	Yes	Yes	Yes ¹
29Cr-4Mo-2Ni (S44800)	Yes	No	No

¹ At 155 C (310 F).

Chart II

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TABLE 1—Nominal compositions of stainless steels and related alloys.*

Type	Composition, percent by weight				
	Chromium	Nickel	Molybdenum	Carbon, max	Other
430	14.0 to 18.0	...	...	0.12	Mn—1.0 max; Si—1.0 max
446	23.0 to 27.0	...	...	0.20	Mn—1.50 max; Si—1.0 max; N—0.25 max
304	18.0 to 20.0	8.0 to 12.0	...	0.08	Mn—2.0 max; Si—1.0 max
304L	18.0 to 20.0	8.0 to 12.0	...	0.03	Mn—2.0 max; Si—1.0 max
310	24.0 to 26.0	19.0 to 22.0	...	0.25	Si—1.50 max
316	16.0 to 18.0	10.0 to 14.0	2.00 to 3.00	0.08	Mn—2.0 max; Si—1.0 max
316L	16.0 to 18.0	10.0 to 14.0	2.00 to 3.00	0.03	Mn—2.0 max; Si—1.0 max
317L	18.0 to 20.0	11.0 to 15.0	3.0 to 4.0	0.03	Mn—2.0 max; Si—1.0 max
321	17.0 to 19.0	9.0 to 12.0	...	0.08	%Ti = 5 × %C min
347	17.0 to 19.0	9.0 to 13.0	...	0.08	Cb = 10 × %C min
Carpenter 20 Cb-3	19.0 to 21.0	32.5 to 35.0	2.00 to 3.00	0.06	%Cb + Ta = 8 × %C; Cu—3.00 to 4.00
Hastelloy Alloy C	14.5 to 16.5	~54	15.0 to 17.0	0.08	Fe—5.5; W—4; Co—2.5
Hastelloy Alloy C-276	14.5 to 16.5	~54	15.0 to 17.0	0.02	W—4; Co—2.5 max; Si—0.05 max
Hastelloy Alloy G	18.0 to 21.0	~50	5.5 to 7.5	0.05	Cu—2; Nb—2; Fe—19.5
Inconel Alloy 600	14.0 to 17.0	72 min	...	0.15	Fe—8; Cu—0.5
Inconel Alloy 625	20.0 to 23.0	~62	8.0 to 10.0	0.10	Cb—3.6; Fe—5 max
Incoloy Alloy 800	19.0 to 23.0	30.0 to 35.0	...	0.10	Ti—0.5; Cu—0.75; Fe ~45
Incoloy Alloy 825	19.5 to 23.5	38.0 to 46.0	2.5 to 3.5	0.05	Ti—0.9; Cu—2.2; Fe—33

* Compositions for other ferritic stainless steels are given in Tables 6 and 7.

Chart III

WHC-SD-WM-TA-157
Rev. 0

FINGER

ALLIHN
DRIP TIP

ALLIHN
MODIFIED

ALLIHN
MODIFIED
WITH TRAP

Figure 1 - Boiling points of aqueous magnesium chloride solutions at one atmosphere as a function of concentration. Data from I. B. Casale.⁶ For the range 40 to 46% $MgCl_2$, the following equation may be applied: $t^{\circ}C = (3.51) (\text{wt } \% MgCl_2) - 2.91$.

Figure 2 - Modification of Allihn condenser to prevent loss of

Figure 3 - Assembly of glass apparatus for stress corrosion test in boiling magnesium chloride with U-bend specimen in place.

Figure 5

Equilibrium Concentration of Oxygen in Air-Saturated Water
(Water-Saturated Air)

FIG. 4 Methods of Stressing U-Bend Specimens—Single-Stage Stressing

NOTE—The welds may be oriented 90° to the direction shown.

Fig. 8 Effect of Strain Rate on Stress-Strain Curves of Type 304 in Boiling 42% $MgCl_2$ Solution

Procedure:

- (a) Specimen size—as required.
- (b) Note grain direction and weld longitudinally or across grain.
- (c) For multiple-pass welds, grind between passes. Use back gouging from opposite side to attain 100 % weld penetration.
- (d) Discard weld ends.
- (e) Remove test sections as required. Sections may be taken across the weld or longitudinally with the weld.

FIG. 1 Flat Weldment

Procedure:

- (a) Specimen size: 100 by 100 by 3 to 12 mm (4 by 4 by 1/8 to 1/2 in.)
- (b) Clamp or tack weld the edges of the test specimen to a base plate to obtain restraint.
- (c) Weld a 50-mm or 2-in. diameter circular bead using the selected weld process (Table 1).
- (d) Examine both sides of specimen after exposure.

FIG. 2 Circular Bead Weldment

The Effect of Condenser Design on Time to Cracking
of Type 304 in Boiling Magnesium Chloride
(U-bend Specimens)

Solution		Time to Cracking, hr				
Conc.	Temp.	Finger	Allihn, drip-tip		Modif. Allihn	
(wt%)	(°C)		(length)		(sparging)	
			1 cm	5 cm	none	oxygen
13	105	1000	—	—	—	—
24	110	63	933	1250	1513	47
28	115	61	548	745	1600	22
32	120	12	28	48	879	16
37	130	5	6	10	21	2
42	145	1	1	—	1	—
45	155	1	1	—	1	—
47	160	1.3	—	—	1.3	—
50	170	2	—	—	2	—

Effect of Condenser Design on Stress Corrosion Cracking
of Type 304 in NaCl Solutions
(Effect of pH)

Solution		Time to Cracking, hr		
Composition	pH	Finger	Modif. Allihn	
			(sparging) none	oxygen
26% NaCl ⁽¹⁾	5.0	144	>1500 ^{*(2)}	248
<hr/>				
25% NaCl + H ₃ PO ₄	4.0	198	>1000 [*]	-
		344	>1000 [*]	-
25% NaCl + H ₃ PO ₄	2.0	61	178	-
		48	312	-

* No cracking

(1) Average of three U-bend specimens.

(2) Also tested in flask with drip tip (3 cm) condenser.

There was no cracking after 3500 hr.

Stress Corrosion Cracking in Boiling 25%NaCl at pH=1.0 (H₃PO₄)
(Finger Condenser, U-bend Specimens)

Alloy	Time to Cracking, hr
304	1
316	26
<hr/>	
Ferrallium 255	85
Carpenter 20 Cb-3	2200 [*]
<hr/>	
Fe-29Cr-4Mo	1250 [*]
Fe-29Cr-4Mo-2Ni	2200 [*]

* No cracking

(A) GENERAL REACTION FLASK

(B) CUP-TYPE FLASK

(C) HEATED-ARM FLASK

(D) SIPHON-ACTION FLASK FOR
STRESS-CRACKING STUDIES

FIGURE 3—Corrosion Test Apparatus

Memorandum to K. K. B.
May 12, 1992

Figure 2.10

Caustic soda service chart for austenitic stainless
steels in sodium hydroxide.⁽³⁰⁾(30) R. K. Swandby, Chemical Engineer, Vol. 69, (23), November
1972, pg 186.

FIGURE 12 - Caustic stress corrosion cracking. Welded U-bends exposed 134 hours in 50% NaOH solution at 200 C. The specimens were cleaned in inhibited acid after testing. Severe cracking on Type 304 (left), and severe general corrosion on 28Cr-4Mo alloy (middle) without cracking. No cracking or general corrosion on 28Cr-4Mo-2Ni alloy (right).

STRESS CORROSION IN 50% NaOH
AT 300°C
U-bend Specimens

ALLOY	Ni CONTENT % by wt.	RESULTS	
		Type of Cracking	Time (hr)
AISI 310	20	Transgranular	less than 4
Incoloy alloy 800	32	Transgranular	less than 4
Carpenter 20 Cb-3	34	Inter- and transgranular	between 4 and 20.5
Incoloy alloy 825	42	Transgranular	between 4 and 20.5
Hastelloy alloy G	45	Intergranular *	between 4 and 20.5
Hastelloy alloy F	47	Transgranular and intergranular	between 4 and 20.5
Hastelloy alloy C-276	56	Intergranular	less than 48
Inconel alloy 625	63	Transgranular	between 92 and 117
Hastelloy alloy C-4	67	Transgranular	283
Inconel alloy 600	77	None	981 hr

Inconel alloy 600 sensitized 1 hr at 1300°F	77	None	981 hr

* A second specimen showed a mixed crack path, inter- and transgranular.

M.A. Streicher-ESD/rz
12/9/76

MICHAEL A. STREICHER

Corrosion Consultant

January 12, 1993

Memorandum

To: Dr. Kamal K. Bandyopadhyay, BNL

Discussions based on items derived from the Panel
Meetings at Augusta, GA, December 7-8, 1992

- 1) Is there evidence of leakage from SSTs by pitting or other forms of corrosion at the liquid-vapor interface?
 - 2) Comments on corrosion program proposal by Dr. R. E. Ricker of NIST.
 - 3) Laboratory corrosion tests for the selection of a stainless alloy for new DSTs at Hanford.
 - 4) Comments on Draft for "Elements of a Tank Structural Integrity Program".
-

- 1) Is there evidence of leakage from SSTs by pitting or other forms of corrosion at the liquid-vapor interface?
-

This question is of importance because, if leaks occur at this location, it may be possible to extend the use of the tank by simply draining some liquid to establish a new, lower liquid-vapor interface. Such "Interim Stabilization" is the problem discussed in your "Issue Paper on Interim Stabilization of Single Shell Tanks at Hanford" of November 6, 1992, in which some findings and conclusions from a meeting at Richland, WA, on October 15, 1992, are summarized.

At the December 7-8, 1992, meeting in Augusta, Dick Wullaert showed me several photographs taken in a SST at Hanford in the seventies. On the interior walls of this tank there were several vertical, black streaks which all started at the same level: an old liquid-level interface? According to Dick Wullaert these streaks are the result of preferential pitting attack at the liquid-vapor interface. When the tank wall was penetrated by pitting attack there was loss of waste liquid through the wall and penetration of material from the asphalt coating on the outside of the steel tank wall into the tank at the liquid vapor interface and subsequent black streaking down the

interior wall. He pointed out that the asphalt coating is under pressure because of the expansion of the steel tank against the steel shell when it is filled.

My observations on this "theory" include the following points.

- a) The only proven source of leaks in waste tanks was established at the SRP. It was found that the very large number of leaks on the tank walls (Tank 16, DST) were at nitrate stress corrosion cracks at or near weldments. They were not at the liquid-vapor interface. J. E. Marra of the SRP Technical Center described this tank failure and the metallographic analysis at the Augusta meeting. His findings were confirmed by Robert Ondrejcin, SRP, retired, who was also present at the Augusta meeting, 12/8/92. Welds are used to join the steel plates and, therefore, occur at all levels in the tank. No other tanks at SRP or at Hanford have been emptied and examined for the source of leaks.
- b) If the soft asphalt coating on the outside of the tank between the steel wall and the reinforced concrete shell is under pressure when a pit at the interface penetrates the tank wall, it can be expected that the inflowing asphalt of the Wullaert "theory" would prevent outflow, leakage, of waste liquid from the tank by plugging the pits and, therefore, greatly reduce or even prevent leakage of waste solution.
- c) However, it is highly likely that the asphalt coating has become brittle after 10-20-30 years of service at temperatures up to boiling water and that it, therefore, would not flow into the tank at a pit or a stress corrosion crack.

The 3-volume Handbook on "Bituminous Materials" edited by Arnold J. Hoiberg states, page 273 in Volume II that "In general, the effect of heat on a reaction involving organic compounds is that of accelerating the reaction. With respect to the weathering of asphalt, a similar effect is generally realized. So universal is the acceptance of this principle that the number of research papers dealing specially with the effects of temperature on asphalt weathering or on degradation is somewhat limited."

Also it is stated on page 296 of this volume that failure by weathering or degradation at elevated temperature is by embrittlement and cracking. My telephone inquiries about the effect of time and temperature on asphalt coatings provided the same verdict: embrittlement with cracking. Source: conversations with Dr. Walter Rossiter, Roofing Technology at NIST and with a materials engineer at a refinery. (W. Rossiter phone: 301/975-6719)

Furthermore, "All asphaltic materials harden as a result of exposure to radiation." See Hoiberg, Volume I, pp 308-9.

Thus, it appears unlikely that asphalt will be extruded into the tanks at points of penetration by pitting or any other form of corrosion from the inside of the tank.

- d) A much more likely explanation for the black streaks on the inside walls of the Hanford tank, as shown in the photographs by Dick Wullaert, was provided by Robert Ondrejcin at the Augusta meeting when he was shown these photographs. He pointed out that the Hanford wastes contain organics and nitates and that the reactions between them at elevated temperatures may lead to tarry, black products which then float on the surface of the liquid wastes. When the liquid level drops, these black tars may adhere to the walls and produce black streaks. (The SRP tanks do not contain organics and no such black streaks have been observed in them, according to Robert Ondrejcin.)

Thus, there is as yet no proof that there is preferential corrosion, such as pitting or stress corrosion cracking, at the liquid-vapor interface, and no support for "interim stabilization", or "buying time" by merely dropping the the liquid level a few inches or feet.

2) Comments on corrosion program proposal by Dr. R. E. Ricker of the National Institute of Science and Technology (NIST)

Dr. Rickert's approach to corrosion is highly theoretical and mathematical, as presented to the Panel in Augusta. He gave a similar talk on November 17, 1992, at an ASTM Symposium in Miami, FL, on "Application of Accelerated Corrosion Tests to Service Life Predictions of Materials" where I also heard him. Thus, he was asked to apply his specialized mathematical and statistical skills to the tank corrosion problems on a DOE contract.

Members of our Panel have now spent as many as 17 days learning the details available on waste tanks at four locations in presentations by a large number of personnel now active in the management of waste tanks. There were ample opportunities for discussions and questions which made it possible to learn about the great number of details on the history and present conditions of the tanks. There were also numerous discussions of information on the tanks which is not available at this time, some of which is unobtainable for various reasons, such as the conditions of the bottoms of the tanks because they are inaccessible or information on the history of the materials in the tanks because there are no records, and information on the effect of corrosion on the steel in the tanks because it would require emptying and cutting up of tanks to carry out metallurgical examinations of the forms of corrosion which have caused leaks. It is difficult to see how someone who is new to the subject can encompass the problem of developing "lifetime prediction models" by reviews of reports.

There is a huge gap in information on the history of the tanks, the compositions of the wastes in each tank, and the occurrence of leaks, dates and extent. There is a possibility that all of the tanks at Hanford, none of which were stress relieved, i. e., the old SSTs, have nitrate stress corrosion cracks. Thus, there is a great amount of uncertainty about the conditions of the tanks and the amount and dates of leaks. Recent events involving an apparent loss of wasteliquid from the 67 th leaking tank at Hanford illustrate some of these problems.

When the mathematical tools have been developed at NIST, certain assumptions will have to be made about data to be put in the equations. Will there be enough reliable results of the type required to make the mathematical treatment worthwhile? Is there enough information available for conducting accelerated laboratory tests for simulating the large variety of conditions in the tanks, i.e., do we know enough to specify the parameters for the corrosion tests as proposed in the NIST program to provide some of the data needed for the mathematical treatment?

- 3) Laboratory corrosion tests for the selection of a stainless alloy for new DSTs at Hanford.
-

Type 304L stainless steel is being considered for these tanks. However, this alloy is very susceptible to two kinds of stress corrosion cracking: chloride and caustic. The wastes to be put into and treated in these tanks will contain significant amounts of chlorides and will range in pH from 5 to 14. In the event that the laboratory corrosion tests in liquid, vapor and condensate phases of the synthetic waste solutions show that Type 304L alloy fails by stress corrosion, pitting or general corrosion, another alloy will have to be specified.

At present, Carpenter 20 Cb-3 and Incoloy alloy 800 have been proposed for inclusion in the test program, as stated by W. Brehm and W. Carlos at the Augusta meeting.

Resistance to both chloride and caustic stress corrosion cracking increases with the nickel content above 8% Ni. Type 304L has 10% Ni and is the most susceptible to stress corrosion. Carpenter 20 Cb-3 and Incoloy alloy 800 both have 34% Ni and are considerably more resistant. Even better resistance is available with alloys containing 42% Ni or more.

- a) Because the nickel contents of Carpenter 20 Cb-3 and Incoloy alloy 800 are the same (34%), it seems better to test an alloy with more nickel than Incoloy alloy 800, e. g. Incoloy alloy 825, which has 42% Ni and 3% Mo. (Incoloy alloy 800 has no molybdenum, which improves resistance to chloride pitting.
- b) There is considerable turmoil in the nickel-rich alloy market at present. I have been told, 12/4/92, by a representative of Inco Alloys International

that it may be possible to purchase Haselloy alloy C-276 (54%Ni, 16%Cr, 16%Mo) or C-22 (56%Ni, 22%Cr, 13%Mo) at the same price as Incoloy alloys 800 and 825.

I have made inquiries at Haynes International of Kokomo, IN, Michael Rothman, (317/456-6223), and at their Windsor, CT office, B. K. Vasko, (203/688-7771) about the price of C-22 for a tank 75 ft in diameter, 60 ft high, with 3/8 in plate. According to B. K. Vasko, the weight of C-22 would be 245,00 lb. A quotation was given, 12/22/92, for \$6.00 per pound. C-22 is the newest version of C-276. Both are now sold at the same price. This price is no higher than that of Incoloy 825 and near that of Incoloy 800.

Therefore, the Incoloy 800 now proposed for testing should be replaced by either C-22 or C-276, or one of these should be added to the test program at Hanford.

This information has been passed on to William Brehm and William Carlos at Hanford by telephone.

In response to questions, I have made suggestions about the surface finish of corrosion test specimens: the degree of polish required. To reduce the cost, I suggested that on U-bend stress corrosion specimens only the outside surface which is under tensile stress receive the finest polish: 600-grit. The finish on the remaining surfaces can be 120- or 240-grit. On specimens intended for determination of general and pitting corrosion there should also be one 600-grit surface. In each case, the 600-grit finish is intended to facilitate microscopic examination for the first indications of stress corrosion cracks, pits and general corrosion.

- c) The corrosion test program at Hanford for the selection of a stainless alloy for the new DDS waste tanks should include tests in the: 1) liquid, 2) slurry, 3) vapor and 4) condensate phases. The tests in condensate are to simulate the condition at the walls of the tanks above the liquid surface. The composition of the condensate, including the pH, should be monitored. A variety of condensing conditions should be simulated with a view towards control of oxygen content of the condensate. When vapor is condensed during cooling it absorbs oxygen from the air and may thereby become more corrosive.

The vapor above the liquid waste, and, therefore, also the condensate, can be expected to contain fluoride and chloride compounds. These would lower the pH and might make the vapor from the waste liquid, as well as the condensate, more corrosive than the waste liquid.

4) Comments on Draft for "Elements of a Tank Structural Integrity Program".

I) In connection with the October 15, 1992, meeting at Richland on "SST Stabilization Technical Issues Program Review", I prepared a summary of "Findings and Conclusions" by a group of 14 persons who met to review the status of corrosion problems in the waste tanks at the Hanford and Savannah River Plants. This meeting was chaired by Dick Wullaert and included the input of Robert Ondrejcin, who retired recently from the SRP. He worked on the corrosion problems there for decades and developed the nitrite inhibition procedure now in use at the SRP to prevent nitrate stress corrosion cracking. A copy of the Memorandum, dated October 19, 1992, is attached.

The items in this Memorandum contain the relatively few "hard" data points and conclusions that form the basis for:

- a) assessing the current conditions of the tanks;
- b) making a list of the data which will be needed to make predictions about the years of future service which can be expected for each tank, including a list of qualifiers which limit the firmness of these forecasts, such as data which are needed, but which are unobtainable, such as the conditions of the bottoms of the tanks; and,
- c) developing a corrosion testing program for laboratory and in-tank tests to provide additional data for estimates of future service life of the tanks and strategies for dealing with problem tanks.

II) As mentioned in Section 1)-d above, some of the Hanford tanks contain organics which react with nitrates and even tend to decompose with time at elevated temperatures in the absence of nitrates. (None of the SRP tanks contain organics.) The "Program" should include detailed examinations of the effects of the degradation of organics and an examination of the generation of hydrogen from the organics, as well as other sources, such as corrosion and radiolysis. The effect of hydrogen on embrittlement of the steel tanks and on potential explosions must be examined.

To facilitate this aspect of the Panel's efforts, there is a need for presentations before the Panel of a detailed analysis of the numerous aspects of potential explosions by one or more nationally recognized experts with extensive practical experience in analysing the causes of explosions. These experts should be asked to examine the five potential sources for explosions in the tanks and their effects on the structural integrity of the steel in the tanks which are very likely to contain numerous stress corrosion cracks concentrated at weldments. These five potential sources of explosions, according to the report, WHL-EP-0347, March, 1991, by G.L. Borsheim and N.W. Kirch, Pg 6-1, are:

- a) ammonium nitrate,
- b) solvent vapor,
- c) hydrogen ,
- d) ferrocyanide-nitrate reaction, and
- e) organic-nitrate reaction.

Even though explosions and seismic events are the subjects of other panels, it appears essential that our Panel have an opportunity to review the analyses of experts on explosions to determine the extent to which the three areas of explosions, seismic events and corrosion may be interrelated and interdependent.

- III) To implement the "Program" there will be a need to compile a list of current and planned test programs for data collection on the tanks; e.g., the program at Hanford for analysing the compositions in the tanks and for determining the temperatures. This list can then be used to establish what other measurements might be made to assist in estimates of future service life.

Finally, a list should be compiled of data which are really needed for reliable, firm estimates of future service life, but which are unavailable or too costly to obtain, such as the conditions of the bottoms of the tanks and the number, types, sizes and locations of stress corrosion cracks, pits and thinning by general corrosion.

M. A. Streicher

encl. Memorandum of October 19, 1992.

MICHAEL A. STREICHER
Corrosion Consultant

October 19, 1992

MEMORANDUM

To: Mr. Dick Wullaert, SAIC
Dr. Kamal K. Bandyopadhyay, BNL

SST Interim Stabilization Technical Issues Program Review

Richmond, WA, October 15, 1992

Summary of Some Comments on SS Tank Corrosion at
Breakout Session #1

The following is in response to a request by the Chairman of Breakout Session #1, Dick Wullaert, for a report of my comments at the end of this meeting. Attendance varied somewhat, but consisted of about 14 people. A list of names is being supplied by Dick Wullaert.

To summarize the presentations and discussions on SS tank corrosion, the following findings and conclusions were presented to the group for review. The entire group was in complete agreement with all of the following items.

FINDINGS

- 1) Stress corrosion cracking and leaks occurred at the Savannah River Plant on tanks which had not been stress-relieved. These were DS tanks.
- 2) Introduction at the SRP of the nitrite inhibitor program stopped further cracking and leaks.
- 3) Stress-relieving of new DD tanks, together with addition of nitrite inhibitor, has prevented all cracking of new DS tanks at the SRP.

(The above observations are based on examination of exterior tank walls in the annular space of DS tanks. The bottoms of the tanks are inaccessible for observation at this time.)

- 4) None of the welded steel liners of the SS tanks at Hanford were stress-relieved. In some early tanks the design of the welds was inferior and resulted in severe buckling of bottom plates.

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- 5) None of the solutions in the SS tanks at Hanford have been inhibited with the SRP nitrite program.
- 6) The concrete walls of the Hanford SS tanks simply rest on concrete pads to permit some movement. No attempt was made to seal this joint.

CONCLUSIONS

It can be assumed that:

- A) all the SS tanks at Hanford have (nitrate) stress corrosion cracks at or near the welds and that there have been leaks at these cracks;
- B) the number and size of these stress corrosion cracks will increase with time and that, therefore leaks will increase with time;
- C) leakage to ground has and will continue to occur when the solution goes through the stress corrosion cracks and the open joint between the concrete wall and the concrete bottom;

(The exception to this process is the case of more concentrated liquid waste seeping through the cracks slowly enough to permit evaporation of the liquid and consequent precipitation of the salts which then plug the cracks.)

- D) addition of nitrite inhibitor to the SS tanks at Hanford will probably not be effective in suppressing leaks or preventing new stress corrosion cracks because of the difficulty of mixing inhibitor solution with the aged sludge, slurries and liquids in the old tanks;
- E) chemical reactions and radiolysis are changing the compositions in the Hanford SS tanks with time in as-yet undetermined ways;
- F) even in inhibited tanks, such as the DS tanks at the SRP, condensate running down the steel walls in the vapor space does not contain nitrite inhibitor and will, therefore, dilute the inhibitor in the liquid waste where the condensate enters the waste and may make the steel surface at the vapor-liquid interface vulnerable to stress corrosion cracking;

G) pumping liquid from a leaking tank will:

- a) reduce the hydrostatic head on leaks which are below the new, lower liquid level,
- b) stop leaks on cracks which are above the new, lower liquid level,
- c) probably not affect the incidence of stress corrosion cracking or other forms of corrosion, such as pitting and general corrosion.

(Additional Note: During sluicing of slurries and solids there may be new leakage if the sluicing action dissolves the salt deposits which now are plugging stress corrosion cracks, and, perhaps, pits.)

M. F. Streicher

SST Interim Stabilization Technical Issues Program Review
Thursday October 15, 1992
Richland Public Library

Breakout Session # 1: Single Shell Tank Corrosion

Attendees:	Phil Ohl	EM-36 (WHC)
	Dick Wullaert	EM-36 (SAIC)
	Ed Escalante	NIST
	Bill Carlos	WHC
	Mo Anantatmula	WHC
	Keith Scott	WHC
	Bill Brehm	WHC
	* Harry Harmon	WHC
	Mike Streicher	Consultant (University of Delaware)
	John Marra	WSRC
	Bob Ondrecjin	Consultant (WSRC Retired)
	Claude Goodlett	Consultant (WSRC Retired)
	* Howard Eckert	EM-36
	* Cherrie Defigh-Price	WHC
	* Bob Vandercook	WHC
	* Harold Sullivan	LANL
	Gene Senat	DOE-RL
	* Guy Bishop	DOE-RL
	* Kamal Bandyopadhyay	BNL
	* Rick Raymond	WHC

* Denotes partial attendance

NOTE: Attendance was not recorded during session. This list was generated after the fact.

ATTACHMENT 11

MICHAEL A. STREICHER

Corrosion Consultant

Subject: Visuals for presentations by M. A. Streicher
at the Corrosion Workshop in San Diego, CA
on December 3, 1993.

=====

I) Introduction on factors governing resistance to
Stress Corrosion Cracking and Chloride Pitting
in Stainless Alloys.

Figure 1 shows that the resistance to chloride stress corrosion cracking is governed by the nickel content of the Fe-Cr alloys in this magnesium chloride test. At very low concentrations of Ni (less than about 0.8%) the alloys are resistant. However, the time to cracking drops rapidly as a concentration of 8%Ni is reached. Thus, the most widely used nickel content in stainless steels makes the alloy most vulnerable to chloride cracking.

Increasing the nickel content rapidly increases the resistance. Above about 42% Ni the alloys are completely resistant in the boiling (154 C) magnesium chloride test.

Table 1 provides analyses of some commonly used stainless alloys. Only those alloys whose nickel content is above 42% will be resistant to the most severe chloride stress corrosion test, the magnesium chloride test of Fig. 1.

However, less nickel is required for immunity to cracking in sodium chloride tests of various kinds. Such tests simulate more realistically various service environments. This is shown in:

Figure 2 this illustrates that the results in sodium chloride have the same shape, but lie within the magnesium chloride curve and that the amount of nickel required for complete resistance is lower, 34%.

The curve for the magnesium chloride test in Figure 2 was determined with U-bend specimens (not wires, as in Fig.1) and was based on a number of commercial alloys, not only on Fe-Cr alloys. This curve shows the same characteristics as the curve in Fig. 1 and demonstrates that chloride stress corrosion resistance is essentially independent of the chromium, molybdenum, iron and copper content of the alloys. The alloy with 8 to 10% Ni in the curves of Fig. 2 is Type 304 stainless steel.

Table 2 provides data on Caustic Cracking in 50% NaOH in an autoclave test at 300 C. This is a very severe test on U-bend specimens. These tests were made on ten commercial alloys. Again, this form of stress corrosion cracking is also dependent on the nickel content. Increasing the nickel content increases the time to failure. At 77% Ni there was no cracking even after almost 1,000 hours. At lower temperatures and lower concentrations of NaOH cracking is much less severe. This is demonstrated in the graph on Table 2 for various Type 304 stainless steels, which are more vulnerable to cracking than any of the alloys listed in Table 2.

Appendix A This publication provides additional data on the effect on concentration of nickel on stress corrosion cracking in various chloride environments.

Conclusion on Stress Corrosion Cracking : Resistance to chloride and caustic stress corrosion cracking depends on the nickel content of the stainless alloy. With only 8 to 10% Ni in Type 304 or 316 stainless steel these alloys are the most vulnerable to cracking. Resistance to both kinds of cracking increases with the nickel content. For a significant increase in resistance to cracking at least about 35% Ni are required. The preferred range is 48 to 55% Ni.

Figure 3 Crevice Corrosion and Pitting are illustrated on the basis of two large test series carried out at the marine testing station at Wrightsville Beach, North Carolina. Sea water at 30 C with the crevice devices shown is a severe test. The devices are made of Teflon and are bolted on the front and rear of the test panels. Filtered sea water was used to prevent the formation of extensive marine growths on the surfaces outside the crevice devices. Eliminating marine growths actually increases the test conditions.

Typical results after a 30 day test period are shown on the right. These panels were cut out of the large panels to conserve space in the photograph. All the "teeth" on the crevice device resulted in attack on Type 317 stainless steel. On A. L. 6X only three "teeth" produced break-down and on the Fe-29-4 alloy there was no attack. The results on 36 mostly commercial alloys are listed in order of resistance to crevice attack in:

Table 3 The criterion for resistance to attack was the Crevice Corrosion Index, the product of the greatest depth of attack and the number of panel sides which showed any attack out of 3 panels , i. e., a total of 6 sides.

Analysis of the results shows that resistance to chloride crevice corrosion is a function of the chromium and molybdenum contents of the alloys and that the nickel content is essentially without effect. For example, Carpenter 20 Cb-3, which has 33.2% Ni but only 19.4% Cr and 2.2% Mo has somewhat improved resistance to chloride stress corrosion (it is resistant in the NaCl, but not the MgCl₂ test) is actually less resistant to crevice corrosion than Type 316.

Conclusion on Chloride Crevice Corrosion : For greatest resistance select alloys high on the rating table, alloys having the highest sum of %Cr + 3X %Mo. Among these, select the alloys with more than 45 to 55% Ni for optimum resistance to chloride and caustic stress corrosion cracking.

II) Some Data on Alloy A. L. 6XN (20%Cr-6%MO-24%Ni-0.2%N)

Table 4 This version of the "6X" alloy has been improved by the addition of 0.2% nitrogen which can be expected to increase its resistance to chloride crevice attack over that shown in Table 3.

However, A. H. Tuthill and A. Garner have reported some problems on field weldments on the 6XN version in a test made on welded pipe in a pulp and paper bleach process. Details on this realistic plant test are given in Table 4.

It was found that Hastelloy G-30 failed not only at the weldment, but also on the base plate. Alloy A. L. 6XN alloy failed (pitted) in this highly oxidizing chloride environment at the weldment in the molten, but unmixed zone. In this part of the weldment the base plate is melted during welding but is not mixed with the molten weld rod. Upon solidification there appears to be some non-uniform separation of molybdenum in the "cast" structure that is produced.

Table 5 Tuthill and Garner verified their findings in the simple laboratory ferric chloride test. In this test resistance to chloride attack in an oxidizing environment at low pH (2) is determined by increasing the test temperature and recording the temperature at which pitting begins. They concluded that alloys (non-welded) which resisted pitting in the ferric chloride test up to 70 C were also resistant in the bleach plant environment.

III) The Wick Test for Assessing Resistance to Chloride Stress Corrosion

Figure 4 shows this simple laboratory test for evaluating insulation materials to be used on stainless steel surfaces (e. g. pipes); for evaluating stainless alloys for resistance to chloride cracking; and to evaluate solutions for their tendency to cause chloride stress corrosion. This test was first described by A. W. Dana and W. B. DeLong (Appendix B-1 and 2). It has been standardized for evaluating insulation in ASTM C-692. The specimen is heated to the desired temperature by passing an electrical current through it. Plant solutions can be simulated by additions to the water in the dish. A porous inert material is set in the solution, but the specimen is set into this material above the solution so that it reaches the surface by wicking.

Figure 1

Effect of nickel content on the susceptibility to stress corrosion cracking of stainless steel wires containing 18-20% chromium in a magnesium chloride solution boiling at 154°C. (After Copson.) Wire specimens.

From "Physical Metallurgy of Stress Corrosion Fracture",
By H. R. Copson, Interscience, 1959, pg. 247.

Table 1

TABLE OF ALLOY COMPOSITIONS

<u>Alloy</u>	<u>Percent by Weight</u>			
	<u>Cr</u>	<u>Ni</u>	<u>Mo</u>	<u>Other</u>
Incoloy 825	19.5-23.5	38-46	2.5-3.5	2.2 Cu, 33 Fe, 1Ti
Hastelloy C-22	20.0-22.5	56-58	12.5-14.5	3 W, 3 Fe, 2.5 Co
Carpenter 20Cb-3	19.0-21.0	32.0-38.0	2.0-3.0	3.5 Cu, 0.5Nb 39 Fe
Inconel 625	20.0-23.0	60-63	8.0-10.0	3.6 Nb, 5 Fe
Hastelloy C-276	14.5-16.5	60-64	15.0-17.0	4 W, 2.5 Co
A.L. 6XN	20.0-22.0	23.5-25.5	6.0-7.0	49 Fe
254 SMO (Avesta)	19.5-20.5	17.5-18.5	6.0-6.5	0.8 Cu, 55 Fe
304L	18.0-20.0	8.0-12.0	-	70 Fe
316L	16.0-18.0	10.0-14.0	2.0-3.0	66 Fe

Time to Failure in Chloride Stress Corrosion Tests

Tests made on U-Bend specimens on a variety of commercial alloys (and a few laboratory alloys).

Table 2

STRESS CORROSION IN 50% NaOH
AT 300°C
U-bend Specimens

ALLOY	Ni CONTENT % by wt.	RESULTS	
		Type of Cracking	Time (hr)
AISI 310	20	Transgranular	less than 4
Incoloy alloy 800	32	Transgranular	less than 4
Carpenter 20 Cb-3	34	Inter- and transgranular	between 4 and 20.5
Incoloy alloy 825	42	Transgranular	between 4 and 20.5
Hastelloy alloy G	45	Intergranular *	between 4 and 20.5
Hastelloy alloy F	47	Transgranular and intergranular	between 4 and 20.5
Hastelloy alloy C-276	56	Intergranular	less than 48
Inconel alloy 625	63	Transgranular	between 92 and 117
Hastelloy alloy C-4	67	Transgranular	283
Inconel alloy 600	77	None	981 hr
<hr/>			
Inconel alloy 600 sensitized 1 hr at 1300°F	77	None	981 hr

* Temperature and concentration limits for caustic cracking of type 304, 316, and 321 stainless steels. (After Speidel.)

M. A. Streicher

Table 3

TABLE 12 — Ranking of Alloys in Navy Tests for Resistance to Crevice Corrosion
In Filtered Sea Water at 30 C
(30 day tests on 3 panels with 120 grit finish and torque of 75 in.-lb)

Rank	Alloy	Composition (Wt%)						Cu	Other	Number of Sides (S) Attacked	Maximum Depth (D) of Attack (mm)	CCI (S x D)
1	Hastelloy C-276	15.5	54.7	15.5	0.5	0.1	3.8 W	—	3.8 Nb	0	0.00	0.00
	Inconel 625	22.3	61.0	8.5	0.1	—	—	—	3.8 Nb	0	0.00	0.00
	20-4 (A.L.)	29.8	0.1	4.0	—	—	—	—	—	0	0.00	0.00
	29-4-2 (A.L.)	29.5	2.2	4.0	—	—	—	—	—	0	0.00	0.00
	29-4C ¹⁰ (A.L.)	29.8	0.8	3.8	0.2	—	—	—	0.8 Ti	0	0.00	0.00
2	Monit (Uddeholm)	23.3	4.1	3.8	0.4	0.4	—	—	—	0	0.00	0.00
	Crucible SC-1	25.8	2.1	2.9	0.2	—	—	—	0.5 Ti	1	0.05	0.05
	Ferrallum 255 (Cabot)	26.2	5.6	3.2	0.8	1.8	0.19 N	—	—	2	0.04	0.16
	Hastelloy G-3 (Cabot)	22.8	43.7	7.0	0.8	1.8	3.5 Co	—	—	1	0.21	0.21
	Haynes 20 Mod (Cabot)	21.8	25.5	5.0	0.9	—	0.5 Co	—	—	2	0.46	0.92
3	20-15	25.0	0.2	1.0	0.2	—	—	—	1.1 Ti	4	0.30	1.2
	20MO-6	23.9	33.4	5.6	0.4	3.3	—	—	—	3	0.53	1.6
	EB 20-1 (A.L.)	25.9	0.1	1.0	—	—	—	—	0.1 Nb	4	0.46	1.8
	A.L. 4X	20.2	24.4	4.4	1.4	1.5	0.019 P	—	—	4	0.50	2.0
	A.L. 8X	20.1	21.8	8.1	1.4	—	—	—	—	4	0.82	2.3
4	254 SMO (Avesta)	20.0	17.9	6.1	0.5	0.8	0.2 N	—	—	5	0.51	2.6
	Hastelloy G (Cabot)	22.2	46.8	5.8	1.5	1.8	3.5 Co	—	—	4	0.87	3.5
	904L (Uddeholm)	20.5	24.7	4.7	1.5	1.6	—	—	—	5	0.74	3.7
	AISI 216	20.0	6.0	2.5	0.0	—	0.35 N	—	—	6	0.64	3.8
	254 SFR (Avesta)	29.1	22.2	2.1	1.7	0.1	0.15 N	—	—	5	0.90	4.3
5	254 SLX (Avesta)	19.9	25.0	4.7	1.6	1.7	0.04 N	—	—	6	0.92	5.5
	Rex 734	21.3	9.4	2.7	3.8	—	0.42 N	—	—	6	1.00	8.0
	Type 317 LM	19.5	14.5	4.1	1.3	0.2	0.058 N	—	—	6	1.07	6.4
	Nitronic 50	21.1	13.7	2.3	4.8	—	0.28 N	—	—	6	1.10	6.8
	Jessop 700	20.7	25.2	4.4	1.6	0.2	0.28 Nb	—	—	5	2.00	10
6	Type 316	17.5	10.7	2.4	1.8	0.3	—	—	—	6	1.93	12
	Carpenter 20 Cb-3	19.4	33.2	2.2	0.4	3.2	0.51 Nb	—	—	5	3.10	16
	Jessop 777	20.8	25.6	4.5	1.4	2.2	0.24 Nb	—	—	6	2.90	17
	44 LN	23.0	5.9	1.5	1.8	0.1	0.2 N	—	—	6	3.35	20
	AISI 444	18.9	0.1	2.0	0.4	—	0.4 Nb	—	—	6	1.21	7.2
7	AISI 329	27.0	4.2	1.4	0.3	0.1	—	—	—	6	1.29	7.7
	34 LN	16.6	13.8	4.2	1.6	—	0.14 N	—	—	6	1.04	6.2
	AISI 439	17.7	0.3	—	0.3	—	0.4 Ti	—	—	6	0.72	4.3
	AISI 317L	18.9	12.2	3.6	1.7	—	0.058 N	—	—	6	1.92	12
	AISI 317L +	18.3	15.8	4.2	1.5	0.2	0.18 Co	—	—	6	1.08	6.5
8	Incoloy 625	22.0	44.0	2.7	0.4	1.7	0.7 Ti	—	—	6	2.42	15

¹⁰Three additional panels were tested for 82 days with the same results.

M. A. Streicher, Materials Performance, 22, pp 37-50, (1983)

(Tests were made at the La Que Center, Wrightsville Beach, N.C.
under the supervision of R. M. Kain; the ranking was by MAS.)

Table 4

EVALUATION OF BLEACH PLANT PIPING MATERIALS

A. H. Tuthill and A. Garner
TAPPI Journal, 73, pp 147-151, (1990) June

<u>Alloy</u>	<u>Composition, per cent by weight</u>				
	<u>Cr</u>	<u>Mo</u>	<u>Ni</u>	<u>Fe</u>	<u>Other</u>
A. L. 6XN	20	6	24	50	0.2N
Hastelloy G-30	29.5	5.5	55	15	2 Cu, 2.5W, 0.7Nb
Inconel 625	21.5	9	60	5	4Nb
Hastelloy C-276	15.5	16	59	5.5	4W
Hastelloy C-22	21.5	13	60	3	3W

TESTING CONDITIONS

ClO_2 - 0.02 - 0.06 g/L

Cl^- - 5,600 ppm

pH - 3.0 - 4.7

Temperature - 68 - 74 C

Length of test - 14 months

Piping - Test Sections: 24 in long, 10 in diameter,
3/16 in wall thickness

Table 5

CITICAL PITTING TEMPERATURE IN 10% FERRIC CHLORIDE

<u>Base Metal</u>	<u>Critical Temperature</u>
Hastelloy G-30	60 C
AL-6XN	72.5 C
Inconel 625	90 C
Hastelloy c-276	>100 C
Hastelloy C-22	>100 C

Tests were made on upper face of duplicate samples of uncorroded base metal at constant temperature, which was increased by 2.5 C every working day.

A. Tuthill and A. Garner, TAPPI Journal, 73, pp147-151, (1990)

Figure 4

Wick Test Arrangement

Solution: 1500 ppm Cl as NaCl

M. A. Streicher, "Stainless '77"

Final

ATTACHMENT 12
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Corrosion Consultant

May 25, 1994

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Number of pages including this page: 8

Hanford Tanks: Material of Construction

Objectives of Corrosion Panel MeetingM. STREICHER
1-10-94
14 1.

As part of the Tenth Structural Integrity Workshop held in San Diego, a special meeting was arranged for December 3, 1993, to discuss the selection of a stainless alloy for the new waste storage tanks at Hanford. A panel of metallurgists and corrosion experts with 30 or more years of experience in the process industries (Joseph J. Demo, C. Paul Dillon, Oliver Siebert) was asked to join with two members, also corrosion experts, from our regular Structural Integrity Panel, John Weeks and Michael Streicher. (Absentee, Spencer Bush, also from this Panel.)

The objectives of this one-day meeting were to:

- a) review PNL laboratory test data on Type 304L and Carpenter 20 Cb-3 (alloy 20) stainless steels; (Compositions in attached table)
- b) discuss industrial experience and current practices in preventing chloride and caustic stress corrosion cracking and in preventing pitting and crevice corrosion; and,
- c) identify stainless alloys for use in the new waste tanks at Hanford.

Both before and during the discussions at this meeting the following requirements for the stainless alloy selected were enumerated:

- a) the alloy must be listed in the ASME B&PV Code, Section III, Class 2, Division 1;
- b) the tanks will be welded in the field, and there will be no thermal stress relieving;
- c) the pH of the solutions may vary from 5 to 14, and the temperature up to 121 C;
- d) there may be a wide variation in the concentrations and the compositions of the solutions, including cases when there are no nitrates or nitrites in the waste; (The absence of the latter can have a major effect on the action of chlorides which cause chloride stress corrosion and/or pitting and crevice corrosion; the PNL tests did not include such nitrate/nitrite-free compositions; nitrates and nitrites can act as inhibitors of various forms of chloride attack.)
- e) the life of the stainless tanks was first estimated as 50 years, but recent views on the potential use of the tanks not only for mixing and treating of wastes for vitrification, but also for storage of waste from single shell carbon steel tanks, and, thus, the life has been forecast far in excess of 50 years. No repairs will be possible after the start of operations.

Requirements for Corrosion Resistance

The alloy selected must be resistant to general corrosion, chloride pitting and crevice corrosion, and most importantly, chloride and caustic stress corrosion cracking. (The most important failure mode in the carbon steel waste tanks has been nitrate stress corrosion cracking at weldments. Nitrate cracking is not thought to be a problem in stainless alloy tanks.) A major problem with the specification of alloys for the new waste tanks is that there is essentially no information available on corrosion resistance of such alloys. The PNL tests are the main source of information, but their duration of necessity was only a few months for application in tanks to be used for 50 years or more. This long period of use also exceeds almost all applications of these alloys in industry. In fact, most of the alloys were developed within the last 25 years. Only Type 304 is about 70 years old. Thus, selection of alloys must largely be based on information provided on the effects of alloying elements from laboratory tests and a wide range of industrial applications. An important source of this information is the 30 years of industrial experience which four of the members of this Corrosion Panel have had. They have seen many failures on plants and have learned what it takes to avoid them. (The PNL tests were limited to two alloys.)

Extensive experience in laboratory and field tests by users and producers of stainless alloys has led to the following findings on the effect of alloying elements:

- a) for resistance to chloride and caustic stress corrosion a concentration of at least 34% Ni is essential (Alloy 20); resistance to stress corrosion increases with the nickel content above 8%; therefore, the higher the nickel content is the greater the resistance to cracking :
A.L. 6XN only 24% Ni, but Hastelloy C-276 and C-22 with about 58 to 62% Ni can be expected to have the greatest resistance to chloride and caustic stress corrosion;
(traces of Pb and SiO₂ have been found to promote stress corrosion of nickel-base alloys in caustic solutions;
- b) the table in the Appendix on stress corrosion in caustic solutions shows that more nickel is required to significantly increase resistance to caustic cracking than to chloride cracking; it has also been found that increasing the pH of a boiling 26% NaCl solution from 7.3 to 10 and above prevents stress corrosion on U-bend specimens in this solution; without NaOH the time to cracking is 72 hr.

- c) for resistance to general corrosion nickel is required for caustic environments, and chromium for oxidizing conditions (nitrate);

(in industry a general corrosion rate of 3 mil, thousandths of an inch) is considered desirable for long-time applications; such a rate would remove 0.3 in in 100 years)

- d) for resistance to chloride pitting and crevice corrosion chromium and molybdenum are required (nickel is essentially without effect); a rule of thumb is that resistance to these forms of corrosion is proportional to : %Cr plus 3 times the %Mo;

Type 304	18-20
Alloy 20	27.5
A.L 6XN	40.5
Hastelloy C-276	63.5
Hastelloy C-22	61.5

for resistance to chlorides at high temperatures, an index of at least 40 is needed; there are cases where weldments in molybdenum-bearing alloys did not have the resistance of the base plate;

high pH serves as an inhibitor for chloride corrosion and oxidizing agents(nitrate) can inhibit attack, but when present in small amounts can also increase pitting and crevice corrosion by chlorides.

Data on the above items, a, b, and c, were presented at the beginning of the meeting and are given in the Appendix to this report.

Data on the relative costs of various stainless alloys were supplied by a representative of Rolled Alloys (for plates, for quantities over 50,000 lb , November 10, 1993):

<u>Alloy</u>	<u>Ratio</u>	<u>(Alloy/304)</u>
Type 304L	1.0	(because the price of Type 304
Alloy 20	2.9	is approximately \$1/lb these
A.L. 6XN	3.2	ratios are also approx. the
C-276 (C-22)	5.4	cost per lb.)

Because of the large total cost of a double shell tank at Hanford, the cost of the alloy selected is not a decisive factor in the selection , see report of meeting.

A further note about caustic cracking - The effect of nickel in stainless alloys in increasing the resistance to stress corrosion in caustic solutions is much "slower" than its effect on increasing resistance to chloride cracking. As a result, there are statements in the literature to the effect that the nickel content in stainless alloys is without effect on susceptibility to cracking. Furthermore, oxidizing agents, such as nitrates, can passivate stainless alloys in sodium hydroxide solutions and, thereby, prevent caustic cracking, even in the case of Type 304 alloy. (G. J. Theus, Technical Paper RDTPA 75-18, Babcock & Wilcox Co. and Y. S. Park, et al, DOE Report C00-2421-04). If, however, the oxidizing agents are absent, the corrosion potential may fall in the active range and there may then be rapid stress corrosion cracking. This applies also to alloys with as much as 77% Ni (Inconel 600, 16% Cr-77% Ni-8% Fe). This alloy resisted up to 981 hr in the test of Table 1 in the Appendix. However, in tests also at 300 C R. S. Pathania (Corrosion/76, Paper No. 98, 1976) found that even this alloy fails after 3,800 hr. Only pure nickel is completely resistant in sodium hydroxide stress corrosion tests.

Conclusions

Currently, Westinghouse Hanford Company (WHC) plans to use Type 304L stainless steel for both the primary and the secondary tanks. In response to a question at the Corrosion Panel meeting about the pH and temperature at which Type 304 might be used, the statement was made that the temperature would have to be kept below 60 C and the pH above 11.

There was disagreement among Hanford and PNL personnel at the meeting as to whether these conditions could be guaranteed for 50 to 100 years of operation of all of the stainless tanks to be built.

None of the five corrosion experts recommend the use of Type 304L stainless steel for the new Hanford waste tanks under the restricted or any other operating conditions.

When the experts were polled for their preferred alloy selection, the unanimous choice was Hastelloy C-276, and in second place, the newer Hastelloy C-22.

In third place, 6Mo alloys were selected. However, only one of the two such alloys, A. L. 6XN, qualifies, because the other, 254SMO, contains only 18% Ni as compared with 24.5% Ni in A. L. 6XN. (Note that both of these alloys contain much less nickel than the Alloy 20 with 34% Ni.) Also, for the A.L. 6XN alloy there is a need to establish whether the field weldments on relatively thick plates will have the corrosion resistance of the base plate.

To make a meaningful choice between Hastelloys C-276 and C-22, it will be necessary to determine whether the higher nickel in C-276 (62%) as compared with the 59% Ni in C-22 is more important than the higher chromium in C-22 (21%) as compared with that in C-276 (15.5% Cr). To establish this point there is a need for some accelerated tests of the "Wick" type for stress corrosion resistance and some determination of general corrosion in simulated waste solutions.

Note on Caustic Stress Corrosion

As discussed on page 4 and shown in Table 2, none of the alloys tested were resistant in 50 % caustic at 300 C; i. e., even Inconel 600 with 77% Ni cracked after 3,800 hr in tests by Pathania (see page 4 above). Therefore, none of the alloys can be considered "immune" to caustic cracking in the sense in which this word is used by O. W. Siebert for chloride stress corrosion cracking in his attached letter dated January 13, 1994.

Appendix A

TABLE OF ALLOY COMPOSITIONS

Alloy	Percent by Weight			
	<u>Cr</u>	<u>Ni</u>	<u>Mo</u>	<u>Other</u>
Incoloy 825	19.5-23.5	38-46	2.5-3.5	2.2 Cu, 33 Fe, 1 Ti
Hastelloy C-22	20.0-22.5	56-58	12.5-14.5	3 W, 3 Fe, 2.5 Co
Carpenter 20Cb-3	19.0-21.0	32.0-38.0	2.0-3.0	3.5 Cu, 0.5 Nb 39 Fe
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254 SMO (Avesta)	19.5-20.5	17.5-18.5	6.0-6.5	0.3 Cu, 55 Fe
304L	18.0-20.0	8.0-12.0	-	70 Fe
316L	16.0-18.0	10.0-14.0	2.0-3.0	66 Fe

Table 2

STRESS CORROSION IN 50% NaOH
AT 300°C
U-bend Specimens

ALLOY	Ni CONTENT % by wt.	RESULTS	
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Incoloy alloy 825	42	Transgranular	between 4 and 20.5
Hastelloy alloy G	45	Intergranular *	between 4 and 20.5
Hastelloy alloy F	47	Transgranular and intergranular	between 4 and 20.5
Hastelloy alloy C-276	56	Intergranular	less than 48
Inconel alloy 625	63	Transgranular	between 92 and 117
Hastelloy alloy C-4	67	Transgranular	283
Inconel alloy 600	77	None	981 hr
<hr/>			
Inconel alloy 600 sensitized 1 hr at 1300°F	77	None	981 hr

Temperature and concentration limits for caustic cracking of type 304, 347.

M. A. Streicher

A

RESULTS OF STRESS CORROSION TESTS

Reported by phone, 6/27/94, by Marty Caruso, Haynes International, Kokomo, IN.

Tests based on my caustic testing memo.

U-bends, 0.125 in thick, 5 in long, 0.5 in wide. C-276 bolts with Teflon insulators.

<u>Solution</u>	NaOH —	18.2%
	Cl —	7100 ppm
	F —	190 ppm

<u>Temperature</u>	200°C
--------------------	-------

<u>Time</u>	1008 hr.
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B

Alloy	Nickel, %	Results
304L	8-10	cracked
AL6XN	23.5-25.5	cracked
20 Cb-3	32-38	No cracking
G-30	43	No cracking
C-22	56-58	No cracking
C-276	60-64	No cracking
C-4	65	No cracking
600	72	No cracking

General corrosion on all alloys was less than 0.5 mil/year.

Streicher Memorandum 7/1/94

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