MASTER

PR. 2897

A STUDY OF THE CORROSIVE EFFECT ON ALUMINUM AND
CP TITANIUM OF MIXTURES OF AMMONIA AND SEAWATER
THAT MAY BE ENCOUNTERED IN OTEC HEAT EXCHANGERS

Final Report

C. F. Schrieber

W. D. Grimes

W. F. McIlhenny

Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

Prepared for the
U. S. Department of Energy
Division of Central Solar Technology
under Contract W-31-109-Eng-38

SOLAR ENERGY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

The facilities of Argonne National Laboratory are owned by the United States Government. Under the terms of a contract (W-31-109-Eng-38) among the U. S. Department of Energy, Argonne Universities Association and The University of Chicago, the University employs the staff and operates the Laboratory in accordance with policies and programs formulated, approved and reviewed by the Association.

MEMBERS OF ARGONNE UNIVERSITIES ASSOCIATION

The University of Arizona	The University of Kansas	The Ohio State University
Carnegie-Mellon University	Kansas State University	Ohio University
Case Western Reserve University	Loyola University of Chicago	The Pennsylvania State University
The University of Chicago	Marquette University	Purdue University
University of Cincinnati	The University of Michigan	Saint Louis University
Illinois Institute of Technology	Michigan State University	Southern Illinois University
University of Illinois	University of Minnesota	The University of Texas at Austin
Indiana University	University of Missouri	Washington University
The University of Iowa	Northwestern University	Wayne State University
Iowa State University	University of Notre Dame	The University of Wisconsin-Madison

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights. Mention of commercial products, their manufacturers, or their suppliers in this publication does not imply or connote approval or disapproval of the product by Argonne National Laboratory or the U. S. Department of Energy.

Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy \$7.25, Microfiche \$3.00

6-5-8

ANL/OTEC-BCM-004

Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

A STUDY OF THE CORROSIVE EFFECT ON ALUMINUM AND
CP TITANIUM OF MIXTURES OF AMMONIA AND SEAWATER
THAT MAY BE ENCOUNTERED IN OTEC HEAT EXCHANGERS

Final Report

C. F. Schrieber
W. D. Grimes
W. F. McIlhenny

Dow Chemical U.S.A.
Texas Division
Freeport, Texas 77541

March 1979

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Prepared under
Subcontract No. B-42805-A-E

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Key

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

TABLE OF CONTENTS

	Page
MANAGEMENT SUMMARY.	ix
I. INTRODUCTION.	1
II. SUMMARY AND CONCLUSIONS	3
III. EXPERIMENTAL PROCEDURES	6
A. Program Methodology	6
B. Test Unit Description	6
C. Specimen Procedure	14
IV. AMMONIA IN SEAWATER	24
A. Scale Formation	24
B. Corrosion	25
V. SEAWATER IN AMMONIA	35
A. Anhydrous Ammonia	35
B. Anhydrous Ammonia plus 0.1% Seawater.	35
C. Anhydrous Ammonia plus 1.0% Seawater.	37
D. Anhydrous Ammonia plus 2.5% Seawater.	37
VI. SPECIAL CLEANING TESTS.	38
VII. RECOMMENDATIONS	40
BIBLIOGRAPHY.	41
APPENDICES.	42
A. Detailed Tabular Data	42
B. Equipment and Scale Photographs	98

LIST OF FIGURES

	<u>Page</u>
I-1. Weight Losses for 1100, 3003, 5052, and 6063 Alloys Exposed One Month in 0-100% Ammonia-Seawater Solutions (from Bonewitz, July 1977).....	2
III-1. Simplified Flowsheet of Corrosion Test Units to Determine Effect of Low Conc. of NH ₃ in Seawater (Units 1&2).....	8
III-2. Simplified Flowsheet of Corrosion Test Unit to Determine Effect of Low Conc. of Seawater in Ammonia (Unit 3).....	10
III-3. Flowsheet for Installation of Cleaning Loss Specimens and Uncontaminated Corrosion-Scaling Controls.....	11
III-4. Incoming Seawater Temperature at Dow Chemical Company, Freeport, Texas Plant.....	13
III-5. Teflon Weight-Loss and Pitting Specimen Holder.....	16
III-6. Specimen Holder Scheme.....	17
III-7. Crevice Corrosion Specimen Assembly.....	18
III-8. Alloy Corrosion Performance: Penetration vs. Time.....	20
III-9. Brush Arrangement Used for Mechanical Cleaning.....	23
IV-1. Fouling Formation.....	26
IV-2. Ammonia Concentration vs. pH.....	27
IV-3. Scale Composition and Formation.....	28
IV-4. Scale Formation on Crevice Test Assembly, 880 ppm Ammonia in Seawater at 30°C.....	29
IV-5. Corrosion Summary: Final Interval Corrosion Rate and Maximum Pit Depth, Seawater Mixed with Ammonia, Evaporator, 30°C.....	30

List of Figures (concluded)Page

IV-6.	Corrosion Summary: Final Interval Corrosion Rate and Maximum Pit Depth, Seawater Mixed with Ammonia, Condensor, 5°C.....	31
V-1.	Corrosion Summary: Final Interval Corrosion Rate and Maximum Pit Depth, Ammonia Mixed with Seawater, Condensor, 5°C.....	36
VI-1.	Total Average Penetration vs. Cleaning Method..	39
IX-1.	Test Unit 1: Seawater Mixed with Ammonia at 30°C.....	99
IX-2.	Test Unit 2: Seawater Mixed with Ammonia at 5°C.....	100
IX-3.	Test Unit 3: Liquid Anhydrous Ammonia Mixed with Seawater at 5°C.....	101
IX-4.	Test Unit 4: Once Through Ambient Temperature Seawater System for Cleaning Test and Seawater Corrosion Controls.....	102
IX-5.	Crevice Corrosion Specimen Assembly.....	103
IX-6.	Fouling on Crevice Test Assembly, 8 ppm Ammonia in Seawater at 5°C and 30°C.....	104
IX-7.	Scale Formation on Crevice Test Assembly, 30 ppm Ammonia in Seawater at 5°C and 30°C.....	105
IX-8.	Scale Formation on Crevice Test Assembly, 83 ppm Ammonia in Seawater at 30°C.....	106
IX-9.	Scale Formation on Crevice Test Assembly, 78 ppm Ammonia in Seawater at 5°C.....	107
IX-10.	Scale Formation on Crevice Test Assembly, 880 ppm Ammonia in Seawater at 30°C.....	108
IX-11.	Scale Formation on Crevice Test Assembly, 916 ppm Ammonia in Seawater at 5°C.....	109

LIST OF TABLES

	<u>Page</u>
III-1. Final Program Methodology.....	7
III-2. Seawater Composition and Range - Gulf of Mexico.....	12
III-3. Chemical Composition or Specification of the Test Alloys.....	15
IV-1. Total Average Penetration of Ambient Temperature Seawater Controls.....	33
IX-1. Final Interval Corrosion Rate (mpy) for Ambient Temperature Seawater Controls.....	43
IX-2. Final Interval Corrosion Rates for Test Exposures of 8.0 ppm Ammonia in Seawater.....	44
IX-3. Total Average Penetration (mils) for Test Exposures of 8.0 ppm Ammonia in Seawater.....	45
IX-4. Corrosion Data for Test - 30°C Seawater + 7.5 ppm Ammonia.....	46
IX-5. Corrosion Data for Test - 5°C Seawater + 8.5 ppm Ammonia.....	49
IX-6. Fouling Formation - Seawater + Nominal 8.0 ppm Ammonia and Ambient Temperature Seawater Controls.....	51
IX-7. Summary of Exposure Conditions - Nominal 8 ppm NH ₃	52
IX-8. Final Interval Corrosion Rates for Test Exposures of 30.0 ppm Ammonia in Seawater.....	53
IX-9. Total Average Penetration (mils) for Test Exposures of 30 ppm Ammonia in Seawater.....	54
IX-10. Corrosion Data for Test - 30°C Seawater + 27.2 ppm Ammonia.....	55
IX-11. Corrosion Data for Test - 5°C Seawater + 26.6 ppm Ammonia.....	57
IX-12. Fouling Formation - Seawater + Nominal 30 ppm Ammonia and Ambient Temperature Seawater Controls.....	59

List of Tables (continued)Page

IX-13.	Summary of Exposure Conditions - Nominal 30 ppm NH ₃	60
IX-14.	Final Interval Corrosion Rates for Test Exposures of 80 ppm Ammonia.....	61
IX-15.	Total Average Penetration (mils) for Test Exposures of 80 ppm Ammonia in Seawater.....	62
IX-16.	Corrosion Data for Test - 30°C Seawater + Nominal 80 ppm Ammonia.....	63
IX-17.	Corrosion Data for Crevice Corrosion Test - 30°C Seawater + 83 ppm Ammonia for 50 Days.....	65
IX-18.	Corrosion Data for Test - 7°C Seawater + Nominal 80 ppm Ammonia.....	66
IX-19.	Corrosion Data for Crevice Corrosion Test - 7°C Seawater + 78 ppm Ammonia for 51 Days.....	68
IX-20.	Scale Formation - Seawater + Nominal 80 ppm Ammonia.....	69
IX-21.	Summary of Exposure Conditions (~80 ppm NH ₃).....	70
IX-22.	Final Interval Corrosion Rates (mpy) for Test Exposures of 800 ppm Ammonia in Seawater.....	71
IX-23.	Total Average Penetration (mils) after Ten Days for Test Exposures of 800 ppm Ammonia in Seawater.....	72
IX-24.	Corrosion Data for Test - 30°C Seawater + 800 ppm Ammonia.....	73
IX-25.	Corrosion Data for Test - 5°C Seawater + 916 ppm Ammonia.....	74
IX-26.	Scale Formation - Seawater + 800 ppm Ammonia.....	75
IX-27.	Summary of Exposure Conditions (~800 ppm NH ₃).....	76
IX-28.	Corrosion Data for Test - Final Interval Corrosion Rates - Ammonia plus Seawater at 5°C.....	77
IX-29.	Corrosion Data for Test - 5°C Anhydrous Ammonia.....	78

List of Tables (concluded)

Page

IX-30.	Summary of Exposure Conditions for Anhydrous Ammonia Test.....	80
IX-31.	Total Average Penetration (mils) for a Test Exposure in Anhydrous Ammonia + .14% Seawater at 5°C.....	81
IX-32.	Corrosion Data for Crevice Corrosion Test Anhydrous Ammonia + .14% Seawater at 5°C for 24 Days.....	82
IX-33.	Summary of Exposure Conditions for Anhydrous Ammonia Test Periods.....	83
IX-34.	Corrosion Data for Test - 5°C Anhydrous Ammonia + 1.12% Seawater.....	84
IX-35.	Summary of Exposure Conditions for Anhydrous Ammonia + 1% Seawater Test Periods.....	86
IX-36.	Corrosion Data for Test - 5°C Anhydrous Ammonia + 2.5% Seawater.....	87
IX-37.	Summary of Exposure Conditions for Anhydrous Ammonia + 2.5% Seawater.....	89
IX-38.	Cleaning Solution Screening - Test Results on Al 3003-H14 (Fouled).....	90
IX-39.	Cleaning Tests: Corrosion Summary Final Interval Corrosion Rate (mpy).....	91
IX-40.	Cleaning Tests: Corrosion Summary Total Average Penetration (mpy).....	92
IX-41.	Cleaning Tests - Ambient Temperature Unfiltered Seawater.....	93

MANAGEMENT SUMMARY

The design currently most favored for an Offshore Thermal Energy Conversion power plant would use an ammonia cycle energy system as powered by the small thermal differences existing between warm surface and deep ocean waters. A possibility therefore exists for ammonia or seawater leakage within the evaporator or condenser. The objective of this work is to assess the extent to which small concentrations of seawater would affect corrosion of aluminum and CP titanium by ammonia and the extent to which small concentrations of ammonia might affect the same alloys by seawater.

Testing was conducted using coupons of aluminum alloys 3003-H14, 5052-H32, and 5086-H32, CP titanium, and aluminum alloy 5052-H32 as pretreated for 8 hours in boiling deionized water. Four pilot units were constructed to investigate different possible OTEC heat exchanger environments. Experimentation on ammonia leakage into seawater employed two units containing recirculating (~6 gal.), temperature-controlled (5°C or 30°C) seawater at 5.6 and 2.5 fps with continuous seawater refreshment (2.0-0.5 gpm). Ammonia leakage was simulated in these two units by injection of ammonia hydroxide into the refreshment seawater. A third unit with the same seawater supply utilized seawater on a once-through, 5 fps, ambient temperature basis to simulate optimum, no-leak OTEC seawater service. Performance of the subject alloys in ammonia and ammonia containing seawater utilized recirculating ammonia with temperature controlled to 5°C.

Exposures were completed for nominal 8, 30, 80, and 800 ppm additions of ammonia to seawater at 5°C and 30°C. The change in pH resulting from the ammonia addition has resulted in scaling at all ammonia concentrations, with calcite formation followed by aragonite and then brucite as concentrations increased. It is anticipated that a continuous cleaning process could control scale at 8 ppm, 30°C and 5°C, and at 30 ppm, 5°C, but that scaling at 80 ppm and 800 ppm additions is not economically controllable. Corrosion has been minimal except for measureable pitting on Al 3003, Al 5052, Al 5086 at 8 ppm, 30°C, and on Al 5052 at 8 ppm, 5°C. Ambient temperature seawater controls show general corrosion attack but insignificant pit attack.

Exposures were also completed for 0, 0.1, 1.0, and 2.5% nominal seawater additions to commercially pure ammonia at 5°C. Both corrosion and scaling have been minimal for these exposures.

Exposures reported herein indicate CP titanium will give superior performance in an OTEC heat exchanger followed by pretreated aluminum alloy 5052.

Results contained in this report are based on limited surface area specimens and should not be used to wholly qualify or disqualify an alloy for consideration in the OTEC application.

I. INTRODUCTION

A principal Ocean Thermal Energy Conversion (OTEC) concept under consideration is based upon the use of an ammonia-cycle generator system powered by small thermal differences available between surface and deep ocean waters. The purpose of this contractual effort was to assess the influence of seawater-ammonia mixtures on proposed OTEC heat exchanger materials at environmental conditions which may possibly be encountered in OTEC heat exchangers.

Testing was to remain on a coupon test scale, and relevant information sought included degree and definition of chemical scaling, average uniform penetration, final test interval corrosion rate, pitting, crevice corrosion, and influence of intermittent but sequential chemical and mechanical cleaning. Heat exchanger materials, as proposed by the Department of Energy included commercially pure (CP) titanium, and aluminum alloys 3003, 5052, and 5086. Additionally, at the recommendation of Dow personnel, specimens of aluminum alloy 5052, as pretreated in boiling deionized water, were included in all exposures.

The possibility of either an ammonia or seawater intrusion (leak) in either the OTEC evaporator or condenser, constituted the stimulus for this research on candidate OTEC heat exchanger materials. The concern was that low concentrations of ammonia in seawater, and conversely, low concentrations of seawater in ammonia, may act to seriously impair material performance. Previous work, as shown in Figure I-1 (Bonewitz, July 1977) has indicated that aluminum alloys may suffer accelerated attack under these conditions.

FIGURE I-1
 WEIGHT LOSSES FOR 1100 (◻), 3003 (▽), 5052 (△) and 6063 (○) ALLOYS
 EXPOSED ONE MONTH IN 0-100% AMMONIA-SEAWATER SOLUTIONS

(from Bonewitz, July, 1977)

II. SUMMARY AND CONCLUSIONS

Tests were conducted to assess scaling and corrosion behavior of CP titanium and aluminum alloys in environments which may possibly be encountered in OTEC heat exchangers. Results of this effort are summarized by the following:

1. In all cases CP titanium performed in a manner superior to that of the aluminum alloys tested. Final interval corrosion¹ rates for this material were less than 0.0028 mm/yr (0.11 mpy) in all environments tested. This compares to final interval corrosion rates of 0.065 mm/yr (2.6 mpy) for aluminum alloys in seawater and 0.0074 mm/yr. (0.29 mpy) in ammonia. Pit and crevice attack was minimal, and no significant penetration (>1 mil) was observed at any exposure. In contrast, pit attack of varying degrees was observed on all aluminum alloys tested.

Additionally, chemical scales forming on titanium surfaces were less tenacious and therefore more readily removed than scales which formed on the aluminum surfaces. CP titanium also showed negligible corrosion rates in the limited scope 10-month mechanical and chemical cleaning tests.

2. Aluminum alloy 5052, which had been pretreated by immersion in boiling deionized water for 8 hours, was the best performer of the aluminum alloys tested. The pretreated aluminum concept was inserted in the test program at Dow's recommendation based upon highly encouraging results obtained from corrosion studies completed for the Office of Saline Water, U.S. Department of the Interior. The boiling water pretreatment forms an impervious boehmite film on aluminum which prohibits the plating of pit-inducing heavy metal ions. The effect of this pretreatment is to significantly reduce the initially high corrosion rate associated with aluminum.

In ambient temperature seawater, pretreated aluminum alloy 5052 has a final interval corrosion rate of 0.015 mm/yr. (0.59 mpy) as opposed to a final

¹ "Final Interval" corrosion rate is a predicted long-term corrosion rate which the metal should experience after the surface has become passivated from continued exposure. The methodology involved in calculating this rate is given in Section III.C.3, "Data Resolution".

interval corrosion rate of 0.056-0.065 mm/yr. (2.20-2.57 mpy) for untreated aluminum alloys 3003, 5052, and 5086. In mixtures of 30°C seawater plus lower concentrations of ammonia, the performance of pretreated aluminum alloy 5052 was also superior to other aluminum alloys, particularly to pit resistance which was minimal in all seawater-ammonia mixtures.

In anhydrous ammonia and ammonia-seawater mixtures, pretreated aluminum alloy 5052 showed an initial weight loss greater than that of the untreated aluminum alloys. However, the final interval corrosion rates for the pretreated alloy in this environment were consistently superior to the other aluminum alloys. In addition, the etched surface attack often observed on aluminum alloys was not apparent on pretreated aluminum alloy 5052. The surface appearance of this alloy was virtually unchanged by the exposure to the subject environments.

Scale and fouling removal was observed to occur as readily on pretreated aluminum alloy 5052 as on CP titanium. The effect of abrasive cleaning techniques on the extended performance of this alloy is currently unknown.

3. The addition of ammonia to seawater will result in alkaline scale formation which may impair heat transfer. The increase in pH resulting from ammonia addition has resulted in scaling at all trial concentrations of ammonia in seawater (8, 30, 80, and 800 ppm), with calcite scale forming initially followed by aragonite and brucite as concentrations increase. It is anticipated that a continuous cleaning process could control scale at 8 ppm, 30°C and 5°C, and at 30 ppm, 5°C, but that scale control at ammonia concentrations above 80 ppm (scale growth above 0.013 mm/day) is not economically controllable.
4. The addition of seawater to anhydrous ammonia within the scope of these tests has not resulted in any relevant scale formation.
5. The final interval corrosion rates for the aluminum alloys was generally greater in the control ambient temperature seawater than in seawater plus ammonia mixtures. Aluminum alloys 3003, 5052, and 5086 showed final interval corrosion rates of 0.056-0.065 mm/yr (2.20-2.57 mpy) in ambient temperature seawater. Treated aluminum alloy 5052 in this

environment exhibited a rate one-fourth the above or 0.015 mm/yr. (0.59 mpy). Pitting was minimal in ambient temperature seawater although measurable pitting was observed on the untreated aluminum alloys in seawater containing 8 ppm at 30°C.

6. Addition to anhydrous ammonia of greater quantities of seawater from 151 ppm to 2.5% was generally observed to increase the final interval corrosion rate of untreated aluminum alloys 3003, 5052, and 5086. No conclusive observation may be made concerning treated aluminum alloy 5052 and CP titanium.
7. The results of this test were inconclusive in determining a preferred velocity for the OTEC system.

III. EXPERIMENTAL PROCEDURES

A. Program Methodology

In order to meet the program objectives, an experimental plan was reviewed with Battelle contract personnel on October 27, 1977, in Freeport, Texas. The subsequent occurrence of heavy calcareous scale in the ammonia-in-seawater tests necessitated concentration changes in this portion of the program. In addition, tests to establish ambient temperature seawater corrosion controls were incorporated and run in parallel with all ammonia in seawater tests after January 30, 1978. The revised, final program methodology is shown in Table III-1.

B. Test Unit Description

Four test units were constructed to meet the requirements of the corrosion test program. The exposure conditions required included seawater with small additions of ammonia at 5°C and 30°C, anhydrous ammonia with small additions of seawater at 5°C, and once-through ambient temperature seawater.

1. Test Units: Seawater Containing Ammonia

Two test units designed to test the subject alloys in seawater plus small concentrations of ammonia at 30°C and 5°C were constructed as depicted in the generalized schematic in Figure III-1. One unit operates at 30°C and is temperature controlled by either cooling water or steam. The low temperature, 5°C unit employs an external chiller circuit which removes heat from the loop by a cold glycol-water solution. Units are constructed of plastic-lined steel (polypropylene, Saran®, Teflon®, and Kynar®) and Alloy 20 stainless steel.

The test units contain approximately 22.7 liters (6 gal.) recirculating seawater. The seawater is refreshed at a rate of 7.6-1.9 l/min. (2.0-0.5 gpm), for a seawater renewal rate and system stabilization period of about 3-12 minutes. Exact blowdown rates for each test are given in Appendix A, Tables IX-7, IX-13, IX-21, and IX-27.

Ammonia leakage into seawater was simulated by injection of ammonia solution into the refreshment seawater. Adequate mixing was assured by injection downstream of the recirculating pump and the use of aqueous ammonia (ammonium hydroxide) as an injection fluid. Concentrations of ammonia in seawater are routinely obtained by analysis of the system blowdown. Both units contain all instruments necessary for automatic control and failsafe shutdown to prevent specimens from experiencing excessive ammonia concentrations.

TABLE III-1
FINAL PROGRAM METHODOLOGY

I. SEAWATER MIXED WITH AMMONIA

<u>Test</u>	<u>Ammonia (ppm)</u>	<u>Exposures (days)</u>	<u>Materials</u>	<u>Velocity (fps)</u>
Unit I: Evaporator Simulation	7.4 ^(a) 33 ^(a) 83 880 ^(a)	8,29,64 14,30,59 10,30,50 ^(b) 10 ^(b)	CP titanium Al 3003-H14 Al 5052-H32 Al 5086-H32 Al 5052-H32 (treated)	2.5 & 5.6
Unit II: Condenser Simulation, 5°C	8.5 ^(a) 24 ^(a) 78 916 ^(a)	8,29,64 14,30,59 12,32,51 ^(b) 9.5 ^(b)		

II. AMMONIA MIXED WITH SEAWATER

<u>Test</u>	<u>Seawater, %</u>	<u>Exposures (days)</u>	<u>Materials</u>	<u>Velocity (fps)</u>
Unit III: Condenser Simulation 5°C	(151 ppm) 0.14 1.1 3.3	10,40 10,24 10,28,59 10,30,53	CP titanium Al 3003-H14 Al 5052-H32 Al 5086-H32 Al 5052-H32 (treated)	2.5 5.6

III. SPECIAL CLEANING TESTS

<u>Test</u>	<u>Exposure (months)</u>	<u>Materials</u>	<u>Velocity (fps)</u>
Unit IV: Ambient Temperature	1,3,6,10	CP titanium Al 3003-H14 Al 5052-H32 Al 5086-H32 Al 5052-H32 (treated)	5.0

- (a) Run in parallel with ambient temperature seawater controls
 (b) Terminated early due to extensive calcareous scaling

Figure III-1

SIMPLIFIED FLOWSHEET OF CORROSION TEST UNITS TO
DETERMINE EFFECT OF LOW CONC. OF NH_3 IN SEAWATER (UNITS 1 & 2)

2. Test Unit: Ammonia Containing Seawater

A test unit to employ mixtures of anhydrous ammonia plus low concentrations of seawater while operating at 5°C was constructed according to the generalized schematic in Figure III-2. Construction material is welded stainless steel 304 alloy, Teflon-lined steel, and Alloy 20 stainless steel. The loop contains a suitable pump, temperature detectors, flow control and monitoring devices, as well as all automatic controls necessary for failsafe system operation. A chiller is incorporated in the circuit to maintain a 5°C environment within the test loop.

The test loop is designed for total recycle of 100 lbs. of anhydrous ammonia. The reservoir of anhydrous ammonia-seawater solution so formed created a volume-to-specimen area ratio believed to simulate proposed OTEC conditions. Analysis performed on the ammonia-seawater mixtures included water content, chloride ion concentration, and sodium ion concentration. In Tables IX-30, IX-33, IX-35, and IX-37 detailed analyses of the tests conducted are given.

3. Seawater Controls and Cleaning Test Unit

This unit, as depicted in Figure III-3, consists of a once-through seawater loop with automatic flow control downstream of the specimens. Cleaning test specimens were exposed to unfiltered seawater while seawater controls were located downstream of the filter. This unit employs ambient temperature seawater, and temperature is not controlled.

4. Seawater

Seawater utilized in these tests is from the Gulf of Mexico intake basin located at the Dow Chemical Texas Division industrial site "A" at Freeport, Texas. After large incoming debris is screened out at the Dow intake basin, the seawater is transferred through flumes (canals) to a second smaller sedimentation basin near the OTEC test facility. The seawater is then transferred through a system of copper-free piping to the test units where (with the exception of the cleaning test specimens) the seawater is filtered to contain a maximum particle size of 25 microns. The composition and range of the seawater used in these tests appears in Table III-2.

The variation of seawater temperature for selected years is shown in Figure III-4. Included on this figure are temperatures for the 1978 ambient temperature seawater testing program as well as previous temperature data. This variation is important since seawater temperature may significantly affect corrosion rates.

Figure III-2

SIMPLIFIED FLOWSHEET OF CORROSION TEST UNIT TO
DETERMINE EFFECT OF LOW CONC. OF SEAWATER IN AMMONIA (UNIT 3)

Figure III - 3

FLWSHEET FOR INSTALLATION OF CLEANING LOSS SPECIMENS
AND UNCONTAMINATED CORROSION-SCALING CONTROLS

Table III-2
SEAWATER COMPOSITION AND RANGE
GULF OF MEXICO

Annual Average at Freeport, Texas

<u>Measured Parameters</u>	<u>Range, mg/l</u>	<u>Typical Value, Annual Average, mg/l</u>
Alkalinity as CaCO_3	75 - 125	100
Aluminum as Al	--	0.5
Ammonium ion as NH_4^+	1.01 - 0.1	0.05
Calcium as Ca	240 - 400	340
Carbon Dioxide (free) as CO_2	2 - 5	3
Chloride as Cl	11,700 - 19,400	16,500
Copper as Cu (total)	0.01 - 0.1*	0.01
Hydrogen Sulfide as H_2S	--	<0.01
Iron as Fe (total)	0.5 - 5.0*	2
Magnesium as Mg	780 - 1,300	1,100
Mercury as Hg	--	<0.0001
Oxygen, dissolved, as O_2	1.5 - 6.0	5
pH	7.5 - 8.6	8.4
Potassium as K	230 - 380	325
Salinity, % "Normal"	60 - 100%	85%
Sodium as Na	6,340 - 10,560	9,000
Sulfate as SO_4	1,800 - 3,000	2,600
Suspended solids	5 - 50	20
Temperature, °F	60 - 80	70 - 75

* Varies with suspended solids present.

NOTE: When specific gravity = 1, mg/l = ppm.

Figure III-4

INCOMING SEAWATER TEMPERATURE AT
DOW CHEMICAL COMPANY, FREEPORT, TEXAS PLANT

-13-

Dow
Freeport
Seawater
Temperature
(°F)

C. Specimen Procedure

In the course of these tests, specimens of three aluminum alloys and CP titanium were exposed to determine their corrosion behavior in simulated OTEC environments. Preparation and handling procedures for these specimens were more elaborate than for tubes entering an actual OTEC heat exchanger, but conducted within the recommendations of the National Association of Corrosion Engineers.

1. Test Alloys

The alloys specified for use in these tests include aluminum alloys 3003, 5052, and 5086, and CP titanium. Table III-3 shows the chemical specifications for the test alloys.

An addition made by Dow to the test alloy scheme consisted of a sample series of aluminum alloy 5052 pretreated in boiling deionized water for eight hours. One of the findings of the Office of Saline Water desalination materials programs indicated that the higher general and pitting corrosion attack of aluminum which occurs during the initial few weeks can be effectively reduced or eliminated by this pretreatment.

2. Specimen Preparation

Test requirements dictated that specimen holders be prepared for both crevice and coupon corrosion testing.

General and pitting corrosion rate determinations utilized (6" x 3/4" x (0.06-0.08")) nominal size coupons. These specimens were held in pipe spools lined with polytetrafluoroethylene (TFE, Teflon®) plastic. Fluid velocity past the specimens was accurately fixed by knowledge of the flow rate and available cross sectional area in the holder. Figure III-5 shows a separate coupon holder assembly and Figure III-6 shows the generalized specimen holder scheme.

Crevice corrosion determinations utilized (3" x 3" x (0.06-0.08")) nominal size specimens with a centered (1/2") diameter hole. These specimens were mounted on a rod holder and individually separated by special crevice contactors. These contacts were specifically designed to form eight crevice areas on each side of the specimen faces with fluid stagnation points between the crevice areas. Contact pressure between separators and specimens was applied from each end of the crevice assembly. All portions of the assembly were fabricated of glass-filled TFE plastic. Mounting of the assembly in the test environment is accomplished through connections at the rod ends. Figure III-7 shows a crevice specimen assembly.

Table III-3

CHEMICAL COMPOSITION OR SPECIFICATION OF
THE TEST ALLOYS

<u>Alloy</u>	<u>Si</u>	<u>Fe</u>	<u>Cu</u>	<u>Mn</u>	<u>Mg</u>	<u>Cr</u>	<u>Zn</u>	<u>Ti</u>	<u>Others</u>	<u>Aluminum</u>
Al 3003-H14	0.6	0.7	0.1	1.2	--	--	0.1	--	0.15	Remainder
Al 5052-H32	(0.45 Si + Fe)		0.1	0.1	2.5	0.2	0.1	--	0.15	Remainder
Al 5086-H32	0.4	0.5	0.1	0.4	4.0	0.1	0.2	0.15	0.15	Remainder

CP Titanium meets Grade 2, ASTM Spec. B265.

NOTE: Aluminum Alloy 5083 was called for in the RFP. Alloy 5086 was substituted with permission because of an availability problem with 5083.

Figure III-5

TEFLON WEIGHT-LOSS AND PITTING SPECIMEN HOLDER

Figure III-6
SPECIMEN HOLDER SCHEME

- Each spool contains two TFE specimen holders.
- Each holder contains five specimens, one of each alloy (or alloy condition).
- In the cleaning effects test, the spools contain the above but are designated as follows:

Mechanical Cleaning	Chemical Cleaning	Controls
------------------------	----------------------	----------

Figure III-7

CREVICE CORROSION SPECIMEN ASSEMBLY

All specimens were prepared such that all edges have a 400 grit or better surface finish, with all edge and center hole burrs removed. The coupon plate surface remained in a factory-received condition. For identification, all specimens were numbered in the lower right-hand corner using an electric scribe. Specimens were then degreased using Chlorothene® solvent in an ultrasonic cleaner for a minimum of five minutes. At this point, a portion of the aluminum alloy 5052 specimens were pretreated in slowly boiling deionized water for eight hours. The specimens were stored in a desiccator prior to use and weighed just prior to insertion into the test environment.

Upon removal from the test environment, photographs were made of the fouled/scaled specimens, thickness of the scale determined, and specimens submitted for analysis of surface deposits. Specimens were then acid-cleaned using an ultrasonic cleaner to reduce specimen exposure time to the acid solution. Solutions and times are indicated below:

<u>Metal</u>	<u>Solution</u>	<u>Time Exposed</u>
CP titanium	23% HNO ₃ (25°C)	5 min.
Aluminum alloys	2% CrO ₃ , 5% H ₃ PO ₄ Sol'n. (70°C)	30 min.

Specimen blanks were similarly cleaned to determine the extent of the cleaning loss.

After acid cleaning, specimens were degreased and weighed. Weight losses were determined for calculation of general corrosion rates.

3. Data Resolution

Weight loss and microscopic data was resolved into average penetration, final interval corrosion rate, maximum pit depth, and approximate pit density.

In order to facilitate data usage by the OTEC community, corrosion was expressed as corrosion penetration for the given period of exposure. This was calculated in the following manner:

$$(\text{Metal Penetration}) = \frac{(\text{Specimen Weight Loss})}{(\text{Specimen Area})(\text{Metal Density})}$$

Data is commonly expressed in mils (mm.) penetration. However, passivating alloys often experience a high initial penetration which is not indicative of long-term alloy performance, as indicated in Figure III-8. Thus, corrosion rate assessment of long-term performance of passivating alloys is often more accurately represented by the "final interval" corrosion rate, or the time and penetration difference

Figure III-8
 ALLOY CORROSION PERFORMANCE
 PENETRATION vs. TIME

-20-

generated using the final two specimen pulls. The final interval corrosion rate (FICR) was calculated in the following manner:

$$\text{FICR} = \frac{\text{Penetration}(t_{\ell}) - \text{Penetration}(t_{\ell-1})}{(t_{\ell}) - (t_{\ell-1})}$$

where

$(t_{\ell}) \equiv$ Time of exposure for last specimen pulled
 $(t_{\ell-1}) \equiv$ Time of exposure for next to last specimen pulled
and $\text{Penetration}(t) \equiv$ Penetration at time "t"

Data for the extrapolated final interval corrosion rate is expressed in terms of mpy (mm/yr.).

Pit and crevice attack was assessed using the following general format:

Incipient pitting: Pits less than 0.5 mils deep,
discernable as pits under 25x
magnification.
Small pits: Pits 1.0-0.5 mils deep, discernable as
pits under 10x magnification and visible
to naked eye.
Pits: Pits 1-2 mils deep (unless otherwise indicated),
readily visible as pits to naked eye.
Very Few: Less than 5/sq.in.
Few: 5-10/sq.in.
Several: 10-15/sq.in.
Numerous: More than 15/sq.in.

This format was developed to assess observations from the limited surface area exposed. Each specimen was completely examined under 10x magnification to generate the required information. Pits greater than 0.50 mm (2 mils) deep were measured using an Ames depth gauge (No. 11B-202P).

4. Special Considerations: Cleaning Test

The purpose of this test is to compare the influence on corrosion of mechanical and chemical techniques. Further, it is desired that the cleaning technique remove surface deposits and growth but not disturb the passive surface film. The selection of cleaning techniques used in these very preliminary tests should not be inferred as a choice of the superior cleaning method available.

Handling of these specimens before exposure is as outlined in the previous section. Under test, these specimens were exposed to unfiltered seawater free of debris and macroscopic marine life. Then at periods of 1, 3, 5, and 10 months the specimens were removed for test purposes.

The mechanical cleaning technique employed consisted of a simulated M.A.N.[®] brush system. Four test tube brushes were mounted parallel so that, when viewed from the brush ends, a square was formed, 1-3/8 inches to a side as measured center-to-center on the brushes. Specimen cleaning consisted of six highly oscillating passes through the brushes (~25% brush compression) in a direction perpendicular to the mounted brushes. Cleaning was performed under flowing tap water. A schematic of this apparatus is shown in Figure III-9.

Chemical cleaning chosen utilized a non-proprietary mix that can be foamed. Four chemical solutions were screened for application in this test:

1. Mild - 1/2% wt. (maximum) hydrogen peroxide in deion water for 12 hours at ambient temperature. Deion water rinse.
2. Mild - 5% wt. sodium hypochlorite in deion water; 0.5% wt. sodium metasilicate; 12 hours at ambient temperature. Deion water rinse.
3. Alkaline - 5% wt. sodium carbonate in deion water; 5% wt. monosodium phosphate; 5% wt. trisodium phosphate; 0.5% wt. sodium metasilicate; 12 hours at ambient temperature. Deion water rinse.
4. Harsh-acid - 10% vol. conc. H_2SO_4 in deion water; 2% wt. chromic acid; 4 hours at ambient temperature. Deion water in rinse.

Of the solutions screened, the harsh acid cleaning solution provided the best results, based upon observed cleaning ability and solution corrosivity. Results of the screening tests are presented in Appendix A, Table IX-37. Specimens used in the tests were severely fouled aluminum alloy 3003-H14.

Upon sequential removal from the test environment, designated specimen groups were cleaned as indicated, photographed, observed, and reinserted in the test environment. In addition to specimens for sequential chemical and mechanical cleaning, a set of specimens was installed which were not cleaned until the conclusion of the test. After the 10-month observations were concluded, all specimens were ultrasonically acid cleaned, as described in Section IV-B, degreased, and weighed. Corrosion calculations and inspections were then performed, and a final photograph record of the specimen condition made.

Figure III-9

BRUSH ARRANGEMENT USED FOR MECHANICAL CLEANING

IV. AMMONIA IN SEAWATER

Ammonia in recirculating seawater tests were performed at both 5°C and 30°C to simulate OTEC condenser and evaporator temperature regimes. Leakage severity was tested by forming nominal ammonia concentration levels in the seawater of 8, 30, 80, and 800 ppm at the two temperatures. In addition, ambient temperature seawater controls were run in parallel with the 8, 30, and 800 ppm ammonia in seawater tests to assess the corresponding influences of seawater corrosion and fouling behavior. Relevant information sought consisted of fouling formation and corrosion performance of the subject alloys.

A. Scale Formation

Mixing of ammonia and water will result in hydrolysis of the ammonia to form ammonium and hydroxyl ions. The resulting solution is thus more alkaline, and in seawater an increase in alkalinity enhances calcium carbonate and magnesium hydroxide precipitate formation. Precipitates so formed may then nucleate and form scales on heat exchanger surfaces in a manner which will seriously impair heat transfer.

This set of problems is due to the nature of the hydrolysis of ammonia and to the formation of hydroxyl ion:

As a result of the hydroxyl ion formation, solutions of ammonia in water are very basic. Then, the hydroxyl ion in seawater reacts with bicarbonate (the predominant ionic form of carbon dioxide) to produce carbonate ion:

which in turn will react with calcium present to precipitate calcium carbonate:

Or, alternately, the hydroxyl ion produced by the hydrolysis of ammonia can react directly with the magnesium present in seawater to precipitate magnesium hydroxide:

In general, if sufficient ammonia is present, the sequence of chemical events would be:

1. conversion of HCO_3^- to $\text{CO}_3^{=}$
2. precipitation of CaCO_3
3. precipitation of $\text{Mg}(\text{OH})_2$
4. elevation of solution pH

In these tests ammonia was added to the recirculating seawater loop (with continuous refreshment) as ammonium hydroxide, ammonia already hydrolyzed to its product ions. Levels of addition were as previously stated. The results, summarized in Figure IV-1, indicate greater rates of scale/fouling growth at higher temperatures and concentrations of ammonia. Figure IV-2 is presented to indicate the corresponding increase in pH. Not indicated is a slight difference observed in initial scale nucleation rates for the subject alloys, in which CP titanium and pretreated aluminum alloy 5052-H14 were observed to very slightly retard initial scale growth.

Crystalline components of the scale were determined using X-ray diffraction, energy dispersive X-ray, and infrared spectral analysis. Scale composition development followed the pattern shown in Figure VI-3, with calcite forming initially followed by aragonite and brucite at higher ammonia concentrations and temperatures. At zero and 8 ppm ammonia in seawater primary constituents of the surface deposit are amorphous muds and organics.

Observations indicated that fouling/scale formation may be controllable at 8 ppm ammonia in seawater, 5°C and 30°C, and 30 ppm ammonia in seawater, 5°C, if a continuous cleaning process is employed. It is believed, however, that concentrations of ammonia in seawater above 80 ppm would not be economically controllable. Of the subject alloys tested, fouling appeared to be more easily removed from CP titanium and pretreated aluminum alloy 5052-H14. Figure IV-4 shows the scale at 10 days for the 800 ppm exposure.

B. Corrosion

Experience with the use of aluminum has indicated that this metal can be sensitive to pit attack in alkaline media. As seawater is slightly alkaline, and seawater plus ammonia is more alkaline, it was necessary to perform preliminary screening tests to evaluate specified aluminum alloys under environmental conditions as close as possible to conditions which may be encountered in an OTEC heat exchanger. Titanium, another contender for OTEC heat exchanger use, was also tested. Information sought in these coupon scale tests is final interval corrosion rate*, maximum pit penetration, and crevice attack. The resolved data for the subject alloys is summarized in Figures IV-5 and IV-6.

* "Final Interval" corrosion rate is a predicted long-term corrosion rate which the metal should experience after the surface has become passivated from continued exposure. The methodology involved in calculating this rate is given in Section III.C.3, "Data Resolution".

FIGURE IV-1

FOULING FORMATION *

* As formed on
Crevice Test Assembly
(~0.26 fps)

Ammonia Concentration (ppm)

FIGURE IV-2

AMMONIA CONCENTRATION VS pH

FIGURE IV-3

SCALE COMPOSITION
&
FORMATION

Figure IV-4

SCALE FORMATION ON CREVICE TEST ASSEMBLY
880 ppm AMMONIA IN SEAWATER AT 30°C

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

FIGURE IV-6
CORROSION SUMMARY: FINAL INTERVAL CORROSION RATE¹ AND MAXIMUM PIT DEPTH
SEAWATER MIXED WITH AMMONIA²
CONDENSER: 5°C

¹ FINAL INTERVAL CORROSION RATE DEFINITION AND CALCULATION IS DISCUSSED IN SECTION III.C.3, "DATA RESOLUTION."

² INCLUDES AMBIENT TEMPERATURE CONTROLS (~23°C) - MEAN VALUE FROM TABLE IX-1

1. Seawater Controls

Corrosion control tests were conducted using ambient temperature seawater at 5.0 fps in a once-through system. Seawater temperature was previously presented in Figure III-4. Control tests were run at periods coinciding with the 8, 30, and 800 ppm ammonia in seawater exposures. Detailed data for these tests is reported in Tables IV-1 and IX-1.

Corrosion on the seawater controls was marked by general, uniform surface attack and the absence of significant pitting. Corrosion rate for the untreated aluminum alloys was significantly influenced by the seawater temperature at test initiation. A comparison of like exposure periods in Table IV-1 indicates direct correlation between higher seawater temperature and increased corrosion penetration.

Average final interval corrosion rates for aluminum alloys 3003, 5052, and 5086, as based upon the final specimen pulls for the 8, 30, and 800 ppm ammonia in seawater, seawater corrosion controls was 2.2-2.6 mpy, with aluminum alloy 5086 giving the most consistent performance of the three untreated alloys. Treated aluminum alloy 5052 was superior to all aluminum tested with a average final interval corrosion rate of 0.60 mpy. CP titanium showed negligible attack and was generally superior to all metals on test.

2. Addition of 8 ppm Ammonia to Seawater

Tests at 5°C and 30°C in seawater with a nominal 8 ppm added ammonia were completed after 8, 29, and 64 day specimen pulls. For the test exposure at 30°C, aggressive pit attack was noted on aluminum alloys 3003, 5052, and 5086. Also, at 5°C, aggressive pit attack was noted on aluminum alloy 5052. Parallel ambient temperature seawater controls showed greater average corrosion penetration but insignificant pit attack on these same alloys. Performance of the crevice test specimens was generally superior to that of the weight loss coupons. CP titanium showed negligible pit attack and constituted the superior metal at these exposures followed by pretreated aluminum alloy 5052.

Tables IX-2 Through IX-6 in Appendix A list the corrosion and analytical data for the 8 ppm ammonia addition tests.

3. Addition of 30 ppm Ammonia to Seawater

Exposures utilizing a nominal 30 ppm ammonia addition at 5°C and 30°C were terminated after 14, 30, and 59 day specimen pulls. At 30°C, one or two pits 1-2 mils deep were noted on aluminum alloys 3003, 5052, and 5086. At 5°C, no significant

Table IV-1

CORROSION DATA FOR TEST

Total Average Penetration (mils) of
Ambient Temperature Seawater Controls

Average Seawater Temperature (°F) ¹		55°	70°	85°
Material	Exposure ¹ (days)			
Al 3003-H14	8	-	.157	-
	10	.094	-	-
	14	-	-	.456
	29	-	.337	-
	30	-	-	.677
	59	-	-	.909
	64	-	.414	-
Al 5052-H32	8	-	.165	-
	10	.090	-	-
	14	-	-	.391
	29	-	.322	-
	30	-	-	.562
	59	-	-	.763
	64	-	.400	-
Al 5052-H32 (treated)	8	-	.026	-
	10	.025	-	-
	14	-	-	.019
	29	-	.026	-
	30	-	-	.029
	59	-	-	.091
	64	-	.031	-
Al 5086-H32	8	-	.116	-
	10	.060	-	-
	14	-	-	.311
	29	-	.291	-
	30	-	-	.562
	59	-	-	.795
	64	-	.538	-
CP Titanium	8	-	W.G.	-
	10	W.G. ²	-	-
	14	-	-	.0008
	29	-	.003	-
	30	-	-	.0002
	59	-	-	.0008
	64	-	W.G.	-

¹ Each pull of the NH₃ in seawater corrosion test had a companion seawater control. This accounts for the variety of exposure time during the year.

² Weight Gain.

pit attack occurred. Crevice corrosion was not observed at the 30°C temperature exposure. At 5°C, 1-2 mils crevice attack penetration was noted on aluminum alloys 3003, 5052, and 5086. CP titanium gave the best corrosion performance of any metal tested at this exposure followed by pretreated aluminum alloy 5052.

Tables IX-8 through IX-13 in Appdneix A list the corrosion and analytical data for the 30 ppm ammonia addition tests.

4. Addition of 80 ppm Ammonia to Seawater

Exposures at 5°C and 30°C were completed with pulls at 10, 30, and 51 days. The proposed 60-day exposures were cut short because of extensive calcareous scaling within the units. Final interval corrosion rates for the aluminum alloys at 30°C were generally 50-100% of the average final interval corrosion rate of th ambient temperature seawater controls. Final interval corrosion rates at 5°C were minimal. Maximum observed pit depth on any specimen was estimated at less than 1 mil penetration. No significant crevice attack was noted on either test after 50 days although some slight impressions were present at the lower temperature. Again, CP titanium and pretreated aluminum alloy 5052 showed overall superior performance.

Tables IX-14 through IX-21 in Appendix A list the corrosion and analytical data for the 80 ppm ammonia in seawater exposures.

5. Addition of 800 ppm Ammonia to Seawater

The 5°C and 30°C exposures at 800 ppm ammonia in seawater were terminated at 10 days because of excessive scaling. Both final interval corrosion rates and pitting were negligible, a factor probably related to the rapid scaling.

Tables IX-22 through IX-27 in Appendix A list the corrosion and analytical data for the 800 ppm ammonia in seawater exposure.

V. SEAWATER IN AMMONIA

Seawater in ammonia tests were performed at 5°C, the OTEC condenser temperature, and at addition severities of a nominal 0*, 0.1, 1.0, and 2.5% seawater concentration. Analysis performed for each exposure included percent water by volumetric evaporation or barium oxide absorption, sodium ion concentration by atomic adsorption analysis, and chloride ion concentration by the Volhard method of analysis. Scale was not observed to form within the test unit over the range of seawater concentrations investigated. In addition to scaling possibilities, relevant information sought consisted of final interval corrosion rates, maximum pit depth, and crevice attack for the subject alloys. Pit and final interval corrosion rates for these test exposures are summarized in Figure V-1.

A. Anhydrous Ammonia

Corrosion tests in 5°C commercially pure anhydrous ammonia (151 ppm water) were terminated after 10 and 38 day specimen exposures. Pit, crevice, and uniform corrosion attack were minimal on all alloys tested. Initial high penetrations

observed on pretreated aluminum alloy 5052 did not increase significantly for subsequent exposure periods, so that at the conclusion of the test all aluminum alloy penetrations were comparable. CP titanium demonstrated corrosion resistance superior to that of any metal tested, followed in order by pretreated aluminum alloy 5052 and aluminum alloys 5052, 3003, and 5086.

Tables IX-28 through IX-30 in Appendix A list the corrosion and analytical data for this exposure.

B. Anhydrous Ammonia plus 0.1% Seawater

Corrosion tests in 5°C anhydrous ammonia with 0.1% nominal seawater were terminated after 10 and 24 day exposure periods. Pitting and crevice attack was negligible for all alloys tested. Final interval corrosion rates for aluminum alloys 3003, 5052, and 5086 are less than 0.12 mpy at 2.5 fps and 0.43-0.69 mpy at 5.6 fps, thus indicating a significant velocity effect at this exposure. Initial high average corrosion penetrations for pretreated aluminum alloy 5052 give a final interval corrosion rate at 24 days which is negligible. The superior metals at this exposure are CP titanium and pretreated aluminum alloy 5052.

Tables IX-28, 31, 32, and 33 summarize the corrosion and analytical data for this exposure.

* Measured water content ~150 ppm.

FIGURE V-I
CORROSION SUMMARY: FINAL INTERVAL CORROSION RATE¹ AND MAXIMUM PIT DEPTH
AMMONIA MIXED WITH SEAWATER
CONDENSER: 5°C

FPS.
2.5 5.6

¹ FINAL INTERVAL CORROSION RATE IS DISCUSSED IN SECTION III.C.3, "DATA RESOLUTION."

C. Anhydrous Ammonia plus 1.0% Seawater

Corrosion tests in 5°C anhydrous ammonia plus 1% nominal seawater were terminated after specimen exposure periods of 10, 28, and 59 days. Pitting and crevice attack was negligible except for one pit observed on aluminum alloy 5052 at 5.6 fps. Initial high corrosion penetrations on pretreated aluminum alloy 5052 did not continue to increase significantly so that after 59 days this alloy showed negligible additional attack. CP titanium constituted the superior metal at this exposure followed by pretreated aluminum alloy 5052.

Tables IX-28, 34, and 35 in Appendix A list the corrosion and analytical data for this exposure.

D. Anhydrous Ammonia plus 2.5% Seawater

Corrosion tests in 5°C anhydrous ammonia plus a nominal 2.5% seawater were terminated after 10, 30, and 53 day exposures. Pit and crevice attack were negligible at this exposure although final interval corrosion rates for aluminum alloys 3003, 5052, and 5086 were greater than for ammonia exposures with lower seawater percentages. Initial high penetrations on pretreated aluminum alloy 5052 did not continue to increase significantly through the 53-day exposure. CP titanium again constituted the superior metal for this exposure followed by pretreated aluminum alloy 5052.

Tables XI-28, 36, and 37 in Appendix A list the corrosion and analytical data for this exposure.

VI. SPECIAL CLEANING TESTS

Cleaning test specimens were continuously exposed to ambient temperature, unfiltered seawater for a total of 10 months with specimen cleaning pulls at 1, 2, 3, and 7 months. Additionally, an extra set of specimens (Group 2) was entered and specimen cleaning pulls conducted at 1½, 6, and 9 month intervals. Mechanical (M.A.N.® Brush) and chemical (sulfuric/chromic acid) cleaning procedures were as previously outlined in the section "Specimen Procedures". In addition to these tests, a set of uncleaned corrosion control blanks were inserted in the test. At 10 months all specimens were ultrasonically acid cleaned to permit determination of specimen corrosion rate.

Neither the chemical or mechanical cleaning tests conducted were intended to be sufficiently comprehensive to suggest a cleaning system for use in an OTEC plant. More extensive testing on a more continuous basis is strongly suggested.

Results of this testing are summarized in Figure VI-1. Uncleaned corrosion control specimens gave the best corrosion performance, closely followed by specimens cleaned using the simulated M.A.N.® brush system. Film buildup on the uncleaned controls was severe, however, and it is believed that the resulting loss of heat transfer could not be tolerated in an OTEC plant. Further, corrosion rates which might be attributed to the daily use of a M.A.N.® brush system cannot accurately be extrapolated from these tests. However, based on these cursory results, a mechanical cleaning system is the preferred mechanism of fouling control for the aluminum alloys tested.

The performance of CP titanium was independent of cleaning techniques employed, showing overall excellent performance. Pretreated aluminum 5052 provided the lowest general corrosion rate of any aluminum alloy; however this material was subject to very severe pit attack under debris which would accumulate at the upstream specimen end. Severe pit attack was not noted on aluminum alloys 3003, 5052, and 5086, although very broad but shallow pit depressions would again occur at the upstream specimen end. For the uncleaned corrosion controls, aluminum alloy 5086 was followed in corrosion performance by aluminum alloy 5052 and 3003, although mechanically cleaned specimens of these same alloys gave almost identical corrosion rates.

FIGURE VI-1

TOTAL AVERAGE PENETRATION vs. CLEANING METHOD*

Cleaning Method:

C : Uncleaned Controls

M : Mechanical (MAN Brush)

A : Acid Chemical Cleaning

*Bar "C" is representative of a 10-month exposure without intermediate cleaning. Bars "M" and "A" represent 3-5 sequential cleaning experiences over 9-10 months. Final cleaning was standard laboratory practice.

VII. RECOMMENDATIONS

1. Coupon tests are generally not designed to qualify specific materials for extended use application. These results indicate that further qualification tests of aluminum alloys for OTEC should proceed under a more rigorous environmental test simulation. Specifically, tubes should be tested with once-through flowing seawater having simulated ammonia leakage. Ultimately, full-scale mechanical cleaning equipment should be installed and employed.
2. In addition to aluminum alloys and CP titanium, it is recommended that a chloride-resistant stainless steel and copper alloy 706 be included in further qualification testing.

BIBLIOGRAPHY

1. Barkman, E. F. and R. I. Lindberg. "Aluminum Alloys for Use in Heat Exchanger Tubing for OTEC Applications", R. H. Gray (ed), Proceedings of the Ocean Thermal Energy Conversion (OTEC) Bio-fouling and Corrosion Symposium, National Technical Information Service, Springfield, Va. PNL-SA-7115, Oct. 1977. pp. 305-318.
2. Bonewitz, R. A. "Application of Aluminum Alloys", G. E. Ioup (ed), Proceedings Fourth Annual Conference On Ocean Thermal Energy Conversion, July 1977. pp. VI:37-40.
3. Bonewitz, R. A. "Corrosion of Aluminum in Ammonia-Water Mixtures", Aluminum Co. of America, Alcoa Center, Pa., March 1973.
4. Dow Chemical Co. "Seawater Corrosion Test Program, Part IV", for O.S.W., U.S. Dept. of the Interior, April 1975.
5. Fritsch, A., W. Adamson, and W. Castelli. "An Evaluation of Mechanical Cleaning Methods for Removal of Soft Fouling from Heat Exchanger Tubes in OTEC Power Plants", R. H. Gray (ed), Proceedings of the Ocean Thermal Energy Conversion (OTEC) Bio-fouling and Corrosion Symposium, National Technical Information Service, Springfield, Va. PNL-SA-7115, Oct. 1977. pp. 159-166.
6. Griffin, O. M. "Power from the Oceans' Thermal Gradients", Sea Technology, Vol. 18, No. 8, August 1977. pp. 11-15, 38-39.
7. LaQue, F. L. "Ocean Thermal Energy Conversion Corrosion Problems and Possible Solutions", R. H. Gray (ed), Proceedings of the Ocean Thermal Energy Conversion (OTEC) Biofouling and Corrosion Symposium, National Technical Information Service, Springfield, Va. PNL-SA-7115, Oct. 1977. pp. 209-222.
8. McIlhenny, W. F. "Chapter 21: Extraction of Economic Inorganic Materials from Seawater", Riley and Skirrow (eds), Chemical Oceanography, 2nd Ed., Vol. 4, Academic Press, New York, 1975. pp. 155-218.
9. National Association of Corrosion Engineers. "Laboratory Corrosion Testing of Metals for the Process Industries", N.A.C.E., Katy, Tex. NACE Standard TM-01-69 (Revised 1972).
10. Perrigo, L. D., and G. A. Jensen. "Ocean Thermal Energy Conversion System Biofouling and Corrosion Problems", Battelle Pacific Northwest Laboratories, Seattle, Wash. No. BNWL-SA-5970, Sept. 1976.
11. Uhlig, H. H. Corrosion and Corrosion Control, John Wiley & Sons, Inc., New York, 1971.
12. York, J. L., and B. J. Schorle. "Chapter 10: Scale Formation and Prevention", K. S. Spiegler (ed), Principles of Desalination, Academic Press, New York, 1966. pp. 497-514.

Appendix A
Detailed Tabular Data

TABLE IX-1

FINAL INTERVAL CORROSION RATE (mpy)¹
FOR AMBIENT TEMPERATURE SEAWATER CONTROLS

Material	Average Seawater Temperature (°F)	Final Intervals Considered (Days)	Final Interval Corrosion Rate (mpy) Average
Al 3003-H14	55°	0-10	2.4
	70°	29-64	
	85°	30-59	
Al 5052-H32	55°	0-10	2.22
	70°	29-64	
	85°	30-59	
Al 5052-H32 (treated)	55°	0-10	.59
	70°	29-64	
	85°	30-59	
Al 5086	55°	0-10	2.57
	70°	29-64	
	85°	30-59	
CP Titanium	55°	0-10	Nil
	70°	29-64	
	85°	30-59	

¹ "Final Interval" corrosion rate is a predicted long-term corrosion rate which the metal should experience after the surface has become passivated from continued exposure. The methodology involved in calculating this rate is given in Section III.C.3, "Data Resolution."

TABLE IX-2

FINAL INTERVAL CORROSION RATES (mpy)¹⁻² FOR
TEST EXPOSURES OF 8.0 PPM AMMONIA IN SEAWATER

Temperature Ammonia Concentration (ppm) Velocity (fps)	31°C 7.4		5°C 8.5	
	<u>2.5</u>	<u>5.6</u>	<u>2.5</u>	<u>5.6</u>
<u>Material</u>				
Al 3003-H14	.55	.11	.006	.039
Al 5052-H32	.15	1.05	.049	.11
Al 5052-H32 (treated)	.13	.009	.004	.071
Al 5086-H32	Nil ³	.18	.039	.094
Cp Titanium	Nil	Nil	Nil	Nil

¹ Based on 29 to 64 day corrosion data

² "Final Interval" Corrosion rate is a predicted long-term corrosion rate which the metal should experience after the surface has become passivated from continued exposure. The methodology involved in calculating this rate is given in Section III.C.3, "Data Resolution."

³ Nil-zero or negative corrosion rate.

TABLE IX-3

TOTAL AVERAGE PENETRATION (mils) FOR
TEST EXPOSURES OF 8.0 PPM AMMONIA IN SEAWATER

Temperature		31°C			5°C		
Ammonia Concentration (ppm)		7.4			8.5		
Velocity (feet per sec.)		<u>Crevice</u>	<u>2.5</u>	<u>5.6</u>	<u>Crevice</u>	<u>2.5</u>	<u>5.6</u>
<u>Material</u>	<u>Exposure (days)</u>						
Al 3003-H14	8	--	.057	.085	--	.068	.077
	29	--	.068	.108	--	.081	.087
	64	.033	.120	.119	.047	.082	.091
Al 5052-H32	8	--	.092	.148	--	.070	.079
	29	--	.075	.122	--	.079	.087
	64	.031	.089	.223	.052	.084	.098
Al 5052-H32 (Treated)	8	--	.026	.024	--	.025	.029
	29	--	.013	.025	--	.020	.023
	64	.021	.026	.026	.017	.021	.030
Al 5086-H32	8	--	.102	.110	--	.068	.084
	29	--	.131	.123	--	.078	.087
	64	.040	.100	.142	.142	.082	.096
CP Titanium	8	--	W.G. ¹	W.G.	--	W.G.	W.G.
	29	--	W.G.	W.G.	--	W.G.	.002
	64	.0002	W.G.	W.G.	.0002	W.G.	W.G.

¹ W.G. signifies weight gain (zero penetration).

TABLE IX-4

CORROSION DATA FOR TEST
30°C SEAWATER + 7.5 PPM AMMONIA
Total Average Penetration (mils)¹ and (Max. Pit Depth, mils)

Exposure (days)	8		29		64		Crevice	Pitting Observations ²
	2.5	5.6	2.5	5.6	2.5	5.6		
A1 3003-H14	.057		.068		.120		.033	<p>At 2.5 fps, a very few incipient pits at 8 days, increasing to 1 pit, and 4 larger pits (up to 0.15 cm long and 3 mils deep) at 29 days, and at 64 days 1 pit 0.3 cm in diameter and 14 mils deep.</p> <p>At 5.6 fps, a very few incipient pits at 8 days, increasing to 2 pits up to .15 cm long and 2 mils deep at 29 days, with 2 small pits and 2 pits observed at 64 days.</p> <p>A very few incipient pits, 1 pit, and slight surface attack were noted at the crevice of the crevice specimen.</p>
		.085		.108		.119		
	(<0.5)	(3)		(14)				
	(<0.5)		(2)		(2)		(2)	
A1 5052-H32	.092		.075		.089		.031	<p>At 2.5 fps, a few incipient pits at 8 days, 1 small pit, and 15 large pits with lengths up to 0.5 cm and depths to 14 mils. At 29 days, a very few incipient pits, 2 small pits, and 1 pit 0.25 cm across and 10 mils deep were observed. At 64 days, a very few incipient pits, 2 small pits, and 9 larger pits (up to 1 cm length and 21 mils deep) were observed.</p> <p>At 5.6 fps, a very few incipient pits and 22 large pits (up to 0.7 cm long and 15 mils deep) were observed, and at 64 days 1 small pit, 3 pits, and 1 pit 0.5 cm long and 8 mils deep were observed.</p> <p>On the crevice specimen, crevice attack 1-2 mils deep was noted at 4 locations under the artificial crevice. In addition, a very few incipient pits, 3 small pits, and 1 pit were observed over the specimen surface.</p>
		.148		.122		.223		
	(14)		(10)		(21)		(2)	
		(15)		(1)		(8)		

(continued)

Table IX-4 (continued)

Exposure (days) Velocity (fps)	8		29		64		Crevice	Pitting Observations
	2.5	5.6	2.5	5.6	2.5	5.6		
A1 5052-H32 (Treated)	.026 (<0.5) (1.0)	.013 (<0.5) (<0.5)	.026 (2)	.021 (2)				At 2.5 fps, a very few incipient pits at 8 and 29 days, increasing to 3 small pits and 2 pits at 64 days. At 5.6 fps, a very few incipient pits and 1 small pit present at 8 days, and 2 pits present at 64 days. Slight crevice attack was noted at one point of the crevice specimen. A very few incipient pits, 2 small pits, and 1 pit were observed elsewhere on the specimen.
A1 5086-H32	.102 (11) (6)	.131 (14) (10)	.100 (12)	.040 (2)				At 2.5 fps, a very few incipient pits and 4 large pits (up to 0.25 cm long and 11 mils deep) were observed at 8 days. At 29 days, a few incipient pits, 2 small pits, and 1 pit 0.3 cm long and 14 mils deep were observed, and at 64 days, 2 small pits, 4 pits, and 2 large pits (up to 0.3 cm in length and 12 mils penetration) were observed. At 5.6 fps, a few incipient pits, and 4 large pits (up to 0.15 cm in diameter and 6 mils deep) were observed at 8 days, 2 large pits (up to a diameter of .35 cm and 10 mils deep) were observed at 29 days, and 3 small pits, 1 pit, and 3 large pits (to 0.10 cm diameter and 3 mils deep) were observed at 64 days. Crevice attack was noted at 9 points under the artificial crevice of the crevice specimen. In addition, a few incipient pits and 3 small pits were also observed.

(continued)

Table IX-4 (continued)

Exposure (days)	8		29		64		Crevice	Pitting Observations
	2.5	5.6	2.5	5.6	2.5	5.6		
C.P. Titanium	W.G. ³		W.G.		W.G.		.0002	At 2.5 fps, a very few indipient pits at 8 days, and a few incipient pits at 29 and 64 days were observed. At 5.6 fps, a few incipient pits at 8 and 29 days and several at 64 days were observed. A few incipient pits, no crevice attack, were observed on the crevice specimen.
		W.G.		W.G.		W.G.		
	(<.5)		(<.5)		(<.5)		(<.5)	
		(<.5)		(<.5)		(<.5)		

¹ Total Average Penetration corrected for losses occurring during post exposure cleaning.

² Because of the small surface area of the coupons and the short period of exposure, pitting data was based upon the following key:

Incipient pitting: Pits less than 0.5 mils deep, discernable as pits under 25 x magnification.

Small pits: Pits 1.0-0.5 mils deep, discernable as pit under 10x magnification and visible to naked eye.

Pits: Pits 1-2 mils deep (unless otherwise indicated), readily visible as pits to naked eye.

Very Few: Less than 5/sq. in.

Few: 5-10/sq. in.

Several: 10-15/sq. in.

Numerous: More than 15/sq. in.

³ Weight Gain

TABLE IX-5
CORROSION DATA FOR TEST
5°C SEAWATER + 8.5 PPM AMMONIA
Total Average Penetration (mils)¹ and (Max. Pit Depth, mils)

Exposure (days) Velocity (fps)	8		29		64		Crevice	Pitting Observations ²
	2.5	5.6	2.5	5.6	2.5	5.6		
Al 3003-H14	.068 (<0.5)	.077 (<0.5)	.081 (1.0)	.087 (1.0)	.082 (1.0)	.091 (1.0)	.047 (2)	At 2.5 fps, a very few incipient pits at 8 days, increasing to a few incipient pits and 39 small pits at 29 days and a few incipient pits at 64 days. At 5.6 fps, a few incipient pits and 37 small pits present at 29 days and 3 small pits present at 64 days. One pit 2 mils deep resulting from crevice attack on crevice specimen; a few incipient pits, 4 small pits and 2 pits were also observed.
Al 5052-H32	.070 (<0.5)	.079 (<0.5)	.079 (1.0)	.087 (1.0)	.084 (2.0)	.098 (21)	.052 (1.0)	At 2.5 fps, a very few incipient pits at 8 days, increasing at 29 days to 7 small pits, increasing at 64 days to a few incipient pits, 2 small pits, and 1 pit. At 5.6 fps, a very few incipient pits at 8 days, increasing to a few incipient pits and 4 small pits at 29 days, increasing to several incipient pits, 2 small pits, and two large pits (up to 0.25 cm length and 21 mils deep). A very few incipient pits were noted on the crevice specimen with one surface etch and 1 small pit at the crevice.
Al 5052-H32 (Treated)	.025 (<0.5)	.029 (<0.5)	.020 (<0.5)	.023 (1.0)	.021 (2.0)	.030 (<0.5)	.017 (1.0)	At 2.5 fps, a very few incipient pits were observed at 8 and 29 days, and one pit was observed at 64 days. At 5.6 fps, a very few incipient pits were observed at 8 and 29 days, with 1 small pit at 29 days and a few incipient pits at 64 days. A very few incipient pits and 1 small pit were noted on the crevice specimen.

(continued)

Table IX-5 (continued)

Exposure (days) Velocity (fps)	8		29		64		Crevice	Pitting Observations
	2.5	5.6	2.5	5.6	2.5	5.6		
A1 5086-H32	.068		.073		.082		.142	<p>At 2.5 fps, a few incipient pits were observed at 8 and 29 days, with 17 small pits present at 29 days and several incipient pits and 1 small pit at 64 days.</p> <p>At 5.6 fps, several incipient pits at 8 days, and a few incipient pits and 11 small pits at 29 days and 1 small pit at 64 days.</p> <p>A few incipient pits and 2 small pits were noted on the specimen surface.</p>
		.084		.087		.096		
	(<0.5)		(1.0)		(1.0)		(1.0)	
		(<0.5)	(1.0)		(1.0)		(1.0)	
C.P. Titanium	W.G. ³		W.G.		W.G.		.0002	A few incipient pits were observed at all indicated exposures.
		W.G.		.002		W.G.		
	(<0.5)		(<0.5)		(<0.5)		(<0.5)	
		(<0.5)		(<0.5)		(<0.5)		

¹ Total Average Penetration corrected for losses occurring during post exposure cleaning.

² Because of the small surface area of the coupons and the short period of exposure, pitting data was based upon the following key:

Incipient pitting: Pits less than 0.5 mils deep, discernable as pits under 25 x magnification.

Small pits: Pits 1.0-0.5 mils deep, discernable as pit under 10x magnification and visible to naked eye.

Pits: Pits 1-2 mils deep (unless otherwise indicated), readily visible as pits to naked eye.

Very Few: Less than 5/sq. in.

Few: 5-10/sq. in.

Several: 10-15/sq. in.

Numerous: More than 15/sq. in.

³ Weight Gain

TABLE IX-6

FOULING FORMATION
Seawater + Nominal 8.0 ppm Ammonia
and Ambient Temperature Seawater Controls

Substrate:		Titanium		Aluminum ¹		Crevice Unit (0.26 fps)	Comments
Velocity (fps)		2.5	5.6	2.5	5.6		
Temp., °C	Period, days	Scale Thickness, mils		Thickness, mils			
30°	8	1		1.5			A dark brown deposit, thin and adherent, with a tendency to flake when dry. On aluminum, corrosion products form a thicker deposit formation than the surrounding scale. Crystalline deposit components are aluminum and amorphous components are probably sulfates, iron oxide (hydroxide), and possibly CaCO ₃ .
			1.5		1		
	29	1.5		2			
			1		1		
5°	64	1.5		2		1.5	A dark brown adherent deposit covers the specimen in a uniform layer. Composition is as for 30°C.
			2		2		
	8	<.5		0.5			
			<.5		0.5		
Ambient	29	1.5		1			Initially a surface stain which develops into a brown tan fouling deposit. Mud with traces of organic matter is the final product. Composition is as for 30°C.
			1.5		1		
	64	1.5		1		1	
			1.5		1		
Ambient	8	<.5		.5			Initially a surface stain which develops into a brown tan fouling deposit. Mud with traces of organic matter is the final product. Composition is as for 30°C.
			<.5		<.5		
	29	<.5		0.5			
			<.5		0.5		
Ambient	64	1.5		1			Initially a surface stain which develops into a brown tan fouling deposit. Mud with traces of organic matter is the final product. Composition is as for 30°C.

¹ Pretreated aluminum alloy 5052 had a fouling behavior more similar to titanium than the remaining aluminum alloys.

TABLE IX-7

SUMMARY OF EXPOSURE CONDITIONS
Nominal 8 ppm NH₃

<u>Dates</u>	<u>Temp. (°C)</u>	<u>Blowdown (gpm)</u>	<u>Ca⁺⁺ (ppm)</u>		<u>pH</u>	<u>NH₃ Conc.</u>	
			<u>In</u>	<u>Out</u>		<u>Days</u>	<u>ppm</u>
2-28-78	30	0.5	365	321	8.4	8	7.4
3-3-78						29	7.1
						64	7.5
2-28-78	5	0.5	365	337	8.6	8	8.7
3-3-78						29	8.2
						64	8.5
2-28-78 (controls)	Ambient	--	365	365	7.9	--	--

TABLE IX-8

FINAL INTERVAL CORROSION RATES (mpy)^{1,2} FOR
TEST EXPOSURES OF 30.0 PPM AMMONIA IN SEAWATER

Temperature	32°C		5°C	
Ammonia Concentration (ppm)	27.2		26.6	
Velocity (fps)	2.5	5.6	2.5	5.6
<u>Material</u>				
Al 3003-H14	.035	.013	.013	.094
Al 5052-H32	.047	.035	.055	.074
Al 5052-H32 (treated)	.097	.13	.059	.079
Al 5086-H32	Nil ³	.086	.057	.016
CP Titanium	Nil	Nil	.004	Nil

¹ Based on 30 to 59 day corrosion data.

² "Final Interval" corrosion rate is a predicted long-term corrosion rate which the metal should experience after the surface has become passivated from continued exposure. The methodology involved in calculating this rate is given in Section III.C.3, "Data Resolution."

³ Nil-Zero or negative corrosion rate.

TABLE IX-9

TOTAL AVERAGE PENETRATION (mils) FOR
TEST EXPOSURES OF 30 PPM AMMONIA IN SEAWATER

Temperature		32°C			5°C		
Ammonia Concentration (ppm)		33.4			24.3		
Velocity (feet per sec.)		<u>Crevice</u>	<u>2.5</u>	<u>5.6</u>	<u>Crevice</u>	<u>2.5</u>	<u>5.6</u>
<u>Material</u>	<u>Exposure (days)</u>						
Al 3003-H14	14	-	.026	.033	-	.029	.031
	30	-	.028	.036	-	.033	.036
	59	.016	.031	.037	.057	.034	.044
Al 5052-H32	14	-	.021	.026	-	.031	.036
	30	-	.021	.028	-	.030	.033
	59	.016	.024	.031	.117	.034	.039
Al 5052-H32 (Treated)	14	-	.020	.020	-	.003	.012
	30	-	.028	.021	-	.010	.010
	59	.023	.029	.031	.003	.015	.016
Al 5086-H32	14	-	.026	.024	-	.020	.018
	30	-	.025	.029	-	.021	.023
	59	.015	.024	.035	.188	.026	.024
C.P. Titanium	14	-	.002	.002	-	.0004	.002
	30	-	.0006	W.G.	-	.0008	.0008
	59	W.G. ¹	W.G.	.0006	.0005	.0011	.0006

¹ Weight Gain

TABLE IX-10

CORROSION DATA FOR TEST
30°C Seawater + 27.2 ppm Ammonia

Total Average Penetration (mils)¹ and (Max. Pit Depth, mils)

Exposure (days) Velocity (fps)	14		30		59		Crevice	Pitting Observations ^{2,4}
	2.5	5.6	2.5	5.6	2.5	5.6		
Al 3003-H14	.026 (<0.5)	.033 (2.0)	.028 (2.0)	.036 (2.0)	.013 (2.0)	.037 (1.0)	.016 (<0.5)	At 2.5 fps, a very few incipient pits were observed at 14 days with several incipient pits, one small pit, and one pit at 30 days and one pit observed at 59 days. At 5.6 fps, a very few incipient pits and one pit were observed at 14 days, several incipient pits, one small pit, and one pit at 30 days, and one small pit at 59 days. A few incipient pits were observed on the crevice specimen.
Al 5052-H32	.021 (<0.5)	.026 (<0.5)	.021 (2.0)	.028 (<0.5)	.024 (<0.5)	.031 (<0.5)	.016 (<0.5)	At 2.5 fps, a very few incipient pits were observed at 14 days, with an additional pit at 30 days and a few incipient pits observed at 59 days. At 5.6 fps, a few incipient pits were observed. A few incipient pits were observed on the crevice specimen.
Al 5052-H32 (Treated)	.020 (<0.5)	.020 (<0.5)	.028 (<0.5)	.021 (<0.5)	.029 (1.0)	.031 (<0.5)	.023 (1.0)	At 2.5 fps, a few incipient pits were observed at 14 days and an additional two small pits were observed at 59 days. At 5.6 fps, a few incipient pits were observed. The crevice specimen had a very few incipient pits and 2 small pits.

(continued)

Table IX-10 (continued)

Exposure (days) Velocity (fps)	14		30		59		Crevice	Pitting Observations ^{2,4}
	2.5	5.6	2.5	5.6	2.5	5.6		
Al 5086-H32	.026 (<0.5)	.024 (<0.5)	.025 (<0.5)	.029 (2.0)	.024 (1.0)	.035 (<0.5)	.015 (<0.5)	At 2.5 fps, a very few incipient pits were observed at 14 and 30 days, with the addition of one small pit at 59 days. At 5.6 fps, a very few incipient pits were observed with one pit present at 30 days. A very few incipient pits were observed on the crevice specimen.
C.P. Titanium	.002 (<0.5)	.002 (<0.5)	.0006 (<0.5)	W.G. (<0.5)	W.G. ³ (1.0)	.0006 (<0.5)	W.G. (<0.5)	A few incipient pits were observed on all exposures except for a small pit observed at 59 days at 2.5 fps.

¹ Total Average Penetration corrected for losses occurring during post exposure cleaning.

² Because of the small surface area of the coupons and the short period of exposure, pitting data was based upon the following key:

Incipient pitting: Pits less than 0.5 mils deep, discernable as pits under 25x magnification.
Small pits: Pits 1.0-0.5 mils deep, discernable as pits under 10x magnification and visible to naked eye.

Pits: Pits 1-2 mils deep (unless otherwise indicated), readily visible as pits to naked eye.

Very Few: Less than 5/sq. in.

Few: 5-10/sq. in.

Several: 10-15/sq. in.

Numerous: More than 15/sq. in.

³ Weight Gain.

⁴ Max. pit depth 0.5-2.0 mil on any specimen.

TABLE IX-11

CORROSION DATA FOR TEST
5°C Seawater + 26.6 ppm Ammonia
Total Average Penetration (mils)¹ and (Max. Pit Depth, mils)

Exposure (days)	14		30		59		Pitting Observations ^{2,3}
Velocity (fps)	2.5	5.6	2.5	5.6	2.5	5.6	
Al 3003-H14	.029 (<0.5)	.031 (<0.5)	.033 (<0.5)	.036 (1.0)	.034 (<0.5)	.057 (2.0)	At 2.5 fps, a few incipient pits were observed. At 5.6 fps, a few incipient pits were observed at 14 days, one small pit at 30 days, and four small pits at 59 days. On the crevice specimen, several incipient pits and one pit were observed in addition to eight small pits and nine pits resulting from crevice attack.
Al 5052-H32	.031 (<0.5)	.036 (<0.5)	.030 (<0.5)	.033 (1.0)	.034 (2.0)	.117 (1.0)	At 2.5 fps, a few incipient pits were observed at 14 and 30 days, with an additional small pit and pit present at 59 days. At 5.6 fps, a few incipient pits were observed with two small pits present at 30 days. On the crevice specimen, several incipient pits were observed in addition to three small pits resulting from crevice attack.
Al 5052-H32 (Treated)	.003 (<0.5)	.012 (<0.5)	.010 (<0.5)	.010 (<0.5)	.015 (<0.5)	.003 (<0.5)	A few incipient pits were observed at all exposures.

(continued)

Table IX-11 (continued)

Exposure (days)	14		30		59		Crevice	Pitting Observations ²
	2.5	5.6	2.5	5.6	2.5	5.6		
Al 5086-H32	.020		.021		.026		.188	<p>At 2.5 fps, a few incipient pits at 14 days increasing to one small pit at 59 days.</p> <p>At 5.6 fps, a few incipient pits were observed.</p> <p>On the crevice specimen, several incipient pits and eight small pits were observed with and additional nine small pits and three pits resulting from crevice attack.</p>
		.018		.023		.024		
	(<0.5)		(<0.5)		(2.0)		(2.0)	
		(<0.5)		(<0.5)		(<0.5)		
C.P. Titanium	.0004		.0008		.0011		.0005	<p>At 2.5 fps and 5.6 fps, several incipient pits were noted.</p> <p>On the crevice specimen, a very few incipient pits were present.</p>
		.002		.0008		.0006		
	(<0.5)		(<0.5)		(<0.5)		(<0.5)	
		(<0.5)		(<0.5)		(<0.5)		

¹ Total Average Penetration corrected for losses occurring during post exposure cleaning.

² Because of the small surface area of the coupons and the short period of exposure, pitting data was based upon the following key:

Incipient pitting: Pits less than 0.5 mils deep, discernable as pits under 25x magnification.

Small pits: Pits 1.0-0.5 mils deep, discernable as pits under 10x magnification and visible to naked eye.

Pits: Pits 1-2 mils deep (unless otherwise indicated), readily visible as pits to naked eye.

Very Few: Less than 5/sq. in.

Few: 5-10/sq. in.

Several: 10-15/sq. in.

Numerous: More than 15/sq. in.

³ Max. pit depth 0.5-2.0 mil on any specimen.

TABLE IX-12

FOULING FORMATION
Seawater + Nominal 30 ppm Ammonia
and Ambient Temperature Seawater Controls

Substrate:		<u>Titanium</u>		<u>Aluminum</u> ¹		Crevice Unit (0.26 fps)	Comments
Velocity (fps)		2.5	5.6	2.5	5.6		
Temp., °C	Period, days	Scale Thickness, mils					
30	14	0.5		2.0			A hard, adherent, light brown scale which may be removed from the specimen by flexing the metal coupon. Primary constituents of the scale are two crystalline forms of CaCO_3 , calcite and aragonite.
			0.5		1.5		
	30	4		6			
			1.5		3		
	59	27		29		17	
			14		14		
5	14	<0.5		<0.5			A thin, adherent, light brown deposit with no tendency to chip or flake. Calcite is the major crystalline component present, with trace amounts of Ca(OH)_2 , CaCl_2 , and quartz also present.
			<0.5		<0.5		
	30	0.5		1.0			
			0.5		<0.5		
	59	1.5		1.5		4	
			0.5		1.0		
Ambient	14		1.0		1.0		A muddy, dark brown deposit on specimen surface. A clay of the mica group (ferriphlogopite) is the primary crystalline component present.
	30		1.0		1.0		
	59		1.5		3.0		

¹ Pretreated aluminum alloy 5052 had a fouling behavior more similar to titanium than the remaining aluminum alloys.

TABLE IX-13

SUMMARY OF EXPOSURE CONDITIONS
Nominal 30 ppm NH₃

<u>Dates</u>	<u>Temp.</u> <u>(°C)</u>	<u>Blowdown</u> <u>(gpm)</u>	<u>Ca⁺⁺ (ppm)</u>		<u>pH</u>	<u>NH₃ Conc.</u>	
			<u>In</u>	<u>Out</u>		<u>Days</u>	<u>ppm</u>
5-15-78	30	0.5	460	400	8.91	14	33.4
7-15-78						30	24.5
						59	27.2
5-16-78	5	0.5	460	449	8.99	14	24.3
7-15-78						30	25.7
						59	26.6
5-16-78 7-15-78 (controls)	Ambient	--	460	460	8.0	--	--

TABLE IX-14

FINAL INTERVAL CORROSION RATES (mpy)^{1,2} FOR
TEST EXPOSURES OF 80 ppm AMMONIA

Temperature Ammonia Concentration (ppm) Velocity (fps)	30°C 83		7°C 78	
	<u>2.5</u>	<u>5.6</u>	<u>2.5</u>	<u>5.6</u>
<u>Material</u>				
Al 3003-H14	1.68	2.46	Nil ³	.025
Al 5052-H32	1.43	1.80	Nil	.040
Al 5052-H32 (treated)	.60	Nil	Nil	Nil
Al 5086-H32	1.22	1.53	Nil	.20
CP Titanium	Nil	.11	Nil	Nil

¹ Based on 30 to 50 (30°C) and 32 to 51 (5°C) corrosion data.

² "Final Interval" corrosion rate is a predicted long-term corrosion rate which the metal should experience after the surface has become passivated from continued exposure. The methodology involved in calculating this rate is given in Section III.C.3, "Data Resolution."

³ Nil-Zero or negative corrosion rate.

TABLE IX-15

TOTAL AVERAGE PENETRATION (mils) FOR
TEST EXPOSURES OF 30 PPM AMMONIA IN SEAWATER

Temperature Ammonia Concentration (ppm) Velocity (fps)		30°C 83			7°C 78		
		<u>Crevice</u>	<u>2.5</u>	<u>5.6</u>	<u>Crevice</u>	<u>2.5</u>	<u>5.6</u>
<u>Material</u>	<u>Exposure (days)</u> <u>30°C/7°C</u>						
Al 3003-H14	10/12	-	.078	.140	-	.009	.007
	30/32	-	.081	.147	-	.023	.022
	50/51	.034	.173	.281	.019	.015	.021
Al 5052-H32	10/12	-	.063	.102	-	.009	.007
	30/32	-	.067	.102	-	.024	.027
	50/51	.036	.144	.199	.025	.022	.029
Al 5052-H32 (treated)	10/12	-	W.G.	W.G.	-	.0003	.004
	30/32	-	.004	W.G.	-	.021	.011
	50/51	.028	.037	.023	.007	.008	W.G. ¹
Al 5086-H32	10/12	-	.034	.052	-	.010	.006
	30/32	-	.039	.050	-	.037	.007
	50/51	.021	.106	.133	.021	.018	.018
CP Titanium	10/12	-	.0008	.0013	-	.0003	.0013
	30/32	-	.0008	.0038	-	.006	.006
	50/51	.0025	.0003	.0069	.0004	.005	.005

¹ Weight Gain

TABLE IX-16

CORROSION DATA FOR TEST

30°C Seawater + Nominal 80 ppm Ammonia (Avg. 83 ppm)
Total Average Penetration (mils)¹ and (Max. Pit Depth, mils)

Exposure (days)	10		30		50		Pitting Observations ²
Velocity (fps)	2.5	5.6	2.5	5.6	2.5	5.6	
Al 3003-H14	.078 (<0.5)	.140 (<0.5)	.081 (1.0)	.147 (1.0)	.173 (1.0)	.281 (<0.5)	At 2.5 fps, several incipient pits present at 10 days, numerous incipient pits and 1 small pit at 30 days. Pitting at 50 days was no worse than at 30 days. At 5.6 fps, very few incipient pits present at 10 days, increasing to numerous incipient pits at 50 days. Also 3 small pits observed at 30 days.
Al 5052-H32	.063 (<0.5)	.102 (<0.5)	.067 (1.0)	.102 (1.0)	.144 (1.0)	.199 (1.0)	At 2.5 fps, a few incipient pits at 10 days, with several incipient pits and 1 small pit at 30 days. Pitting at 50 days was no more than at 30 days. At 5.6 fps, very few incipient pits present at 10 days, increasing to 6 small pits and a few incipient pits at 30 days. Pitting at 50 days shows no increase.
Al 5052-H32 (Treated)	W.G. ³ (<0.5)	W.G. (<0.5)	.004 (2.0)	W.G. (1.0)	.037 (2.0)	.023 (1.0)	At 2.5 fps, no pitting observed at 10 days, increasing to a very few incipient pits, 3 small pits, and 3 pits at 30 days. At 50 days, 4 small pits and 1 pit were observed. At 5.6 fps, no pitting observed at 10 days, increasing to 3 small pits and a few incipient pits at 30 days. The 50 day exposure showed no increase in pitting. This alloy showed least incipient pitting and general corrosion but deepest pits of any aluminum.
Al 5086-H32	.034 (<0.5)	.052 (<0.5)	.039 (1.0)	.050 (<0.5)	.106 (1.0)	.133 (1.0)	At the 2.5 fps, very few incipient pit sites at 10 days, increasing to a few incipient pits and 1 small pit at 30 days, increasing to 3 small pits at 50 days. At 5.6 fps, a very few incipient pits were observed until 50 days, when a few incipient pit sites and 1 small pit were observed. Best pit resistance of any Al alloy tested.

(continued)

TABLE IX-16 continued

Exposure (days) Velocity (fps)	10		30		50		Pitting Observations
	<u>2.5</u>	<u>5.6</u>	<u>2.5</u>	<u>5.6</u>	<u>2.5</u>	<u>5.6</u>	
CP Titanium	.0008		.0008		.0003		Showed a very few incipient pits throughout runs. Superior metal.
	.0013		.0008		.0069		
	(<0.5)		(<0.5)		(<0.5)		
		(<0.5)		(<0.5)		(<0.5)	

¹ Total Average Penetration corrected for losses occurring during post exposure cleaning.

² Because of the small surface area of the coupons and the short period of exposure, pitting data was based upon the following key:

Incipient pitting: Pits less than 0.5 mils deep, discernable as pits under 25 x magnification.

Small pits: Pits 1.0-0.5 mils deep, discernable as pit under 10x magnification and visible to naked eye.

Pits: Pits 1-2 mils deep (unless otherwise indicated), readily visible as pits to naked eye.

Very Few: Less than 5/sq. in.

Few: 5-10/sq. in.

Several: 10-15/sq. in.

Numerous: More than 15/sq. in.

³ Weight Gain

TABLE IX- 17

CORROSION DATA FOR CREVICE CORROSION TEST
30°C Seawater + 83 ppm Ammonia for 50 Days

<u>Alloy</u>	<u>Total Average Penetration mils</u>	<u>Crevice Attack and¹ Pitting Observations</u>
Al 3003 H-14	.034	A surface mar was observed on the crevice area, and a few incipient pits were noted on the outlying surface.
Al 5052 H-32	.036	A surface mar was observed on the crevice area, and two incipient pits were noted on the outlying surface.
Al 5052 H-32 (Treated)	.028	No indication of any crevice effect. One small pit and a few incipient pits were noted on the outlying surface.
Al 5086 H-32	.021	A slight surface mar was observed on the crevice area and two incipient pits were noted on the outlying surface.
CP Titanium	.0025	A slight surface mar was observed on the crevice area and two incipient pits noted on the outlying surface.

¹ Legend for pitting observations are as for previous table. A surface mar is considered to be a surface discoloration on the metal surface with no measurable depth attack.

TABLE IX-18

CORROSION DATA FOR TEST

7°C Seawater + Nominal 80 ppm Ammonia (Avg. 78 ppm)
 Total Average Penetration (mils)¹ and (Max. Pit Depth, mils)

Exposure (days) Velocity (fps)	Total Average Penetration						Pitting Observations ²
	12		32		51		
	2.5	2.6	2.5	2.6	2.5	2.6	
A1 3003-H14	.009 (1.0) (1.0)	.007 (1.0)	.023 (1.0)	.022 (<0.5)	.015 (2.0) (1.0)	.021 (1.0)	At 2.5 fps, a few incipient pits were observed at 12, 32, and 51 days, with one small pit present at 12 and 32 days, increasing to one pit at 51 days. At 5.6 fps, a few incipient pits were present at 12 days, increasing to numerous incipient pits at 32 days. Two small pits were also observed at 12 and 51 days.
A1 5052-H32	.009 (<0.5) (<0.5)	.007 (2.0) (<0.5)	.024 (2.0) (1.0)	.027 (2.0) (2.0)	.022 (2.0) (2.0)	.029 (2.0)	At 2.5 fps, a few incipient pits were observed at 12, 32, and 51 days, with three small pits and one pit present at 32 days and four small pits and one pit observed at 51 days. At 5.6 fps, a few incipient pits were observed at 12, 32, and 51 days, with one small pit present at 32 days and two small pits and one pit observed at 51 days.
A1 5052-H32 (Treated)	.0003 (1.0) (<0.5)	.004 (1.0) (<0.5)	.021 (1.0) (1.0)	.011 (1.0)	.008 (2.0) (2.0)	W.G. ³ (2.0)	At 2.5 fps, a few incipient pits and one small were observed at 12 days, increasing to a few incipient pits, three small pits, and four pits after 51 days. At 5.6 fps, a few incipient pits were observed at 12, 32, and 51 days, including one small pit at 32 days, increasing to four small pits and one pit at 51 days.

(continued)

Table IX-18 Continued

Exposure (days)	12		32		51		Pitting Observations
Velocity (fps)	2.5	2.6	2.5	2.6	2.5	2.6	
Al 5086-H32	.010 (1.0)	.006 (1.0)	.037 (<0.5)	.007 (<0.5)	.018 (2.0)	.018 (2.0)	At 2.5 fps, a few incipient pits were observed at 12, 32, and 51 days, with five small pits observed at 12 days and three small pits and one pit present at 51 days. At 5.6 fps, several incipient pits and three small pits were observed at 12 days, increasing to three small pits and three pits at 51 days.
CP Titanium	.0003 (<0.5)	.0013 (<0.5)	.006 (1.0)	.006 (1.0)	.005 (1.0)	.005 (2.0)	At 2.5 fps, a few incipient pits were present at 12 days, increasing to several incipient pits and two small pits at 32 days, increasing to several incipient pits and four small pits at 51 days. At 5.6 fps, several incipient pits were present at 12, 32, and 51 days, with seven small pits present at 32 days and three small pits and one pit present at 51 days.

- 1 Total Average Penetration corrected for losses occurring during post exposure cleaning.
- 2 Because of the small surface area of the coupons and the short period of exposure, pitting data was based upon the following key:

Incipient pitting: Pits less than 0.5 mils deep, discernable as pits under 25x magnification.

Small pits: Pits 1.0 - 0.5 mils deep, discernable as pits under 10x magnification and visible to naked eye.

Pits: Pits 1 - 2 mils deep (unless otherwise indicated), readily visible as pits to naked eye.

Very Few: Less than 5 /sq. in.

Few: 5 - 10/sq. in.

Several: 10 - 15/sq. in.

Numerous: More than 15/sq. in.

TABLE IX-19

Corrosion Data for Crevice Corrosion Test
7°C Seawater + 78 ppm Ammonia for 51 Days

Alloy	Total Average Penetration (mils)	Crevice Attack and Pitting Observation ¹
Al 3003 H-14	.019	Slight surface attack was noted on the crevice area, and a few incipient pits; two small pits, and one pit were present on the outlying surface.
Al 5052 H-32	.025	Slight surface attack and three small pits were present at the crevice, and several incipient pits and two small pits were observed on the outlying surface.
Al 5052 H-32 (Treated)	.007	One slight mar was noted at the crevice, and a very few incipient pits and one small pit were observed on the outlying surface.
Al 5086 H-32	.021	Surface attack and four small pits were observed at the crevice, and a few incipient pits and one small pit were observed on the outlying surface.
CP Titanium	.0004	A few incipient pits and eight small pits were found distributed over the specimen surface.

¹ Legend for pitting observations are as for previous table. A surface mar is considered to be a surface discoloration on the metal surface with no measurable depth attack.

TABLE IX-20

SCALE FORMATION

Seawater + Nominal 80 ppm Ammonia

Substrate:		Titanium		Aluminum		Crevice Unit (0.26 fps)	Comments
Velocity (fps)		2.5	5.6	2.5	5.6		
Temp., °C	Period, days	Scale Thickness, mils					
30°	10	6		--			A hard, tan scale with a tendency to chip & flake in thicker layers. Thin scale initially with broken scale depositing downstream to give 50 mil thick layers at 30 days, increasing to complete jam of scale between coupons and holder at 50 days. Primary constituent is calcium as 1:3 ratio of calcite to aragonite.
			6		--		
	30	11		17			
			8		12		
	50	28		25		45	
			8		14		
7°	12	7		7			A gummy, light tan, scale at 12 days, showing second layer crystal formation at 32 & 51 days. The 12-day scale formed an easily removed powder upon drying. No tendency to chip observed at 12 or 32 days, although thicker layers at 51 days were removable by repeatedly flexing the metal specimen. Primary constituent is calcium as an 1:1 ratio of calcite to aragonite. Crystalline components are calcite, aragonite, and $\text{CaCO}_3 \cdot \text{H}_2\text{O}$.
			3		3		
	32	10		10			
			15		15		
	51	15		15		12	
			15		27		

TABLE IX-21

SUMMARY OF EXPOSURE CONDITIONS
(~80 ppm NH₃)

<u>Dates</u>	<u>Temp.</u> <u>(°C)</u>	<u>Blowdown</u> <u>(gpm)</u>	<u>Ca⁺⁺ (ppm)</u>		<u>pH</u>	<u>Average</u> <u>Ammonia Conc.</u>	
			<u>In</u>	<u>Out</u>		<u>Days</u>	<u>ppm</u>
Test Unit I							
10-7-77 - 11-29-77	30	2.0	433	361	9.4	10	87
						30	84
						50	83
Test Unit II							
10-26-77 - 12-19-77	7	.5	408	364	9.8	12	88
						32	84
						51	78

TABLE IX-22

FINAL INTERVAL CORROSION RATES (mpy)^{1,2,3} FOR
TEST EXPOSURES OF 800 PPM AMMONIA IN SEAWATER

Temperature	30°C			5°C		
Ammonia Concentration (ppm)	880			916		
Velocity (fps)	2.5	5.6	Crevice Unit	2.5	5.6	Crevice Unit
<u>Material</u>						
Al 3003-H14	.04	.10	.11	W.G.	.10	.09
Al 5052-H32	.10	.09	.21	.12	.12	.13
Al 5052-H32 (Treated)	.65	.49	.63	.32	.48	.59
Al 5086-H32	.18	.05	.08	.03	.08	W.G.
C.P. Titanium	W.G.	W.G.	W.G.	W.G.	W.G.	W.G.

¹ Based on 0 to 10 day corrosion data

² Corrosion rates show a high degree of variability and inconsistency when compared to those obtained at lower ammonia additions. This is attributed to the extremely rapid scale which formed on the specimen surface. Scale was difficult to remove and rates may reflect minor cleaning losses.

³ "Final Interval" corrosion rate is a predicted long-term corrosion rate which the metal should experience after the surface has become passivated from continued exposure. The methodology involved in calculating this rate is given in Section III.C.3, "Data Resolution."

TABLE IX-23

TOTAL AVERAGE PENETRATION (mils) AFTER 10 DAYS FOR
TEST EXPOSURES OF 800 ppm AMMONIA IN SEAWATER¹

Temperature Ammonia Concentration (ppm)	30°C 880			5°C 916		
	2.5	5.6	Crevice Unit	2.5	5.6	Crevice Unit
<u>Material</u>						
Al 3003-H14	.001	.003	.003	W.G.	.003	.002
Al 5052-H32	.003	.002	.006	.003	.003	.003
Al 5052-H32 (Treated)	.018	.013	.017	.008	.012	.015
Al 5086-H32	.005	.001	.002	.0008	.002	W.G.
C.P. Titanium	W.G.	W.G.	W.G.	W.G.	W.G.	W.G.

¹ Penetrations show a high degree of variability and inconsistency when compared to those obtained at lower ammonia additions. This is attributed to the extremely rapid scale which formed on the specimen surface. Scale was difficult to remove and rates may reflect minor cleaning losses.

TABLE IX-2⁴CORROSION DATA FOR TEST⁵

30°C Seawater + 880 Ammonia (10 days)

Total Average Penetration (mils)¹ and (Max. Pit Depth, mils)

Velocity (fps)	Total Average Penetration			Pitting and Crevice Attack ^{2, 4}
	2.5	5.6	Crevice	
A1 3003 H-14	.001 (1.0)	.003 (<0.5)	.003 (<0.5)	At 2.5 fps, a very few incipient pits & one small pit. At 5.6 fps, a very few incipient pits. A very few incipient pits on the crevice specimens. A surface mar was present on the crevice area.
A1 5052 H-32	.003 (<0.5)	.002 (<0.5)	.006 (1.0)	A very few incipient pits, with one small pit occurring on the crevice specimen. A surface mar on the crevice area.
A1 5052 H-32 (treated)	.018 (<0.5)	.013 (<0.5)	.017 (1.0)	A very few incipient pits were present, with one small pit present on the crevice specimens.
A1 5086 H-32	.005 (<0.5)	.001 (1.0)	.002 (<0.5)	At 2.5 fps, a very few incipient pits. At 5.6 fps, a very few incipient pits & one small pit. A very few incipient pits & a surface mar on the crevice area.
C.P. Titanium	W.G. ³ (<0.5)	W.G. (<0.5)	W.G. (<0.5)	A very few incipient pits.

1 Total Average Penetration corrected for losses occurring during post exposure cleaning.

2 Because of the small surface area of the coupons and the short period of exposure, pitting data was based upon the following key:

Incipient pitting: Pits less than 0.5 mils deep, discernable as pits under 25 x magnification.

Small pits: Pits 1.0-0.5 mils deep, discernable as pit under 10x magnification and visible to naked eye.

Pits: Pits 1-2 mils deep (unless otherwise indicated), readily visible as pits to naked eye.

Very Few: Less than 5/sq. in.

Few: 5-10/sq. in.

Several: 10-15/sq. in.

Numerous: More than 15/sq. in.

3 Weight Gain

4 Max. pit depth observed was <1.0 mil for any specimen.

5 Discontinued at 10 days because of severe scaling.

TABLE IX-25

CORROSION DATA FOR TEST ⁵
5°C Seawater + 916 ppm Ammonia (10 days)

Total Average Penetration (mils) ¹ and (Max. Pit Depth, Mils)				Pitting and Crevice Attack ^{2, 4}
Velocity (fps)	2.5	5.6	Crevice	
Al 3003 H-14	W.G. ³ (<0.5)	.003 (1.0)	.002 (1.0)	At 2.5 fps, a very few incipient pits. At 5.6 fps, a very incipient pits & one small pit. The crevice specimens showed a very few incipient pits, 2 small pits, & a small surface mar on the crevice area.
Al 5052 H-32	.003 (<0.5)	.003 (<0.5)	.003 (<0.5)	A very few incipient pits. A small surface mar is present on the crevice area.
Al 5052 H-32 (Treated)	.008 (<0.5)	.012 (<0.5)	.015 (<0.5)	A very few incipient pits.
Al 5086 H-32	.0008 (<0.5)	.002 (<0.5)	W.G. (<0.5)	A very few incipient pits.
C.P. Titanium	W.G. ³ (<0.5)	W.G. (<0.5)	W.G. (<0.5)	A few incipient pits at 2.5 fps and 5.6 fps, and a very few incipient pits on the crevice specimens.

¹ Total Average Penetration corrected for losses occurring during post exposure cleaning.

² Because of the small surface area of the coupons and the short period of exposure, pitting data was based upon the following key:

Incipient pitting: Pits less than 0.5 mils deep, discernable as pits under 25 x magnification.

Small pits: Pits 1.0-0.5 mils deep, discernable as pit under 10x magnification and visible to naked eye.

Pits: Pits 1-2 mils deep (unless otherwise indicated), readily visible as pits to naked eye.

Very Few: Less than 5/sq. in.

Few: 5-10/sq. in.

Several: 10-15/sq. in.

Numerous: More than 15/sq. in.

³ Weight Gain

⁴ Max. pit depth observed was <1.0 mil for any specimen.

⁵ Discontinued at 10 days because of severe scaling.

TABLE IX-26

SCALE FORMATION
Seawater + 800 ppm Ammonia

Substrate:		<u>Titanium</u>		<u>Aluminum</u>		Crevice Unit (0.26 fps)	Comments
Velocity (fps)		2.5	5.6	2.5	5.6		
Temp., °C	Period, days	Scale Thickness, mils		Scale Thickness, mils			
30°	10	46		42		45	A hard, tan, brittle scale with a tendency to form small chips (~2 cm sq.) and showing no tendency to break free without specimen flexing. Primary constituents are aragonite (CaCO ₃) and magnesium hydroxide (Mg(OH) ₂) in an ~3.1-3.7 ratio.
			25		28		
5°	9.5	17		14		11	A white, soft, gummy scale with a tendency to form second layer crystals. No tendency to chip. Primary constituents are aragonite and magnesium hydroxide in an ~2.6-5.2 ratio.
			25		40		
Ambient		<1		<1		--	A very thin scale forming at most a discoloration on the metal surface.
			<1		<1		

TABLE IX-27

SUMMARY OF EXPOSURE CONDITIONS
(~800 ppm NH₃)

<u>Dates</u>	<u>Temp.</u> (°C)	<u>Blowdown</u> (gpn)	<u>Ca⁺⁺ (ppm)</u>		<u>pH</u>	<u>Average Ammonia Conc.</u>	
			<u>In</u>	<u>Out</u>		<u>Days</u>	<u>ppm</u>
Test Unit I							
1/30/77 -	30°	.5	329	224	10.5	10	880
2/9/78							
Test Unit II							
1/30/78 -	5°	.5	329	264	11.5	9.5	916
2/9/78							
Test Unit IV							
1/30/78 -	Ambient	--	329	--	--	10	0
2/9/78							

TABLE IX-28

CORROSION DATA FOR TEST
FINAL INTERVAL CORROSION RATES ^{1,2}
AMMONIA PLUS SEAWATER AT 5°C

Seawater Concentration Velocity (fps)	150 ppm		0.14%		1.12%		3.3%	
	2.5	5.6	2.5	5.6	2.5	5.6	2.5	5.6
Al 3003-H14	.09	.13	Nil ³	.43	.21	.19	.53	.61
Al 5052-H32	.08	.11	.009	.69	.35	.40	.98	1.09
Al 5052-H32 (treated)	.08	.05	Nil	Nil	.29	.026	.11	.033
Al 5086-H32	.23	.29	.12	.63	.51	.67	.87	1.19
CP Titanium	Nil	.006	Nil	Nil	Nil	Nil	Nil	.003

¹ Based upon corrosion data for final two specimen pulls.

² "Final Interval" corrosion rate is a predicted long-term corrosion rate which the metal should experience after the surface has become passivated from continued exposure. The methodology involved in calculating this rate is given in Section III.C.3, "Data Resolution"

³ Nil-Zero or negative corrosion rate.

TABLE IX-29

CORROSION DATA FOR TEST
5°C ANHYDROUS AMMONIATotal Average Penetration (mils)¹ and (Max. Pit Depth, mils)

Exposure (days) Velocity (fps)	10		38		Crevice	Pitting Observations ^{2,3}
	2.5	5.6	2.5	5.6		
Al 3003-H14	.006		.014		.014	At 2.5 fps, a very few incipient pits were observed, at 10 days, increasing to a few incipient pits at 38 days. At 5.6 fps, a few incipient pits were observed at 10 and 38 days with two small pits observed at 38 days. A very few incipient pits were observed on the crevice specimen.
	($<.5$)	.009	($<.5$)	.019	($<.5$)	
		($<.5$)		(1.0)		
Al 5052-H32	.007		.014		.016	At 2.5 fps, a few incipient pits at 10 days increased to numerous incipient pits at 38 days. At 5.6 fps, numerous incipient pits were observed. A few incipient pits were observed on the crevice specimen.
	($<.5$)	.012	($<.5$)	.021	($<.5$)	
		($<.5$)		($<.5$)		
Al 5052-H32 (treated)	.019		.026		.018	A very few incipient pits were observed at all exposures.
	($<.5$)	.023	($<.5$)	.027	($<.5$)	
		($<.5$)		($<.5$)		
Al 5086-H32	.014		.032		.021	At 2.5 fps, a few incipient pits at 10 days increased to numerous incipient pits at 38 days. At 5.6 fps, numerous incipient pits were observed, with five small pits observed at 10 days and eleven small pits observed at 38 days. A very few incipient pits were observed on the crevice specimens.
	($<.5$)	.023	($<.5$)	.046	($<.5$)	
		(1.0)		(1.0)		

(continued)

Table IX-29 continued

Exposure (days) Velocity (fps)	10		38		Crevice	Pitting Observations
	2.5	5.6	2.5	5.6		
CP Titanium	.0005		.0003		.0002	At 2.5 fps, a few incipient pits and 3 small pits were observed at 10 days and several incipient pits at 38 days. At 5.6 fps, a few incipient pits at 38 days. A few incipient pits were observed on the crevice specimen.
	(1.0)	.0001	($<.5$)	.0006	($<.5$)	
		($<.5$)		($<.5$)		

- 1 Total Average Penetration corrected for losses occurring during post exposure cleaning.
- 2 Because of the small surface area of the coupons and the short period of exposure, pitting data was based upon the following key:
 - Incipient pitting: Pits less than 0.5 mils deep, discernable as pits under 25 x magnification.
 - Small pits: Pits 1.0-0.5 mils deep, discernable as pit under 10x magnification and visible to naked eye.
 - Pits: Pits 1-2 mils deep (unless otherwise indicated), readily visible as pits to naked eye.
 - Very Few: Less than 5/sq. in.
 - Few: 5-10/sq. in.
 - Several: 10-15/sq. in.
 - Numerous: More than 15/sq. in.
- 3 Max. pit depth 0.5-1.0 mil on any specimen.

TABLE IX- 30
SUMMARY OF EXPOSURE CONDITIONS
FOR ANHYDROUS AMMONIA TEST

Date	Period, days	Temperature °C	Water, ppm
8-17-73	0 through	5°	110
8-27-78	10		
8-29-73	10 through	5°	151
9-26-78	38		

TABLE IX- 31

TOTAL AVERAGE PENETRATION (mils)¹ FOR A TEST EXPOSURE
IN ANHYDROUS AMMONIA PLUS 0.14% SEAWATER AT 5°C⁴

Material	Period, days	Crevice Test, 0.26 fps	Velocity		Pitting Observations ^{2, 5}
			2.5 fps	5.6 fps	
Al 3003-H14	10		.009	.012	At all indicated velocities & exposure periods, only a very few incipient pits.
	24	.007	.009	.028	
Al 5052-H32	10		.012	.008	At 2.5 fps, a very few incipient pits at 10 days, increasing to a few incipient pits and one small pit at 24 days. At 5.6 fps, a few few incipient pits at 10 and 24 days.
	24	.007	.012	.034	
Al 5052-H32 (treated)	10		.030	.029	At all indicated velocities & exposure periods, only a very few incipient pits.
	24	.032	.027	.024	
Al 5086-H32	10		.013	.020	A few incipient pits at all indicated velocities & exposures
	24	.006	.018	.044	
C.P. Titanium	10		.0005	.0008	At 2.5 fps, a very few incipient pits at 10 days, increasing to a few incipient puts & one small pit at 24 days. At 5.6 fps, a very few incipient at 10 & 24 days.
	24	W.G. ³	.0001	.0001	

¹ Total Average Penetration corrected for losses occurring during post exposure cleaning.

² Because of the small surface area of the coupons and the short period of exposure, pitting data was based upon the following key:

Incipient pitting: Pits less than 0.5 mils deep, discernable as pits under 25 x magnification.
Small pits: Pits 1.0-0.5 mils deep, discernable as pit under 10x magnification and visible to naked eye.

Pits: Pits 1-2 mils deep (unless otherwise indicated), readily visible as pits to naked eye.

Very Few: Less than 5/sq. in.

Few: 5-10/sq. in.

Several: 10-15/sq. in.

Numerous: More than 15/sq. in.

³ Weight Gain.

⁴ Water content measured 0.6% for 10 days & 0.14% for final 14 days.

⁵ Max. pit depth 0.5-1.0 mil on any specimen.

TABLE IX-32

CORROSION DATA FOR CREVICE CORROSION TEST
ANHYDROUS AMMONIA PLUS 0.14% SEAWATER AT 5°C FOR 24 DAYS¹

<u>Alloy</u>	<u>Corrosion Rate (mpy)</u>	<u>Crevice Attack and Pitting Observations²</u>
Al 3003 H-14	.007	A few incipient pits & one small pit on the specimen surface. No crevice attack.
Al 5052 H-32	.007	A very few incipient pits.
Al 5052 H-32 (Treated)	.032	A very few incipient pits & one pit on surface.
Al 5036 H-32	.006	A few incipient pits & one small pit on surface.
C.P. Titanium	W.G. ³	A very few incipient pits.

¹ Water content was 0.6% for 10 days and 0.14% for 14 days.

² Max. pit depth was 0.5-1.0 mil on any specimen.

³ Weight Gain

TABLE IX-33

SUMMARY OF EXPOSURE CONDITIONS
FOR ANHYDROUS AMMONIA
TEST PERIODS

<u>Date</u>	<u>Period, days</u>	<u>Temp., °C</u>	<u>Water, %</u>	<u>Cl⁻, ppm</u>	<u>Na⁺ ppm</u>
2-17-78 2-27-78	0 through 10	5	.6	90	7
2-28-78 3-14-78	10 through 24	5	.14	34	1.5

TABLE IX-34

CCORROSION DATA FOR TEST
5°C Anhydrous Ammonia + 1.12% Seawater

Exposure (days) Velocity (fps)	Total Average Penetration (mils) ¹ and (Max. Pit Depth, mils)							Pitting Observations ^{2, 4}
	10		28		59		Crevice	
	2.5	5.6	2.5	5.6	2.5	5.6		
A1 3003-H14	.012 (<0.5) (<0.5)	.009 (<0.5)	.016 (<0.5) (1.0)	.012 (1.0)	.034 (1.0)	.027 (1.0)	.019 (1.0)	At 2.5 fps, surface discoloration indicative of surface attack was observed at 10 days. In addition, a few incipient pits were observed at 28 days and one small pit was observed at 59 days. At 5.6 fps, surface attack was observed at 10 days and at 28 and 59 days a few incipient pits and one small pit were observed. One small pit was observed at the crevice of the crevice specimen.
A1 5052-H32	.013 (<0.5) (<0.5)	.005 (<0.5)	.016 (<0.5)	.008 (<0.5)	.045 (1.0)	.042 (2.0)	.026 (<0.5)	At 2.5 fps, some surface discoloration indicative of surface attack and a few incipient pits were observed at 10 days, with the addition of one small pit observed at 59 days. At 5.6 fps, some surface attack was observed at 10 and 28 days, and a few incipient pits, two small pits, and 1 pit were observed at 59 days. No crevice corrosion was observed.
A1 5052-H32 (Treated)	.023 (<0.5) (<0.5)	.027 (<0.5)	.025 (<0.5) (<0.5)	.027 (<0.5)	.030 (<0.5)	.029 (<0.5)	.022 (1.0)	At 2.5 fps and 5.6 fps, a very few incipient pits were observed. A few incipient pits and 1 small pit were observed at the crevice on the crevice specimen.

(continued)

Table IX-34 continued

Exposure (days)	10		28		59		Crevice	Pitting Observations ^{2 4}
Velocity (fps)	2.5	5.6	2.5	5.6	2.5	5.6		
A1 5086-H32	.012		.017		.059		.030	<p>At 2.5 fps, some surface discoloration indicative of surface attack and a few incipient pits were observed.</p> <p>At 5.6 fps, some surface attack and a few incipient pits were observed at 10 days, and an additional two small pits were observed at 28 and 59 days.</p> <p>On the crevice specimen, several incipient pits and two small pits were observed at locations independent of the crevice.</p>
	(<0.5)	.006	(<0.5)	.012	(<0.5)	.069	(1.0)	
		(<0.5)		(1.0)		(1.0)		
C.P. Titanium	W.G. ³		W.G.		W.G.		.002	A few incipient pits were detected at all exposures.
		.0003		.0002		W.G.		
	(<0.5)	(<0.5)	(<0.5)	(<0.5)	(<0.5)	(<0.5)	(<0.5)	

¹ Total Average Penetration corrected for losses occurring during post exposure cleaning.

² Because of the small surface area of the coupons and the short period of exposure, pitting data was based upon the following key:

Incipient pitting: Pits less than 0.5 mils deep, discernable as pits under 25x magnification.

Small pits: Pits 1.0-0.5 mils deep, discernable as pits under 10x magnification and visible to naked eye.

Pits: Pits 1-2 mils deep (unless otherwise indicated), readily visible as pits to naked eye.

Very Few: Less than 5/sq. in.

Few: 5-10/sq. in.

Several: 10-15/sq. in.

Numerous: More than 15/sq. in.

³ Weight Gain.

⁴ Max. pit depth 0.5-1.0 mil on any specimen.

TABLE IX-35

SUMMARY OF EXPOSURE CONDITIONS
FOR ANHYDROUS AMMONIA + 1% SEAWATER
TEST PERIODS

<u>Date</u>	<u>Period, days</u>	<u>Temp., °C</u>	<u>Water, %</u>	<u>Cl⁻, ppm</u>	<u>Na⁺ ppm</u>
3-17-78 3-28-78	0 through 10	5	1.03	2.6	65
3-30-78 4-17-78	10 through 28	5	1.03	250	60
4-19-78 5-19-78	28 through 59	5	1.12	229	70

TABLE IX-36

CORROSION DATA FOR TEST
5°C Anhydrous Ammonia +2.5% Seawater

Total Average Penetration (mils)¹ and (Max. Pit Depth, mils)

Exposure (days) Velocity (fps)	9		30		53		Crevice	Pitting Observations ^{2,4}
	2.5	5.6	2.5	5.6	2.5	5.6		
Al3003-H14	.002 (<0.5)	.003 (1)	.004 (<0.5)	.005 (<0.5)	.038 (<0.5)	.044 (<0.5)	.042 (<0.5)	At 2.5 fps, a very few incipient pits were observed at 9 and 30 days increasing to a few incipient pits at 53 days. At 5.6 fps, a very few incipient pits were observed with two small pits present at 9 days. On the crevice specimen, a very few incipient pits were noted.
Al 5052-H32	.005 (<0.5)	.005 (<0.5)	.007 (<0.5)	.008 (<0.5)	.069 (<0.5)	.078 (<0.5)	.056 (<0.5)	In all cases, a very few incipient pits were observed.
Al5052-H32 (Treated)	.022 (<0.5)	.027 (<0.5)	.024 (<0.5)	.026 (<0.5)	.031 (<0.5)	.028 (<0.5)	.022 (<0.5)	In all cases, a very few incipient pits were observed.
Al5086-H32	.005 (<0.5)	.007 (<0.5)	.009 (<0.5)	.007 (<0.5)	.064 (<0.5)	.082 (<0.5)	.063 (<0.5)	In all cases, a very few incipient pits were observed.

(Continued)

Table IX-36 continued

Exposure (days)	9		30			53		Crevice	Pitting Observations ^{2,4}
Velocity (fps)	2.5	5.6	2.5	5.6	2.5	5.6	5.6		
C. P. Titanium	.0001		.0007		.0006		.0001		At 2.5 fps and 5.6 fps, several incipient pits were observed.
	(<0.5)	W.G. ³	(<0.5)		.0008		.0010	(<0.5)	A few incipient pits were observed on the crevice specimen.
		(<0.5)		(<0.5)		(<0.5)			

¹ Total Average Penetration corrected for losses occurring during post exposure cleaning.

² Because of the small surface area of the coupons and the short period of exposure, pitting data was based upon the following key:

Incipient pitting: Pits less than 0.5 mils deep, discernable as pits under 25x magnification.

Small pits: Pits 1.0-0.5 mils deep, discernable as pits under 10x magnification and visible to naked eye.

Pits: Pits 1-2 mils deep (unless otherwise indicated), readily visible as pits to naked eye.

Very Few: Less than 5/sq. in.

Few: 5-10/sq. in.

Several: 10-15/sq. in.

Numerous: More than 15/sq. in.

³ Weight Gain.

⁴ Max. pit depth 0.5-1.0 mil on any specimen.

TABLE IX-37
 SUMMARY OF EXPOSURE CONDITIONS
 FOR ANHYDROUS AMMONIA
 PLUS 2.5% SEAWATER

<u>Date</u>	<u>Period, Days</u>	<u>Temp. °C</u>	<u>Water,¹ %</u>	<u>Cl-, ppm</u>	<u>Na+ ppm</u>
6-6-78	0 through				
6-15-78	10	5°	7.7	406	191
6-19-78	9 through				
7-10-78	30	5°	3.7	536	270
7-11-78	30 through				
8-3-78	53	5°	3.3	614	287

¹ Actual water analysis. A known 2.5% seawater initially added to anhydrous NH₃.

TABLE IX-38

CLEANING SOLUTION SCREENING

Test Results on Al 3003-H14 (Fouled)

Solution	Results
I. Mild	
1/2% wt. hydrogen peroxide 12 hr. exposure Deionized water rinse	Extensive pit attack on the aluminum. No significant cleaning observed.
II. Mild	
5% wt. calcium hypochlorite (substitute 7.7% HTH dry chlorine for pool use) 1/2% wt. sodium metasilicate At ambient temperature 12-hr. exposure Deionized water rinse	This solution, although filtered to remove inert material, left a white powder residue on a clean aluminum surface. Secondary choice as a cleaning solution.
III. Alkaline	
5% wt. sodium carbonate in deionized water 5% wt. monosodium phosphate 5% wt. trisodium phosphate 0.5% wt. sodium metasilicate 12 hrs. at ambient temperature 12-hr. exposure Deionized water rinse	No observed effect.
IV. Harsh-Acid	
10% vol. concentration H_2SO_4 in deionized water 2% wt. chromic acid At ambient temperature 4-hr. exposure Deionized water rinse	Clean metal surface.

TABLE IX-39
CLEANING TESTS: CORROSION SUMMARY
FINAL INTERVAL CORROSION RATE (mpy)^{1, 2}

Material	Uncleaned Controls	Mechanical ⁴ Cleaning	Chemical ⁴ Cleaning
Al 3003-H14	1.31	1.60	3.05
Al 5052-H32	1.21	1.62	2.70
Al 5052-H32 (treated)	.48	.83	1.93
Al 5086-H32	1.03	1.60	2.84
CP Titanium	W.G. ³	W.G.	W.G.

¹ Based on 0-10 month exposure corrosion data.

² "Final Interval" corrosion rate is a predicted long-term corrosion rate which the metal should experience after the surface has become passivated from continued exposure. The methodology involved in calculating this rate is given in Section III.C.3, "Data Resolution."

³ Weight Gain

⁴ Described in Section III.C.4.

TABLE IX-40
CLEANING TESTS: CORROSION SUMMARY
Total Average Penetration (mils)

Specimen Treatment	Uncleaned Controls	Mechanical ¹ Cleaning	Chemical ¹ Cleaning
Average Exposure (days)	319	313	313
Material			
Al 3003-H14	1.14	1.37	2.62
Al 5052-H32	1.06	1.39	2.32
Al 5052-H32 (Treated)	.42	.71	1.66
Al 5086-H32	.90	1.37	2.43
CP Titanium	W.G. ²	W.G.	W.G.

¹ Described in Section III.C.4.

² Weight Gain

TABLE IX- 41

CLEANING TESTS

AMBIENT TEMPERATURE UNFILTERED SEAWATER

Alloy	Cleaning ¹	Period (months)		Cleaning and Corrosion Observations
		Group 1	Group 2	
Al 3003-H14	None	1		A mud layer, heavier than average, covers the specimen. Slight crevice attack is noted.
		2		A mud layer, heavier than average, covers the specimen. Evidence of edge and pit attack observed.
		3		As observed at 2 months.
		7		As observed at 2 months.
		10		As observed at 2 months.
	Mechanical	1		A very thin mud film remains after cleaning; no corrosion observed.
			1½	A very thin mud film remains; no corrosion observed.
		2		A thin, tight mud film remains; and there is evidence of edge and pit attack
		3		As observed at 2 months.
			6	As observed at 1½ months.
		7		As observed at 2 months.
			9	A thin mud stain; mild surface attack observed.
		10		Mud film 1-2 mils thick covers specimen.
	Chemical	1		Specimen clean, evidence of pit initiation.
			1½	Specimen clean, no observed corrosion.
		2		As observed at 1 month.
		3		As observed at 1 month.
			6	As observed at 1½ month.
		7		As observed at 1 month.
			9	Specimen clean, mild surface attack observed.
		10		As observed at 9 months.

¹ Described in Section III.C.4.

Table IX-41 continued

Alloy	Cleaning	Period (months)		Cleaning and Corrosion Observations
		Group 1	Group 2	
Al 5052-H32	None	1		A slightly heavier mud layer is present, and slight crevice attack is present.
		2		A mud layer, heaviest of any metal, is present, and slight crevice attack is present.
		3		As observed at 2 months.
		7		Average fouling layer present; evidence of slight pitting present.
		10		As at 7 months.
	Mechanical	1		A thin mud film remains; there is no observed corrosion.
			1½	As at 1 month.
		2		A thin, tight mud layer remains, and slight crevice attack is present.
		3		A thin, tight mud layer remains, and evidence of pit attack is observed.
			6	As at 1 month.
		7		A thin mud stain remains on the specimen, slight surface attack observed.
			9	A thin mud stain; small pit at specimen end.
		10		Mud film 1-2 mils thick covers specimen.
	Chemical	1		Specimen is clean, no observed attack.
			1½	As observed at 1 month.
		2		As observed at 1 month.
		3		Specimen is clean, uniform surface attack present.
			6	As observed at 1 month.
		7		As observed at 3 months.
			9	As observed at 3 months.
		10		As observed at 3 month.

(continued)

Alloy	Cleaning	Period (months)		Cleaning and Corrosion Observations
		Group 1	Group 2	
Al 5052-H32 (treated)	None	1		Thinnest mud layer of any alloy, however significant pit attack has occurred at the upstream ends.
		2		Thinner than average mud layer is present; pit and edge attack have occurred.
		3		As observed at 2 months.
		7		As observed at 2 months.
		10		As observed at 2 months.
	Mechanical	1		Cleanest of any mechanically cleaned metal, although mud spots are present at corrosion (corrosion product) sites. Pitting at ends such that specimen number is obscured.
			1½	Clean surface, except at corrosion products around pit at one end.
		2		Clean surface with pit attack as before plus additional edge attack.
		3		As observed at 2 months.
			6	As observed at 1½ months.
	Chemical	7		As observed at 2 months.
			9	As observed at 1½ months.
		10		As observed at 2 months.
	Chemical	1		Specimen is clean; pit and crevice attack is present.
			1½	Thin mud film remains, evidence of end and crevice attack is present.
		2		Specimen is clean, pit attack as before with additional edge attack.
		3		As observed at 2 months.
			6	As observed at 1½ months.
	Chemical	7		As observed at 2 months.
			9	Specimen is half covered by 1-2 mil mud layer; uniform attack present.
		10		Specimen is clean; uniform surface attack and moderate pit and crevice attack is present.

(continued)

Table IX-41 continued

Alloy	Cleaning	Period (months)		Cleaning and Corrosion Observations
		Group 1	Group 2	
Al 5086-H32	None	1		A mud layer covers the specimen, and no evidence of corrosion is apparent.
		2		As observed at 1 month.
		3		As observed at 1 month.
		7		As observed at 1 month.
		10		As observed at 1 month.
	Mechanical	1		A thin mud film remains; there is no observed corrosion.
			1½	As observed at 1 month.
		2		As observed at 1 month.
		3		As observed at 1 month.
			6	As observed at 1 month.
		7		A thin mud film remains, uniform corrosion attack evident.
			9	As observed at 7 months.
		10		Mud deposits 1-2 mils thick remain on specimen.
	Chemical	1		Specimen is clean; no corrosion is observed.
			1½	As observed at 1 month.
		2		As observed at 1 month.
		3		As observed at 1 month.
			6	As observed at 1 month.
		7		Specimen is clean; uniform corrosion is apparent.
			9	As observed at 7 months.
		10		As observed at 7 months.
CP Titanium	None	1		A mud layer, thinner than average, is present, and no corrosion is observed.
		2		As observed at 1 month.
		3		As observed at 1 month.
		7		As observed at 1 month.
		10		As observed at 1 month.

(continued)

Table IX-41 continued

Alloy	Cleaning	Period (months)		Cleaning and Corrosion Observations
		Group 1	Group 2	
CP Titanium	Mechanical	1		A very thin mud film remains; there is no observed corrosion.
			1½	Surface is clean, no observed corrosion.
		2		As observed at 1 month.
		3		As observed at 1 month.
			6	Some mud remaining after cleaning, although specimen is predominately clean. No evidence of corrosion.
		7		As observed at 6 months.
			9	As observed at 6 months.
		10		As observed at 6 months.
	Chemical	1		Specimen is clean, no observed corrosion.
			1½	A very thin mud layer remains which is easily removed by hand contact. No evidence of corrosion.
		2		As observed at 1½ months.
		3		As observed at 1½ months.
			6	As observed at 1½ months.
		7		As observed at 1½ months.
			9	Mud layer ~1½ mils thick covers specimen.
		10		Mud layer ~1 mil thick covers specimen.

Appendix B
Equipment and Scale Photographs

Figure IX-1

TEST UNIT 1: SEAWATER MIXED WITH AMMONIA AT 30°C

Figure IX-2

TEST UNIT 2: SEAWATER MIXED WITH AMMONIA AT 5°C

Figure IX-3

TEST UNIT 3: LIQUID ANHYDROUS AMMONIA
MIXED WITH SEAWATER
AT 5°C

Figure IX-4

TEST UNIT 4: ONCE THROUGH AMBIENT TEMPERATURE
SEAWATER SYSTEM FOR CLEANING TEST AND
SEAWATER CORROSION CONTROLS

Figure IX-5

CREVICE CORROSION SPECIMEN ASSEMBLY

Figure IX-6

FOULING ON CREVICE TEST ASSEMBLY

8 ppm AMMONIA IN SEAWATER AT 5°C and 30°C

Figure IX-7

SCALE FORMATION ON CREVICE TEST ASSEMBLY
30 ppm AMMONIA IN SEAWATER AT 5°C and 30°C

Figure IX-8

SCALE FORMATION ON CREVICE TEST ASSEMBLY

83 ppm AMMONIA IN SEAWATER AT 30°C

Figure IX-9

SCALE FORMATION ON CREVICE TEST ASSEMBLY

78 ppm AMMONIA IN SEAWATER AT 5°C

Figure IX-10

SCALE FORMATION ON CREVICE TEST ASSEMBLY

880 ppm AMMONIA IN SEAWATER AT 30°C

Figure IX-11

SCALE FORMATION ON CREVICE TEST ASSEMBLY

916 ppm AMMONIA IN SEAWATER AT 5°C

Distribution for ANL/OTEC-BCM-004

Internal:

P. H. Benson	J. J. Roberts
J. B. Darby, Jr.	N. F. Sather
J. E. Draley (12)	A. Thomas
B.R.T. Frost	ANL Contract Copy
A. B. Krisciunas	ANL Libraries (5)
G. F. Popper	TIS Files (6)

External:

DOE-TIC, for distribution per UC-64 (412)
Manager, Chicago Operations and Regional Office, DOE
Chief, Office of Patent Counsel, DOE-CORO
President, Argonne Universities Association
J. Hilbert Anderson, Sea Solar Power, Inc.
M. Kent Anderson, Trane Air Conditioning
Takaaki Anzai, Florida Institute of Technology
W. H. Avery, Applied Physics Laboratory, Johns Hopkins University
E. Barsness, Westinghouse Electric Corporation
James O. Bates, Energy Technology Engineering Center
Kenneth J. Bell, Oklahoma State University
Robert A. Bonewitz, Aluminum Company of America
R. Cohen, US-DOE, Div. of Central Solar Technology
William A. Corpe, Columbia University
R. S. Dalrymple, Reynolds Metals Company
G. J. Danek, Annapolis, Maryland
James Denton, TRW Systems and Energy
John DePalma, U. S. Naval Oceanographic Office
Stephen Dexter, University of Delaware
John G. Fetkovich, Carnegie-Mellon University
Harry Foust, Trane Air Conditioning
Malcom D. Fraser, Intertechnology Corporation
John Gertz, Westinghouse Electric Corporation
W. D. Grimes, Dow Chemical Company
Sigmund Gronich, US-DOE, Div. of Central Solar Technology
P. H. Hadley, Jr., Gibbs & Cox, Inc.
L. W. Hallanger, Research Corporation, University of Hawaii
William Hartt, Florida Atlantic University
William E. Heronemus, University of Massachusetts
F. K. Hill, Applied Physics Laboratory, Johns Hopkins University
Jules Hirshman, Tracor Marine
J. F. Jenkins, Civil Engineering Laboratory
E. H. Kinelski, US-DOE, Div. of Central Solar Technology
Robert E. Lacey, Southern Research Institute
F. L. LaQue, Verona, New Jersey
Abraham Lavi, Carnegie-Mellon University
T. S. Lee, International Nickel Company
Murray Leitner, Lockheed Missiles and Space Co., Inc.
Lloyd Lewis, US-DOE, Div. of Central Solar Technology
Brenda Little, NORDA
D. Lott, Naval Coastal Systems Center
Richard N. Lyon, Oak Ridge National Laboratory

Frank Mathews, Colorado School of Mines
William F. McIlhenny, Dow Chemical Company
John W. Michel, Oak Ridge National Laboratory
Ralph Mitchell, Harvard University
Robert L. Molinari, NOAA/AMOL
John Morse, University of Miami
John Nicol, Arthur D. Little, Inc.
Merle Olmsted, General Electric Company
T. B. O'Neill, Civil Engineering Laboratory
David Price, U. S. National Oceanic & Atmospheric Administration
W. W. Pritsky, Aluminum Association
J. F. Ryniewicz, Lockheed Missiles and Space Co., Inc.
Donald Sasscer, University of Puerto Rico
C. F. Schrieber, Dow Chemical Company (3)
H. H. Sephton, University of California at Berkeley
William Sheppard, NOAA Data Buoy Office
Wilbur Sherwood, US-DOE, Div. of Central Solar Technology
J. E. Snyder, TRW Systems and Energy
Frank Spiehler, NOAA Data Buoy Office
T. J. Summerson, Kaiser Aluminum and Chemical Corp.
R. B. Teel, Chatham, New Jersey
D. L. Thomas, Radiation Management Corporation
Fred Vukovich, Research Triangle Institute
J. Paul Walsh, Value Engineering Company
E. T. Wanderer, Aluminum Company of America
Ralph Williams, PRC Energy Analysis Co.
David C. White, Florida State University
Hank White, Natural Energy Laboratory of Hawaii