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CORROSION AND WEAR HANDBOOK

D. J. DEPAUL editor

*Bettis plant
operated for
the
U.S. Atomic Energy Commission
by
Westinghouse Electric Corp.*

for water cooled reactors

*sponsored by
naval reactors branch
division of reactor development
U.S. Atomic Energy Commission*

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FOREWORD

This handbook, sixth in a series on basic reactor technology sponsored by the Naval Reactors Branch of the United States Atomic Energy Commission, is devoted to problems resulting from the use of water as a heat transfer medium in a reactor plant. There are many reasons why water has proved advantageous in powerplants, both conventional and nuclear. Water is readily available, cheap, and nontoxic, so that makeup, recovery, and waste disposal problems are minimized. These characteristics of water are very important because leakage in operating power plants can be many hundreds of gallons per day. Water has a low induced radioactivity, which dies away quickly when the reactor is shut down. It is liquid at room temperature. It can be stored in the open air. Technology has been built up over many years for handling it in most of the common commercially available metals. In other words, water is a "natural" material to use, offering a minimum of problems. This is in addition to its excellent characteristics as a heat transfer or working fluid.

It was generally believed, when work began on the pressurized water reactor plant for the *Nautilus* prototype, that the technology of handling water at moderate temperature in stainless-steel equipment was well developed. Compared with other possible reactor coolants, it certainly was. But it turned out that even a technology so well developed as water required a great deal of additional work specific to the peculiar conditions of a nuclear powerplant; this book, containing information developed through the expenditure of millions of dollars and thousands of man-years of effort, is evidence of the extent of that work.

In spite of this work, our basic understanding of water technology is weak. We do not fully understand, for example, the processes by which metals become dissolved or suspended in the reactor cooling water, how the radioactivity is then transported to the external system and how it is deposited on surfaces. We cannot be sure that changes in temperatures, flow rate, or chemical condition of the water will not lead to fouling of heat transfer surfaces, increased radioactivity in external systems, sticking and galling of water-lubricated mechanisms, or other deleterious conditions. We know that such problems can arise and we do not know all the causes and conditions which can create them nor can we assure their prevention. In future plants, differences in operating conditions now thought to be unimportant could mean the difference between a practical powerplant and an expensive toy.

Even with the large backlog of experience with water systems, there is still a great deal that must be learned. I hope that some readers of this handbook will, starting from the data herein, work toward a firmer understanding of these problems.

H. G. RICKOVER,
*Chief, Naval Reactors Branch,
Division of Reactor Development,
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EDITOR'S PREFACE

It is unfortunate that many people believe that most work in the atomic energy field is secret and that only a small fraction of the technology developed is available to them. This is not the case. The Atomic Energy Commission and its contractors are releasing more and more reports on nearly all phases of reactor technology. The series of books sponsored by the Naval Reactors Branch of the Atomic Energy Commission is one such means of making available the technology developed in the naval and Shippingport reactor (PWR) programs. A list of these books is printed on the following page.

This Handbook on corrosion and wear deals with the use of water in a nuclear reactor system. The reasons water is desirable as a coolant for nuclear reactors are discussed in the foreword by Rear Admiral H. G. Rickover.

The Handbook is organized in three parts. Part A gives background information and general principles for the benefit of engineers and scientists who are encountering for the first time the problems associated with the use of high purity, high temperature water as a reactor coolant. This information is intended to help such persons evaluate new problems encountered in this field.

Part B of the Handbook contains tabulated data and detailed information for use as reference material for actual design work. Numerous references to additional data are also included.

Part C of the Handbook contains material on special types of corrosion and application problems involving wear.

Thanks go to all of the authors and contributors for their generous assistance. The editor appreciates the forbearance with which the contributors accepted editorial changes. These changes were generally made, not to correct faults, but to make each chapter fit into the whole. Special thanks go to J. W. Flaherty and S. Petach, of the Bettis Plant of the Atomic Energy Commission, for their untiring efforts and enthusiasm in gathering information and editing.

Acknowledgment is made to Rear Adm. H. G. Rickover, whose foresight and encouragement (prodding) caused this book to be written; to W. H. Wilson, R. R. Roof; and other members of Admiral Rickover's staff in the Naval Reactors Branch for their valuable suggestions and comments.

D. J. DEPAUL, *Editor.*

This handbook is one of a series sponsored by the Naval Reactors Branch of the Atomic Energy Commission to publish in useful form the technology being developed in the naval and Shippingport reactor (PWR) programs. This series includes:

Liquid Metals Handbook.

First edition: Edited by R. N. Lyon, June 1950.

Second edition: Edited by R. N. Lyon, June 1952.

Third edition: (Sodium-NaK Supplement) First printing June 1955; second printing (Revised), November 1955.

Metallurgy of Zirconium. Edited by B. Lustman and F. Kerze, Jr., July 1955.

The Metal Beryllium. Edited by D. W. White and J. E. Burke, July 1955.

Bibliography of Reactor Computer Codes, Report AECU-3078. Edited by R. S. Brodsky, December 1955.

Reactor Shielding Design Manual. Edited by T. Rockwell, III, March 1956.

Corrosion and Wear Handbook for Water-cooled Reactors. Edited by D. J. DePaul, March 1957.

Naval Reactors Physics Handbook. A. Radkowsky, Chairman of Editorial Board, in preparation.

Reactor Core Design Manual. Edited by N. J. Palladino, in preparation.

Reactor Plant Piping Handbook. Edited by M. Shaw, in preparation.

Reactor Heat Transfer Handbook. Edited by J. Zerbe, in preparation.

Radiological Aspects of Naval Nuclear Propulsion Plants. Edited by J. A. Brimson, in preparation.

Metallurgy of Hafnium. Edited by E. T. Hayes and D. E. Thomas, in preparation.

Chapter 8.—RELATIVE IMPORTANCE OF DIFFERENT VARIABLES—Continued	Page
Material Composition	135
Temperature	136
Time	137
Water Velocity	138
Oxygen	139
Hydrogen	140
Effect of Other Gases	141
Electrical Resistivity of Water	141
Stress	142
Heat Treatment	142
Nuclear Radiation	142
Surface Finish	143
 PART C.—SPECIAL STUDIES	
Chapter 9.—CREVICE CORROSION	147
Background Information	147
Methods of Controlling Crevice Corrosion	150
Critical Applications Affected by Crevice Corrosion	159
Summary	171
Appendix: Contact Corrosion on Various Material Combinations	171
Chapter 10.—STRESS CORROSION	187
Section I:	
Introduction	187
General Preventive Measures	188
Details on Effects of Variables and Control Measures	188
Section II:	
Laboratory Tests	191
Auxiliary Boiler Experience	211
Stress Corrosion Failures in Model Heat Exchangers	214
Industrial Experience	219
Chapter 11.—INTERGRANULAR CORROSION	225
Introduction	225
Engineering Importance	225
Mechanism and Control	226
Work Done on Unstabilized Steels	227
Chapter 12.—CORROSION PRODUCTS IN RECIRCULATING SYSTEMS	229
Introduction	229
Properties of System Corrosion Products	230
Deposition of System Corrosion Products	231
Removal of System Corrosion Products	236
Detailed Summary	237
Chapter 13.—APPLICATION CONSIDERATIONS OF WEAR	239
Introduction	239
Discussion and Interpretation of Wear Data in Chapter 7	241
Discussion of Supplementary Data	245
Practical Considerations in Choosing Materials	251
Chapter 14.—MANUFACTURING PROCEDURES AFFECTING CORROSION AND WEAR	263
Introduction	263
General Cleanliness	263
Machining, Grinding, and Polishing	266
Grit and Vapor Blasting	266
Lubrication	266
Acid Cleaning	267
Initial Cleaning	270
Degreasing	270
Water Employed for Cleaning	270

CONTENTS

	Page
FOREWORD.....	iii
VOLUME EDITOR'S PREFACE.....	v
PART A.—BACKGROUND INFORMATION	
Chapter 1.—INTRODUCTION.....	3
Purpose of Handbook.....	3
Scope.....	3
Main Considerations in Choosing Materials.....	4
Stainless Steel.....	5
Carbon Steel.....	6
Industrial Utilization of Information.....	7
Contributing Organizations.....	9
Chapter 2.—FUNDAMENTAL ASPECTS OF IRON CORROSION.....	11
Introduction.....	11
Thermodynamic Considerations.....	12
Mechanism of Iron Corrosion.....	13
Effect of Water Composition.....	16
Future Study Required.....	19
Summary.....	19
Chapter 3.—FUNDAMENTAL ASPECTS OF FRICTION AND WEAR.....	21
Introduction.....	21
Basic Friction Theory.....	22
Coefficient of Friction.....	24
The Process of Wear.....	27
Guides for the Evaluation of Friction and Wear.....	28
Chapter 4.—WATER TECHNOLOGY.....	31
Introduction.....	31
Chemical Processes in the System.....	31
Interdependence of Chemical Processes.....	33
Practical Water Conditions.....	34
Importance of Water Purity.....	36
PART B.—PROCEDURES AND DATA	
Chapter 5.—DESCRIPTION OF TESTING PROCEDURES.....	39
Introduction.....	39
Corrosion Test Systems.....	41
Test Operation.....	51
Procedures for General Corrosion Testing.....	55
Procedures Special for Corrosion Tests.....	60
Wear and Friction Testing.....	64
Chapter 6.—APPROACH TO CORROSION PROBLEMS.....	75
Introduction.....	75
General Corrosion.....	75
Localized Corrosion.....	80
Chapter 7.—TABULATION OF BASIC DATA.....	95
Introduction.....	95
Static Corrosion Test Data.....	96
Dynamic Corrosion Test Data.....	101
Wear Test Data.....	121
Chapter 8.—RELATIVE IMPORTANCE OF DIFFERENT VARIABLES.....	135
Introduction.....	135

CONTENTS

IX

Chapter 14.—MANUFACTURING PROCEDURES AFFECTING CORROSION AND WEAR—	
Continued	
Drying.....	Page 271
Preparation for Storage and Shipment.....	271
Appendix A.—CONTRIBUTING AUTHORS.....	273
Appendix B.—GLOSSARY OF TERMS.....	275
INDEX.....	279

Part A

Background Information

Chapter 1

INTRODUCTION

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PURPOSE OF HANDBOOK.....	Page 3
SCOPE.....	3
MAIN CONSIDERATIONS IN CHOOSING MATERIALS.....	4
STAINLESS STEEL.....	5
CARBON STEEL.....	6
Incentives.....	6
Disadvantages.....	6
Present Information.....	7
Future Outlook.....	7
INDUSTRIAL UTILIZATION OF INFORMATION.....	7
High-Purity Water.....	7
Basic Information.....	8
Boilers.....	9
Other Uses of High-Purity Water.....	9
CONTRIBUTING ORGANIZATIONS.....	9

PURPOSE OF HANDBOOK

Early in 1948, the United States Navy and the Atomic Energy Commission undertook a program for the construction of a submarine that was to be powered with nuclear energy. The use of a nuclear reactor as a source of energy represented a new and untried method for the propulsion of ships at sea. During the initial feasibility studies, several coolants were considered for removing heat directly from the reactor. These included water, liquid metals, and gases.

The investigators chose water as the primary coolant in one of the naval reactors because (1) it possesses desirable nuclear and heat-transfer properties, (2) its technology was more advanced and required the least amount of extrapolation, and (3) it is a readily available and inexpensive coolant. However, the choice of high-purity water gave rise to many questions concerning the corrosion and wear properties of structural materials in pure water at elevated

temperatures; there was essentially no industrial experience along these lines.

Because of the rigorous time schedule adopted for the construction of the atomic reactor and because of the multitude of problems requiring immediate investigation, the Naval Reactors Branch of the Reactor Development Division, Atomic Energy Commission, expedited the project by letting many prime contracts and subcontracts. Consequently, during the past 8 years the various participating organizations have amassed a large amount of information on the corrosion and wear resistance of materials under the expected service conditions.

It is the main purpose of this handbook to accumulate and correlate the pertinent corrosion and wear information developed on this project into one source and in a form that is readily useful to the general engineering profession, particularly to those organizations that will participate in future nuclear reactor programs. It is also intended that the handbook will indicate the many areas that have not been thoroughly investigated and may thereby serve as a source of stimulation for further research by industry and by universities.

SCOPE

The basic data presented in the handbook were obtained from all the government and private organizations who made a significant contribution to the naval reactor project, either as prime or secondary contractors. The scope of the information included is primarily confined to corrosion and wear problems related to the primary, or radioactive, cooling system

in the nuclear reactor portion of the power plant. (See fig. 1-1.)

Corrosion and wear studies were not normally conducted for the selection of materials for the secondary, or nonradioactive, system. However, investigations were made to determine the compatibility of stainless steel with the boiler water in the secondary system. The main heat exchanger, constructed of stainless steel, comes in contact with the primary coolant water on one side and with boiler water on the opposite side. No previous information was available on stainless steel in contact with boiler water. With this single exception, the secondary system parallels other industrial and military plants for which considerable experience is available.

In order to expedite publication and to present corrosion and wear data in a readily available form, it was considered necessary to limit the quantity of information included and to present only pertinent and generalized results. Nevertheless, a sufficient number of references are included so that additional detailed information on a particular subject can be obtained if desired.

It is anticipated that this handbook will be of greatest value to those engineers and technicians who are not corrosion and wear specialists. These engineers are in daily contact with general material problems, for which the handbook may provide solutions. While the handbook is in no way intended to transform these men into corrosion and wear specialists, it is hoped that the book will present all data necessary for the designer or engineer to face with confidence, problems involving corrosion and wear in a water-cooled nuclear reactor system.

Basically, the handbook will deal with three general categories of information.

Part A, consisting of four chapters, is intended to provide the reader with a general background so that the "numbers" and various special subjects discussed in subsequent chapters can be fully appreciated and understood in terms of the particular engineering application. These chapters include general discussions on

the nuclear reactor plant and its relation to conventional powerplants, considerations in choosing materials, fundamental aspects of corrosion and wear, and water technology.

Part B consists of four chapters. These supply basic information on methods of testing and on the inherent corrosion and wear resistance of various materials and combination of materials under several different environmental conditions.

The remaining six chapters constitute part C, which deals primarily with special corrosion and wear problems resulting from the particular engineering application of materials. These include discussions and detailed data on such items as crevice corrosion, stress corrosion, intergranular corrosion, system corrosion deposits, wear, and manufacturing problems.

MAIN CONSIDERATIONS IN CHOOSING MATERIALS

In order that the reader may understand and appreciate more fully the basic problems involved in choosing materials for nuclear reactor applications, it is desirable that some attention be given to the overall characteristics and requirements of the nuclear plant. A schematic layout of the water-cooled nuclear reactor and the steam power plant is shown in figure 1-1.

FIGURE 1-1. Schematic layout of nuclear reactor and powerplant.

The plant consists of essentially two systems: (1) the primary cooling system, which removes heat from the nuclear reactor core and

transfers it to the secondary boiler system through the steam generator, and (2) the secondary cooling system, which may be considered standard and representative of steam systems used with conventional fuels such as coal, oil, and gas. Therefore, the main difference between a conventional and a nuclear plant is the method employed for heating the steam generator. In the nuclear plant, hot water rather than hot gases is circulated through the primary side of the main heat exchanger.

In conventional power and utility plants the purity of the boiler water is controlled by a continuous schedule of blowdown and makeup. Basically, this involves the removal of soluble and insoluble products by draining some water, more or less periodically, and replacing it with fresh water. It is considered easier in a nuclear plant to circulate the same water continuously in the primary radioactive system and to maintain purity by means of a mechanical filter and ion exchanger.

Corrosion products and other impurities in the water of the primary system become radioactive as the water circulates through the reactor core. Some of the radioactivity is long-lived and remains in the system even after the reactor is shut down. The disposal of the water containing radioactive waste products presents an obvious biological health hazard. Since the safety of operating personnel and integrity of the plant are the primary considerations in the design and operation of a nuclear reactor facility, it is necessary to keep the concentration of corrosion products, both soluble and insoluble, below specified safe levels. Only by closely controlling the amount of corrosion products in the primary system can this portion of the nuclear plant be made available for maintenance and repair within a reasonable period of time. This control can be effected by using highly corrosion-resistant materials or larger purification systems with materials of lower corrosion resistance. Thus it is imperative that the corrosion and wear characteristics of all likely materials be known. Through this knowledge, design personnel can

specify the requirements of the purification system.

As previously mentioned, when the project was initiated, there was essentially no experience on materials exposed to high-purity water at elevated temperatures. Owing to this lack of information, a conservative policy was adopted concerning the requirements for a material to be used in nuclear energy applications. Only those materials having the highest known corrosion and wear resistance were chosen for study. Materials were chosen on the basis that components or their parts would not require repair or replacement during the estimated life of the plant.

STAINLESS STEEL

Stainless steel has been chosen as the major material of construction for water-cooled nuclear reactors such as the PWR.

This material was chosen because it possesses many desirable characteristics from a nuclear application point of view and it required the least amount of development in order to make a final material selection. Apart from its physical and fabricating characteristics, it was chosen because it was the most corrosion-resistant material readily available in the forms required.

At the time this decision was made, the degree of corrosion resistance required for such a plant was not definitely known. Nevertheless, it was realized that a more corrosion-resistant material would minimize the various types of problems expected in a water-cooled nuclear reactor. Because of the high corrosion resistance of stainless steel (less than 0.0001 in. per year), no corrosion allowance was employed in designing primary equipment. Consideration of a less corrosion resistant material would have to be based on a compromise between the savings in cost, procurement time, etc., and the size of the purification system needed. Weight and space considerations are especially important in naval applications.

This handbook deals primarily with problems arising from the use of stainless steel and other

highly corrosion resistant alloys. From the preceding discussion it is apparent that many special metals and alloys not commonly used in industry are presently considered for nuclear applications. Most of these materials, although they possess many desirable properties, are special metals and alloys that are not normally employed in the construction of power and utility plants. Many of them are materials that have only recently been put on the market and, consequently, require some development work before they can be used. Also, these materials are, for the most part, expensive and hard to procure and often contain strategic elements.

Although the types of materials chosen have proven satisfactory in the submarine nuclear reactor and its prototype, interest has been steadily growing in the use of more common materials for nuclear power plants. In this connection, a large program has already been undertaken to study the feasibility of using materials that are more standard but less corrosion resistant, e. g., carbon steels.

CARBON STEEL

Early in 1954, work was started to determine the feasibility of employing carbon and low-alloy steels as the major materials of construction for water-cooled nuclear reactors. The carbon steels investigated were of a type similar in composition and properties to ASTM A212, and the low alloy types included steels with chromium up to 5 percent. The incentives leading to this program, disadvantages, and the information obtained to date are discussed briefly in the following sections.

Incentives

The current interest in carbon and low-alloy steel stems from the ultimate desire to be able to construct nuclear power plants with the types of materials that are presently used in conventional industrial and military power and utility plants. It is realized, of course, that the reliability of the plant cannot be reduced

by such material changes. The specific incentives for carbon and low-alloy steel, as compared with stainless steel, are given below:

1. Procurement time and cost for raw materials and components would be reduced materially. Standard materials and techniques for fabrication, welding, and inspection could be employed.

2. There is considerably more industrial and military service experience in power and utility plants. Problems with carbon steel are well known.

3. Fewer materials would be employed which are listed by the Government as containing critical elements.

4. Carbon and low-alloy steels are not susceptible to chloride stress corrosion. This form of corrosion imposes some stringent requirements on certain stainless steel components (see ch. 10, "Stress Corrosion").

5. There would be fewer undesirable elements from the point of view of induced radioactivity (see ch. 4, "Water Technology," and ch. 12, "Corrosion Products in Recirculating Systems").

Disadvantages

There are two main disadvantages expected with the use of carbon or low-alloy steel:

1. The general corrosion rate of carbon and low-alloy steels is considerably greater than stainless steel. This increased corrosion rate will very likely require special attention in order to reduce the possible adverse effects of system corrosion deposits on heat-transfer surfaces and on the radiation aspects of the plant (see ch. 12, "Corrosion Products in Recirculating Systems").

2. Carbon and low-alloy steels are susceptible to pitting type corrosion under certain expected reactor conditions. Special care would have to be taken in order to prevent objectionable pitting (and rusting) of certain carbon and low-alloy steel components during fabrication, storage, service, and shutdown. The main concern for localized corrosion is in thin pressure-containing members.

Present Information

The available corrosion information on carbon and alloy steels is given in ch. 7, "Tabulation of Basic Data." This source gives detailed information on the effects of composition, temperature, velocity, pH, oxygen additions, hydrogen additions, and other chemical additives. Test procedures are given in ch. 5, "Description of Testing Procedures." Additional corrosion data of work performed by Wroughton and Seamon are reported in reference 1.

The following list summarizes the pertinent engineering information available on carbon and low-alloy steel:

1. The expected general corrosion rate of carbon and low-alloy steel is approximately 10 to 50 times greater than stainless steel for comparable conditions.
2. A corrosion allowance based on corrosion during the life of the plant is necessary for pressure-containing vessels made of carbon steel. The customary commercial practice for carbon steel heat exchangers is $\frac{1}{16}$ -in. corrosion allowance.
3. The corrosion rate of carbon steel is reduced fourfold by the use of high pH water (10.5 to 11.5).
4. The difference in the corrosion rates between carbon steel and the low-alloy steels studied is minor and of no practical importance.

Future Outlook

There are many areas which must be studied before a final decision can be made concerning the applicability of carbon and low alloy steels to future nuclear reactors. The next step toward the application of these cheaper and readily available materials would be to construct pumps, valves, heat exchangers, and other nuclear reactor system components for test. If such components show satisfactory results there is no reason why they could not be used in an otherwise stainless steel system.

INDUSTRIAL UTILIZATION OF INFORMATION

It is considered that part of the information given in this handbook may be of general use to industry in applications not necessarily related to nuclear technology. The usefulness of this information falls into three main categories: (1) basic corrosion information on iron-water reactions, (2) boiler applications, and (3) other miscellaneous uses for high-purity water.

High-purity Water

It is not possible to define high-purity water in specific terms since its meaning varies in different applications. In general, however, most definitions of high-purity water will fall into the category of municipal waters which have been purified further by more refined techniques, e. g., distillation and ion exchangers. For most purposes the quality of high-purity water can be described in terms of the electrical resistivity. The presence of insoluble solids or soluble constituents that do not affect resistivity is not likely in most commercial grades of high-purity water. The effect of different dissolved electrolytes on the electrical resistivity (or electrical conductivity) is shown in figure 1-2. The purity of waters is also specified by the total solids content (both soluble and insoluble).

The maximum theoretical electrical resistivity attainable is approximately 26,000,000 ohm-cm. For the most part, the work described in this handbook was performed with water having a nominal electrical resistivity of 500,000 ohm-cm. Some boiler feedwater applications require water having a resistivity between 3,000,000 and 10,000,000 ohm-cm. In contrast, 50,000 ohm-cm. is considered to be high-purity water in pharmaceutical uses. The ultimate purity of water depends on the method by which it is produced. Table 1-1 shows the various qualities which are obtained by different methods of purification.

FIGURE 1-2. Effect of dissolved electrolyte on electrical conductivity of water at 65° F.

TABLE 1-1

QUALITY OF WATER OBTAINED FROM
VARIOUS SOURCES ²

Type of water	Quality, electrical resistance in terms of ohm-cm
Water after 28 distillations in quartz*-----	23, 000, 000
Water treated by strongly acid-strongly basic mixed bed resin (Delaware River water)-----	18, 000, 000
Water after 3 distillations in quartz-----	2, 000, 000
Water after 3 distillations in glass-----	1, 000, 000
Water in equilibrium with the carbon dioxide in the atmosphere-----	700, 000
Water after a single distillation in glass-----	500, 000
Approximate quality of U. S. P. distilled water†-----	100, 000-500, 000
Theoretical maximum quality (calculated)-----	26, 000, 000

*Kohlrausch, 1894.

†The U. S. Pharmacopoeia specifies that U. S. P. distilled water must not contain more than 5 ppm total dissolved solids.

Basic Information

The Joint Research Committee on Boiler Feedwater Studies has indicated a need for the type of information given in the handbook. This committee was organized in 1925 for the purpose of coordinating studies in relation to boiler feedwater problems. It is made up of representatives from various societies and organizations whose prime interest is in boiler-water treatment and water-corrosion problems. The following statement was made by the committee in 1954, in connection with a proposed research project.

We do not know the equilibrium condition toward which the prime step in the corrosion of steel moves at various temperatures in the boiler range. Nor do we know what controls the rate at which the further step of forming magnetic oxide of iron proceeds. Factual knowledge is needed to uncover further possible ways of combatting the corrosion process. Part I of this project accordingly comprises the determination of:

- A. The solubility product of $\text{FeO} \cdot \text{H}_2\text{O}$ at 70° to 600° F. to establish the equilibrium pH and ferrous ion concentration.
- B. The mechanism and the rate of decomposition of $\text{FeO} \cdot \text{H}_2\text{O}$ in pure water and in water at various pH values up to 12 over a temperature range of 70° to 600° F.

Parallel with the search for basic scientific data in part I, an engineering study is scheduled in part II. This will measure the rate of corrosion of low-carbon steel tubing:

- A. In pure water as a function of the following three independent variables: (1) heat transfer rates between 100,000 and 200,000 Btu/hr/sq. ft., (2) mass velocities within and exceeding the nominal range of furnace wall circuits of high-pressure steam generators, and (3) temperatures between 300° and 700° F.
- B. In water containing added sodium hydroxide to give varying pH values up to 13, over the same range variables indicated above.
- C. In water containing typical salts, such as sodium phosphate, sodium sulfate, and sodium chloride. The program for this part of the investigation would best be planned on the basis of the results from A and B, correlated with the results from the studies in part I on $\text{FeO} \cdot \text{H}_2\text{O}$.

Most of the questions raised are discussed in one form or another in the handbook.

Boilers

The largest use of high-purity water from the standpoint of volume is in feed-water applications for high-pressure steam boilers in utility and industrial powerplants. In order to maintain boiler efficiency, it is necessary to keep the amount of scale-forming salts at a minimum. Silica is one constituent which must be maintained at extremely low limits. In modern high-pressure steam plants operating at 1,200 to 1,800 psi and higher, the silica present in the boiler water volatilizes and passes out with the steam. This causes the deposition of silica on turbine blades and, if sufficiently great, can seriously lower the efficiency of the plant to the point where mechanical and/or acid cleaning is required.

The problem of deposits is aggravated further by the recent trend toward increasing operating temperatures and pressures for boilers. As the pressure and temperature are increased above the critical point, water becomes a progressively better solvent for many constituents in boiler water. Iron oxide is considered to be one of these substances. Consequently, it is expected that the steam delivered to a turbine in a supercritical pressure power plant will carry with it substantially more iron oxide than has been experienced in the past.² Whether or not deposition of iron oxide on turbine blades will become a problem comparable to that of silica is a question which has not been answered.

The purity of water employed in once-through boilers is considered to be one of the limiting factors affecting successful operation. In this application, water is forced through a long circuit and is continuously transformed into steam directly on the heat-transfer surfaces. Any substances dissolved in the feed-water must deposit on the heat-transfer surface, pass along with steam to the turbine, or be trapped out as a concentrated brine from that part of the circuit where the last liquid is vaporized. The once-through boilers have been used for more than a quarter of a century in Europe; however, they are presently coming into use in the United States. The water

employed for such units is normally obtained by double distillation. This usually provides water with approximately 0.15 ppm of dissolved salts, which is equivalent to approximately 1,000,000 ohm-cm. In order to minimize contamination by corrosion, these waters have been treated with volatile inhibitors such as hydrazine and ammonia.

Other Uses of High-Purity Water

There are numerous other uses for distilled or demineralized water, many of which are concerned with the problem of handling or containing and maintaining high-purity water conditions. A partial list of the industries and/or processes now using high-purity water, as obtained by Nordell,³ is given below. This list is not considered to be complete; however, it will give the reader a general idea of the various miscellaneous applications of high-purity water.

Air conditioning	Latex paint production
Beverage preparation	Leather manufacture
Catalyst manufacture	Mirror silvering
Ceramics processing	Paper manufacture
Chemicals production	Pharmaceutical manufacture
Cosmetics manufacture	Photography
Diesel powerplants	Plastics manufacture
Distilleries	Power plants
Elastomers production	Printing
Electrochemical processes	Cooling high power electron tubes
Electronics production	Railways
Electroplating operations	Research laboratories
Explosives manufacture	Storage batteries
Elixir compounding	Television tube manufacture
Food processing	Textile processing
Gelatine manufacture	
Glass manufacture	
Ice manufacture	

CONTRIBUTING ORGANIZATIONS

Many organizations, both Government and private, contributed useful information which is included in this handbook. A listing of these contributors follows:

Argonne National Laboratory
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 General Electric Co., Knolls Atomic Power Laboratory

United States Naval Engineering Experiment
Station

United States Naval Research Laboratory
Westinghouse Electric Corp., Atomic Power
Division

Atomic Energy Commission, Naval Reactors
Branch

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Chapter 2

FUNDAMENTAL ASPECTS OF IRON CORROSION

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	Page
INTRODUCTION.....	11
THERMODYNAMIC CONSIDERATIONS.....	12
MECHANISM OF IRON CORROSION.....	13
Film Formation: Early Stages.....	15
Film Formation: Latter Stages.....	15
Occluded Hydrogen.....	16
EFFECT OF WATER COMPOSITION.....	16
Effects of pH.....	16
Effect of Dissolved Salts.....	17
Effect of Dissolved Oxygen.....	17
Effects of Dissolved Hydrogen.....	17
Effects of Velocity.....	18
Effects of Alloying Elements.....	18
FUTURE STUDY REQUIRED.....	19
SUMMARY.....	19

INTRODUCTION

There are many definitions in the literature of the term "corrosion." The most appropriate definition is the one which states that corrosion is any process that involves the transfer of atoms from the metallic to the ionic state. All dissolution and scale-formation reactions come under this definition; however, such a brief definition is sometimes inadequate in light of the complexity of most corrosion processes. A complete understanding of any corrosion process requires a detailed specification of all the possible anodic and cathodic reactions and of how each is affected by many variables, such as temperature, activities of the reacting species, metallurgical condition of the metal, presence of alloying constituents in the metal, and mechanical properties of any oxide films or scales formed. Only a limited number of corrosion systems have been investigated completely. However, there is some pertinent information on iron-water reactions. The discussions in this chapter are based on information in published literature

in addition to basic data obtained in connection with work on the water-cooled nuclear reactor.

The material in this chapter will be restricted mainly to the corrosion of iron and ferrous alloys in high-temperature water. Some of the general considerations will apply to all metal systems.

One of the advantages of water as a reactor coolant is that the radioactive species formed by the interaction of neutrons and hydrogen and oxygen are short lived. Therefore, from a theoretical point of view, water would not present a radioactivity problem were it not for the presence of radioactive corrosion and wear products in the coolant stream. Because of the induced radioactivity (i. e., formation of radioactive species from elements in the reactor coolant) water of high purity is essential. For this reason, many of the inorganic additives commonly employed in boiler systems cannot be used. Organic inhibitors are not considered satisfactory because of their inability to withstand the irradiation and temperatures associated with the reactor. Thus the corrosion problem in a nuclear reactor resolves itself into the reaction of the metal in question with pure water at elevated temperatures.

A great deal of effort has been expended over the past 8 years in determining the behavior of likely materials of construction in high-temperature water. In the case of iron and ferrous alloys, this has consisted mainly of empirical determinations of corrosion rates. Corrosion was measured by gross weight change and more recently by weight changes of descaled coupons (see ch. 5, "Description of Testing Procedures"). During the early investigations only a limited amount of work was devoted to studying the

fundamental aspects of iron corrosion in high-temperature-high-purity water. However, during the past 2 years many basic investigations have been undertaken in connection with nuclear reactor development work.

THERMODYNAMIC CONSIDERATIONS

It is difficult to overemphasize the importance of a knowledge of pertinent thermodynamic quantities to an understanding of an aqueous corrosion system. The ultimate in this regard is indicated in the excellent monograph by M. J. N. Pourbaix.¹ Here are presented in convenient graphical form all the pertinent thermodynamic data for the iron-water system at room temperature. On one graph, a simplified form of which is shown in figure 2-1, oxidation-

tions define regions of explicit corrosion behavior, i. e., regions of corrosion, immunity, and passivation.

Thus a great deal of important information is packed into a small space. It would be a decided advantage to be able to construct such a diagram for all metal systems at high temperatures. Unfortunately, however, the necessary thermodynamic data are not available.

The free energies of formation of the various metal oxides reported in the literature make it possible to estimate the equilibrium constants of the overall metal-water reaction,

The free energies of formation of some metal oxides over the temperature range of interest are shown graphically in figure 2-2.

FIGURE 2-1. Thermodynamic data for the iron-water system at room temperature. (M. J. N. Pourbaix, "Thermodynamics of Dilute Aqueous Solutions," translated by J. N. Agar, Edward Arnold (Publishers), Ltd., London, 1949.)

reduction potential is the ordinate and pH is the abscissa. The various equilibria appear as straight lines. These lines and their intersec-

FIGURE 2-2. Free energies of formation of some metal oxides.

They are expressed in kilocalories per gram-atom of oxygen: A particularly convenient system for comparing their stability with that of the water molecule. Such information can be used to estimate the extent to which a given reaction will take place. Thus, such noble metals as gold and platinum have positive free energies of formation of their oxides (not shown in fig. 2-2), and one would expect these metals to be completely resistant to attack by water. Metals with large negative free energies of oxide formation, e. g., chromium, titanium, aluminum, and zirconium, will react to form metal oxides and hydrogen. Large negative free energies do not necessarily indicate poor corrosion resistance. In many cases the oxide films formed are extremely protective, and the metals are quite satisfactory for use in high-temperature water systems.

Since hydrogen is a reaction product, the possibility of shifting the equilibrium sufficiently to protect the metal by adding hydrogen to the system must be considered. The important metals for which this is possible are nickel, cobalt, and copper. For nickel, copper, and iron the partial pressures of hydrogen required to shift the equilibrium toward the metal (when in contact with liquid water at 600° F) have been calculated and are given in table 2-1.

TABLE 2-1. METAL-WATER EQUILIBRIA

Metal	Oxide	Equilibrium constant at 600° F	"Protective" hydrogen pressure,* atm.
Cu.....	Cu ₂ O.....	10 ⁻¹⁰	10 ⁻¹⁷
Ni.....	NiO.....	2.5 × 10 ⁻⁵	2.5 × 10 ⁻³
Fe.....	Fe ₃ O ₄	1.2 × 10 ³	1.2 × 10 ⁵

*Calculated on the basis that activity of water is equal to the pressure of the saturated vapor and the activity of hydrogen is equal to its partial pressure.

The data show that, in oxygen-free water at temperatures of reactor interest, the principal corrosion product of iron will be magnetite Fe₃O₄; and no reasonable pressure of hydrogen will shift the equilibrium to reverse the reaction.⁶ The possibility of there being

ferrous oxide (wüstite) close to the metal-oxide interface is not precluded since bulk equilibrium might not pertain at the surface. Very little information is available on the many other thermodynamic properties of the iron-water system at the temperatures concerned. For an adequate understanding of the details of the corrosion reactions, much more thermodynamic data are needed, e. g., solubilities of the various hydroxides and oxides, accurate values of the free-energy changes of the many possible reactions, and electrode potentials.

MECHANISM OF IRON CORROSION

Thermodynamic considerations show that certain metals are stable in high-temperature water or in water containing a small amount of hydrogen. Other metals, in particular iron, possess a thermodynamic tendency to react with water to form oxides. Despite this indication, many such metals, including iron, resist corrosive attack. The reason for this, as previously mentioned, is that the oxide films formed on the surface protect the metal from further attack.

The important factors in the study of the corrosion of iron and ferrous alloys are film formation, structure, mechanical properties, and ionic and electronic conductivities of iron oxide films. While very little fundamental work of this nature has been done on films formed by reaction in high-temperature water, a relatively large effort has been directed toward the study of the scaling of iron in air and oxygen. It is possible, by analogy, to use this type of information to understand some of the phenomena observed in the iron-water system.

In any corrosion study it is desirable to consider separately the cathodic and anodic reactions. These reactions proceed simultaneously, the slower one controlling the overall rate of corrosion. For the iron-pure water system, the possible anodic reactions are:

Ferrous hydroxide formation

Ferrous oxide formation

Ferrous ion formation

The eventual formation of magnetite probably takes place through a reaction of the type first suggested by Schikorr:⁷

or

In neutral or slightly basic solutions, which are of primary interest for reactor coolants, the passage of ferrous ions into solution can be neglected. The distinction between reaction (1) followed by (4a) and reaction (2) followed by (4b) is not significant since the ferrous oxide is likely to be hydrated when first formed. In any event the distinction cannot be made without further information as to the stabilities of the two species. The ensuing discussion will assume that ferrous hydroxide is the intermediate formed. In pure water the only possible cathodic reaction is the discharge of hydrogen ions; thus

Once the anodic and cathodic reactions have been postulated, they must be fitted into a more detailed picture of the way in which the overall corrosion proceeds. This picture, to be valid, must be in accord with experimental observations. The following qualitative observations of the corrosion of pure iron in high-temperature water need to be accounted for:

1. In the early stages a tight oxide film is formed. After passing through the interference color region to a black film, the outer layer becomes dull black and can be partially rubbed off.

2. Kirkendall experiments at 460° and 680° F, using both radioactive tracers and inert materials as phase boundary markers, have shown that iron ions diffuse through the oxide film.³⁴

3. Hydrogen is released into the solution and is also absorbed into the metal.⁸ This

behavior is fairly general with aqueous corrosion of metals. The nature of the system, i. e., solubility of hydrogen in the metal and hydride formation, determines the fraction of the total hydrogen which remains in the metal.

4. The time dependence of the oxide-film growth in the early stages is that of a diffusion-controlled process. Experiments conducted by Bloom and Krufeld^{9a} show that the rate decreases with time. This would be expected if diffusion through the film is rate determining. Preliminary tests indicate that in the early stages film growth on pure iron exposed to water at 550° F follows the well-known parabolic law ($W^2 = Kt + K^1$), where W is some measure of film thickness and K and K^1 are constants.¹⁰

A further clue as to the nature of the overall corrosion process may be obtained, reasoning by analogy, from the more thoroughly investigated scaling studies of iron in air and oxygen. Conflicting views are expressed in the literature as to the oxidation of iron at low temperatures. Vernon and coworkers¹¹ studied the oxidation of abraded mild steel and concluded that above 392° F the oxide growth on iron in air or oxygen is due predominantly to the diffusion of iron ions outward through a layer of cubic oxide which is approximately magnetite. The kinetics of this reaction are described by the parabolic law. Davies, Evans, and Agar¹² obtained somewhat different results in their study of the oxidation of pure iron. These workers found that the parabolic law is observed on hydrogen-reduced surfaces only above 570° F. Both $\alpha\text{-Fe}_2\text{O}_3$ and Fe_3O_4 are formed, the latter appearing between the metal and the ferric oxide layer. Below about 570° F, a logarithmic law is followed. Also to be considered are the findings of Davies, Simnad, and Birchenall¹³ which indicate that diffusion in magnetite is predominantly cationic. Wickert and Pilz¹⁴ recently investigated the reaction between water vapor and iron. Activation energies calculated from their results¹⁵ are of

the proper magnitude for a diffusion-controlled process. Unless oxidation by water includes some unknown features, one would expect from the above that the reaction proceeds by diffusion of iron ions outward through a magnetite film and that the kinetics in at least one stage are parabolic.

Film Formation: Early Stages

Based on the observations and information given, the following mechanism is assumed for the early stages of the corrosion of iron in high-temperature water. (Results of corrosion studies indicate that it applies only during the initial period while the oxide film is still intact and protective. At 600° F this period lasts perhaps 150 to 200 hr for an electrolytically polished surface, and the film attains a thickness of about 0.5 μ .) Ferrous ions formed at the metal-oxide interface diffuse through the oxide (Fe_3O_4) by migration into vacant lattice sites. On reaching the oxide-water interface, the ferrous ions combine with hydroxyl ions (or absorbed water molecules) to form ferrous hydroxide. The latter compound decomposes into magnetite, water, and hydrogen. It may well be that at sufficiently low temperatures this reaction (Schikorr's reaction) will be rate controlling. Recent experiments¹⁶ indicate that it will not be rate controlling above about 400° F. Between 400° and 700° F the rate is controlled by the diffusion of ferrous ions, and the kinetics are described by the parabolic law.

To maintain electrical neutrality, electrons must migrate with the ferrous ions. These electrons will neutralize protons at the oxide-water interface, resulting in the formation of hydrogen atoms which will combine to form molecules. This is the cathodic reaction indicated in reaction (5). The fact that hydrogen enters the metal lattice, in some cases in large amounts, means that either hydrogen atoms or protons must migrate from the water interface through the oxide to the metal interface. No valid basis exists for deciding which of the hydrogen species permeates the film. If the film is permeable to protons, some of these will be discharged at

the metal-oxide interface to form hydrogen atoms which then enter the metal. A pictorial presentation of this oxide film growth mechanism is given in figure 2-3. This figure does not

FIGURE 2-3. Oxide film growth mechanism.

show the countercurrent diffusion of lattice vacancies, which are formed at the oxide-water interface. In the case of anion diffusers the entry of hydrogen into the metal is easily accounted for by the migration of hydroxyl ions along with the oxide ions.

Film Formation: Latter Stages

The discussion so far has dealt only with the initial oxide-film formation during which time the kinetics are described by the usual parabolic law. There is considerable evidence that the corrosion rate eventually becomes constant at a low value, and a linear rate law is followed.⁸ This would seem to indicate that the corrosion rate comes under some form of "mechanical

control," i. e., the oxide is no longer completely protective. Two possibilities exist: (1) the scale breaks down at a fairly constant rate, and the overall corrosion is controlled by an interface reaction; and (2) only the outer portions of the scale break down, and a more or less constant thickness of protective scale remains. The first possibility seems unlikely since one would expect an increase in corrosion rate if the scale breaks down completely and exposes fresh metal surface. The second possibility fits with the first of the qualitative observations listed at the beginning of this section. Birchenall¹⁷ has recently suggested a mechanism by which this may take place, namely, the condensation of lattice vacancies which migrate in a direction opposite the ferrous ions.

Since diffusion processes undoubtedly play an important part in the corrosion mechanism, the measurement of diffusion rates of iron ions in magnetite should be carried out. The techniques employed by Birchenall¹⁸ in determining diffusion coefficients in wüstite, magnetite, and hematite at higher temperatures could be extended to the region and conditions of interest.

Occluded Hydrogen

One of the most interesting questions, and perhaps one of the most important, regarding iron corrosion is the role which hydrogen plays in the process. In the case of the metals aluminum¹⁹ and zirconium,²⁰ the takeup of hydrogen by the metal substrate is believed to have a decisive effect on the course of the metal-water reaction. No such drastic situation has been observed with iron or any ferrous alloy; however, there is abundant evidence that the presence of hydrogen in iron can alter its electrochemical behavior. Patrick and Thompson²¹ report on the effect of occluded hydrogen on the standard electrode potential of the iron-ferrous ion couple. Uhlig²² has observed that hydrogen (from cathodic charging) diffusing through chromium steels makes the electrode potential more active by as much as 100 mv. The recent experiments of Bloom and Krufeld²³ indicate that vacuum-annealed steels show higher cor-

rosion rates in the early stages and take longer to reach a constant rate than do hydrogen-annealed steels.

A comprehensive investigation of the problem is needed. One experiment should include simultaneous measurements of the hydrogen released into the water and the hydrogen effused through the corroding metal. A study of the effect of occluded hydrogen on corrosion rate will require the development of an accurate method of determining corrosion other than measuring the hydrogen evolved. This should not be an insuperable obstacle.

Although measured electrode potentials are difficult to interpret in an absolute sense in corrosion systems, relative measurements can give valuable information about the effect of significant variables on corrosion behavior. Before much work in this direction can be done, a satisfactory insulating seal and the container must be developed. Teflon is normally satisfactory up to 600° F. Above that temperature no plastic or ceramic has been found to be completely free of attack.

EFFECT OF WATER COMPOSITION

Corrosion may also be affected by dissolved matter in the water, both ionic and molecular. The possibilities are limitless, of course, and only a few of the more important will be considered here. For the most part, the conclusions made are corroborated by the experimental results which are described in Chapter 7, Tabulation of Basic Data, and Chapter 8, Relative Importance of Different Variables.

Effects of pH

At sufficiently low pH the initial formation of hydroxide or oxide films will be prevented and the anodic reaction will be the simple dissolution of iron as per reaction (3). The result will be excessive corrosion, and this situation is not applicable to this study. Carbon steels and stainless steels have been extensively corrosion tested in water adjusted to pH 9 to 11 with sodium hydroxide, lithium hydroxide, or

ammonia. There is some evidence during at least the initial few hundred hours, that corrosion is less²³; however, the long-term experiments of Bloom and Krufeld show that the final "steady-state" corrosion rates are unaffected by increasing the pH.

From the standpoint of the postulated mechanism, it is instructive to consider the ways in which increasing the pH can affect the corrosion reaction. If a significant number of anion lattice positions are occupied by hydroxyl ions, an increase of pH would increase this number. However, increasing the number of OH ions in lattice positions will increase the number of cation vacancies, which should increase the corrosion rate. Thus this hypothesis appears without foundation. Another possibility, which needs further investigation, is that increased pH affects the rate at which Schikorr's reaction proceeds. Results of the study of this reaction make this seem unlikely.¹⁶ A third possibility is that the hydroxyl ions are effective in polarizing the cathodic discharge of hydrogen ions. This view has been put forth by Mayne, Menter, and Pryor²⁴ to explain inhibited corrosion of iron in deaerated 0.1N NaOH at room temperature.²⁴ Certainly the effect of pH on corrosion rate of pure iron merits further study. Unequivocal results would aid in formulating a valid reaction mechanism.

Effects of Dissolved Salts

Salts of certain complex anions containing oxygen, phosphates, chromates, silicates, borates, etc., are more or less effective as anodic inhibitors in oxygen containing solutions at room temperature. The work of Mayne and Menter²⁵ indicates that this is due mainly to a more effective formation and repair of passive films of $\alpha\text{-Fe}_2\text{O}_3$ or Fe_3O_4 on the metal surface. It appears unlikely that they will have much effect on the corrosion of iron in oxygen-free water at elevated temperatures.

Effects of Dissolved Oxygen

It is not possible to predict the effect of oxygen on the corrosion of iron with the limited

theoretical information available. There are many indications in industrial applications which show that oxygen has a marked effect on corrosion. The information on localized corrosion in high-purity water also shows that oxygen is important. However, it should be mentioned that data on general corrosion (see ch. 8, Relative Importance of Different Variables) do not show an effect of oxygen within the limits studied and in the absence of irradiation. These different observations strengthen the need for additional fundamental data on the effect of oxygen.

The manner in which oxygen acts to increase the corrosion rate can be explained in at least two different ways. One school holds that oxygen serves principally to depolarize the cathodic reaction, as in

Another possibility is that oxygen reacts with the metal in much the same way as in gaseous oxidation. Since the oxidation rates of iron in oxygen at temperatures of about 600° F are somewhat lower than the observed aqueous corrosion rates, the latter mechanism seems unlikely.^{12, 27}

Effects of Dissolved Hydrogen

It has been shown that nominal partial pressures of hydrogen will not effect the iron-water equilibrium appreciably and thus would not be expected to noticeably reduce corrosion rates of iron or carbon steel. In the case of high nickel alloys, the equilibrium can be readily shifted, and small amounts of hydrogen will result in greatly reduced rates of corrosion (see ch. 8, Relative Importance of Different Variables).

If the dissolved hydrogen affects appreciably the amount of hydrogen in iron or steel being corroded, it may influence the electrochemical behavior of the metal. Such effects on corrosion rate cannot be specified at this time because of the great lack of fundamental knowledge of such systems.

Effects of Velocity

One factor which has been omitted in all the foregoing discussions is water velocity. Static water has been assumed throughout. Fast flowing water, such as will be present in a reactor coolant system, may alter the situation materially. If the scale is not tightly adherent to the base metal, one would expect increased corrosion rates in dynamic systems. The effects of velocity on the corrosion rates of specimens are discussed in chapter 8, Relative Importance of Different Variables. The reported increase in the corrosion rate of certain materials with increased velocity can be attributed to an erosion of the oxide film. This provides the iron ions with a shorter diffusion path to the oxide-water interface, where they can react with hydroxyl ions. On the other hand, the 18-8 type stainless steels, which show almost negligible velocity effects, are protected by the Cr_2O_3 or $\text{FeO}\cdot\text{Cr}_2\text{O}_3$ film. This film is not only thinner but also is more adherent than the magnetite film formed on most ferrous alloys.

Effects of Alloying Elements

If the mechanism of the corrosion of pure iron in high-temperature water were sufficiently well understood, it would be possible to predict the behavior of most of the alloys of interest. More important than this, an alloy development program could be undertaken on other than an empirical basis. Although the general scheme is probably correct, the details of the reaction mechanism postulated in the previous pages are lacking. Thus, admittedly, little can be done toward the aspired goal of selecting the best alloy. It is recognized that the best alloy will not have necessarily the ultimum in corrosion resistance; it will be the least expensive one which will do the job satisfactorily. Nevertheless, it will be instructive to bring out the principals involved in "designing" the optimum ferrous alloy.

For any given oxide-scale-formation reaction in which, as is generally accepted, the diffusion takes place by the migration of cations (or anions) from one lattice vacancy to another, the diffusion rate can be altered in two ways:

- (1) changing the number of lattice defects and
- (2) varying the chemical composition and thus the structure of the scale.

In magnetite, as in most other oxides, a certain number of vacancies are in thermodynamic equilibrium in the lattice. Inclusion of certain impurities, either cationic or anionic, will alter the number and efficiency of these defects in such a way as to markedly decrease the diffusion rate. Specifying the effect of any given impurity requires more knowledge of the semiconducting nature of magnetite than is presently available. For a complete discussion of lattice vacancy diffusion, electronic and ionic conductivities, and their importance in oxidation theory, the reader is referred to the excellent monograph by Kubaschewski and Hopkins¹⁰ in which the subject is developed in detail and reference to the original work by Wagner and others will be found.

Increasing the oxidation resistance of a metal by adding sufficient amounts of an alloying constituent to change the chemical structure of the oxide layer is best exemplified by the effect of adding chromium to iron in air or oxygen. Low-chromium steels are a little more resistant to oxidation than iron or carbon steels. Below 1,800° F additions of more than 12 percent chromium and above 1,800° F more than 17 percent, enhance the resistance to oxidation of iron by a factor of nearly 100. This protective effect is due to the formation of a compact layer Cr_2O_3 or $\text{FeO}\cdot\text{Cr}_2\text{O}_3$ which acts as a diffusion barrier to the iron ions. After this film reaches a critical thickness, further oxidation proceeds very slowly. The oxidation resistance of the 18-8 type stainless steels is probably due to a similar effect. Of the ferrous alloys that have been extensively tested in high-temperature water, the 18-8 type stainless steels show a markedly lower corrosion rate than do the steels containing 12 percent or less chromium.²³ However, there are indications that alloys containing as little as 1¼ percent chromium show some improvement over carbon steels in the high-temperature water environment.²⁹ In all likelihood, the same factors are active in the water reactions as in the air oxidation. Until

more fundamental information on the mechanism of iron corrosion becomes available, little more can be said about ferrous alloy behavior in high-temperature water.

FUTURE STUDY REQUIRED

It must be emphasized that the mechanism of the corrosion of iron in water as described above is, to a considerable degree, speculative. A number of fundamental studies are needed before a definitive picture can be drawn. It is hoped that this chapter will serve to stimulate such investigations. Among the more important investigations needed are the following:

A study of the structure of the scale formed at various stages in the corrosion process is required. This could best be done by stripping the films, using one of the techniques described in the literature,^{11,30} and examining the structure with an electron microscope. In particular the film breakdown mechanism responsible for the constant corrosion rate after long exposure might be elucidated.

For years it has been recognized by workers in the corrosion field that Schikorr's reaction, the decomposition of ferrous hydroxide to magnetite, water, and hydrogen, may play an important part in boiler corrosion.^{31,32} While, contrary to Schikorr's original observation, ferrous hydroxide slurried in water appears to be stable up to about the boiling point of water³³ little is known of its chemistry at elevated temperatures. A comprehensive investigation of the stability and reactions of this compound at elevated temperatures (up to 700° F) is being undertaken.¹⁶ It seems certain that at sufficiently low temperatures the film of ferrous hydroxide formed on iron on exposure to pure water is completely protective. The formation of oxide films takes place only when the hydroxide is oxidized by the water to form magnetite.

Certainly there is a need for careful corrosion rate measurements with pure iron and with ferrous alloys. Bloom and Krufeld have made a good start in this direction using an ingenious scheme for measuring the rate at which hydrogen effuses through capsules of carbon steel and stainless steel. The capsules are filled with

water, sealed, and then heated in an evacuated glass system. The pressure increase in the system due to the effused hydrogen is recorded and is used as a direct indication of the corrosion rate. After steady-state conditions are reached, this method gives reliable results.

In the early stages of corrosion, however, there is some question as to whether the corrosion is the only process which controls the rate of hydrogen effusion. Nevertheless, corrosion measurements using a different method show good agreement with Bloom and Krufeld's results. In addition, rate determinations that establish the influence of the many variables are needed.

It will be particularly interesting to establish with certainty the rate law that governs the early stages of film growth (up to about 0.5 μ). As mentioned earlier, preliminary results obtained here indicate that a parabolic law holds, but the possibility of a cubic or other relation must not be ignored. The results of the studies of the air oxidation of iron by Vernon¹¹ and Davies, Evans, and Agar¹² suggest that somewhere in the temperature range 400° to 700° F. the rate law may change from parabolic to logarithmic, the latter holding at the higher temperatures.

Hauffe²⁷ has explained the low temperature oxidation mechanisms (logarithmic and cubic laws are observed for various metals) on the basis of a positive space charge formed in the oxide layer to compensate for a negative surface charge due to chemisorbed oxygen. If this picture is correct, any such effect will be quite different in a pure water system. However, if a film breakdown and repair mechanism, as suggested by Davies, Evans, and Agar, is responsible, then a similar change in rate law somewhere in this temperature range may pertain in water oxidation of iron.

SUMMARY

A review of the limited information on the thermodynamics of the iron-water system at temperatures in the range 500° to 700° F shows that magnetite is the stable oxide. The equilibrium lies far enough on the oxide side so that unreasonably high hydrogen pressures are re-

quired to reverse it sufficiently to prevent attack on iron or carbon steel. The rate of the reaction between iron and water at these temperatures is controlled by the diffusion of iron ions through the magnetite film. In the early stages (up to a thickness of 0.5μ), the parabolic law is most likely followed; on reaching some critical thickness, the outer layers of the film become nonprotective, and a diffusion boundary of approximately constant thickness remains. This results in a constant rate of corrosion. Ferrous alloys, other than carbon steel which behaves very much like a pure iron, have been investigated only in an empirical manner.

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Chapter 3

FUNDAMENTAL ASPECTS OF FRICTION AND WEAR

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INTRODUCTION.....	21
BASIC FRICTION THEORY.....	22
Asperity Deformation.....	22
Actual Contact Area.....	23
Welding of Asperities, Hot Spots.....	23
Interlock-Weld Theory.....	23
COEFFICIENT OF FRICTION.....	24
Interface Materials in Contact.....	24
Influence of Interface Materials on Friction.....	24
Nature of Surface Layers.....	25
Destruction and Maintenance of Surface Layers.....	25
Modifying Factors.....	26
Modifying Environmental Effects.....	26
Mechanical and Metallurgical Factors.....	27
THE PROCESS OF WEAR.....	27
Adhesive Wear.....	27
Abrasive Wear.....	28
Corrosive Wear.....	28
Surface Fatigue.....	28
GUIDES FOR THE EVALUATION OF FRICTION AND WEAR.....	28
Friction.....	28
Wear.....	28

INTRODUCTION

When plans for the first water-cooled and moderated reactors passed from the feasibility study to the design stage, some concern was felt for the problem of wear involving mechanisms in contact with the primary water. However, the wear and friction problems that quickly developed proved to be out of all proportions to original expectations and necessitated a major investigation of the properties of water-lubricated bearings. In the course of these studies, the available wear and friction literature was surveyed. The report of the Franklin Institute Laboratories, "A Survey on

the Literature Dealing With Sliding Friction," proved most useful in this planning stage.

As the Franklin Institute report indicated, man's awareness of friction was recorded in literature predating the Christian era. These observations were gradually supplemented until the classical friction theories were evolved about the time of Leonardo da Vinci. In recent years, rapid progress has been made in evaluating the phenomenon on a scientific basis. Although the development of wear and friction theory over the past 20 years has been rapid, it has often been controversial; therefore the interpretation and evaluation of present theories is difficult.

Recent studies, while yielding considerable data, point out the need for more adequately defined wear and friction theory and the rationalization of anomalous behavior of materials, in short, the desirability of formulating scientifically exact laws of wear and friction.

The purpose of this chapter is to review the mechanisms of wear and friction, touching briefly on classical theory and in more detail on the modern concepts. Some of the classical theories have stood up remarkably well over the years, and present experimentation modifies them only slightly. These continuously occurring modifications of theories preclude the stating of any laws of wear and friction. Therefore, on the basis of the best available information, guides for the evaluation of problems in wear and friction are presented in this chapter.¹

The fundamental considerations of wear and friction involve not only the materials nominally in contact but also the surface films that may

separate them in service. Specifically this chapter deals with coefficient of friction determinations, asperity deformation, weld theory and interlock theory, the modifying effects of environment, mechanical properties, and physical properties. Thus, within this chapter are presented the generally accepted concepts which, along with the modifying conditions, and in the rationalization and perhaps prediction of most wear and friction phenomena encountered in water-lubricated service.

In the interest of presenting the material in the most compact, easily digested manner, a considerable amount of the details are given in the form of references. References are directed toward leading technical journals, widely circulated books dealing with wear and friction, and reports of those organizations that have contributed to the study of wear and friction in a water environment. Some of the references are extracted from unpublished documents and letters that unfortunately may not be readily available.

BASIC FRICTION THEORY

The study of wear and friction involves surface phenomena as well as the fundamental properties of materials. This is particularly true when, as in the case of metal parts wearing in a water environment, the metals are not benefited by conventional lubrication. The smoothly finished surfaces associated with conventional bearing applications are in reality rough and irregular; they include many asperities or high points. Thus, when two smooth metal surfaces are brought in contact, asperities, and not the nominal areas, are brought together. Metal-to-metal contact may be further reduced by the presence of a contaminant or

oxide layer, but once contact has been made there is an altered or distorted layer within the metal itself.

If relative motion is then introduced, wear may occur in one or a combination of the following ways: (1) by asperity contact and welding under pressure, with the weaker of the two metals yielding; (2) by shearing of interface oxides protective to the base metals; (3) by the formation of a junction material that is stronger than either of the base metals; or (4), in the case of similar metals, by work hardening the contacting layers and increasing their shear strength and, as in (3), causing wear to take place in the bulk of the material.

The familiar smooth surface of a ball-bearing race or the even smoother surface of the balls generally ranges from 1 to 4 microinches (millionths of an inch) root mean square (rms) in average roughness. These smooth surfaces are really very rough when compared to atomic dimensions. Four microinches are equal to 1,000 Å, or approximately the distance covered by 1,000 contiguous atoms arranged in a row. When such a surface is magnified 10,000 times, it looks very much like a rolling field with plough furrows across it. A cross section of such a surface is shown in figure 3-1.

Asperity Deformation

It is apparent that, when two such smooth surfaces are brought together, initial contact will be at the peaks of the asperities. These asperities will yield under continued pressure until more and more points are brought into contact and the full load can be supported. The asperities retain their identities even with yielding, as shown in figure 3-2. In this illustrative example

FIGURE 3-1. Sketch of a smooth surface enlarged 10,000 $\times$ (from an electron microscope picture of steel ground to 3-5 rms microinches).

FIGURE 3-2. Identity of deformed asperities.

a finely grooved copper surface was indented by a hard steel cylinder.² The ridges yielded but were not obliterated even though the ball made a substantial dent in the copper. The asperities under contact must be stressed to the pressure required to deform the weaker of the two materials in order to support the applied load, regardless of what the load may be.

Actual Contact Area

The load alone determines the number of asperities or the fraction of the gross area in contact. As shown in figure 3-3, the asperities

FIGURE 3-3. Sketch showing the relation between nominal and actual contact areas.

deform to support the applied load. The plastic flow pressure, as estimated by Brinell hardness, is equal to approximately three times the yield strength for many of the usual engineering materials.^{3, 4} To illustrate this point, consider a high-strength metal with a yield strength of approximately 170,000 psi; the flow pressure would then be very nearly 500,000 psi. If a gross contact stress of 1,000 psi were applied against a harder material, the real area of

contact could be determined from the relation:

$$\text{Area} = \frac{1000}{500,000} \times \text{gross or nominal area}$$

Welding of Asperities, Hot Spots

Bowden and Stone⁵ demonstrated that hot spots accompany relative motion even when two highly finished surfaces are brought into contact and under the lightest loads. The highly polished surfaces of glass and quartz plates were placed in contact, and relative motion was initiated. The hot spots could be observed through the specimens as minute sparks. The resulting local temperature at the asperities may reach the melting point of the material at higher speeds and loads,⁶⁻⁸ but cold welding may take place at low speed, when subject to small loads, and in the absence of appreciable heat.*

A supplementary consideration in the determination of total friction force is a ploughing force which may be illustrated by considering a large asperity pushing the mating material ahead of it in the manner of a bulldozer. This ploughing force has been measured with a steel sphere pushing soft indium. It was found to be about one-third of the total friction force.¹² However, for the usual engineering bearing application of smooth and at least moderately hard materials the ploughing force would be very much less than one-third and may be disregarded.

Interlock-weld Theory

Some facets of the wear picture do not seem to be adequately described by the above

*From the equation for temperature rise developed in reference 7, it may be shown that either load or velocity may be decreased to give a negligible temperature rise; yet experience shows that the coefficient of friction may remain the same.

picture, i. e., the weld theory, as supplemented by the plowing force of hardened surface asperities. As a result, I. Ming Feng has proposed his interlock-weld theory.⁹

FIGURE 3-4. Mechanism of wear according to the interlock weld theory.

In essence, this implies that contact occurs initially between "high spots" or asperities. As the load is applied, the surfaces in contact roughen and interlock until the impressed load can be fully supported (fig. 3-4). If tangential force is then applied, welding may or may not take place depending on the cleanliness of the metals, the degree of mutual solubility, and the thickness of any surface film present. But it is evident that wear particles will be produced even if no welding takes place.

COEFFICIENT OF FRICTION

The force required to move one surface over another must equal the real contact area of the asperities multiplied by some shear strength (the shear strength of whatever is going to slide or shear under movement); likewise the load must equal the product of flow pressure times the real contact area.¹⁰⁻¹³ This can be expressed by the simplified relation:

$$\mu = \frac{\text{shear strength} \times \text{real area}}{\text{flow pressure} \times \text{real area}} = \frac{S}{P}$$

where μ is the dimensionless coefficient of friction and S and P are expressed in W/L^2 units, with W in pounds and L in inches.

Interface Materials in Contact

The simple S/P relation is valid. However, its use requires not only a knowledge of the interface materials in contact but also the properties of these interface materials and the properties of the base materials. Several additional factors have been temporarily disregarded for convenience in establishing this basic relation; these will be brought into the discussion that follows.

The first of these considerations is illustrated by figure 3-5, wherein two exaggerated, very rough surfaces are about to be brought into contact.

FIGURE 3-5. Two very rough surfaces about to be brought into contact.

The upper surface according to asperity theory would be successively raised and then dropped as sliding progresses. This force of sliding has been measured at about one-tenth of the total friction force when the sliding occurred between surfaces with a roughness of about 350 microinches (rms).¹⁴

Influence of Interface Materials on Friction

Because of the negligible effects of surface roughness and ploughing force in applications of interest, the simple equation, $\mu = S/P$, remains as the fundamental friction equation, with S equal to the shear strength of whatever is going to shear and P equal to the flow pressure of whatever is going to flow. One of the principal reasons for friction variation is that the material which shears is frequently not the base material but rather a layer of oxide or of contaminant film that is very thin when compared to the roughness. Thus, although the deformation of the asperities is in the base material, the ratio S/P may contain the shear

strength of a weaker material, e. g., oxide or contaminant film, and the flow pressure of a stronger material which yields a reduced value of μ .

There is another important reason for friction variation. The physical properties S and P may not always vary in the same ratio in response to work hardening (either before rubbing or by the rubbing process) to heat generated at the asperities, or to heat applied externally.^{10 15 16 17}

Nature of Surface Layers

The cross section of a so-called "smooth" surface at high magnification is shown in detail in figure 3-6.¹⁸⁻²¹

FIGURE 3-6. Detailed cross section of smooth surface at high magnification.

The sketch shows such a surface compressed horizontally but substantially to scale vertically. The height from the bottom to the top of the deeper grooves of a 4 microinch (rms) surface may be as great as 15 microinches. Starting at the outermost surface (fig. 3-6), there may be a thin layer of contaminant films anywhere from 1 to 25 Å thick. This layer is composed of the contaminants from handling and processing as well as gases adsorbed on the surface. Beneath these films is an oxide layer which may be from 25 to 250 Å thick. The final layer in figure 3-6 represents the base metal with the outermost portion probably cold worked to some degree from machining or from load application.

Destruction and Maintenance of Surface Layers

When two surfaces such as those just described are brought together, the destruction

or maintenance of surface layers becomes important. For the case in which the contaminant film is unbroken, the coefficient of friction is low, generally ranging from 0.1 to 0.2. However, as soon as the contaminant films are penetrated, the oxide films are exposed and can come in contact. Such oxide films, when unbroken, characteristically have a moderate coefficient of friction, about 0.4. Further wear exposes the base material resulting in the highest coefficient of friction, generally between 0.8 and 1 for fully work-hardened materials.^{10, 22} In any actual case, there is very likely a mixture of the three layers in contact so that friction may vary from the lowest value to the highest value, depending upon the durability of the films, the severity of the attack upon the surface layers, and their ability to repair themselves. During such wear the actual particle size, as determined in specific tests, ranges between 1 and 2,500 Å.²⁵⁻²⁸

FIGURE 3-7. The effects of contaminant films on the coefficient of friction in demineralized water at room temperature.

Figure 3-7 is a graphical representation of the effects of contaminant films on the coefficient of friction, as determined in demineralized water at room temperature by Dewees.^{23, 24} In this investigation a clean Armco 17-4PH rider was run on a clean Stellite No. 3 disk under 40 lb initial load. After 400 cycles of operation the load was reduced to 2.6 lbs, and no significant variation could be observed. However, after 900 cycles the rider was removed

from the test apparatus, and the operator rubbed his finger across the wear surface to provide a contaminant film. Testing was then resumed with the contaminated rider, showing a 4 to 1 reduction in friction. The remainder of the test from 900 cycles to 3,600 shows dramatically the destruction of the contaminant film and the approaching metal-to-metal contact.

Modifying Factors

The preceding example of wear through existing films may, in practice, be further modified by chemical and physical phenomena which may either aid or interfere in the repair of films, and which may change the properties of the base metal. These phenomena are briefly discussed below.

CHEMICAL AND PHYSICAL REACTIONS

(1) *Film Formation*.—Various types of film formation can be observed, depending upon the environment to which the material is exposed. These films may form at the high temperatures of asperity deformation or at room temperature. Whatever the mechanism of formation such films provide a wear layer of low shear strength.

The extreme pressure lubricants developed for automotive applications utilize this principle. These are effective not because the grease has lubricating properties but because the lubricant reacts at the asperity contacts under the influence of rubbing heat and pressure to form a thin film of low shear strength.²⁹ Even at room temperatures some lubricants, such as the fatty acids, react with the metal to provide a thin film of low shear strength.^{18 30}

In addition, films may be formed by chemical and physical adsorption of gases and polar molecules. Some gases and polar molecules adhere to the surface by molecular attraction and provide a thin film of low shear strength.^{18 31}

(2) *Gross Reactions*.—It is of value to consider certain gross reactions in so far as they affect friction. These reactions are principally chemical in nature, involving oxide replenish-

ment, hydroxide formation, and corrosion. If the materials in question can react with oxygen at a rate sufficient to maintain an effective oxide film, then bare metal-to-metal contact is prevented.²⁴

If hydrogen is dissolved in water, the formation of a hydroxide film has been suggested.³² The exact mechanism has not been defined, but tests conducted in high-temperature (500° F) high-purity water with hydrogen additions have, with few exceptions, shown a marked decrease in wear as compared to oxygenated tests.

Modifying Environmental Effects

The environment in which wear takes place is a factor in determining the rate of wear. Daniels and West³² have proposed that moisture causes a decrease in friction when the following two conditions are fulfilled: First, the oxidizing reaction within the area of sliding contact must proceed at a rate sufficiently rapid to reduce effectively the amount of metal-to-metal contact. Second, the oxidation products, together with the underlying metal, must form a low friction combination. Additional experiments by these investigators have shown that liquids may shield metal surfaces from oxygen. Even water containing dissolved oxygen as an additive cannot supply nearly as much oxygen as air. Independent observations by Westphal and Glatter have indicated that for metallic wear combinations of interest the friction observed in air was less than that observed in water. They ascribed this observation, in part, to the inability of any protective film initially present to repair itself with the limited oxygen available in water.³⁶

Some authorities propose that there may be accelerated chemical reactions from the increased high pressures or possibly the high temperatures which may occur in the fluid trapped by the asperities. Certainly all the modifying effects are dependent, to some degree, on the temperature, both the gross temperature of the material and the asperity temperature which may vary with load and velocity.^{6-8, 33}

thus change the nature of the actual contacting surfaces).^{26, 28}

2. Adhesive wear is proportional to load (below some critical load and as long as the nature of the contacting surfaces is not changed by the load).^{26, 28, 33}

3. Abrasive wear is characterized by the ability of a particle to penetrate another, related to the hardness of the metal, and the ability of the particle to remove other particles and present a new wear surface.

4. Corrosive wear is complex and has not been adequately analyzed. However, it appears to be proportional to load, distance traveled, and to some function of frequency and the corrosivity of the environment.^{37, 38}

5. Surface fatigue is a form of wear in which the number of cycles until breakdown of the surface is inversely proportional to the cube of the load.

6. The amount of wear certainly depends upon the materials in contact, but the rules for relating wear and material are still not firmly established.^{22, 39-43}

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Mechanical and Metallurgical Factors

Mechanical and metallurgical factors influencing wear may be examined from the standpoint of those that are inherent to the material and those that are acquired during fabrication and service.

WORK HARDENING

As stated previously, the S/P relations for materials in various work hardened conditions are not yet known with certainty. These relations are further complicated by the fact that the work hardened condition of the asperities is, in all likelihood, different from the base material after initial deformation has taken place.¹⁰

VELOCITY

At very low velocities, in the 10^{-2} to 10^{-4} in. per sec. range, there are indications of an increase in frictional force. This has been attributed to the dependence of shear strength on rate of shear.³⁴ In addition, as the velocity decreases there is increased time for formation of welds. Thus the range of velocities in a mechanical system is of fundamental importance with regard to the frictional characteristics of the device, particularly when traveling in the low-velocity region.

SHEAR STRENGTH VERSUS PRESSURE

When contact pressure is increased, it may be observed that surfaces move across one another with increasing difficulty. This is attributed to the fact that the shear strength of some materials may increase under pressure. Rocksalt, although not a metal, illustrates the case in point. Specimens of this crystalline mineral have displayed a sevenfold increase in shear strength as pressure was increased to the point of failure. Analogous observations have been made for metals. Similar increases, although not so great, may be observed for many engineering materials of interest and, when observed, constitute a departure from the classical theory that friction forces are independent of load.¹

Pressure may also promote the removal of oxide layers normally protective to the base metal. When oxidation takes place, the crystal structure of the oxide formed may differ from the crystal structure of the base metal. Under these circumstances internal stresses between oxide and base metal may contribute to the breaking of the oxide film under applied load.³⁵ The films thus removed very often lose all semblance of protectiveness and may act as abrasives, causing accelerated wear and material damage.

EXTERNAL LOAD

As external stress or load increases, there is an increase in the number of asperities in contact and, if subsequent movement takes place, more wear particles are produced. These wear particles may then add, through abrasion, to more rapid wearing away of surface films than would otherwise be expected.²⁸ In addition, abrasive foreign particles also increase the wearing away or destruction of surface films.

THE PROCESS OF WEAR

In order to clearly establish the term wear as used here, the following definition is presented: Wear is a complex surface phenomenon resulting in mechanical attrition of moving surfaces in contact, as by welding and removal of particles through friction.

Wear resistance is not an inherent property of a metal which may be considered by itself; rather wear is the resultant of the material itself, of the mating material, the environment, and the operation conditions producing the wear. Wear resistance then is complicated by all these factors and cannot be determined apart from the specific conditions of service.

Burwell (and others) propose that the four basic types of wear are adhesive wear, abrasive wear, corrosive wear, and surface fatigue.

Adhesive Wear

Adhesive wear is best described by the weld theory as proposed by Bowden and Tabor and

others. According to this view, friction is due primarily to the cold welding of surfaces when they are brought together under load.

Subsequent motion results in the tearing of the metal, rupture taking place either in the newly formed weld, in the asperity, or in the underlying metal, which ever presents the weakest bond.

Such welding of asperities is normally prevented by using a lubricant film or by providing an intermediate layer of low shear strength.

Abrasive Wear

Abrasive wear (or cutting wear) results from the ploughing of asperities and the cutting action of either entrapped or free-rolling grit particles between the surfaces. In most conventional engineering applications the design engineer can greatly overcome abrasive wear by the proper choice of materials, lubricants, and surface finish; and by providing for a clean environment. Hardness and smooth finish are the primary means of minimizing abrasive wear.

Corrosive Wear

Corrosive wear is characterized by the interaction of the wear surface with a corrosive environment. It should be remembered that the nature of the oxide must be considered for each material. These products can act as wear inhibitors in some applications and as primary causes of excessive wear in others. The integrity of the oxide layer is also a factor to be considered, as in the case of tin oxide. When present as an unbroken film, the oxide is protective and wear is low. However, once the oxide layer has been broken, the removed particles become abrasive and promote accelerated wear.³⁶

Surface Fatigue

Surface fatigue is most often encountered in ball and roller-type bearings, on gear teeth and cams, and other similar types of applications where the surface is subject to a great number

of stress reversals at high unit stress. Spalling, flaking, and eventual destruction of the wear surface are the results of surface fatigue.

GUIDES FOR THE EVALUATION OF FRICTION AND WEAR¹

The brief discussion of this chapter and the supplementary discussions afforded by the referenced articles are directed toward a general understanding of the problems of friction and wear. The guides that are presented here are made available to the reader as aids in the resolution of friction and wear problems. A summary of these guides is given below.

Friction

1. Frictional force is directly proportional to the actual area of contact.¹⁰⁻¹³ This concept has been used and developed in the preceding discussion. If the nominal area of contact is considered rather than the actual area, which includes only the asperities supporting the load, the classical "friction force is independent of the area of contact" would provide a working hypothesis.

2. Frictional force is independent of load, except as the load may cause the breaking through of surface films.¹⁰⁻¹³ Here again if the nominal area of contact is considered rather than the supporting area developed by the load, the classical "frictional force is directly proportional to load" would appear to be valid.

3. The effect of velocity on frictional force is complex. At medium speeds (from about 1 in./sec to a few feet per second, friction appears independent of speed; at lower speeds friction increases; and at higher speeds friction decreases with speed.

4. Frictional force depends upon the nature of the materials in contact.

Wear

1. Adhesive wear (amount of wear produced) is proportional to distance traveled (except as films may be worn through and

Chapter 4

WATER TECHNOLOGY

Editor—D. M. WROUGHTON

	Page
INTRODUCTION.....	31
CHEMICAL PROCESSES IN THE SYSTEM.....	31
Corrosion.....	32
Water Dissociation.....	32
Radiation Syntheses.....	32
Purification by Ion Exchange.....	33
Nuclear Reactions.....	33
INTERDEPENDENCE OF CHEMICAL PROCESSES.....	33
PRACTICAL WATER CONDITIONS.....	34
IMPORTANCE OF WATER PURITY.....	36

INTRODUCTION

The chemistry of the corroding medium is of obvious significance to corrosion and wear processes and therefore to the selection of materials of construction. Several aspects of the effects of water composition upon corrosion are discussed in other sections of this book. It is important to point out here that it may be impractical to maintain an arbitrary water condition in a reactor system and that, to some degree, the system tends to control itself.

At first glance, reactor systems would seem to be exposed to about the same conditions as conventional boiler plants. Operating temperatures are in the range of 400 to 600° F, with some parts at about 200° F. Experience in conventional power boilers covers this temperature range. Analogy between steam plant and reactor system practice cannot be based upon temperature and pressures alone. There are certain differences between the two systems which are of greatest importance to water technology.

First of all, there is the problem of handling radioactivity in such a system. Practically all materials, including water itself, become radioactive when exposed to the intense neutron flux in the reactor core. The accumulation, trans-

port, and disposal of radioactivity is a matter of paramount concern. This, in turn, results in requirements for high-purity water and nearly absolute leak tightness. The use of high-purity water removes reactor water technology at once from the realm of boiler water technology.* Leak tightness results in comparatively greater emphasis on system water changes than on control of feed water.

Secondly, the effect of radiation introduces a parameter upon water chemistry which is foreign to conventional systems. Radiation promotes some chemical reactions of great importance. It may make water chemistry simpler, as will be shown for the case of oxygen control, or it may promote the formation of objectionable substances such as acids which aggravate the corrosion problem. Even a simple boiler control problem such as maintaining an alkaline condition (pH 10 to 11) in the water is severely restricted by considerations of induced radioactivity, radiation decomposition, or nuclear reactions. There are no corrosion inhibitors for stainless, low alloy, or carbon steels which are stable and effective at temperature and which are not decomposed by radiation.

CHEMICAL PROCESSES IN THE SYSTEM

The chemical processes in a reactor system may be represented by relatively few chemical reactions: (1) corrosion, (2) water dissociation, (3) radiation synthesis, (4) purification by ion exchange, and (5) nuclear reactions. However, the interdependence of these processes results in a fairly complex situation. The chemical equations that follow should be considered

*There have been some instances where conventional boilers were operated on high-purity water, but this is not common practice.

descriptive in nature since neither the mechanisms nor the stoichiometry is well understood.

Corrosion

Two reactions contribute to the corrosion of iron exposed to system water

The second is presumed to represent the reaction in the presence of some dissolved oxygen. At temperatures in the range of 400° to 600° F, the oxide produced is magnetite (a black magnetic oxide with a spinel structure) in both bases. In stainless-steel corrosion the chromium and nickel oxides substitute for iron in the oxide lattice. If the oxygen content of the water is very high or the temperature low, a brown oxide, probably Fe_2O_3 , results.

There is a reaction similar to (2) involving oxygen and chromium which results in the formation of soluble chromate

This reaction is discussed in chapter 8, Relative Importance of Different Variables, in the section dealing with the effect of oxygen. The dissolved oxygen is believed to attack the suspended crud in the water since soluble chromate is observed very soon after oxygen is added or generated in detectable quantities.

Water Dissociation

Water is broken down into free radicals by radiation. The reaction may be represented in very elementary form by the following:

Most of the free radicals recombine quickly, but a small fraction reacts in other ways with the resultant formation of small amounts of dis-

*The (H_2O) is used to indicate the reaction occurs with the gaseous element in solution.

solved hydrogen and oxygen. The numbers used in the above equation are only for the purpose of showing that hydrogen and oxygen are formed initially in stoichiometric amounts in a radioactive system.

The dissociation is believed to be attributable primarily to the fast neutrons. At least the dissociation proceeds rapidly only during reactor operation. A recombination reaction between dissolved hydrogen and oxygen is promoted by gamma radiation, however, and the recombination will proceed at a rapid rate for some time after reactor shutdown because of the high gamma field from the fission products in the core.

This reaction is utilized to an advantage to remove oxygen from the system. If a certain level of dissolved hydrogen is maintained, not only will the formation of oxygen by dissociation be suppressed but any oxygen introduced into the plant in feed water will be quickly consumed.

Radiation Syntheses

Some chemical reactions not normally expected in hot water may take place in a reactor system because of the radiation. Depending on the materials present, many such reactions could be postulated. In an operating plant, with conditions as already described, the only reactions observed which influence water chemistry are those which involve nitrogen. Nitrogen may be introduced into the plant in non-deaerated feed water or if air is trapped in the plant during filling. The presence of nitrogen dissolved in the water results in one of two reactions

Thus either ammonia or nitric acid is formed, depending upon whether hydrogen or oxygen is present in excess.

Purification by Ion Exchange

An ion exchanger is usually included in water-cooled nuclear reactor systems primarily to remove radioactive materials in solution and thus reduce radiation levels in the reactor compartment. In addition to such removal, the ion exchanger plays an important part in water chemistry.

Ion exchangers of the granular mixed-bed type are commonly used. If, initially, the cation resin is in the hydrogen form and the anion is in the hydroxyl form, the ion exchanger tends to keep the water nearly neutral. The exchange process may be illustrated simply as follows for the removal of sodium chloride where (CR) and (AR) represent the two resins.

If the two resins are not used in the proper proportion or are not well mixed, the pH may shift from neutral because of the production of excess hydroxyl or hydrogen ions.

Special salt forms of ion-exchange resins may be used to control the pH above neutral. For example, the above equations written for a mixed-bed ion exchanger with the cation resin in the lithium form become:

This will result in a pH corresponding to the resulting lithium hydroxide concentration. (In fact, pure water passed over such a mixed-bed resin will have a pH somewhat above 7.) In a similar way, an ammonia form resin might be used to maintain some level of ammonium hydroxide in the water, and since reaction (6) is reversible under radiation, an ammonia resin may put some hydrogen into the plant.

Nuclear Reactions

Some nuclear reactions which occur in the water are important only to shielding or matters

other than water chemistry; for example, the formation of the N^{16} and N^{17} species. Other reactions result in the formation of radioactive materials from impurities in the water. In the reaction

the Fe^{59} becomes radioactive and emits both beta and gamma radiation. The products of similar reactions are the source of most of the radioactivities in the water with half lives more than a few seconds. Nuclides so formed, which produce hard gammas, interfere with personnel access to the system because of the resultant high gamma field in the compartment. The soft-gamma and pure beta emitters are ingestion hazards when the system is opened.

If lithium hydroxide is used for pH control, the latter situation arises because of a somewhat analogous reaction. The lithium nucleus exposed to neutrons forms tritium:

If the system is opened to the atmosphere or develops a leak, protection from the tritium must be provided.

INTERDEPENDENCE OF CHEMICAL PROCESSES

A study of the interaction of the above processes yields an orderly picture of practical water conditions in an operating reactor. This picture is shown in a very simplified form in figure 4-1. Corrosion is shown to play a major part since without corrosion other problems would not exist or other reactions could be ignored.

It should be remembered that a reactor system is quite leaktight. Therefore the hydrogen generated by corrosion reaction (1) will build up in the system or will tend to maintain any initial hydrogen concentration. If oxygen is present initially because no hydrogen is added, it will be consumed by corrosion reaction (2) until the hydrogen is present in sufficient excess to suppress dissociation reaction (4).

FIGURE 4-1. Interdependence of chemical processes.

If excess hydrogen is present in the water and some oxygen is added, as in aerated feed water, it will be consumed very quickly by the radiation-catalyzed reaction (5). If even small amounts (a few cubic centimeters per kilogram of H_2O) of nitrogen are present, the pH tends to be controlled by the hydrogen concentration according to reactions (6) and (7). Thus dissolved hydrogen in the water plays the multiple role of suppressing dissociation, indirectly reducing corrosion, and controlling pH.

The pH of the water can be controlled by another process if desired. If a mixed-bed H—OH ion-exchange resin is used for purification, it tends to keep the pH of the water near neutral. However, if the ratio of cation to anion resin is changed or if special salt forms of the cation resin are used, the pH of the water can be raised as already noted. By using a mixed-bed resin in about the usual proportions of anion and cation resin but having the cation resin in the salt form, e. g., a lithium form resin rather than a hydrogen form, the water will be raised to a pH of 10 or 11. A lithium form resin is still effective for water purification since practically all soluble impurities will be

removed by such resin. The exchange process, of course, releases lithium hydroxide to the water and also tends to raise the pH.

PRACTICAL WATER CONDITIONS

The most important controls specified for reactor water are the relation of impurities (e. g., chloride), dissolved oxygen, and pH. Since reactor water is of high purity, it is usually sufficient in practice to specify the conductivity, corrected for pH, to guarantee that the soluble solids are satisfactorily low.

In a reactor system the actual source of control may be radically different from what it would be in a conventional boiler. The use of deaerated feed water does not insure oxygen-free water in the system nor does the use of aerated feed water mean that free oxygen will be found in the plant. The pH of the water may be internally controlled by the radiation-induced reactions or by the purification system.

Any discussion of reactor water chemistry at this time cannot advance valid methods for the independent control of all factors. The independent variables may be looked upon as: (1) the hydrogen gas content of the reactor system water, (2) the degree of deaeration of the feed water or the amount of air trapped in the system, and (3) the nature and degree of internal purification. In a sense, the parameters most important to corrosion are dependent variables.

The following requirements have evolved from present knowledge on water chemistry in water-cooled nuclear reactors:

1. Demineralized water should be used for filling and makeup. Deaeration is not objectionable but is not necessary if step (2) is followed.
2. Hydrogen gas should be added to the water to suppress dissociation and remove oxygen. The concentration required is 10 cc per kilogram of H_2O or higher. Higher hydrogen concentrations are not objectionable and may reduce corrosion slightly. It is most convenient to keep the concentration below the solubility limit in cold water at

Part B

Procedures and Data

atmospheric pressure. At times when there is not sufficient radiation in the core to promote the recombination reaction (5) or when circulation through the core is impossible, hydrazine may be used to remove oxygen.

3. Adequate purification of the water within the primary system, by means of ion exchangers and/or mechanical filters, should be provided to keep the radioactivity low and reduce the probability of fouling. A mixed-bed ion-exchange resin will perform effectively for both filtration and demineralization.

4. The pH of the water may be raised to 10 or 11 by adding a base or using a special ion-exchange resin. Whether or not pH control is used depends upon several considerations. The benefits afforded to corrosion, wear, and crud must be weighed against the inconveniences of maintaining the required pH control.

If the above ground rules are followed, satisfactory water conditions are reasonable to maintain. Table 4-1 gives four examples.

TABLE 4-1

PRACTICAL WATER CONDITIONS FOR REACTOR SYSTEM OPERATION

Parameter	Example			
	A	B	C	D
Hydrogen in water, cc/kg.....	10-30	10-30	10-30	<5
Feed water deaeration.....	Yes	No	No	No
Ion-exchange resin form.....	H-OH	H-OH	Li-OH	H-OH
Water conductivity, μ mho.....	1	2-10	25-75	5-15
Oxygen in water, cc/kg.....	≤ 0.05	≤ 0.05	≤ 0.05	0.1-5
pH (reactor operating).....	7-8	8-9.5	10-10.5	6.5-4.5

The first three parameters are those which are considered "controlled" and the last three are the "dependent" variables. The table is greatly simplified and presumes steady-state conditions. Some important items, such as flow rate in the purification system, which have an influence on the values of the dependent variables are not included. Qualitatively, however, the table serves to highlight some important considerations in water chemistry.

Considerable corrosion testing has been done for example in "degassed" water and in water at neutral pH with a few cubic centimeters of oxygen per kilogram. It is doubtful that either of these conditions is realizable in an operating-reactor system.

Two typical operating logs from reactor loops are shown to illustrate the consequences of deviation from the principles set down above. The operating conditions are shown in figure 4-2.

FIGURE 4-2. Water chemistry, typical operating log: temperature, 450° F; power, 8 to 30 percent of full power; filter and demineralizer in service.

Deaerated feed water was being used, and the hydrogen concentration was maintained at an average of 100 cc per kilogram of H₂O by adding gas at intervals in large increments. Conductivity was low, showing little solubles in the water, and pH was only a little above neutral. Oxygen was undetectable and crud levels* were very low (≤ 0.1 ppm). In contrast, figure 4-3 shows the conditions resulting from an attempt to start up the loop without adding hydrogen after considerable air had been

*See Glossary, app. B, for definition.

FIGURE 4-3. Plant startup with air in loop, water chemistry, low power.

trapped in the system on fitting. As the loop heated up, at low reactor power, the pH dropped sharply as nitrate was formed. Conductivity passed through a minimum corresponding to neutral pH. (The pH at start up was high because of previous operating conditions.) There was attack of the chromium or chromium oxide in the system as indicated by the soluble chromate curve. The crud level is not shown because it exceeded the capacity of the normal measuring technique and may have reached values as high as 25 ppm.

It was soon evident that these chemical conditions could not be tolerated, and hydrogen was added in increments to remove the oxygen. Soon after an excess of hydrogen was present, loop chemistry returned to nearly normal and

quite acceptable conditions. Because of the presence of substantial amounts of nitrogen in the air, considerable ammonia was generated, and the pH rose to about 9.

The above illustration shows the dependence of loop chemistry upon the free hydrogen gas content of the water. It also emphasizes the necessity for complete evaluation of any change in water chemistry as outlined in figure 4-1.

IMPORTANCE OF WATER PURITY

The importance of material selection to corrosion rates and to water purity and, conversely, the relation of water composition to corrosion are discussed in chapters 7 to 9 and 13. However, there is one additional area which emphasizes the need for high-purity water, the importance of minor constituents as affected by nuclear irradiation. Relatively small amounts of impurities and minor constituents may be more responsible for higher activity than the major elements.

Three cases serve to illustrate the point. The practicality of using nondeaerated water has been mentioned. However, the argon contained in the dissolved air may contribute as much radioactivity to the water as the sum of all corrosion products. Secondly, sodium hydroxide is unacceptable as a pH control reagent, even though only a few parts per million are required, because of the high sodium activity which results. Finally, in chapter 12, Corrosion Products in Recirculating Systems, it may be noted that a substantial part of the short-lived activity, manganese, comes from a minor element in the steel and some of the long-lived activity, cobalt, comes either as an impurity in steel or possibly from the wear on small surfaces such as bearings. Thus it is necessary in a nuclear reactor system to consider, quite seriously, secondary elements and secondary effects as well as what may seem to be the major problem.

Chapter 5

DESCRIPTION OF TESTING PROCEDURES

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	Page
INTRODUCTION.....	39
Variables.....	40
Use of Statistics.....	40
Scope of Chapter.....	40
CORROSION TEST SYSTEMS.....	41
Static Systems.....	41
Semistatic Systems.....	44
Dynamic Systems.....	46
TEST OPERATION.....	51
Start-up: New Loops.....	51
Start-up: Existing Loops.....	52
Feedwater Purification System.....	54
Water Analysis.....	54
Additives to Test Water.....	55
PROCEDURES FOR GENERAL CORROSION TESTING.....	55
Specimen Preparation.....	56
Specimen Removal and Examination.....	56
Weighing.....	56
Descaling and Corrosion Products.....	57
Metal Lost to Water.....	58
Microscopic Examination.....	58
PROCEDURES FOR SPECIAL CORROSION TESTS.....	60
Galvanic Corrosion.....	60
Crevice Corrosion.....	60
Stress Corrosion.....	60
Corrosion Fatigue.....	63
Heat-transfer Studies.....	63
Velocity Studies.....	64
WEAR AND FRICTION TESTING.....	64
Introduction.....	64
Test Procedures.....	64
Basic Wear Tests.....	65

INTRODUCTION

In this chapter are described the various procedures for investigating corrosion and wear

in high-purity water applications. The test apparatus and procedures have become standardized to the degree that duplicate systems may now be found in several installations engaged in the study of materials considered for use in commercial and naval water-cooled nuclear reactors.

The complexity and number of conditions that may arise in the planning and operating of nuclear power plants has made it unfeasible to thoroughly investigate all the variables involved. This is particularly true since the urgency of time has been felt throughout the entire developmental period. One might well consider the great number of combinations that could evolve from such variables as materials, corrosion environments, temperature, time in service, special service conditions, and design. It is evident that the programs of investigation have been, of necessity, directed toward those conditions that are most likely to occur in service.

The data in this handbook were obtained from many sources; yet the techniques, procedures, and apparatus of each contributing organization were essentially the same. These systems are described in sufficient detail so that future investigators will be able to complete all phases of planning. The references given at the end of the chapter are available for a more complete explanation of any particular apparatus or procedure.

Variables

The requirements for an acceptable test are rigid. Within the confines of the system the following factors must be controlled with precision: (1) water composition, (2) temperature and pressure, (3) water velocity, and (4) maintenance of steady test conditions.

In addition to the test operation, important variables arise in the handling of specimens before and after testing. Some of these variables are: (1) procedures for preparing specimens, (2) procedures for weighing and descaling, (3) observation techniques, and (4) shutdown and startup procedures. These variables can be controlled by adopting and enforcing rigid procedures. However, for specific tests performed to detect localized attack, it sometimes becomes necessary to alter the procedures to satisfy the requirements of the test.

One remaining variable is not readily controllable but can be compensated for, that is, the type of corrosion film formed on specimens is not the same for all materials. These films range from a tightly adhering thin film for the austenitic stainless steels to the loose, powdery film observed on such steels as ASTM A212. Obviously, reliable corrosion rate data cannot be obtained by gross weight change alone if these materials are to be compared. Therefore, the corrosion deposits are removed by one of several available processes, and net weight changes are compared.

Use of Statistics

One of the major problems in both design and experimental work is the proper recognition of all the variables that may affect the satisfactory performance of equipment in service. The major portion of the work covered by this handbook has been in the nature of screening tests and simulated service investigations. These have confirmed the complexity of the factors entering into the corrosion and wear of materials in the various applications considered. Statistical procedures have proved valuable in the correlation and reporting of such data as the relation of corrosion rates to

time.¹⁰ Now that a large number of variables has been shown to be pertinent to corrosion and wear phenomena, as experienced in reactor environments, additional data are required. The statistical design of experimental programs will be particularly helpful to continued work. The quantitative role of the many variables can be more readily determined by the use of that branch of statistics known as "design of experiment" in the choice of test points, variables selected, time intervals, and amount of data required. Standard works are available which discuss in detail the statistical techniques available in the planning of experiments and in the evaluation of the resulting data. Some of these works are listed in part B of the reference section, Statistical References.

Scope of Chapter

The procedures discussed here apply most directly to chapter 7, which deals with tabulations of basic data, and chapter 8, which comments on and evaluates the effects of important variables. Test apparatus and procedures are described here for corrosion and wear in the following general categories: (1) general corrosion in both static and flowing water; (2) local and specialized types of corrosion, such as pitting, galvanic corrosion, and crevice corrosion, and corrosion fatigue; and (3) wear as resulting from rolling, rotating, and sliding motions.

The test systems used to study the corrosion properties of structural materials in water at elevated temperatures can be classified into three types: no flow, low flow (semistatic), and high flow (dynamic). Dynamic test loops are closed circuits characterized by continuous natural or forced circulation of hot water past specimens. Pressurized autoclaves are used to test corrosion and wear specimens in static and semistatic water.

For general corrosion work flat strip specimens with high surface-to-weight ratio are used. For local corrosion and wear representative sections of equipment and simulated parts are used with corresponding test equipment. The

apparatus for wear studies involves the motion of mechanical parts and test specimens actuated by external drives through sealed connections to pressurized autoclaves. The specimens placed inside such test apparatus are designed to simulate the application as closely as possible.

A number of specific engineering applications and tests run to simulate design problems are discussed in separate chapters. These experimental methods and the apparatus involved are described in chapters 3 and 10 to 12.

CORROSION TEST SYSTEMS

Static Systems

The prime advantage of the static tests conducted in autoclaves is that a large number of materials and water conditions may be screened quickly. The more promising results can then be used to establish programs for the more complex dynamic systems. Several dozen small autoclaves can be placed in large electrically heated ovens and maintained at the desired temperature, or individual units can be controlled in insulated heating jackets. The disadvantage to this type of test is that sampling and maintenance of controlled water conditions throughout the test is difficult; however, it is satisfactory for screening purposes.

It has been shown that the corrosion of specimens in static and very low velocity systems differs from that of specimens exposed to water velocities of 30 ft/sec.

DESCRIPTION

Autoclaves suitable for testing may either be obtained commercially or constructed to satisfy the requirements of the test. In most cases the autoclaves are made from AISI type 347 stainless steel, although other 18-8 stainless steels have been used. No standard specimen or arrangement is required for tests of this type, but coupon specimens are the most frequently used. Some representative arrangements are shown in figures 5-1 to 5-3; an autoclave used for static tests is shown in figure 5-4.

FIGURE 5-1. Block-type static specimens, specimen holder, and retaining fixture

For the application shown in figure 5-3, a circular cross-section tensile specimen (fig. 5-2) is inserted in a special holder and spring loaded in tension.

PROCEDURES

Prior to use, the vessels are degreased with trichlorethylene, and thoroughly rinsed with high-purity water.

FIGURE 5-2. Tensile corrosion specimen.

Standard closures for these vessels include spiral-wound stainless steel and asbestos gaskets and solid gaskets such as used in a Bridgman

The methods of filling the autoclaves differ somewhat, depending on the water conditions which are desired. The following procedures have been used successfully.

1. Degassed solutions: The standard filling procedure consists of evacuation of the vessel to a pressure of 25 mm. The vessel is then purged with inert gas which, in turn, is displaced with water from the degassed water supply. The amount of degassed water injected is determined by weight difference.

FIGURE 5-3. Autoclave for static tensile tests.

type of closure with the cone on the cylinder at the gasket tapered about 5 percent for easy removal.

An alternate method for small vessels (100-cc capacity) is to heat the test solution in the autoclave to boiling by means of a torch. Heat is

maintained for several minutes to degas the solution. A 50-cc sample of solution is withdrawn with a vacuum bulb for the pH and conductivity measurements. The autoclave is then sealed and placed in the furnace.

2. Deaerated solution plus gas dissolved under 1 atm of partial pressure: For this type of experiment a modified sealing plug containing a gas inlet tube is used. The vessel is filled to

admitted through the inlet pipe, at the desired pressure, by means of a regulating valve.

INSTRUMENTATION AND SAFETY DEVICES

The pressure vessels heated in the batch ovens are protected by rupture disk safety devices. These thin diaphragms fail safely, causing the vessel to lose its water content

FIGURE 5-4. Autoclave for static tests.

the desired level with degassed water as above, and then the gaseous additive is bubbled through the water. An atmosphere of the gas is obtained above the water. The pressure is adjusted by venting to atmosphere. When sealed, the vessel is ready for test.

3. Deaerated solutions plus gas dissolved under partial pressure greater than 1 atm: For this type of experiment the sealing plug and inlet pipe described in procedure (2) is used. The vessel is filled to the desired level with degassed water. The additive gas is then

before a buildup of pressure can cause damage to the vessel. The vessels heated in individual jackets are also protected by rupture disks. In this application the escaping steam can be directed on the spoon-shaped arm of a pressure switch. The steam striking the switch cuts off the power source, and the heaters automatically cut out. Each individual vessel is also equipped with a pressure gage and a temperature controller-recorder so that the attending personnel can keep a log of test operations.

Semistatic Systems

Autoclaves are not confined in application to static systems. They are the principal elements of the semistatic (low flow) system. Here the velocity is limited to the minimum velocity that will ensure the maintenance of specified water composition.

The general-purpose semistatic test system

loop by blocking valves and can be operated as a static fluid system with a test medium completely foreign to the remainder of the system. In this latter application the external drive may be used at the discretion of the experimenter.

A schematic diagram of a typical general-purpose test loop, instrumented to deliver demineralized-oxygenated water is shown in

FIGURE 5-5. *Semistatic test system.*

is a closed loop that is outstanding because of its versatility. One such loop is shown in figure 5-5. Each autoclave installed in this system is provided with a mechanical drive to impart rotary motion to components within the vessel.

By disengaging or not operating the external drive mechanism, the test can be run with low flow (to maintain specified water chemistry) and no motion of the test piece. In addition, any vessel in the loop can be isolated from the

figure 5-6. The system may be modified to operate as a degassed system by directing the flow from the demineralized water storage tank, through a degassing tower, and then to the main loop pump.

A similar system to circulate hydrogenated water would require degassed water to be delivered to a hydrogen absorber and then to the loop through the main loop pump. The general-purpose loop is designed to permit rapid

FIGURE 5-6. Schematic diagram of a general purpose test loop.

changeover. However, care should be exercised, upon any change, to be certain that all lines are properly purged of any previously used gases or additives that might conflict in any way with the new conditions. This is particularly important where there is any danger of different gases reaching explosive-mixture proportions.

As shown in figure 5-6, city water is taken into the system and purified in a mixed-bed cation-anion exchange demineralizer. Oxygen is added to the water at the heater absorber, and the fluid is then pumped to the test chambers under pressure. Strip heaters raise the water temperature to the specified level prior to admission to the autoclave. Trim heaters fixed to the autoclave wall maintain a constant temperature in the vessel. A back-pressure regulating valve maintains the system pressure at all times. The discharged water from the test chamber is then cooled, directed through filters, and then returned to the demineralizer for recirculation in the system. Once the system has been in use, the only additional city water required is that necessary to compensate for leakage and sampling.

Draley¹ has employed a different arrangement for the corrosion testing of aluminum in

FIGURE 5-7. Schematic diagram of flow type autoclave test.

autoclaves. This arrangement, as shown schematically in figure 5-7, provides for a continuous control of the corrosion environment.

The water conditions are maintained by using a plunger-type pressurizing pump which feeds the water through a preheater into the autoclave near the bottom. The fluid leaves the top of the autoclave, passes through a cooler, and then through a relief valve. The small flow of liquid (10 to 15 cc/min) is thus discharged while the valve maintains the desired pressure in the system. The autoclave can be heated to any desired temperature below the saturation temperature for the pressure used. Gaseous additions are made upstream of the pump by pressurizing the gas space above water in a storage tank with the desired partial pressure of the additive gas.

INSTRUMENTATION AND SAFETY DEVICES

Semistatic test circuits of the general-purpose type have the necessary instrumentation to measure and control temperature, pressure, flow, and other variables of special interest. The instruments used are available commercially and are standard for high-temperature, high-pressure fluid systems. In addition to the automatic control instruments, pen recording devices are used to provide a log of temperature in the autoclaves and differential pressure across a calibrated orifice (flow recorder).

Vessel heaters are arranged so that only a portion of the heat source is under automatic control to permit a smaller gradient in the approach and control of the desired temperature. Temperatures have been held within 3° F of the desired temperature by this method. Other instrumentation is commercially available to obtain control within 1 percent of full-scale deflection.

Circuit pressure is controlled by a pressure recorder-controller which actuates the heaters in the pressurizing boiler. At 2,000 psi the pressure is held within 50 psi of the desired setting.

Indicators of various kinds are used to determine the water level in the pressurizing boiler. Glass water gages have been used, but the difficulty from silica dissolving in the water generally prevents their use in corrosion test work. Therefore remote indicating differential pressure gages are commonly used to indicate water level ranges, on the order of 6 in. in pressurizing boilers.

Water flow is measured by the pressure drop across orifices or flow-type meters. The pressure drop across the meter is impressed on a differential pressure transmitter, and the output is recorded on a continuous chart.

Flow can be controlled either manually or automatically. Manual control is achieved by positioning the valve either in series with the test circuit or in the bypass line between inlet and outlet of the pump. Automatic control is obtained with either pneumatic or motor-operated valves.

SAFETY DEVICES

In addition to the equipment necessary to record data and control the operation of the test apparatus, good practice calls for the use of safety devices. The switches and interlocks used to shut down the system under various unsafe circumstances are listed below.

Safety devices include such items as pressure switches, temperature limit switches, safety valves, and/or rupture disks. Some of these devices are discussed below, with a brief explanation of their role in the system.

1. Pilot-operated switches for an underpressure or an overpressure of about 150 psi: An underpressure shutoff is necessary to prevent steam generation which could affect corrosion data, increase pressure drop, and cause cavitation in the pumps.

2. Pilot-operated switches for an excessive drop in water flow: A drop in flow through the part of the circuit around which the heaters are wrapped or in which immersion heaters are located could cause local overheating.

3. Temperature limit switch to detect overheating of such circuits.

4. Temperature limit switch for detection of overheating in the pressurizing boiler wall.

5. Pilot-operated switches for detection of reduced cooling oil flow through the main pump windings.

6. Safety valve and/or rupture disks in exhaust lines as a final precaution against buildup of excessive steam pressure.

Dynamic Systems

The semistatic loops just described provide environmental control but were lacking in one variable required to give a more realistic duplication of reactor operating conditions. This additional variable is high velocity. It was the dynamic loop which became the workhorse in the latter stages of the corrosion programs.

DESCRIPTION

Dynamic test systems operate above the saturation pressure for the test temperature in

order to avoid a phase change and the effects of boiling and water levels on specimens.

These systems include thermal difference (natural circulation) loops and pump circulation loops.

FIGURE 5-8. Schematic diagram of natural-circulation circuit.

Circulation in the thermal difference loop shown in figure 5-8 is obtained by the density differences in the downcomer and riser legs provided by a heater in the bottom location and a cooler at the top. In order to add and maintain gases in the water, no boiling is permitted, and the density difference of the two legs at 750° and 700° F results in relatively low velocities. Placing the specimens in a venturi flow section provides higher velocities past the specimens and still recovers some of the pressure loss. This circuit has been operated at a pressure of 3,500 psi.

Pump circulated test units are designed and built in accordance with the ASME codes. Design pressure is usually 2,000 psi or 2,500 psi for most of the test work performed at tempera-

tures up to 600° F. Most of the test equipment now in use is built of AISI type 347 stainless steel. However, interest in carbon steel and other low-alloy materials has led to the construction of a number of carbon steel test

FIGURE 5-9. Schematic diagram of forced-circulation circuit.

circuits. Water velocities past specimens in some loops of this type can be as great as 60 ft/sec, although most data were obtained at 30 ft/sec.

A typical forced-circulation test circuit is shown in figures 5-9 and 5-10. The unit shown is representative, but similar systems differ in size, capacity, number of specimens which can be tested simultaneously, and the types of auxiliaries used.

This circuit is one in which water is maintained in forced circulation by a pump and is electrically heated to a desired test temperature. Pressure is maintained above saturation pressure for the test temperature by a separate small electric boiler. In most apparatus of this nature the circulating pumps are of the canned rotor design in which the bearings are submerged in the water being circulated. This makes unnecessary any external packing glands which could contaminate the water within the system. Pumps having a capacity of 30 gal/min are satisfactory in most cases, although larger test circuits for studying corrosion related to heat transfer and other work have used pumps with capacities up to 150 gal/min.

Such pumps are now available commercially with relatively small delivery for experimental purposes and with much greater capacity for final applications. An oil reservoir, oil cir-

Since corrosion effects depend upon many variables that can cause a considerable scatter in test data, a large number of specimens is desirable. Various test circuits have been

FIGURE 5-10. Schematic diagram of forced-circulation circuit showing auxiliaries.

culating pump, and oil cooler are required as auxiliaries.

The auxiliary steam boiler is maintained above saturation pressure at approximately 2,000 psi by electrical resistance heaters.

High-purity makeup water is pumped to the loop to compensate for leakage in the system. The pneumatically operated feed pumps are manually started and stopped whenever the operator adds makeup water.

As indicated in figure 5-11, the specimen holder is flanged to facilitate installation and removal. Within the limits of pressure drop and test velocity, it is desirable to provide space for the maximum number of specimens that can be placed in a given apparatus.

constructed with capacities ranging from 2 to 50 specimens. The details of specimen arrangement inside the holders depend upon the type of test being run since various special shapes are often investigated. For determination of weight changes, most specimens are made in the form of relatively thin, narrow strips, approximately $\frac{1}{16}$ in. thick by $\frac{1}{2}$ in. wide and up to 8 in. long. The flat specimens are arranged in parallel, with the rectangular flow channels between specimens approximately equal to the specimen cross section. Nine such specimens are mounted together in the slotted holder shown in figure 5-11. The separate pieces of the holder are held together by bands and screws and are further restricted by the

FIGURE 5-11. *Dynamic corrosion specimen holder.*

outer flanged holder which forms part of the test circuit. In some cases these specimens are made to resemble tensile specimens. These are assembled as shown in figure 5-12 with washers

FIGURE 5-12. Corrosion specimens and holder.

and screws; insulating spacers are sometimes used in special investigations.

Channel-shaped specimens can also be used, as shown in figure 5-13.

FIGURE 5-13. Channel-shaped specimen used in some dynamic corrosion tests.

MULTICHANNEL ARRANGEMENTS

The evaluation of the corrosion resistance of a particular material or the suitability of a water treatment may be expedited if a number of the operating variables can be studied in one

test. Such a system is shown in figure 5-14; here a relatively large number of flow channels is installed on a single loop. In this multichannel system such conditions as water velocity, thermal cycling, and, to some extent, temperature may be investigated in one test.

The principal advantage of this system is that all the specimens are subjected simultaneously to water of the same chemistry, a condition that cannot be assured if separate tests are run for each of the variables.

The large number of specimens that may be included in any single test tends to yield uniform data and to effect a significant economy of testing.

The multichannel loop, shown in figures 5-14 and 5-15, consists of a header to which twelve separate channels are connected. These channels have been used for various operating conditions, such as velocity, temperature, and thermal cycling.

Test water is circulated by a canned-rotor water pump. Provisions have also been made for the addition of ion exchangers, filters, and other test auxiliaries as required. Flow and temperature can be measured and controlled individually in each separate channel. Specimens can be removed from individual channels while the remainder of the equipment continues in operation.

The arrangement of valves permits immediate admission of water, at test conditions, to specimen holders; it also permits immediate shut off and removal of such specimens. Corrosion tests at high temperature and pressure thus can be run for short time intervals of 1 hr. or less.

Another modification of the dynamic test loop is shown in figure 5-16. The advantage of this loop, as with the multichannel loop, is that specimens can be exposed to the same environment but at two different velocities. The dual-velocity test loop, figure 5-16, is a forced-circulation system.

INSTRUMENTATION AND SAFETY DEVICES

The controlling and recording instruments required for the dynamic test loops are essentially

the same as those described for the semistatic systems. The same elements are controlled in both systems—e. g., pressure, temperature, and

The system is checked for leaktightness by means of the hydrostatic test. Here the system is filled with water and pressurized at

FIGURE 5-14. Schematic diagram of multichannel corrosion circuit.

rate of flow. The safety devices are also similar. Since no additional control or safety problems are involved in the dynamic loops, the reader is referred to the description of these devices given for semistatic systems.

TEST OPERATION

Startup: New Loops

In starting up a new loop, the experimenter is faced with three problems that must be resolved satisfactorily before testing can proceed:

(1) Safety: Is the system leaktight? (2) Preconditioning: The initial high corrosion rates in a new stainless steel system can seriously affect corrosion test results. (3) Cleanliness: Have all contaminants, such as weld particles, weld slag, lubricants, and abrasive particles, been removed from the system?

room temperature. The ASME Boiler Code for Unfired Pressure Vessels is used for determining the hydrostatic test pressure.

After the system has passed the hydrostatic leak test satisfactorily, it is filled with deionized water and operated at temperature for approximately 1 week. During this interval the exposed surfaces of the stainless-steel system are corroded, and the corrosion products, carried off in the flowing stream, are collected in filters or in the resins of the deionizer. At the conclusion of this preliminary hot run, the system has become conditioned to the extent that a protective oxide film is formed.

The third factor, cleanliness, is achieved by first cleaning the system components prior to assembly as indicated in Chapter 14, "Manufacturing Procedures Affecting Corrosion and Wear," and then filtering any assembly products from the system. During the 1-week

FIGURE 5-15. *Multichannel corrosion circuit.*

run-in period, at temperature, 100-mesh screens are inserted at various points in the loop to trap out foreign particles.

Startup: Existing Loops

When a loop that has been previously operated is started up, the following procedure is normally observed. Specimens are installed in the system. The system is evacuated, purged twice with inert gas, and the final purge gas is displaced by deionized, degassed water which fills the system. The tightness of all joints is checked by hydrostatic cold leak test. If the system is leak-free, the heat can be applied, and the test can proceed. Should leak-

age be detected, it becomes necessary to drain the system, repair the fault, and repeat the filling cycle.

As heat is applied, the system water expands and the excess is bled off. If a pressurizer tank is used, some of the excess water can be attributed to the steam head at the top of the pressurizer.

The actual startup of semistatic and dynamic systems is governed by the safety devices previously described. For the loop shown in figure 5-14, the following sequence has been established:

1. Water treatment chemicals or gases are added.

FIGURE 5-16. Schematic arrangement of dual-velocity test loop.

2. The pressurizing unit is brought up to operating conditions, after which the over- and under-pressure cutouts are set.

3. Cooling oil flow is established.

4. The main pumps are started, and the desired waterflow is established through the various portions of the circuit.

5. This waterflow then allows the main heaters to be energized so that the water temperature may be raised to the operating level.

Other loops have been started up in accordance with the following alternate procedure: After the test sections are installed, the loop is

purged, vented, and filled with high-purity deaerated water. Circulation of the system water is then started. During the startup period, which lasts about 8 hr, the system water is circulated at reduced temperature and pressure (200° F and 500 psi). One of the following methods is usually used for reduction of the oxygen concentration in the system water. (1) The surge tank may be operated as a degasifier, or (2) chemical oxygen scavengers may be added to the system water. Hydrazine has been used for this purpose. During the startup period hydraulic injections of the necessary chemicals into the system water provide the

FIGURE 5-17. Diagram of water purification system.

desired water condition for the test. When hydrogen is the only addition, the purification system demineralizer is operated to raise the resistivity of the water to the desired level. When the oxygen concentration has been reduced below about 0.14 ppm, the loop water temperature and pressure are gradually raised to the operating level.

Feedwater Purification System

A flow sheet of a purified water feed and makeup system is shown in figure 5-17. Several analyses of municipal water entering the distilling units gave:

pH.....	9.5 to 10
Cl, ppm.....	13 to 62
Total solids, ppm.....	80 to 520
Ca, ppm.....	65 to 400
Mg, ppm.....	25 to 150
Resistivity, ohm-cm.....	~ 1,000

The water leaving the system contained less than 0.5 ppm total solids and about 0.02 ppm total iron.

Such commercially available distilling units are rated at less than 1 ppm total solids when sea water is used as feed. The actual output has not been analyzed chemically, but the effluent from the Duolite S-10 column in a representative sea water sample had a pH of 6.4, a resistivity of 128,000 ohm-cm, and a total solids content of about 0.71 ppm. About 20 percent of this solids content was lost on ignition at 1,475° F.

The bottom effluent of the boiler-condenser deaerating unit contained about 0.2 cc of oxygen per liter. This was reduced to less than 0.01 cc of oxygen per liter of water by the deoxygenating resin. The oxygen level increased if water was withdrawn at a rate of more than 40 gal per day.

The resistivity of the water from the deionizing resin was between 1,000,000 and 10,000,000 ohm-cm. The lower values were obtained if the water remained in the stainless feed lines; the resistivity increased as this water was replaced. Measurements of pH gave values between 6.1 and 7.2, but these values were not related to the resistivity readings. This water contained less than 0.01 cc of oxygen per liter after the first few days operation. During this initial period the oxygen content was about 0.02 cc per liter, owing to residual oxygen trapped in the bed.

Water Analysis

In order to control the water and gas conditions in the dynamic test circuits used in corrosion studies, satisfactory methods must be used for determining the total volume of oxygen, hydrogen, and nitrogen in two-phase gas-water samples on a routine control schedule. This involves the quantitative transfer of the sample from its stainless-steel container to a volume measuring device and its subsequent transfer to a micro gas analyzer for the determination of

oxygen, hydrogen, and nitrogen. Techniques developed for these determinations are sufficiently simple and rugged for operation by technicians after a short period of training.

Water samples are taken from the corrosion loop in stainless steel containers through which some of the high-pressure hot water is bypassed during intervals of the test. The Toepler pumping principle (mercury displacement) is utilized to transfer the sample from its container to a measuring burette, where the relative volumes of water and undissolved gases are determined. A portion of the gas is then transferred to a modified Blacet-Leighton² apparatus, which is integrated with the measuring burette. There the gas is analyzed for oxygen and hydrogen. Nitrogen is determined by difference.

The total volume of each of these gases is then determined on the basis of gas solubilities by using the gas analysis to calculate the quantity of each gas dissolved in the water.

In cases where there is insufficient free gas for analysis by the Blacet-Leighton technique, a sample of the water can be withdrawn from the measuring burette into a 50-ml McLean type dissolved oxygen flask, with the usual precautions against air contamination. With the use of ASTM referee method D-888, which has been modified for the use of 50-ml samples, the dissolved oxygen content of the water is then determined by using a dead-stop apparatus to detect the end point of the titration.³ Additional details of gas analysis, where the water included carbon monoxide and carbon dioxide, have been reported.^{4,5}

TABLE 5-1.

WATER ANALYSIS

Determination	Procedure	ASTM method
Total iron----	Colorimetric, orthophenanthroline method.	D-1068
Phosphate----	Colorimetric, reduced phosphomolybdate method.	-----
Ammonia----	Colorimetric, sample treated with Nessler's reagent.	-----
Chorides-----	-----	D-512
Solids-----	By evaporation-----	-----

A water portion of the sample is withdrawn from the measuring burette for the determina-

tion of iron, phosphate, ammonia, chloride, and total solids. The methods used are shown in table 5-1.

A recent improvement in the iron determination is to minimize contamination by using zirconium tubing for cooling and withdrawing water samples.

Additives to Test Water

When a gaseous or other additive is specified, a sample bomb containing a predetermined amount of the additive is connected to the circuit, and the gas or liquid in the bomb is flushed into the circuit with loop water. This procedure is used at room temperature and at the elevated temperature to add gas content as desired.

For those tests whose conditions require the use of an ion exchanger, water is continuously bypassed at about 0.04 gal/min through a column of mixed-bed ion-exchange resin, e. g., Amberlite MB1. Samples of the effluent water are checked for conductivity.

Continuous additions of chemicals for pH control can be made by using ion-exchange resins which release such cations as lithium and ammonia into solution while removing other impurities. Recharging methods have been developed for commercially available resins.

PROCEDURES FOR GENERAL CORROSION TESTING

Each of the several test devices described above includes provisions for a large number of specimens when data on general corrosion are to be obtained. The strip specimen shown in figures 5-11 and 5-12, are the most widely used for dynamic testing. These specimens are usually $\frac{1}{16}$ in. thick by $\frac{1}{2}$ in. wide and as much as 8 in. long.

The history of each test specimen is followed carefully from the procurement of material through any metallurgical heat treatment, fabrication, testing, and measurement to final evaluation. Records of chemical composition and procedures of sample preparation and

testing are invaluable in the interpretation of any unexpected general results or local corrosion effects.

Specimen Preparation

All phases of the preparation of corrosion specimens are carefully controlled, particularly shop practice and surface finish. Surface finish is discussed in chapter 14, "Manufacturing Procedures Affecting Corrosion and Wear." A brief description of specimen handling procedures follows.

Uniformity of surface finish is essential to precise corrosion testing. Specimens with poor surface finish and such irregularities as tool marks can usually be improved and made more uniform by polishing treatment on a belt sander (325 grit). Hand rubbing with abrasive cloths provides still smoother surfaces.

Prior to testing, each specimen is marked for future identification, degreased in methyl alcohol or carbon tetrachloride, and washed with soap and water. Further surface treatment sometimes includes a 15-sec dip in 5 percent hydrofluoric acid solution, followed by a hot distilled water rinse and an alcohol rinse. Specimens are dried, weighed, and kept in a desiccator until they are placed in the corrosion circuit for testing.

All materials are not prepared for testing in the same manner. In addition, variations in preparatory treatments are often necessary for specimens with surface platings, metallurgical case treatment, or other surface films. For example, nitrided specimens with thin cases cannot be rough sanded; marking, as by stamping, may not be permissible for specimens with brittle surfaces.

Specimen Removal and Examination

Specimens removed from test are either brushed with a soft camel's-hair brush or washed with soap and water to remove loose foreign particles; they are then dried either in ovens at about 220° F or in desiccators at room temperature. The amount of corrosion product re-

moved by brushing and drying is highly significant for such materials which form thick, loose scale. Therefore, these materials are best evaluated after descaling.

The dried (or descaled) specimens are weighed and examined visually, and all pertinent information is recorded. Observations include visual appearance, weight changes, study of corrosion products, and metallographic examination.

The binocular microscope has proved to be a valuable aid in making detailed observations of the corrosion oxide film. Metallographic examination is used for more thorough study of corrosion phenomena and general oxide composition and adherence. X-ray diffraction is of value in the study of corrosion products and often affords a better insight into corrosion phenomena.

It is often necessary to obtain data on the mechanical properties of a material before and after exposure to the corrodent in order to determine the effects of exposure. The type of information required in such a case is governed by the ultimate application.

Weighing

Weighings should be made on an analytical balance. The sensitivity of the balance should be checked prior to each set of weighings to insure good working condition. The accuracy and precision of weighing cannot be over-emphasized.

For example, tolerances in weight could represent a considerable error in 18-8 stainless steels where overall corrosion is relatively low. This particular error can be reduced by calibrating weights at each set of weighings and by conducting weighings under standardized conditions of temperature and humidity.

Handling of specimens should be kept to a minimum to insure the least amount of change to the sample; that is, the use of instruments, gloves, or fingers in handling should be governed by the quality of results desired, the amount of corrosion being measured, and the sensitivity required.

In evaluating corrosion data, visual and/or microscopic examination should accompany weight change data. Weight changes may be reported as inches penetration per year or milligrams per square decimeter. Whether the rate or the absolute figure is given, it represents a mean corrosion value and may not be indicative of local metal losses due to pitting or other forms of localized corrosion.

Descaling and Corrosion Products

For highly corrosion resistant materials reliable evaluations can be made for a particular environment on the basis of weight changes alone. However, the relatively thick adherent corrosion scale which is encountered in evaluating many materials, particularly carbon steels, makes it desirable to descale such specimens. The adherent scale makes it impossible to determine the amount of metal involved in the corrosion process by gross weight change. For example, two similar specimens, one from a hydrogenated and the other from a low oxygen test, may sometimes be reported as showing identical weight changes although the specimen from the oxygen loop may retain considerable oxide films. However, a comparison of these specimens after removal of their respective films might reveal a considerable difference in the net weight change. For this reason procedures to remove such remaining oxide films are recommended, especially when observing materials that form heavy oxide scales. The appearance of corrosion specimens before and after descaling is shown in figures 5-18 and 5-19.

Descaling procedures require a control specimen so that any weight change due to the descaling procedure will be evaluated when final corrosion results are calculated. Since usual descaling processes are cathodic treatments of specimens in inhibited acid solutions with insoluble anodes, the time of specimen immersion in the acid solution should be kept to a minimum. After being descaled, the specimen is immersed in a neutralizing bath and then dried. After being weighed, the descaled specimens should be reexamined visually.

FIGURE 5-18. Corrosion specimens after removal from test.

FIGURE 5-19. Corrosion specimens after descaling

Some combinations of materials and test conditions exist for which descaling procedures are inadequate.⁶ In general, the descaled data included in this handbook have been obtained from electrolytic descaling procedures. The specimens are made cathodes in a solution containing 5 percent sulfuric acid by weight (2½ percent acid for carbon steels and up to 5 percent for chromium alloys). The solution also contains 1 g. of quinoline ethiodide per liter. Platinum or pure lead is used as an anode in combination with the specimen as a cathode. A voltage sufficient to cause a current density of 1 amp. per square inch of specimen is used. The time necessary for complete scale removal is recorded so that a blank correction can be made if necessary. When a blank is being run for correction purposes, a clean specimen is exposed to the descaling bath for the same amount of time as the descaled specimen. Thus, the amount of scale removed, corrected if necessary for blank losses, gives additional data to be used with gross weight changes.

Immersion in Clarke's solution⁷ is probably the most readily used of the descaling procedures. Clarke's solution will descale carbon and low alloy steels with a small blank correc-

tion, but will not descale many of the other materials tested.

The widest variety of materials are descaled by the sodium hydride bath.⁸ However, the high temperature (370° F) of this caustic bath makes it somewhat more difficult to use and less desirable than the others. In addition, the high-temperature liquid presents a hazard to operating personnel. The sodium hydride method is recommended only where other, safer methods are not applicable.

The following procedure is followed in determining corrosion rates of descaled and undescaled specimens.

Undescaled corrosion rate (milligrams per square decimeter per month)= R_u

$$R_u = \frac{A-B}{D} \times \frac{720}{E}$$

Descaled corrosion rate (milligrams per square decimeter per month)= R_d

$$R_d = \frac{A-C}{D} \times \frac{720}{E}$$

where A =original weight in milligrams

B =weight after exposure, before descaling, in milligrams

C =weight after exposure and descaling, in milligrams

D =specimen surface area in square decimeters

E =duration of exposure in hours

Often it is important to calculate the rate at which the corrosion products are entering the water. Since the corrosion products formed under primary system operating conditions are composed largely of magnetite (Fe_3O_4), a conversion factor of 1.4 can be used to relate the weight of iron entering the corrosion reaction to the weight of corrosion products (oxides) formed. The quantity of oxide entering the water is the total oxide formed minus the oxide scale adhering to the specimen.

Metal Lost to Water

Analyses have been made for soluble corrosion products, but present analytical procedures are somewhat inadequate when these water samples include iron not only in suspension but also in solution. Cycling of temperature and pressure and even sampling procedures can increase iron content by dislodging oxides from loop surfaces. On the other hand, iron compounds deposited on surfaces of the sampling apparatus will reduce iron in the analysis. The size of the water sample that can be withdrawn from test circuits during operation is small and is a distinct disadvantage. By draining the entire water from a corrosion test apparatus and evaporating to dryness, it may be possible to obtain somewhat more reliable results.^{9 10}

Microscopic Examination

For microscopic examination, a plane is prepared perpendicular to the exposed surface of a corrosion test piece in order to measure the actual depth of penetration and to observe the nature of the attack. Descaling is omitted, and care must be taken not to dislodge scale and corrosion products from the surface.

Specimens with curved exposed surfaces, such as tubing, are mounted in plastic. Specimens with flat exposed surfaces, such as sheet or plate, usually are mounted with inserts of silver foil in a supporting metal clamp, the composite sample being polished. This method has the advantage that several flat test specimens may be prepared simultaneously in a single assembly. An additional advantage is the preservation of very sharp, level edges for examination at high magnification. Such an edge cannot be obtained with a plastic mount.

Silver foil inserted between flat test specimens flows enough under clamping pressure to fill in small surface irregularities on the exposed test surface. Thus the space between test specimens is completely closed by silver foil, which prevents the seepage of washing and

etching reagents to the prepared surface after the specimen has been dried in the usual man-

tact between the foil and the specimen surface. The inside curved surface of small diameter

FIGURE 5-20. Photomicrographs of specimens. (a) Simple oxidation of zirconium (1000 $\times$). (b) Corrosion deposit, also oxide inlets in zirconium tubing, cf in. O. D. (500 $\times$). (c) Intergranular attack and surface oxidation of 304 stainless steel (250 $\times$).

ner. Curved surfaces also have been wrapped with silver foil prior to mounting in plastic, but it is often difficult to obtain intimate con-

tact between the foil and the specimen surface. tubing has been satisfactorily prepared by two methods.

1. The tubing is split lengthwise, and foil

is inserted against the inside surface; then a rod or wire of appropriate diameter is pressed into the tubing. The unit is mounted in plastic for preparation of a longitudinal plane through the tubing.

2. One or more layers of silver foil are sometimes inserted and pressed smoothly against the inner surface of a short length of whole tubing, with the silver lapped over the ends. This unit is then mounted in plastic for preparation of a transverse plan; the pressure from the mounting operation should force intimate contact between the foil and tubing.

Since wet polishing has a relatively great tendency to "wash out" any soluble or porous corrosion deposits, as much of the preparation as possible is performed dry on No. 2 through No. 000 papers, and a minimum of time is spent in the final wet polishing steps.

Photomicrographs (fig. 5-20) illustrate various types of specimen examination.

Zirconium is a difficult material to mount for metallographic examination. It requires a much longer time to polish than average metal. During prolonged polishing, a plastic mount wears away more rapidly than zirconium; thus the edge of the specimen becomes rounded and indistinct. As a result, silver is used to minimize this tendency (see part a, fig. 5-20). At a magnification of 1,000 the oxidized edge would have been rounded too much in plastic to permit either photographing or accurate measuring.

The primary constituent in this transported corrosion deposit is magnetic iron oxide. Visually, it appears as a black powdery deposit that can be flaked or rubbed off with little effort. It is impossible to retain this deposit for examination in various plastic mounts. However, by pressing silver foil into the small diameter tubing containing the deposit, the black-appearing porous layer is kept intact, as shown in part b, figure 5-20.

Silver foil has also been used successfully in the preparation of flat stainless steel specimens.

Several stainless sheets were held in a single clamp with silver foil inserted between each sheet specimen. The silver foil not only helped

to maintain a sharp edge but also by intimate contact prevented seepage which surely would have occurred with other types of mounts. The foil provides still another advantage: since most surface films or deposits appear gray or black under a microscope, the silver, which appears white, sharply outlines the boundary of the film or deposit. On the other hand, plastics appear in the gray or black range and cannot be readily distinguished from the oxide (see part c, fig. 20).

PROCEDURES FOR SPECIAL CORROSION TESTS

Although general corrosion of a structural material is of considerable interest in maintenance of water purity, reduction of corrosion products, and optimum system operation, the acceptability of a material for a given application may be determined primarily by localized corrosion attack. In most cases such phenomena as galvanic corrosion, crevice corrosion, stress cracking, and fatigue are found and evaluated by careful observation and metallographic examinations. Chapters 6 and 9 to 11 describe the effects and the engineering importance of the different forms of localized corrosion considered. The equipment, test circuits, and operating procedures used are similar to those already described; both autoclaves and dynamic systems have been used. The type and arrangement of specimens used for tests to determine susceptibility to localized attack simulate actual components used in service. This section describes the special types of test specimens and equipment which have been employed in making various investigations for corrosion.

Galvanic Corrosion

Standard specimens may be prepared to include a weld between dissimilar metals; however preliminary tests may be run with plate-type specimens in contact with each other. Specimens may be assembled as shown in figure 5-21.

Intimate contact is maintained between specimens in this assembly by means of retaining wires. In this case the space between

specimens, or the degree of contact, can be fairly well controlled by the use of insulating spacers.

FIGURE 5-21. Galvanic corrosion specimens.

Crevice Corrosion

Preliminary crevice corrosion tests are normally conducted with plate-type specimens fastened together with or without spacers. A second type of specimen used to study crevice corrosion is the journal-sleeve test couple. This arrangement simulates service conditions more closely.

FIGURE 5-22. Assembled journal-sleeve crevice corrosion specimen before test.

FIGURE 5-23. Journal-sleeve crevice corrosion specimen showing location and extent of crevice corrosion buildup.

Diametrical clearances can be maintained accurately. The couple provides a simple means for determining the effect of corrosion buildup in the annular crevice on the relative motion between the two parts. Such an arrangement is shown before testing in figure 5-22; figure 5-23 shows a journal-sleeve couple disassembled after test. A detailed description of crevice corrosion is given in chapter 9, "Crevice Corrosion."

Stress Corrosion

The different types of stress specimens employed and the various testing techniques used, are discussed in chapters 6 and 10.

FIGURE 5-24. Diagram of corrosion fatigue test fixture.

Corrosion Fatigue

Corrosion fatigue studies are conducted to evaluate the effects of corrosion on the fatigue properties of materials. Tests of this type are conducted in a simulated reactor environment at 600° F and 2,000 psi. The tapered shape of a cantilever bend specimen is used. This provides a large area of the specimen under the same stress. Five specimens, each of different thickness, are tested simultaneously. All specimens are deflected equally by a plunger-type drive which supports one end of each specimen. The test apparatus is a modification of the piston-cylinder wear test device of Westphal and Glatter.

The assembly and test specimens are shown schematically in figure 5-24.

Counters attached to the internal rig record the number of cycles endured by individual specimens; recording stops if a specimen breaks. Thus, in the event of fracture, the number of cycles to failure can be observed directly.

Specimens are accurately machined and the surface roughness did not normally exceed 4 microinches (rms).

The toluol-acetone-distilled water rinse technique is used to remove all traces of grease prior to testing. The specimens were sufficiently grease free so that no water droplets were observed clinging to the surface after final rinsing in water.

The test apparatus can be installed in any 5 in. by 12 in. autoclave where water of the desired composition can be circulated.

Heat-Transfer Studies

To investigate the deposition of corrosion products on heat-transfer surfaces, some tests have been run in which circulating pressurized hot water is the source of heat. The transfer of heat is through a tube wall to boiling water. The apparatus for such a test is shown in figure 5-25. In this unit the hot water at 2,000 psi and up to 600° F. flows through the inside of the U-shaped tube. Boiling water at approximately 1,000 psi is in the chamber outside

FIGURE 5-25. Simulated boiler for heat-transfer studies.

the tube. Steam is condensed by the cooling air blown over the outside of the cylinder.

Heat-transfer rates are measured continuously and observed over a period of time.

Velocity Studies

The effect of velocity on a specimen immersed in water can be studied by means of the test apparatus shown in figure 5-26. In this system an externally mounted motor drive is used to impart rotary motion to the disk type specimens.

FIGURE 5-26. Schematic diagram of autoclave system used for velocity studies.

A standard 5 in. by 12 in. autoclave is used. The vessel may be an element of a static system or a valved-off vessel from a general-purpose loop.

At startup the specimens are placed in the vessel, and the vessel is evacuated. Test water of the desired composition is then pumped to the vessel from the makeup tank. Additional makeup is necessary following sampling of the test water for chemical analysis.

Specimens are evaluated by observing the various velocity regions which exist at different radii on the disks. The water in the vessel is prevented from swirling by fin type projections on the test jig that extend between the specimens.

WEAR AND FRICTION TESTING

Introduction

An extensive program has been directed toward the determination of wear and friction

properties of materials and the performance features of simulated components.^{11 12} Basic wear tests include the reciprocating motion type (piston-cylinder) and the rotating motion type (journal sleeve) each conducted at elevated temperatures in autoclaves. Basic wear and friction studies are also conducted on the pendulum-slide mechanism for the screening of materials with respect to friction and wear in water at room temperature.

The simulated component tests include tests of special linkages and bearings at elevated temperatures. These tests are conducted to determine the operating characteristics of the components, the primary consideration being those of wear and friction.

Test Procedures

Many types of test arrangements have been used to investigate the wear properties of materials in a high-temperature (500° F) water environment. Most of these utilize members whose shape, relative motion, and load simulate the design and application of a component being studied. The shape of these specimens depends, to a large degree, on the final application. Journals rotating in sleeves, shafts rotating against flat plates, spherical specimens moving against conical slotted pieces, and pistons moving within cylinders are some of the shapes that have been used successfully.

The specimen types given above are suitable primarily where sliding contact exists. There are cases, such as ball bearings, where the primary motion is rolling. However, true rolling occurs only at the elliptical area of contact which exists where the ball contacts the race. Since the motion between the balls and the retainer is entirely sliding, the standard specimen types used for the sliding applications also have value for some nominal rolling applications.

The test apparatus used is similar to that previously described for static and semistatic systems. Likewise, water treatment and analysis procedures are used as described above. Variations in the apparatus are made to provide

for the specific type of simulated component and the motion required.

Basic Wear Tests

PISTON-CYLINDER TESTS

The type of motion observed in the piston-cylinder tests is linear, the reciprocating motion taking place by moving a piston within a restraining cylinder.

Specimens

The specimens consist of a split piston which fits within a cylinder. Chevron springs located between the piston halves load the system by forcing the piston halves outward against the cylinder wall. Piston cylinder specimens are shown in figure 5-27, and their location in the assembled piston-cylinder test apparatus is shown in figure 5-28.

FIGURE 5-27. Piston-cylinder specimen assembly.

The dimensions of the piston-cylinder specimens are standardized. The piston is 0.500 in. long and has a diameter of 0.7470 to 0.7472

FIGURE 5-28. Drawing of piston-cylinder wear test rig.

in. before splitting; the cylinder is 1.250 in. long, with an outside diameter of 1.000 and an inside diameter of 0.7500 to 0.7502 in.

FIGURE 5-29. Assembled piston-cylinder wear apparatus.

Piston-cylinder specimens are prepared with a surface finish of 8 microinch (rms). This finish is obtained by honing.

Prior to testing, the specimens are cleaned and degreased as described in chapter 14. Care is taken during cleaning, assembly, and measuring to prevent marking of the wear surfaces.

Test Procedure

The piston-cylinder test apparatus is mounted

FIGURE 5-30. Layout of parts and specimens for piston-cylinder wear test rig.

in a standard 5 in. by 12 in. autoclave as shown in figure 5-29. The parts, shown in figure 30, are assembled greasefree and installed in the test vessel.

By one procedure, the vessel is partially filled with water prior to placing the test rig. Thus, if oxygen is to be added, a blanket of sigma argon (5 percent oxygen) is introduced above the water. The test water absorbs oxygen as the test progresses, aided by turbulence created by the reciprocating test mechanism. Should hydrogen be desired as an additive, the

vessel is sealed and degassed by heating the water to boiling and venting the gases to atmosphere. A blanket of hydrogen is provided by admitting pressurized hydrogen to the vessel, where it is absorbed by the water.

In applications of this type the test rig is installed in a static autoclave or a blocked off unit of the general purpose (semistatic) loop.

Another procedure, more desirable since it permits accurate control of water composition, consists of placing the test rig in a vessel of a semistatic test loop in which water of the desired composition is circulated. Here the test is installed and the vessel secured. Water is admitted from the loop, and the vessel heaters are turned on. By this procedure the test is run in a solid water system with the pressure maintained above the saturation pressure for the test temperature.

After the vessel has been filled, the test is brought to the required temperature, and a water sample is withdrawn for chemical analysis. Counters are set, and the air motor is actuated (see fig. 5-28). At the completion of test the air motor is stopped, a water sample is withdrawn, and the system is secured.

Evaluation.—Piston-cylinder test specimens are first evaluated by visual examination. Some of the features observed are smoothness, roughness, galling, wear patterns, and the nature of surface films. They can be further evaluated by physical measurements including pretest and posttest determinations of component weights, diameters on wearing surfaces, surface finish. By observing the measurements indicated above, the wear factor can be calculated (see ch. 13). The wear factor has the dimensions of milligrams weight lost per million cycles per pound load.

JOURNAL-SLEEVE TESTS

Since most wear problems can be broken down into two basic types of motion, i. e., reciprocating and rotating, it was logical to use a journal-sleeve-type test to complement the piston-cylinder tests. Here the specimens consist of a journal with a nominal outside diam-

eter of 0.7500 in. and three sleeves. The two end sleeves are 0.500 in. long, and the center sleeve is 1.000 in. long. All sleeves have a common internal diameter of 0.7500 in. The journal-sleeve test specimens were so designed that the nominal wear area is the same as that encountered in the piston-cylinder tests. Dimensional adjustments must be made for different materials to account for possible differential thermal expansion at elevated temperatures. It was determined in trial runs that, if this clearance were maintained at 0.008 in. at 500° F, most combinations of interest would operate without seizure during the initial phases of the test. As with the piston-cylinder specimens, honing of the wear surfaces was used where applicable as a means of obtaining a uniform surface finish for various wear combinations. This gave a surface finish of 8 microinches (rms) or better. Cleaning and degreasing procedures were identical with those employed for the piston-cylinder tests. Figures 5-31 and

FIGURE 5-31. Drawing of journal-sleeve wear test rig.

FIGURE 5-32. *Journal-sleeve wear test rig.*

5-32 show the details of the journal-sleeve test specimens and apparatus.

Test procedure—Test procedures are identical to those employed for the piston-cylinder tests, except that the journal-sleeve apparatus is driven by an electric motor mounted outside of the autoclave.

Evaluation—Evaluation of journal-sleeve specimens is based upon visual examination, weight change, and, to a lesser degree, dimensional changes. The methods employed are essentially the same as those used to evaluate piston-cylinder specimens.

PENDULUM-SLIDE APPARATUS ¹²

The pendulum-slide test apparatus is used to determine the friction and wear characteristics of materials in water at room temperature. This device, developed by Dewees, is shown in figure 5-33. The data resulting from tests run on this machine correlate with data obtained by other investigators in high-temperature water. Thus the findings are usable in the solution of wear problems encountered in reactor environments.

The apparatus is shown schematically in figure 5-34. A pendulum is attached through a

FIGURE 5-33. Closeup of pendulum slide machine.

ball bearing to one end of a horizontal connecting rod; the rider specimen is mounted in a receiver at the opposite end of the rod. When the pendulum swings, the connecting rod and, consequently, the rider are actuated horizontally. The mating element of the wear couple is in the disk, which is mounted rigidly in room-temperature water. The rider, moving on the disk with a reciprocating motion, produces a wear track on the disk specimen.

FIGURE 5-34. Schematic diagram of pendulum slide machine.

The movement of the rider is perpendicular to the long axis of its face, and the total movement is 0.160 in. Test specimens are shown in figure 5-35.

FIGURE 5-35. Specimens for pendulum slide wear and friction test.

Loads are suspended in the system through a hook-shaped load pan support, as shown in figure 5-33. Standard weights for these tests are 2.6, 10, and 40 lb.

Relative wear data can be obtained by driving the pendulum a prescribed number of cycles for each set of specimens tested. Kinetic friction data can be attained by releasing potential energy to the system and counting the number of swings before the pendulum comes to a standstill.

Specimens.—The specimens used in the pendulum-slide system consist of a disk and a rider. The arrangement of the specimen is shown in figure 5-34, and the dimensions are given in figure 5-35. The rider moves perpendicular to the long axis of its face, and the total movement is 0.160 in.

The test specimens are machined to have a surface roughness of 16 microinch (rms) as obtained commercially. Prior to testing the specimens, the cup, cover, and tools are cleaned and degreased, preferably by a toluol-acetone-distilled water rinse technique. In the final rinse, no droplets may be observed to cling to the specimens, tools, or cup.

Test Procedure.—A standard procedure has been developed for most of the tests reported. The connecting rod is wiped with acetone. After the specimens are installed with clean tools, the

cup is filled with deionized water, and the lid is installed, the rig is ready for test. Three friction determinations are made in succession at each test point. Friction is usually measured at every 100 cycles of operation. For the first 1,800 cycles the test load is 2.6 lbs (1,287 psi Hertz stress); for the second the load is 10 lbs (2,585 psi Hertz stress); and for the next 7,200 cycles the load is 40 lbs (5,060 psi Hertz stress). Following this series, a second series is undertaken which includes 1,600 cycles each at loads of 10 lbs and 2.6 lbs and a final 400 cycles at 40 lbs. During this operation there are frequent disturbances, such as pushing the connecting rod at the specimen end from one side of its guide to the other, a distance of about 0.010 in. There are occasional stops for visual inspection of the wear surfaces and also measurement of the rider length. (The primary wear measurement was the weight of specimens before and after test. The rider length change was frequently less than 0.0001 in.)

A test usually requires about 2 days from beginning to end. The apparatus can be set up in any clean relatively vibration free area. No special piping, heating, or auxiliaries are required.

Evaluation.—Means must be provided to measure the amount of wear so that comparisons and evaluations may be made. The test data which have been obtained show that weight change is one of the most sensitive and reproducible measures of wear. With some materials, particularly porous or soft metals, dimensional measurements are of greater significance than with such hard materials as the Stellites. In all of this work the dimensions should be measured as accurately as specimen configuration will allow. Weights should be accurate to 0.1 mg, and surface roughness should be obtained in microinches (rms).

For the pendulum-slide apparatus, wear is evaluated on the basis of weight change, dimensional change, visual appearance of the wear tracks, and changes in surface roughness. The weight change factor used here has the units microinches per pound load per square

inch of wear area per 1×10^6 in. travel. Dimensional change studies include such factors as depth of wear track and change in length of the rider. Surface appearance and roughness changes indicate galling and seizing, etc., but in a larger sense these changes indicate the compatibility of the materials. This wear factor (weight change) can be compared approximately to the factor of Westphal and Glatter¹¹ by multiplying by 3.

$$W. F. (Dewees) \times 3 = W. F. (Westphal and Glatter)$$

Kinetic friction in this system can be computed from the following equation:

$$P. E. = W_f \times d + f_m$$

where $P. E.$ = potential energy of the system provided by releasing the pendulum from a latched position

W_f = work of the friction force

d = distance traveled by the pendulum from the point of release to a standstill

f_m = friction work of the machine, which is approximately 1, 3, and 10 percent for the 40-, 10-, and 2.6-lb loads, respectively.

During the course of a test, three friction determinations are made at each of the load levels. These three observations are made 100 cycles apart.

SIMULATED COMPONENT TESTS

Simulated component tests determine the operating characteristics under simulated reactor conditions of all types of mechanisms, linkages, and such parts as ball bearings. These tests are operated on a "one shot" basis in many cases, but items such as ball bearings are tested in comprehensive programs. For the most part these tests are conducted in general purpose test loops.

Specimens.—The specimens used in the testing of simulated components are nonstandard in that the number of tests run on any single item

FIGURE 5-36. Typical test station showing autoclave and instrumentation.

FIGURE 5-37. *Layout and assembly of a full housing type thrust-loaded ball-bearing test rig.*

FIGURE 5-38. *Layout and assembly of a full housing type radially loaded ball-bearing test rig.*

or apparatus are usually small and very often require special test rigs and special modifications of test loops.

A common procedure to all tests in this group, however, is that they are degreased prior to testing and assembled grease free. (Degreasing procedures are given in ch. 14.)

The preferred method is that of cleaning with toluol, vapor degreasing with inhibited trichloroethylene, and drying in a forced circulation oven. This method is impractical for some large parts, including the autoclaves. These parts are degreased by wiping with acetone and rinsing with distilled water.

Test Procedures.—The test procedures are non-standard. The exceptions, however, comprise the bulk of the component wear tests; ball bearings and lead screws. The test assemblies are placed in autoclaves that are filled with appropriate test water from the general purpose test loop. Most of these tests are driven by an externally mounted motor. A typical autoclave station used to test ball bearings is shown in figure 5-36. A pressure gage, pressure switch, differential pressure transmitter, and differential pressure controller can be identified in this photograph.

Several types of apparatus have been used to test ball bearings. One spring-loaded, thrust-type jig is shown in figure 5-37. In this unit two bearings are tested simultaneously. A radially loaded test jig (also loaded by a coil spring) is shown in figure 5-38. This device is used to test four bearings simultaneously. Other jigs are available, and foremost among these is a deadweight loaded jig used to test a single bearing in thrust.

Evaluation.—Component tests are evaluated in keeping with the specific problems that make the test necessary. Ball-bearing and lead-screw tests are evaluated on the basis of appearance, weight change, and internal looseness developed during test.

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ics, and organic substances. For purposes of rapid screening and evaluation, a test known as the static autoclave test was developed. A detailed description of this test is given in chapter 5. Basically, the test consists of placing specimens of the material in question in a stainless steel autoclave containing high-purity water, with oxygen added, and heating the vessel to 500° F. Oxygen is added to the water because, for most of the materials under investigation, this represents the most aggressive corrosive condition that might exist in the reactor. For screening tests of this type, a 7-day period of exposure is sufficient to provide an indication of the corrosion resistance of most materials. Depending on the material being studied, evaluations can be made by appearance, weight changes, analysis of the test waters, and microscopic examination. As indicated, the static autoclave corrosion test is employed mostly for preliminary screening. Although water chemistry can be controlled only to a limited extent, the autoclave test retains certain advantages for screening, i. e., a standard rig or specimen is not required and tests are of short duration.

Photographs of the equipment normally employed for autoclave static corrosion tests are shown in figures 6-1 and 6-2. One type of corrosion specimen frequently used is shown in figure 6-3.

These specimens are machined to a surface finish of 125 microinches (rms) and are cleaned and degreased prior to testing. Several specimens of this type can be tested simultaneously in a static autoclave. To illustrate the kind of results normally observed, an "example" test was performed. Details of the test conditions and the results obtained are given in tables 6-1 and 6-2 and in figures 6-4 to 6-8.

Since the weight changes given include the weight of the corrosion film on the specimen, they are not truly representative of corrosion rate. However, because the film formed is normally thin and adherent, the weight changes do permit general evaluations and comparisons with other materials. Two important conclusions can be drawn from the results of this test.

FIGURE 6-1. Static autoclave in operation.

First, the material is considered to be sufficiently resistant to general corrosion to warrant further investigation. Secondly, the localized attack observed underneath the fastening wires

Chapter 6

APPROACH TO CORROSION PROBLEMS

Editors—D. J. DePAUL, W. F. BRINDLEY

	Page
INTRODUCTION.....	75
GENERAL CORROSION.....	75
LOCALIZED CORROSION.....	80
Crevice Corrosion.....	80
Galvanic Corrosion.....	83
Stress Corrosion.....	86
Intergranular Corrosion.....	92
Fatigue, Fretting, and Erosion Corrosion.....	93

INTRODUCTION

The main purpose of this chapter is to describe the general method of approaching corrosion problems. In addition, it illustrates some of the more important special techniques employed in studying corrosion problems and some typical results observed.

AISI type 410 stainless steel was chosen to illustrate the forms of corrosion under consideration because it is susceptible to many of the various types of corrosion involved. This chapter is not intended to be a general corrosion study on the material employed since the studies and evaluations are not complete.

Before recommending a material for a given engineering application, many phases of corrosion must be investigated to determine its overall suitability with respect to corrosion. Good general corrosion resistance, defined as a uniform loss of metal resulting from corrosive attack, is not the only criterion for acceptance. The various forms of localized corrosion which may occur under normal or abnormal operating conditions must be considered in the evaluation of any material. The forms of localized corrosion considered important in water-cooled nuclear reactor applications are crevice, galvanic, stress, inter-granular fatigue, fretting, and erosion corrosion. Those forms

which have been considered to be a problem are discussed in detail in separate chapters.

Depending on the application, one form of localized corrosion may be more important than another. For instance, in mechanical and welded joints crevice corrosion is not nearly as important a factor as in bearing applications, where relatively small amounts of corrosion products could adversely affect the operational characteristics of components. Pitting type corrosion is particularly harmful in thin-walled pressure members since it may readily result in complete penetration. Intergranular corrosion must also be considered in evaluating any material for a given application. Galvanic corrosion is always a possibility and must also be considered in those applications where dissimilar metals are in contact with one another in a corrosive environment.

The choice of any material, regardless of the application, should be based upon a thorough consideration of both general corrosion and the various types of localized corrosion discussed in this chapter. The extent to which each type of corrosion must be investigated will depend on the particular problem.

GENERAL CORROSION

As indicated in chapter 1, when the project was initiated, there was little or no specific information on the corrosion resistance of materials exposed to high-purity water at temperatures on the order of 500° F. Consequently, tests had to be made on all materials which showed some promise of being useful to the project. This required the testing of literally hundreds of materials, including metals, ceram-

FIGURE 6-2. Disassembled equipment used in static autoclave test.

FIGURE 6-3. Specimens used for general corrosion test.

FIGURE 6-4. General corrosion specimens, as rigged, after test.

FIGURE 6-5. General corrosion specimens showing localized corrosion under retaining wire.

TABLE 6-1. RESULTS OF GENERAL CORROSION TESTS ON AISI TYPE 410 STAINLESS STEEL

Specimen No.	Heat treatment	Run No. 2463 (7 days)			Run No. 2523 (21 days)*			Run No. 2612 (35 days)		
		Weight gain		Observations	Weight gain		Observations	Weight gain		Observations
		mg/dm ²	mg/dm ² /mo		mg/dm ²	mg/dm ² /mo		mg/dm ²	mg/dm ² /mo	
D-2321	Hard†	9.0	38.6	Bluish-black color, faint crevice corrosion around separating wire.	12.0	17.5	Bluish-black color, crevice corrosion around separating wire.	11.0	12.8	Bluish-black color, crevice corrosion with pitting around separating wire.
D-2322	Hard†	14.0	60.0	Same	20.0	28.6	Same	20.0	23.3	Same.
D-2323	Hard†	9.0	38.6	Same	13.0	18.5	Same	12.0	14.0	Same.
D-2324	Hard†	13.0	55.7	Same	16.0	22.8	Same	15.0	17.5	Same.
D-2325	Annealed†	7.0	30.0	Same	8.0	11.4	Same	7.0	8.2	Same.
D-2326	Annealed†	5.0	21.4	Same	8.0	11.4	Same	5.0	5.0	Same.
D-2327	Annealed†	4.0	17.2	Same	5.0	7.1	Same	4.0	4.7	Same.
D-2328	Annealed†	7.0	30.0	Same	8.0	11.4	Same	7.0	8.2	Same.

*Observations and weight measurements for run No. 2489 (7 to 14 days' total exposure) were not made.

†R., 40-44; 1,800° F for 15 min; drawn at 600° F for 2 to 3 hr.

‡1,650° F followed by furnace cool.

TABLE 6-2. CHEMISTRY LOG FOR GENERAL, CREVICE, AND GALVANIC CORROSION TESTS

	Speci- fied	Run No. 2463			Run No. 2489			Run No. 2523			Run No. 2612			
		Pretest	At tem- perature	Post- test	Pre- test	At tem- perature	Post- test	Pre- test	At tem- perature	Post- test	Pre- test	At tem- perature	7-day	Post- test
O ₂ , ppm.....	3-8	8.70	*0.01	(†)	19.1	17.63	1.92	24.1	16.0	3.84	14.98	13.6	0.84	0.05
pH.....	6-8	6.4	6.4	(†)	6.2	5.7	5.7	6.6	6.3	5.4	6.9	6.0	(†)	5.6
Specific resistance (ohm-cm) × 10 ³	>500	1124	33	(†)	824	103	94	431	248	84	599	77	(†)	84
Water temperature, ° F.....	500	-----	500	500	-----	500	500	-----	500	500	-----	500	500	500

*Resulted from temporary leak.

†Not analyzed.

‡After adjustment.

(see figs. 6-5 and 6-7) suggests the possibility of either crevice or galvanic corrosion.

Materials which successfully pass the static autoclave tests may then be tested under more elaborate conditions, with closer control, and for relatively long periods of time. One of the main tests employed for this purpose is the dynamic corrosion loop test. A description of this

test and the types of specimens employed is given in chapter 5. Basically this test consists of a stainless steel pressure vessel through which water is circulated by means of a pump or by thermal circulation. Precise control of the water chemistry is maintained by the use of a by-pass ion exchanger and a mechanical filter. The water is heated to 500° F by means

FIGURE 6-6. Pitting observed 1 in. from retaining wire on general corrosion specimen (20 ×).

FIGURE 6-7. Pitting which developed beneath retaining wire on general corrosion specimen (20 $\times$).

of immersion heaters. The water velocity was normally 30 ft/sec. Dynamic corrosion loop tests usually run for several thousand hours for the evaluation of a particular material or condition. They are employed primarily to provide reliable information on the general corrosion rate of materials under study. The results of a typical long-term dynamic corrosion test are shown in figure 6-9.

This curve is characteristic of most materials in that the corrosion rate usually decreases with time. It should be pointed out that this type of test provides reliable corrosion rates only if the corrosive attack is uniform. If localized attack occurs, the overall weight changes are not representative of the corrosion rate. In this particular example there was no evidence of localized attack.

Normally, dynamic loops are not employed in making specific studies on any of the localized forms of corrosive attack discussed herein. In such studies specific rigs are prepared for the particular tests, which are usually conducted in autoclaves in either a static or semistatic environment. In the semistatic tests the flow is set at the minimum required to control the water chemistry.

LOCALIZED CORROSION

Crevice Corrosion

The importance of crevice corrosion as it affects the operational characteristics of components is discussed in chapters 5 and 9. These chapters describe two types of crevice corrosion

FIGURE 6-8. Photomicrograph of general corrosion specimen showing base metal and oxide film (500 $\times$).

specimens commonly employed for studying this problem. The first of these specimens is a simple plate type used for preliminary screening tests. The second type is the journal-sleeve variety used for long-term tests. The journal-sleeve corrosion test is considered to be the

more reliable of the two because it simulates actual service conditions more closely. It also permits control of the clearances, which is considered extremely important in this type of corrosion.

An example of the plate type crevice corrosion specimen is shown in figure 6-10.

The conditions and results of typical tests on this type of specimen are shown in tables 6-2 and 6-3 and figures 6-11 to 6-13. This clearance between the two plates was not controlled and provided metal-to-metal contact.

The results of similar tests conducted on the journal-sleeve-type specimens, shown in figures 6-14 and 6-15, are described and illustrated in table 4 and figures 6-16 and 6-17.

As in the case of general corrosion, the weight changes shown in tables 6-3a and 6-3b for the plate samples are not considered to be truly indicative of the corrosion rate and are included for general information only. Figures 6-12, 6-13, and 6-17 show the typical corrosion build-

FIGURE 6-9. Curve showing results of a typical long-term dynamic corrosion test.

FIGURE 6-10. *Plate type crevice corrosion specimen before test.*

up observed on practically all parts in contact which are exposed to high-purity water. Figure 6-6 shows pitting on the general corrosion sample. Although not clearly demonstrated in the examples chosen, past experience has shown that pitting comparable to that shown in figure 6-6

occurs more frequently on surfaces within crevices than on surfaces exposed to the normal environment.

Similar results are observed on journal-sleeve specimens, except that specimens of this type may eventually bind as a result of the restraint

FIGURE 6-11. *Plate type crevice corrosion specimen after test.*

TABLE 6-3a. RESULTS OF PLATE TYPE CREVICE CORROSION TESTS ON AISI TYPE 410 STAINLESS STEEL SPECIMENS HARDENED

Specimen No.†	Heat treatment	Run No. 2463 (7 days)			Run No. 2523 (21 days)*			Run No. 2612 (35 days)		
		Weight gain		Observations	Weight gain		Observations	Weight gain		Observations
		mg/dm ²	mg/dm ² /mo		mg/dm ²	mg/dm ² /mo		mg/dm ²	mg/dm ² /mo	
D-2329a	Hard†	9.0	38.6	Discoloration on mating surface.	17.0	24.3	Faint line of crevice corrosion on mating surface.	22.0	18.9	Crevice corrosion around outer edge of mating surface.
D-2330a	Same†	7.0	30.0	Same	13.0	18.5	Same	17.0	14.6	Same.
D-2331b	Same†	11.0	47.2	Same	31.0	44.3	Same	36.0	42.0	Same.
D-2332b	Same†	11.0	47.2	Same	29.0	41.5	Same	33.0	38.5	Same.
D-2333c	Same†	8.0	34.3	Same	17.0	24.3	Same	20.0	23.3	Same.
D-2334c	Same†	9.0	38.6	Same	21.0	30.0	Same	25.0	29.2	Same.

*Observations and weight measurements for run No. 2489 (7 to 14 days' total exposure) were not made.

†R_c, 40-44; 1,800° F for 15 min; drawn at 600° F for 2 to 3 hr.

‡Specimens with the same letter designation formed a single couple.

TABLE 6-3b. RESULTS OF PLATE TYPE CREVICE CORROSION TESTS ON AISI TYPE 410 STAINLESS STEEL SPECIMENS ANNEALED

Specimen No.	Heat treatment	Run No. 2463 (7 days)			Run No. 2523 (21 days)*			Run No. 2612 (35 days)		
		Weight gain		Observations	Weight gain		Observations	Weight gain		Observations
		mg/dm ²	mg/dm ² /mo		mg/dm ²	mg/dm ² /mo		mg/dm ²	mg/dm ² /mo	
D-2335	Annealed†	7.0	30.0	Faint line of crevice corrosion on mating surface.	20.0	28.6	Crevice corrosion around outer edge of mating surface.	21.0	24.5	Heavy crevice corrosion around edge of mating surface.
D-2336	Annealed†	10.0	42.9	Same	25.0	35.7	Same	28.0	32.7	Same.
D-2337	Annealed†	6.0	25.8	Same	33.0	47.2	Same	36.0	42.0	Same.
D-2338	Annealed†	7.0	30.0	Same	36.0	51.4	Same	42.0	49.0	Same.
D-2339	Annealed†	7.0	30.0	Same	34.0	48.5	Same	39.0	45.5	Same.
D-2340	Annealed†	7.0	30.0	Same	28.0	40.0	Same	31.0	36.2	Same.
D-2341	Annealed†	5.0	21.4	Same	22.0	31.4	Same	22.0	18.9	Same.
D-2342	Annealed†	6.0	25.8	Same	25.0	35.7	Same	27.0	23.2	Same.

*Observations and weight measurements for run No. 2489 (7 to 14 days' total exposure) were not made.

†1,650° F followed by furnace cool.

produced by the corrosion buildup within the annular crevice.

These general results would indicate that the localized attack observed on the initial general corrosion samples may have been caused by crevice corrosion effects. However, the possibility of the simultaneous occurrence of galvanic corrosion should not be overlooked since different materials were employed for the retaining wire and the specimen. The wire was AISI type 304, and the test specimens were AISI type 410 stainless steel.

Galvanic Corrosion

It is desirable to study galvanic corrosion in any system where dissimilar metals are in contact in a corrosive environment. However, it was essential in the illustrative cases given because accelerated attack (pitting) occurred at the point of contact between two dissimilar materials. The corrosion buildup in the crevice would not normally be expected to result from galvanic corrosion because the materials in contact are similar. Consequently tests were

FIGURE 6-12. Plate type crevice corrosion specimen, showing corrosion buildup at perimeter of mating surface.

TABLE 6-4. RESULTS OF JOURNAL-SLEEVE CREVICE CORROSION TESTS ON AISI TYPE 410 STAINLESS STEEL SPECIMENS HARDENED*

Specimen No.	Diametrical clearance, mils	Run No. 2463 Total exposure 7 days			Run No. 2523† Total exposure 21 days			Run No. 2612 Total exposure 35 days		
		Seized	Torque to break	Observation	Seized	Torque to break	Observation	Seized	Torque to break	Observation
D-2343.....	8	No	0	Faint line of crevice corrosion around top and bottom of journal.	No	0	Crevice corrosion with buildup around top and bottom of journal.	No	0.....	Crevice corrosion with heavy buildup around top and bottom of journal.
D-2348.....	8	No	0	Same.....	No	0	Same.....	No	0.....	Same.
D-2352.....	8	No	0	Same.....	No	0	Same.....	No	0.....	Same.
D-2353.....	8	No	0	Same.....	No	0	Same.....	No	0.....	Same.
D-2344.....	2	No	0	Same.....	Yes	(‡)	Same.....	Yes	0.4 ft-lb...	Same.
D-2345.....	2	No	0	Same.....	Yes	(‡)	Same.....	Yes	(‡).....	Sam
D-2346.....	2	No	0	Same.....	No	0	Same.....	Yes	(‡).....	Same.
D-2347.....	2	No	0	Same.....	Yes	(‡)	Same.....	No	0.....	Same.
D-2349.....	2	No	0	Same.....	No	0	Same.....	Yes	(‡).....	Same.
D-2350.....	2	No	0	Same.....	No	0	Same.....	No	0.....	Same.
D-2351.....	2	No	0	Same.....	No	0	Same.....	No	0.....	Same.
D-2354.....	2	No	0	Same.....	No	0	Same.....	No	0.....	Same.

* *R_c*, 40-44; 1,800° F for 15 min; drawn at 600° F for 2 to 3 hr.

† Observations for run No. 2489 (7 to 14 days total exposure) were not made.

‡ Although the specimen stuck, the components were parted by slight pressure by the fingers.

TABLE 6-5. RESULTS OF GALVANIC CORROSION TESTS ON HARDENED* AISI TYPE 410 STAINLESS STEEL WELDED TO AISI TYPE 304 STAINLESS STEEL

Specimen No.	Area ratio 304 to 410	Run No. 2523 (14 days)			Run No. 2612 (28 days)		
		Weight gain		Observation	Weight gain		Observation
		mg/dm ²	mg/dm ² /mo		mg/dm ²	mg/dm ² /mo	
D-5673.....	3/1	+2.0	+8.57	No evidence of accelerated corrosion.	+1.0	+1.17	No evidence of accelerated corrosion.
D-5674.....	3/1	+2.0	+8.57	Same.....	+1.0	+1.17	Same.
D-5675.....	1/3	+2.0	+8.57	Same.....	0	0	Same.
D-5676.....	1/3	+3.0	+12.8	Same.....	+1.0	+1.17	Same.

* R_c , 40-44; 1,800° F for 15 min; drawn at 600° F for 2 to 3 hr.

made on specimens similar to those shown in figure 6-18 to determine if galvanic corrosion would occur under similar environmental conditions. Since the susceptibility to galvanic corrosion increases with the extent of contact between metals, the two materials in question were welded in order to provide intimate con-

tact.* Figure 6-19 shows the manner in which they were assembled for testing. The test conditions are shown in table 6-2, and the results are given in table 6-5 and figures 6-20 to 6-22.

*More reliable results would be obtained if AISI type 308 electrode had been used, however the results with AISI type 310 are considered to be indicative.

FIGURE 6-13. Enlarged view of corrosion buildup on plate type crevice corrosion specimen (20 X).

FIGURE 6-14. *Journal-sleeve crevice corrosion specimen, disassembled, before test.*

FIGURE 6-15. *Assembled journal-sleeve crevice corrosion specimen before test.*

FIGURE 6-16. *Journal-sleeve crevice corrosion specimen after test.*

Figure 6-22 shows the fusion zone between the two metals. No evidence of accelerated corrosion was observed at the point of contact between the two metals. Thus the attack observed in the general corrosion test can be attributed to crevice corrosion.

Stress Corrosion

Since there are many areas in any installation where high stresses may develop either in

FIGURE 6-17. Corrosion buildup on disassembled journal-sleeve crevice corrosion specimen.

normal or emergency operation, it is exceedingly important that stress corrosion be considered as a routine matter. Obviously the specific tests required will depend on the

FIGURE 6-18. Galvanic corrosion specimens before test.

application. For instance, in choosing a material for a spring application, one would do considerably more testing and evaluating than in choosing materials for an internal structural part not normally subjected to high stresses. Likewise, more consideration would be given to cyclic than to static stress applications.

There are many methods for determining the stress corrosion resistance of a material. The types of specimens employed for stress cor-

FIGURE 6-19. Galvanic corrosion specimens, as-rigged, before test.

FIGURE 6-20. Galvanic corrosion specimens, as-rigged, after test.

TABLE 6-6. RESULTS AND CHEMISTRY LOG OF CORROSION TESTING OF HARDENED* AISI TYPE 410 STAINLESS STEEL SPRINGS

A. CONDITION OF SPECIMENS											
Specimen No.	Stress, psi	Run No. 2507 (7 days)			Observations Run No. 2539 (14 days)			Run No. 2594 (28 days)			
D-5706.....	100,000	Longitudinal cracks, heavy deposit around washers, specimen cracked along torsion stress line.									
D-5708.....	100,000	Same as D-5706.....									
D-5707.....	100,000	Longitudinal cracks, heavy deposit around washers.			No change.....			No change.			
D-5713.....	100,000	Same as D-5707.....			Same.....			No change.			
D-5714.....	50,000	Heavy deposit around washers.....			Same.....			No change.			
D-5717.....	50,000	Same as D-5714.....			Same.....			Longitudinal cracks.			
D-5720.....	50,000	Same as D-5714.....			Same.....			Same.			
D-5721.....	50,000	Same as D-5714.....			Same.....			Same.			
D-5710.....	30,000	Same as D-5714.....			Same.....			Same.			
D-5711.....	30,000	Same as D-5714.....			Same.....			Same.			
D-5716.....	30,000	Same as D-5714.....			Same.....			Same.			
D-5723.....	30,000	Same as D-5714.....			Same.....			Same.			

B. ENVIRONMENTAL CONDITIONS											
Chemistry log	Specified	Run No. 2507			Run No. 2539			Run No. 2594			
		Pretest	At temperature	Post-test	Pretest	At temperature	Post-test	Pretest	At temperature	7-day	Post-test
O ₂ , ppm.....	3-8	16.9	†5.6	0.37	23.5	†7.5	3.8	20.7	†4.6	3.4	0.10
H ₂	6-8	7.1	6.0	6.2	6.0	6.0	5.7	6.2	6.2	-----	7.0
Specific resistance, ohm-cm.....	500,000	814,000	160,000	108,790	585,206	210,674	170,900	510,000	205,000	-----	225,000
Water temperature, ° F.....	500	-----	500	500	-----	500	500	-----	500	500	500

*R_c, 40-44; 1,800° F for 15 min; drawn at 600° F for 2 to 3 hr

†After adjustment.

rosion studies described in this handbook were horseshoe bend, fulcrum loading, and compression springs. The horseshoe specimen is simple and readily provides high stresses. Fulcrum-loaded specimens permit good control on the stress level. The compression-spring type specimen also offers good control of the stress level and, in addition, provides a more

FIGURE 6-21. Galvanic corrosion specimens after test.

representative stress pattern for important applications such as pressure-containing members. The first two specimens are stressed in tension whereas the compression spring is stressed in torsion (biaxial stress). It should be mentioned that a given level of torsional stress is considerably more aggressive in producing stress corrosion than the same stress level in straight tension. This undoubtedly results from the difference between the moduli of elasticity of a given metal under the same tensile and torsional stresses. In general, however, materials which are susceptible to stress corrosion in torsion are also susceptible to stress corrosion in tension. The main difference is the magnitude of the stress and the time required to produce failure.

Horseshoe-type specimens are very useful in preliminary screening tests where many condi-

tions must be examined in a short period of time. The fulcrum-loading and compression-spring specimens are used where information on different stress levels is desired. The choice between these two specimens should depend on the types of stresses expected in service.

Regardless of the expected service stresses, it is desirable in any stress corrosion study to investigate the effect of stress levels up to the yield point of the material in question. Operational and emergency stress conditions are sometimes very difficult to calculate or estimate.

Because of the many uncontrollable and unknown variables involved in stress corrosion, the number of specimens for a given condition should be large enough to permit adequate interpretation of the results. In some cases a hundred specimens have been employed for studying one condition. Variations in the results obtained will dictate the number of specimens required.

Figure 6-23 illustrates the spring-type specimens employed and the manner in which they were stressed in an actual test. A group of 12 springs were tested in accordance with the conditions shown in table 6-6. The results are described in table 6-6 and figures 6-24 to 6-27.

With regard to the above discussion, it is interesting to note that:

- (1) Two of the four specimens stressed to 100,000 psi cracked in 28 days.
- (2) None of the lower stressed specimens cracked during the test period.
- (3) Cracks longitudinal to the wire would not be expected in stress corrosion with this type of specimen. These cracks represent wire drawing defects. Cracks corresponding to torsional lines of stress would be anticipated with springs made from sound wire.

Strictly speaking, the longitudinal cracks observed would invalidate the entire test since they could alter the stress pattern in the spring and thereby induce torsional cracks.

In such a case, the investigator should repeat the test with springs made from sound wire. The results of horseshoe and fulcrum-loading-type specimens are occasionally obscured by

*AISI type 410 stainless steel**AISI type 310 stainless
steel weld metal*

FIGURE 6-22. *Fusion line between dissimilar metals, galvanic corrosion specimen (20 ×).*

FIGURE 6-23. *Stressed helical springs before test.*

rolling seams in the original plate material from which the specimens are prepared.

This test serves to illustrate just one of the many difficulties which can arise in stress corro-

FIGURE 6-24. Stressed helical springs showing crack in most highly stressed specimen.

sion testing. Accurate determination of stress levels, reproducibility, rate of strain, certain metallurgical changes, and relaxation of test rig are some other items which make it difficult to study stress corrosion.

The final decision concerning a stress corrosion problem which is demonstrated in the laboratory or in service should always be based on pilot-plant tests or actual service trial runs under controlled conditions. Complete de-

pendence on laboratory tests is not recommended.

Intergranular Corrosion

Regardless of the application, any metal subjected to a corrosive environment should always be examined for possible intergranular attack. Since extremely small amounts of metal are involved in this form of corrosion, it

FIGURE 6-25. Cracked helical springs, stressed to 100,000 psi

cannot be readily detected by weight changes or visual inspection. Evaluations should be based on metallographic examinations. Any

FIGURE 6-26. Torsional and longitudinal cracks observed in an unstressed cracked spring.

FIGURE 6-27. Longitudinal cracks in a stressed spring.

type of specimen employed for corrosion testing may be used for examination.

Fatigue, Fretting, and Erosion Corrosion

Generally, fatigue, fretting, and erosion corrosion are not considered to be a problem with the 18-8 type stainless steels or the other corrosion-resistant materials presently employed in reactor construction. However, the investigation of new materials and/or different operating conditions should include a consideration of these forms of corrosion. The present interest in carbon steel as a possible substitute for stainless steel makes it even more mandatory to consider these forms of corrosion on a routine basis.

Chapter 7

TABULATION OF BASIC DATA

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	Page
INTRODUCTION.....	95
STATIC CORROSION TEST DATA.....	96
DYNAMIC CORROSION TEST DATA.....	101
WEAR TEST DATA.....	121

INTRODUCTION

The development and construction of a water-cooled nuclear power plant necessitated a thorough investigation of the corrosion and wear properties of numerous materials. Essentially all the work performed in this connection was related to those specific problems arising from the contact of these materials with the cooling water in the primary or radioactive system (see fig. 1-1, ch. 1). Corrosion and wear problems relating to the secondary or nonradioactive cooling system were not extensively investigated since there was considerable information and experience on materials exposed to conventional boiler water environments.

The magnitude of the problem required the cooperative efforts of numerous laboratories under Government subcontracts in order to obtain the desired information in the allotted time. Many reports on the subject have been issued, varying in scope and treatment, but only a few papers have been published in technical journals to date.

An endeavor has been made to summarize the pertinent data accumulated by the cooperating laboratories by means of a group of tables for ready reference. It is intended that the infor-

mation in these tables will be useful in determining the general corrosion and wear characteristics of materials employed in the project. It was not considered practical to present all the data since this large volume of information, together with the added complexity of interpretation, would detract from the usefulness of this handbook.

The data are presented to provide the maximum amount of information concerning the relative importance of the environmental variables normally considered important in making material selections. Only average values are included in the tables to simplify comparisons and evaluations. Where the reader may not find the specific information needed for choosing a material, or combination of materials, for a given application, it is possible that related tabulated data will provide a reasonable basis for making a reliable extrapolation.

The reader will observe in examining the tables that all the materials were not investigated to the same extent. This disparity resulted from the expeditious manner in which the project was carried out. For instance, at the point where a material showed a lack of a requisite property, further investigation of that material would normally be terminated. Experience showed that it was more advantageous to go to a new material or process rather than to modify an existing material or process. However, in certain cases where a material possessed very desirable properties, it was mandatory

that the details of its limitations be investigated so that the material could be exploited to its fullest advantage. Such was the case with zirconium metal, which has extremely desirable nuclear properties, and AISI type 410 stainless steel, which possess good hardening and magnetic characteristics; both materials presented many corrosion problems.

As is frequently the case with testing procedures and equipment, several conditions may vary from test to test. In many cases, the interactions of variables may make it difficult to evaluate the importance of one particular variable. The reader will undoubtedly encounter this problem when using the tables in this chapter. Since only condensed information is given in the tables and since there is no discussion of individual tests, it may be difficult at times to interpret the results to the satisfaction of the reader. To cope with this difficulty a separate chapter (ch. 8) has been prepared in which the relative importance of each variable is discussed in detail. It is intended that these discussions will aid substantially in the interpretation of the data, especially in those areas where several variables are involved.

The corrosion and wear information in this chapter is summarized in three tables:

Table 7-1 is a classification of all the materials studied. It is divided into three categories based on the material's corrosion resistance or stability under reactor water service conditions. These categories were based entirely on the results of preliminary short-term corrosion tests that were designed to cover a multitude of materials in the shortest possible time. Individual corrosion rates are not given since the values obtained would not provide a better understanding of the table. Furthermore, their incorporation could lead to misunderstanding if certain conditions, all of which are not necessarily covered herein, were not taken into account. Corrosion rates on these tests are not considered important enough to warrant a detailed discussion of their interpretation. The main purpose of table 7-1 is to provide the reader with a list of all the materials studied and their approximate relation by corrosion resistance.

Specific choices should not be made solely on the basis of this table.

Table 7-2 presents the corrosion results obtained on materials that were actually considered for use in the water-cooled reactor plant. These tests were conducted under more closely controlled conditions than the tests on which table 7-1 was based. Specific information is given on composition, corrosion rate, and the effect of pertinent environmental conditions.

Table 7-3 lists all the important combinations of bearing materials that were tested under simulated service conditions. The combinations are arranged in order of decreasing resistance to wear and the table includes the effect of water chemistry, the types of motion studied, temperature, effects and materials used.

In addition to these three tables, supplementary corrosion and wear data will be found throughout the handbook. It was felt that the specialized nature of this information lends itself more readily to incorporation in the appropriate chapters rather than in a general tabulation in this chapter.

FOREWORD TO TABLE 7-1—STATIC CORROSION TEST DATA

Test Conditions

The classification of materials was based on corrosion tests conducted in high-pressure autoclaves containing high-purity water at 500° F. No circulation of the water was provided for, other than movement resulting from thermal circulation. In general, the water contained 10 to 30 cc of oxygen (STP) per kilogram of water, and the initial electrical resistivity was 500,000 ohm-cm or greater. The tests ranged in duration from 3 to 6 months. Details of the test procedures are given in chapter 5.

Interpretation of Classification

Class I: Materials showing the highest resistance to corrosion. These may be used with the least amount of consideration for the particular application. Weight changes in this group were generally on the order of ± 10 mg/dm²/mo (weight gain attributed to adherent scale).

Class II: Materials with appreciably less corrosion resistance than those listed in class I. They require some consideration in their application in order to insure satisfactory performance. Weight changes in

this group were generally on the order of ± 50 mg/dm²/mo. Many of the materials are subject to minor pitting, especially in crevices.

Class III: Materials in this group usually show weight changes on the order of several hundred mg/dm²/mo and/or are susceptible to severe localized attack.

Special Notes

(1) Some testing was performed with water containing additions of hydrogen as a corrosion inhibitor. In

general, the addition of hydrogen improved the corrosion resistance, but the relative position of each material was essentially unchanged. Additions of hydrogen ranged from 200 to 500 cc of hydrogen (STP) per kilogram of water.

(2) Metallic specimens were machined or ground to a surface finish of 63 microinch (rms).

(3) Materials, such as plastics and ceramics, were tested in the "as-received" condition. They were evaluated on the basis of solution rate and/or chemical stability.

TABLE 7-1

CLASSIFICATION OF MATERIALS ON THE BASIS OF STATIC CORROSION TESTS

Class I	Class II	Class III
	<i>Stainless steel (AISI No.)</i>	None
301		
302	304 (Si, 2.5%)	
303	316 (Cb, 1%; Si, 1%)	
304	316 (Si, 2.5%)	
304 modified*	410	
304 ELC	414	
305	416	
308	420	
309	431	
310	440 BM	
	440 C	
316		
317	440 F	
318	442	
321	443	
329	446	
347	450 BM	
348		
	<i>Special stainless steels</i>	
Armco 17-4PH	Carpenter 18-5	Octalloy
Armco 17-7PH	Crucible 3311	
Carpenter 10		
Carpenter 20		
Durimet 20		
USS 18-8 W	Universal Cyclops 17-A	
Worthite		
	<i>Cobalt-base alloys</i>	
Stellite No. 1	Bachrach alloy	Crane special alloy (Co, 54%; Cr, 20%; W, 15%; Ag, 10%; Mn, 1%)
Stellite No. 3	Elgiloy	Haynes Multimet 98 M2
Stellite No. 6	Refractalloy 70	Refractalloy 120
Stellite No. 12	Refractalloy 80	Rexalloy
Stellite No. 19	Stellite Star J Metal	Stellite No. 33
Stellite No. 21		Stellite No. 42
Stellite No. 23		Vascaloy Ramet 166
Stellite No. 26		Vascaloy Ramet 171
Stellite No. 31		Vascaloy Ramet 192
Haynes alloy No. 25		

TABLE 7-1—Continued

CLASSIFICATION OF MATERIALS ON THE BASIS OF STATIC CORROSION TESTS

Class I	Class II	Class III
	<i>Copper-base alloys</i>	
None	Copper-Nickel 70-30	Aluminum Bronze Brass Copper Copper Alloy (Ni, 18%; Zn, 17%; bal. Cu) Copper Alloy (Al, 3-5%; Ni, 3-5%; bal. Cu) Copper-Nickel 90-10 Leaded bronze Phosphor bronze Silicon bronze
	<i>Iron-base alloys</i>	
None	Duraloy Discaloy 24	Alnico 6 Armco iron ASTM A212 Carnegie Hi-tensile steel Chromoco tool steel Cimet Duriron Invar Kovar Ni-Hard Ni-Resist Nusite Ontario tool steel
	<i>Nickel-base alloys</i>	
None	Colmonoy No. 4 Colmonoy No. 5 Colmonoy No. 6 Duranickel Hastelloy C Inconel-X K-Monel Monel Nichrome Nickel (A) Nickel (E) Nickel (L) Refractalloy 26	Carbon graphite Monel Ceco 100 Hastelloy A Hastelloy B Hastelloy D High Ni Monel (Ni, 83%; Cu, 17%) Incolloy Inconel Hipernik Illium G Illium R L Nickel-Moly (9604) Molypermalloy Mumetal S-Monel
	<i>Miscellaneous Alloys and Elements</i>	
Chromium-plated† (hard), AISI type 347 SS	AISI type 304 SS, nitrided AISI type 329 SS, nitrided	AISI type 302 SS, Scottsonized AISI type 347 SS, Armco chromate treatment
Chromium-plated† (hard), USS 18-8 W	AISI type 347 SS, nitrided Armco 17-4PH, nitrided	AISI type 347 SS, MOS treatment
Chromium-plated† (hard), Armco 17-4PH	Armco 17-7PH, nitrided Colmonoy Nicrobraz	AISI type 347 SS, Scottsonized
Gold	Gotalota chrome	AISI type 410 SS, chrome-enriched surface

TABLE 7-1—Continued

CLASSIFICATION OF MATERIALS ON THE BASIS OF STATIC CORROSION TESTS

Class I	Class II	Class III
	<i>Miscellaneous Alloys and Elements—Continued</i>	
Hafnium	Haynes Multimet, nitrided	AISI type 410 SS, wet hydrogen oxidized
Platinum	Jeliff 1000	AISI type 440A SS (hardened), Armco treatment
Titanium	Titanium, nitrided	AISI type 440C SS, chrome-enriched surface
Zircaloy 1, 2, and 3	USS 18-8 W, nitrided	AISI type 440C SS, wet hydrogen oxidized
Zirconium		AISI type 440C SS, nitrided
		Aluminum
		Beryllium
		Beryllium-copper (4-96)
		Cadmium
		Chromized 2½% Si steel
		Chromized Hipernik
		Cobalt
		Cobalt, electrolytic
		Haynes 25, nitrided
		Columbium (Niobium)
		Frank alloy (Ge, 12%; Au, 88%)
		G. E. Magnet Alloy (Pt, 77%; Co, 23%)
		Hevimet
		Hiperco 27
		Hiperco 35
		Indium plating
		Lead
		Magnesium
		Nitrided nickel Nitralloy
		Mallory 1000
		Molybdenum
		Moly-Sulfide
		Rhenium
		Rhodium
		SAE 52-100 with Penetrate coating
		Silver
		Silver-bearing alloy (Ag, 85%; Cu, 5%; MoS ₂ 10%)
		Silver braze (Cu, 16%; Zn, 16%; Cd, 18%; bal. Ag)
		Silver cadmium
		Silver-copper (40-58)
		Tin
		Vanadium
		Zinc
	<i>Ceramics, cermets, and allied materials</i>	
None	Chromium carbide (Ni binder)	Alumina bodies
	Graphitar 14	Alumina (fused)
	Metamic LT-1	Asbestos (gasket material)
		Boron carbide
		Colmonoy Graphalloy #5

TABLE 7-1—Continued

CLASSIFICATION OF MATERIALS ON THE BASIS OF STATIC CORROSION TESTS

Class I	Class II	Class III
	<i>Ceramics, cermets, and allied materials—Continued</i>	
		Graphalloy Babbitt
		Graphalloy (copper)
		Graphalloy (gold)
		Graphite
		Karbate A
		Karbate C
		Mica (natural and glass bonded)
		Quartz
		Silica (fused)
		Solaramic (glass enamel)
		Titania (fused)
		Titanium boride
		Tungsten carbide (Co binder)
		Titanium carbide (Ni binder)
		Titanium carbide (Pt binder)
		Tungsten carbide (Pt binder)
		Zirconium boride
	<i>Plastics</i>	
None	Teflon	Baked phenolic resin
	Teflon impregnated with asbestos	Kel-F
	Teflon impregnated with copper	Plexiglass
		Polyethylene
		Rulon
		Silastic

*Carbon, 0.06% max.

†Thickness: 0.0002 in.—0.0005 in., or 0.002 in.

FOREWORD TO TABLE 7-2—DYNAMIC CORROSION TEST DATA

Test Conditions

The corrosion rates in this table were based on tests conducted in closed stainless steel loops through which high-purity water was circulated over test samples included in the loop. Most tests were conducted at 500° F; however, some results are given at 600° F. Principal additives studied were oxygen, hydrogen, and lithium hydroxide. Water velocities ranged from one foot per minute (1/60 ft/sec) to 60 feet per second. Details of the test procedures are given in chapter 5.

Interpretation of Corrosion Rates

Corrosion rates given in the table are nominal figures.* Weight gains or losses are indicated by the prefixed plus or minus sign. It should be noted that the corrosion rates are based on overall corrosion for total time in test.

Validity Factors

The validity factor indicates the reliability of the corrosion rate given. This factor is based on a weighted consideration of the number of samples, duration of test, and consistency of results. Generally speaking, materials which had the highest validity rating were tested for periods ranging from 1,500 to 5,000 hr (average about 2,000 hr) and at least 10 samples were tested for each environment. Materials which had the lowest validity rating were generally tested for a period of about 500 hr and consisted of a few samples; or showed inconsistent results.

Validity Factor "A"—Considered to be a representative value for the particular condition.

Validity Factor "B"—Considered to be a representative value for the particular condition but lacking in the extent of data required for a validity factor of A.

Validity Factor "C"—Some doubt concerning the validity of the corrosion rate. Usually indicates inconsistent results or insufficient data.

Abbreviations and Symbols

(1) Environment:

D, degassed water, less than 0.5 cc of oxygen (STP) per kilogram of water.

NA, no analysis made for constituent. When NA appears in hydrogen column, the implication is that hydrogen is probably present in the range 0 to 20 cc of hydrogen (STP) per kilogram of water.

This amount of hydrogen generally results from corrosion reactions which evolve hydrogen.

*For simplification corrosion rates were originally grouped in ranges which were subsequently assigned nominal rates. For example, a reported rate of +5 mg/dm²/mo may have actually showed a slightly different rate. The nominal rate represents a well-rounded average.

(2) Condition of specimen:

SA—Solution annealed	S—Sensitized (carbide precipitation)
H—Hardened	W—Welded
M—Malcomized	E. P.—Electropolished
N—Nitrided	N. B.—Microbrazed
P—Pickled	SD—Sanded

Index of Materials

STAINLESS STEELS

AISI type 302
AISI type 303
AISI type 304
AISI type 304 ELC
AISI type 316
AISI type 321
AISI type 347
AISI type 410
AISI type 420
AISI type 440-C

SPECIAL STAINLESS STEELS

USS 18-8 W
Armco 17-4PH
Armco 17-7PH
Carpenter 20

COBALT-BASE ALLOYS

Stellite No. 3
Stellite No. 6
Stellite No. 19
Stellite No. 21
Haynes Alloy No. 25

COPPER-BASE ALLOYS

Copper-nickel (70-30)

IRON-BASE ALLOYS

ASTM A179
ASTM A212 (grade A)
ASTM A212 (grade B)
ASTM A302
Croloy 1¼
Croloy 2¼
Low manganese carbon steel No. 1

IRON-BASE ALLOYS—con.

Low manganese carbon steel No. 2
Reference carbon steel
Special carbon steel No. 3
Special carbon steel No. 4
Special carbon steel No. 5
Special carbon steel No. 6
Special carbon steel No. 8
Special carbon steel No. 9

NICKEL-BASE ALLOYS

A-Nickel
Inconel
Inconel-X
Monel
K-Monel

MISCELLANEOUS METALS AND ALLOYS

Hafnium
Hard chromium plate
Titanium
Zircalloy-2
Zirconium crystal bar
Special alloy (15% Pd, 30 & Cd, 55% Ag)
Special alloy (20% Pd, 30% Cd, 50% Ag)

Special Notes

- (1) The majority of weight changes recorded were negative. Positive weight changes were, in most cases, small (less than 5 mg/dm²/mo) and are considered to result from thin tightly adherent oxide films.
- (2) Unless otherwise indicated metallic samples were machined or ground to a surface finish of 63 microinch (rms).
- (3) The sensitized specimens reported in table 7-2 were heated at 1,200° F for 2 hrs and air cooled.

MATERIAL
AISI Type 302 Stainless Steel

NOMINAL COMPOSITION	Element	C%	Cr	Ni	Mn%	P%	S%	Si%	Fe
	Percent	0.15	17-19	8-10	2.0	0.045	0.030	1.0	Bal
Maximum									

TEST CONDITIONS

ENVIRONMENT						Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH	Undescaled Weight Change			Descaled Weight Change			
					Rate			Validity	Rate	Validity	
1	500	1/60, 30	0-5	NA	7		Machined, pickled	+5	A	-10	A
2	500	1/60, 30	D	0-21	7		Machined	-10	A		
3	500	1/60, 30	D	25-100	7		Machined	-5	A	-5	B

GUIDE TO APPLICATION: Used for nuts and bolts, general hardware and unwelded miscellaneous structural parts.

MATERIAL
AISI Type 303 Stainless Steel

NOMINAL COMPOSITION	Element	C%	Cr	Ni	Mn%	P%	S	Si%	Fe
	Percent	0.15	17-19	8-10	2.0	0.20	0.15	1.0	Bal
Maximum									

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Unde-scaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60	0-5	NA	7		Machined	+5	A	-10	A
2	500	30	0-5	NA	7		Machined	-5	A		
3	500	1/60, 30	D	0-21	7		Machined	-5	A		
4	600	1/60	D	NA	8		Machined	+25	C		
5	500	1/60	D	25	7		Machined	-5	B	-15	C
6	500	30	D	25	7		Machined	+5	C	-5	C
7	500	1/60, 30	D	50	7		Machined	-5	A	-5	A

GUIDE TO APPLICATION: Used for nuts and bolts, general hardware and unwelded miscellaneous structural parts.

MATERIAL
AISI Type 304 Stainless Steel

NOMINAL COMPOSITION	Element	C%	Cr	Ni	Mn%	P%	S%	Si%	Fe
	Percent	0.08	18-20	8-12	2.0	0.045	0.030	1.0	Bal
Maximum									

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Unde-scaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60, 30	0-1	NA	7-10	Lithium Hydroxide	Machined, sensitized	-5	A	-10	B
2	500	1/60, 30	1-5	NA	7		Machined	+5	A	-5	A
3	500	30	0-5	NA	7-10	Lithium Hydroxide	Machined, sensitized	-5	A		
4	500	30	0-5	NA	10		Welded, sensitized	-10	B		
5	600	30	D	NA	8.5		Machined	-15	C		
6	500	10	D	NA	10	Lithium Hydroxide	Machined, electropolished	-5	A		
7	500	1/60, 30	D	25-500	7		Machined, sanded, electropolished	-5	A		
8	600	1/60	D	100	7		Sensitized, sanded	+10	B	-15	B
9	600	30	D	100	7		Sensitized, sanded	-10	B	-15	B
10	600	1/60, 30	D	100	7		Sensitized, sanded, electropolished	+5	B	-5	B

GUIDE TO APPLICATION: Used as general structural material for both internal and pressure containing parts.

TABULATION OF BASIC DATA

103

MATERIAL
AISI Type 304 Stainless Steel (continued)

NOMINAL COMPOSITION	Element								
	Percent								

TEST CONDITIONS

ENVIRONMENT						Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH	Undescaled Weight Change			Descaled Weight Change			
								Rate	Validity	Rate	Validity
11	600	1/60	NA	200	7		Sensitized, sanded	-5	A	-15	A
12	600	30	NA	200	7		Sensitized, sanded	-15	A	-15	A
13	600	1/60	NA	200	7		Sensitized, sanded, electropolished	+5	A	-5	A
14	600	30	NA	200	7		Sensitized, sanded, electropolished	-5	A	-5	A
15	600	1/60, 30	NA	200	11	lithium Hydroxide	Sensitized, sanded	-5	A	-5	A
16	600	1/60, 30	NA	200	11	lithium Hydroxide	Sensitized, sanded, electropolished	-5	A	-5	A

GUIDE TO APPLICATION: Used as general structural material for both internal and pressure containing parts.

MATERIAL
AISI Type 304 Stainless Steel (ELC)

NOMINAL COMPOSITION	Element	C%	Cr	Ni	Mn%	P%	S%	Si%	Fe
	Percent	0.03	18-20	8-12	2.0	0.045	0.030	1.0	Bal

#Maximum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60	0-1	NA	7		Machined, pickled	+5	A	-10	B
2	500	30	0-1	NA	7		Machined, pickled	+5	A	-5	B
3	500	30	0-1	NA	7		Malcomized	-15	C		
4	500	1/60	1-5	NA	7		Machined, pickled	+5	A	-5	C
5	500	20, 30	1-5	NA	6-7		Malcomized	+15	C		
6	600	1/60	D	NA	8.5		Machined	+25	C		
7	500	1/60	D	5-20	7		Machined	+5	B		
8	500	30	D	NA	7		Malcomized	-200	C		
9	500	10	D	NA	10	Lithium Hydroxide	Machined	-5	A	-5	A
10	500	30	D	25-50	7		Machined	-5	A	-5	A
11	500	30	D	25-50	7		Malcomized	-200	C		

GUIDE TO APPLICATION: Used as general structural material for both internal and pressure containing parts.

MATERIAL
AISI Type 316 Stainless Steel

NOMINAL COMPOSITION	Element	C%	Cr	Ni	Mn%	P%	S%	Si%	Mo	Fe
	Percent	0.10	16-18	10-14	2.0	0.045	0.030	1.0	2.0-3.0	Bal

#Maximum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature OF	Velocity f.p.s.	Oxygen cc/Kg	Hydrogen cc/Kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60, 30	0-5	NA	7-10		Machined, sensitized, welded	-5	A	-5	A
2	500	1/60, 30	D	0-500	7		Machined	-5	A	-5	B

† Obtained for tests at pH 7 only.

GUIDE TO APPLICATION: Considered satisfactory corrosion wise, however this material was not normally used in the first water cooled reactor or its prototype because of possible welding difficulties.

MATERIAL
AISI Type 321 Stainless Steel

NOMINAL COMPOSITION	Element	C%	Cr	Ni	Mn	P%	S%	Si%	Ti	Fe
	Percent	0.08	17-19	9-12	2.0	0.045	0.03	1	5 x min. C	Bal

*Maximum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temperature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	30	1-5	NA	7		Machined	+5	B		
2	600	30	D	D	8.5		Machined	-25	C		
3	500	30	1-2	NA	7		Machined	-5	A		

GUIDE TO APPLICATION: Considered satisfactory corrosion-wise, however, AISI Type 321SS was not normally used in the first water cooled reactor or its prototype.

MATERIAL
AISI Type 347 Stainless Steel

NOMINAL COMPOSITION	Element	C%	Cr	Ni	Mn	P	S	Si	Ta - Cb	Fe
	Percent	0.08	17-19	9-13	2.0	0.045	0.030	1.0	10 x min. C	Bal

*Maximum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60, 30	0-1	NA	7		Machined, annealed, microbrazed	-5	A	-10	B
2	500	30	0-1	NA	7		Malcomized	-25	C		
3	500	30	1-5	NA	7		Machined, sensitized	-5	A	-5	B
4	500	30	1-5	NA	7		Malcomized	+15	C		
5	500	30	1-5	NA	10	Sodium Hydroxide		-5	A		
6	600	30	25	NA	7		Machined	-5	C		
7	500	1/60	D	NA	7		Malcomized	-50	C		
8	500	30	D	0-20	10	Lithium Hydroxide	Malcomized	-200	C		
9	500	10, 30	D	NA	10.5	Lithium Hydroxide	Machined, electropolished	-5	A		
10	600	30	D	NA	8.5		Machined	-15	C		
11	500	1/60, 30	D	25-500	7		Solution annealed, sensitized, pickled, malcomized, electropolished	-5	A		
12	600	1/60, 30	NA	100	7		Sensitized, sanded	-10	A	-15	A
13	600	1/60, 30	NA	100	7		Electropolished, sensitized, solution annealed	-5	A	-5	A

GUIDE TO APPLICATION: General structural material for both internal and pressure containing parts.

MATERIAL
AISI Type 347 Stainless Steel (continued)

NOMINAL COMPOSITION	Element									
	Percent									

TEST CONDITIONS

ENVIRONMENT						Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH	Undescaled Weight Change			Descaled Weight Change			
								Rate	Validity	Rate	Validity
14	600	1/60, 30	NA	200	7		Sensitized, sanded	-5	A		
15	600	1/60, 30	NA	200	7		Sensitized, sanded, electropolished	0	A	-5	A
16	600	1/60, 30	NA	200	11	Lithium Hydroxide	Sensitized, sanded, electropolished	-5	A	-5	A

GUIDE TO APPLICATION: General structural material for both internal and pressure containing parts.

MATERIAL	NOMINAL COMPOSITION	Element	C	Cr	Ni	Mn	P	S	Si	Fe
		Percent	0.15	11.5-13.5	0.50	1.0	0.04	0.03	1.0	Bal

Maximum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60, 30	1-5	NA	7-10	Sodium Hydroxide	Hardened	-5	A		
2	600	30	D	NA	8.5		Hardened	-100	C		
3	500	10, 20	D	NA	10	Lithium Hydroxide	Hardened	-10	A		
4	500	10, 20	D	NA	10-10.5	Lithium Hydroxide	Hardened	-10	C		
5	500	10	D	100	7		Hardened	-5	B		
6	500	1/60, 30	D	200-500	7		Hardened	-10	A		

GUIDE TO APPLICATION: Has good bearing characteristics; not used for bearing application because of its susceptibility to crevice corrosion. Shows tendency toward pitting in oxygen bearing water. Subject to stress corrosion in the hardened and stressed condition.

MATERIAL	NOMINAL COMPOSITION	Element	C	Cr	Ni	Mn	P	S	Si	Fe
		Percent	0.15	12-14		1.0	0.04	0.03	1.0	Bal

Maximum

TEST CONDITIONS

ENVIRONMENT						Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH	Undescaled Weight Change			Descaled Weight Change			
					Rate			Validity	Rate	Validity	
1	500	30	0-1	NA	7		Hardened	-15	B		
2	500	1/60	1-5	NA	7		Hardened	-5	A		
3	500	30	1-5	NA	10	Lithium Hydroxide	Hardened	-5	A		
4	500	30	D	NA	7		Hardened	-5	A		

GUIDE TO APPLICATION: Has good bearing characteristics; not used for bearing application because of its susceptibility to crevice corrosion. Shows tendency toward pitting in oxygen bearing water. It is suspected that this material is subject to stress corrosion in the hardened and stressed condition.

MATERIAL	NOMINAL COMPOSITION	Element	C	Cr	Ni	Mn	P	S	Si	Mo	Fe
		Percent	0.95-1.2	16-18		1.0	0.04	0.03	1.0	0.75	Bal

Maximum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temperature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	30	0-1	NA	7		Hardened	-15	B		
2	500	30	0-1	NA	10	Sodium Hydroxide	Hardened	-15	A		
3	500	1/60	1-5	NA	7		Hardened	-10	A		
4	500	30	1-5	NA	7		Hardened	-50	C		
5	500	30	D	NA	7		Hardened	-15	A		
6	500	1/60	D	NA	7		Hardened	-100	C		
7	500	1/60, 30	D	500	7		Hardened	-25	A		

GUIDE TO APPLICATION: Has good bearing characteristics; not used for bearing application because of its susceptibility to crevice corrosion. Shows tendency toward pitting in oxygen bearing water. It is suspected that this material is subject to stress corrosion in the hardened and stressed condition.

MATERIAL
USS 18-8W

NOMINAL COMPOSITION	Element	C	Cr	Ni	Ti	P	S	Si	Al	Mn	Fe
	Percent	0.06	17.6	7.3	0.90	0.16	0.016	0.58	0.17	0.54	Bal

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60, 30	O-1	NA	7		Machined	+5	B		
2	500	1/60, 30	D	NA	7		Machined	-5	A		
3	500	1/60, 30	D	NA	7		Malcomized	-50	B		
4	600	30	D	NA	8.5		Machined	-25	C		
5	500	30	D	25-50	7		Malcomized	-200	C		
6	500	1/60, 30	D	50-200	7		Machined	-10	C		

GUIDE TO APPLICATION: Used in bearings and in those applications requiring special mechanical properties.
Not normally welded for pressure containing parts. Susceptible to stress corrosion
in hardened and stressed condition.

MATERIAL
Armco 17-4 PH (hardened)

NOMINAL COMPOSITION	Element	C [#]	Mn [#]	P [#]	S [#]	Si [#]	Ni	Cb - Ta	Cr	Cu	Fe
	Percent	0.07	1.00	0.04	0.03	1.00	3.0-5.0	.25-.45	15.5	3.0	Bal
	[#] Maximum										

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60, 30	1-5	NA	7		Machined	-5	A	-20	B
2	500	1/60, 30	1-5	NA	7		Pickled	-5	B		
3	500	1/60	D	NA	7		Machined	-5	B		
4	500	1/60	D	NA	7		Pickled	-5	B		
5	500	30	D	NA	7		Machined	-25	B		
6	500	30	D	NA	7		Pickled	-50	B		
7	500	10, 20	D	NA	8.5	Lithium Hydroxide	Machined, chromium plated	-5	A		
8	500	30	D	NA	8.5		Machined	-20	C		
9	500	30	D	NA	8.5		Machined	-15	C		
10	500	10, 20	D	2.0	9.8 10.5	Lithium Hydroxide	Machined	-5	A		
11	500	30	D	5-22	7		Machined	-100	B		
12	500	10, 30	D	NA	10.0- 10.5	Lithium Hydroxide	Machined	-5	B		
13	500	1/60	D	50	7		Machined	-5	B		
14	500	30	D	50	7		Machined	-50	C	-100	C

GUIDE TO APPLICATION: Used in bearings and in those applications requiring special mechanical properties. Not normally welded for pressure containing parts. Susceptible to stress corrosion in hardened and stressed condition.

TABULATION OF BASIC DATA

107

MATERIAL
Armco 17-4 PH (hardened) (continued)

NOMINAL COMPOSITION	Element									
	Percent									

TEST CONDITIONS

ENVIRONMENT						Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH	Undescaled Weight Change			Descaled Weight Change			
					Rate			Validity	Rate	Validity	
15	500	30	D	50	7		Nitrided	-50	C		
16	500	10	D	100	7		Machined	-25	B		
17	500	10	D	100	7		Chromium plated	0	C		
18	500	30	D	100	8-9		Machined	-15	A		
19	500	30	D	200	7		Chromium plated	-5	A		
20	500	30	25	200	7		Machined, chromium plated	-5	A		

GUIDE TO APPLICATION: Used in bearings and in those applications requiring special mechanical properties. Not normally welded for pressure containing parts. Susceptible to stress corrosion in hardened and stressed condition.

MATERIAL
Armco 17-7 PH (hardened)

NOMINAL COMPOSITION	Element	C%	Mn%	P%	S%	Si%	Ni	Cr	Al	Fe
	Percent	0.09	1.00	0.04	0.03	1.00	6.50-7.8	16-18	0.75-1.50	Bal

Maximum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/cm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60	0-5	NA	7		Machined	+5	A	-25	C
2	500	30	0-5	NA	7		Machined	+5	A	-5	A
3	500	1/60, 30	0-5	NA	7		Malcomized	-15	C		
4	500	1/60, 30	D	NA	7		Machined	-5	B		
5	500	1/60, 30	D	0-22	7		Machined, malcomized	-50	B		
6	500	30	D	50	8-9		Malcomized	-100	B		
7	500	1/60	D	100	7		Machined	-5	C		
8	500	30	D	100	7		Machined	-50	B	-100	C
9	600	30	D	NA	8.5		Machined			-50	C

GUIDE TO APPLICATION: Used in bearings and in those applications requiring special mechanical properties. Not normally welded for pressure containing parts. Susceptible to stress corrosion in hardened and stressed condition.

MATERIAL
Carpenter 20

NOMINAL COMPOSITION	Element	C	Cr	Ni	Si	Mo	Cu%	Fe	
	Percent	0.07	20	29	1	2	3	Bal	

Minimum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temperature °F	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60, 30	0-5	NA	7		Machined	-5	B		
2	500	1/60, 30	D	0-50	7		Machined	-5	A		

GUIDE TO APPLICATION: Used in rivet applications where non-work hardening properties are desired.

MATERIAL
Stellite No. 3

NOMINAL COMPOSITION	Element	C	Cr	Ni	Co	Fe	W	Others	
	Percent	2.5	31	3	46	3	13	1	

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/cm ² /mo			
	Temp- erature °F	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60	0-1	NA	7		Machined	-5	C		
2	500	1/60	0-1	NA	7		Machined	-25	C		
3	500	1/60	0-5	NA	7		Machined	-10	A		
4	500	1/60	0-5	NA	10	Sodium Hydroxide	Machined	-25	B		
5	500	30	0-5	NA	7-10	Sodium Hydroxide for pH 10	Machined	-50	B		
6	500	1/60, 30	0	500	7		Machined	-5	A		

GUIDE TO APPLICATION: Used for bearing applications.

MATERIAL
Stellite No. 6

NOMINAL COMPOSITION	Element	C	Cr	Ni	Co	Fe	W	Others	
	Percent	1.25	30	3	56	3	5	1	

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature OF	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	10-30	0-25	0-200	7-10	Sodium Hydroxide for pH 10	Machined	-5	A		

GUIDE TO APPLICATION: Used for bearing applications.

MATERIAL
Stellite No. 19

NOMINAL COMPOSITION	Element	C	Cr	Ni	Co	Fe	W	Others	
	Percent	1.8	31		52	3	10	2	

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60	0-1	NA	7		Machined	-50	C		
2	500	30	0-1	NA	7		Machined	-100	B		
3	500	1/60, 30	0-2	NA	7		Machined	-100	C		
4	500	1/60, 30	D	0-50	7		Machined	-10	B		

GUIDE TO APPLICATION: Used for bearing applications.

MATERIAL
Stellite No. 21

NOMINAL COMPOSITION	Element	C	Cr	Ni	Co	Fe	Mo	W	Others
	Percent	0.2- 0.35	25- 30	1.5- 3.5	Bal	2	4.5- 6.5		

Maximum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature °F	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60, 30	0-1	NA	7		Machined	-10	B		
2	600	1/60, 30	D	NA	8.5		Machined	-25	C		
3	500	1/60, 30	D	5-22	7		Machined	-10	A		
4	500	1/60	NA	25	7		Machined	-50	C		
5	500	30	D	25	7		Machined	-10	B		
6	500	1/60, 30	NA	50	7		Machined	-5	B		

GUIDE TO APPLICATION: Used for bearing applications.

TABULATION OF BASIC DATA

109

MATERIAL
Haynes Alloy No. 25

NOMINAL COMPOSITION	Element	C*	Cr	Ni	W	Si*	Mn	Fe*	Co
	Percent	0.15	19-21	9-11	14-16	1.00	1.0-2.0	2.0	Bal

*Maximum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/cm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60	1-2	NA	7		Machined	+5	C		
2	500	30	1-2	NA	7		Machined	+100	C		
3	500	1/60	NA	100	7		Machined	-10	C		
4	500	30	NA	100	7		Machined	-5	C		

GUIDE TO APPLICATION: Used for bearing application.

MATERIAL
Copper-Nickel (70-30)

NOMINAL COMPOSITION	Element	Cu	Ni	Fe*	Mn*	Zn*	Sn*	Pb*	
	Percent	Bal	29-33	0.6	1	1	1.5	0.05	

*Maximum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60	0-2	NA	7		Machined	+300	C		
2	500	30	0-2	NA	7		Machined	-1000	C		
3	200	30	1-5	NA	7		Machined	-5	A		
4	500	1/60	D	NA	7		Machined	+25	C		
5	500	30	D	NA	7		Machined	-200	C		
6	500	10-20	D	NA	10	Lithium Hydroxide	Machined	-25	B		
7	600	1/30	D	NA	8.5		Machined	-1500	C		
8	500	1/60, 30	D	500	7		Machined	-5	A		

GUIDE TO APPLICATION: Used in applications involving short term intermittent exposure to both primary water and sea water at service temperatures. Intergranular (stress?) cracking has been observed under thermal shock conditions.

MATERIAL
ASTM A 179

NOMINAL COMPOSITION	Element	C	Mn	P*	S*				
	Percent	0.06 - 0.18	0.27 - 0.63	0.048	0.058				

*Maximum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo				
	Temperature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change	Descaled Weight Change			
									Rate	Validity	Rate	Validity
1	600	30	< 0.2	500	11	Lithium Hydroxide,	Cnd, machined, electropolished, pickled, as r'cyd			80	A(28CC)	
2	600	30	< 0.2	20-500	11	Lithium Hydroxide,	Cnd, machined, electropolished, pickled, as r'cyd			70	A(20CC)	
3	600	30	< 0.1	500	11	Lithium Hydroxide,	Cnd, sanded, pickled, machined, as r'cyd			85	A(15CC)	
4	600	30	< 0.1	100	11	Ammonium Hydroxide	Cnd, sanded, electropolished, pickled, annealed			230	B(2CC)	
5	600	30	< 0.1	100	11	Lithium Hydroxide,	Cnd, sanded, pickled, annealed			180	B(2CC)	

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water cooled nuclear reactors.

*Hours of test time follow letter.

MATERIAL
ASTM A 212 GRADE A

NOMINAL COMPOSITION	Element	C	Mn	Si	P	S			
Percent		0.27	0.62	0.26	0.012	0.04			

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity*
1	600	2	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 1-2 ppm	Machined finish			70	A(2500)
2	600	20	<0.10	20	9.5	Ammonia - 1-2 ppm	Machined finish			220	A(2500)
3	600	21	<0.10	70	9	Ammonium Hydroxide, Ammonia - 10 ppm	Machined finish			180	A(2000)
4	600	20	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 1-2 ppm	Machined finish			230	A(2000)
5	600	21	<0.10	70	9	Ammonium Hydroxide Ammonia - 10 ppm	Machined finish (inserted with oxidized specimens)			140	A(1750)
6	500	10-12	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 1-2 cc/l	Machined finished			95	A(1500)
7	600	21	<0.10	30	10	Lithium Hydroxide; Ammonia - 5 ppm	Machined finish			130	A(1500)
8	600	12	<0.10	20	10	Lithium Hydroxide; Ammonia - 5 ppm	Machined finish			140	A(1500)
9	500	12	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 1-2 cc/l	Machined finish (inserted with oxidized specimens)			120	A(1200)
10	500	10	<0.10	20	9.5	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			130	A(1200)
11	500	10	<0.10	20	9.5	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			230	B(1200)
12	600	12	<0.10	20	10	Ammonium Hydroxide	Machined finish			240	B(1200)
13	500	0.5-17	<0.10	20	9.5	Ammonium Hydroxide Ammonia 1-2 ppm, no Ion-X	Machined finish			260	B(1100)
14	500	12	<0.10	20	9.5	Ammonia - 0.2 cc/l	Machined finish			200	B(1000)
15	600	36	<0.10	20	9.5	No Ion-X	Pickled, H. T.**			220	B(1000)

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water cooled nuclear reactors.

*Hours of test time follow letter.
 **Air exposed at 950°F.
 †First 200 hours at 200°F.

MATERIAL
ASTM A 212 GRADE A (continued)

NOMINAL COMPOSITION	Element	C	Mn	Si	P	S			
Percent		0.27	0.62	0.26	0.012	0.04			

TEST CONDITIONS

	ENVIRONMENT					C'ther Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity*
16	500	23	<0.10	20	9.5	Ammonium Hydroxide, Ammonia - 1-2 ppm	Machined finish			320	B(1000)
17	600	36	<0.10	20	9.5	No Ion-X; Ammonia - 1-2 ppm Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			540	C(1000)
18	600	33	<0.10	30	7-9	No Ion-X; Ammonium Hydroxide Ammonia - 1-2 ppm	Exposed to steam at 750°F for 24 and 48 hours			720	C(1000)
19	600	20	<0.10	20	9.5	Ammonia - 1-2 ppm	Machined finish			190	B(750)
20	600	2	<0.10	20	9.5	No Ion-X; Ammonia - 1-2 ppm	Machined, H. T.,** H. T. and pickled, morpholine preconditioning			290	B(750)
21	2-600	20	<0.10	20	9.5	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			290†	B(750)
22	600	20	<0.1	20	9.5	No Ion-X; Ammonia 1-2 ppm	Machined finish; morpholine preconditioning			380	C(750)
23	600	20-36	<0.10	20	9.5	No Ion-X; Ammonia 1-2 ppm Ammonium Hydroxide	Machined, H. T.,** H. T., and pickled, morpholine preconditioning			430	C(750)
24	500	21	<0.10	10	10	Lithium Hydroxide	Machined finish			210	C(500)
25	600	21	<0.10	30	10	Lithium Hydroxide	Machined, H. T.,** H. T. and pickled, morpholine preconditioning			290	C(500)
26	600	3	<0.1	20	7	No Ion-X; Ammonia - 1-2 ppm, Ammonium Hydroxide	Steam pretreated 15 hours at 700°F			345	C(500)
27	600	2.5	<0.1	20	7	No Ion-X; Ammonium Hydroxide, Ammonia 1-2 ppm	Heated in air at 800°F for 25 hours			360	C(500)
28	600	20-25	<0.10	20	7	No Ion-X; Ammonium Hydroxide, Ammonia 1-2 ppm	Heated in air at 600°F, Steam pretreated 15 hours			400	C(500)
29	600	15	<0.10	20	7	No Ion-X; Ammonia - 1-2ppm	Machined finish			430	C(500)
30	600	15	<0.10	20	7	No Ion-X; Ammonia - 1-2ppm	Steam pretreated for 15 hours - 700 Heated in air at 800°F for 25 hours			500	C(500)

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water cooled nuclear reactors.

*Hours of test time follow letter.
 **Air exposed at 950°F.
 †First 200 hours at 200°F.

TABULATION OF BASIC DATA

111

MATERIAL	ASTM A 212 GRADE A (continued)	NOMINAL COMPOSITION	Element	C	Mn	Si	P	S			
			Percent	0.27	0.62	0.26	0.012	0.04			

TEST CONDITIONS

ENVIRONMENT						Other Additive	Condition of Specimen	Corrosion Rate - mg/in ² /mo			
Temperature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH	Underscaled Weight Change			Descaled Weight Change			
					Rate			Validity	Rate	Validity	
31	600	15	<0.10	20	7	No Ion-X; Ammonia - 1-2 ppm	Machined finish, H. T.**			540	C(500)
32	600	15	<0.10	20	7	No Ion-X; Ammonium Hydroxide, Ammonia - 1-2 ppm	Steam pretreated 6 hours at 700°F			570	C(500)
33	600	15	<0.10	20	7	No Ion-X; Ammonia - 1-2 ppm	Heated in air at 600°F for 25 hours			580	C(500)
34	600	21	<0.10	20	10	Lithium Hydroxide,	Machined finish			180	C(200)

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water

*Hours of test time follow letter.

**Air exposed at 950°F.

Ø First 200 hours at 200°F.

cooled nuclear reactors.

MATERIAL	ASTM A 212 GRADE B	NOMINAL COMPOSITION	Element	C	Mn	Si	P	S			
			Percent	0.35	0.90	0.15 - 0.30	0.04	0.04			

*Maximum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/cm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Underscaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	600	30	<0.1	D	11	Lithium Hydroxide,	Sanded, electropolished, pickled, and machined			30	A(4000)
2	600	30	<0.3	500	11	Lithium Hydroxide,	Gnd, machined, electropolished, pickled, as rec'd			80**	A(2800)
3	600	30	<0.1	500	11	Lithium Hydroxide,	Sanded, electropolished, pickled			35	A(2000)
4	600	30	<0.1	D	11	Lithium Hydroxide,	Sanded, electropolished, pickled			45	A(2000)
5	600	30	<0.3	20	11	Lithium Hydroxide,	Gnd, machined, electropolished pickled, as rec'd			70**	A(2000)
6	540	30	<0.3	Equil	7-10	Lithium Hydroxide	Machined finish			320†	A(2000)
7	600	30	<0.2	20	7-10	Ammonium Hydroxide, Ammonia = 1-2 ppm	Sanded, electropolished, pickled			360	A(2000)
8	600	30	<0.1	20	9	Ammonium Hydroxide,	Sanded, electropolished, pickled			230	A(1900)
9	600	30	<0.2	500	11	Ammonium Hydroxide, Ammonia = 100 ppm	Gnd, machined, sanded, pickled, as rec'd			70	A(1500)
10	600	30	<0.2	500	11	Lithium Hydroxide,	Gnd, sanded, pickled, machined, as rec'd			85	A(1500)
11	500	30	<0.01	500	11	Ammonium Hydroxide, Lithium Hydroxide,	Sanded, grounded			150	B(1000)
12	600	30	<0.1	D	11	Lithium Hydroxide,	Sanded, electropolished, pickled, machined			180	B(1000)
13	600	30	<0.14	20	7-10	Ammonium Hydroxide, Ammonia = 1-2 ppm	Sanded, electropolished, pickled			430	B(1000)
14	600	30	<0.1	40	7	Pickled	Pickled			720	B(1000)
15	600	30	<0.2	100	11	Lithium Hydroxide,	Gnd, sanded electropolished, pickled, sanded			180	B(800)

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water

*Hours of test time follow letter.

**Frequent shutdowns.

† Heavy reddish scale.

Ø Effects of high pH did not persist.

cooled nuclear reactors.

MATERIAL
ASTM A 212 GRADE B

NOMINAL COMPOSITION	Element	C ^a	Mn ^a	Si	P ^a	S ^a			
	Percent	0.35	0.90	0.15-0.30	0.04	0.04			

^aMaximum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temperature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
16	600	30	<0.2	20	11		Grd. solution annealed, electro- polished, pickled, annealed			230	B(800)
17	540	30	<0.3	Equil.	7	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			610	C(650)
18	500	30	<0.1	500	7	(500 hours)	Sanded, ground			270	C(500)
19	500	30	<0.01	20	7		Surface ground			430	C(500)
20	2-600	30	~100	Low	7-9	Ammonium Hydroxide, Ammonia - 10 ppm	Sanded, electropolished, pickled			85†	B(500)
21	500	30	<0.01	D	11	Ammonium Hydroxide	Sanded and ground			190	C(500)
22	600	30	~100	Low	7-9	Ammonium Hydroxide, Ammonia - 10 ppm	Sanded, electropolished, pickled			210†	B(500)

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water cooled nuclear reactors.

^aHours of test time follow letter.

**Frequent shutdowns.

[†]Heavy reddish scale.[‡]Effects of high pH did not persist.

MATERIAL
ASTM A 302

NOMINAL COMPOSITION	Element	C	Mn	P	S	Si	Mo		
	Percent	0.12	0.10	0.012	0.027	0.24	0.45		

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	600	2	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 1-2 ppm	Machined finish			72	A(2500)
2	600	20	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 1-2 ppm	Machined finish			220†	A(2500)
3	500	0.5-17	<0.10	20	9.5	Ammonium Hydroxide No 100-X	Machined finish			260	B(1100)
4	600	33	<0.10	30	7.9	Ammonium Hydroxide, Ammonia 1-2 ppm; No 100-X	Exposed to steam at 750°F for 25 hrs			360	B(1000)
5	600	20	<0.10	20	9.5	Ammonium Hydroxide	Machined finish			280†	B(750)
6	500	21	<0.10	10	10	Lithium Hydroxide	Machined finish**			210	C(500)
7	600	21	<0.10	20	10	Lithium Hydroxide	Machined finish			180	C(200)

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water cooled nuclear reactors.

^aHours of test time follow letter.

**10H pre-treatment for first 500 hours.

[†]In loop with other SFR materials.[‡]First 200 hours at 200.

MATERIAL
Croloy 1-1/4

NOMINAL COMPOSITION	Element	C	Mn	S	P	Si	Cr	Mo	Fe
	Percent ^a	0.15	0.3-0.6	0.03	0.03	0.5-1.0	1.0-1.5	0.45-0.65	Bal

^aMaximum percentage shown unless range is given.

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/in ² /mo			
	Temperature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	600	30	200-1000	NA	9-10	Ammonium Hydroxide (2 ppm)	Pickled, sanded			-50	C
2	600	30	200-1000	NA	9-10	Ammonium Hydroxide (2 ppm)	Electropolished			-25	A
3	600	30	D	NA	11	Lithium Hydroxide	Ground			-200	C
4	600	30	D	NA	11	Lithium Hydroxide	Electropolished			-100	C
5	600	30	D	NA	10.5	Potassium Orthophosphate	Pickled, sanded, electropolished			-100	C
6	600	20	D	100	7		Machined	-100	C	-200	C
7	600	30	D	500	11	Lithium Hydroxide	Pickled, sanded, electropolished			-25	A
8	600	30	D	500	11	Ammonium Hydroxide	Ground			-200	C

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water cooled nuclear reactors.

TABULATION OF BASIC DATA

113

MATERIAL
Croloy 2-1/4

NOMINAL COMPOSITION	Element	C*	Mn	S*	P*	Si*	Cr	Mo	Fe
Percent		0.15	0.3-0.6	0.03	0.03	0.5	2.0-2.5	0.9-1.1	Bal

*Maximum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature °F	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	600	30	D	NA	11	Lithium Hydroxide	Electropolished, shaped			-15	A
2	600	30	D	NA	11	Lithium Hydroxide	Surface ground			-25	A
3	450	30	D	13-33	11	Lithium Hydroxide	Surface ground			-120	C
4	600	30	D	20	11	Lithium Hydroxide	Electropolished			-150	C
5	600	30	D	20	11	Lithium Hydroxide	Surface ground, shaped			-200	C
6	600	30	D	500	11	Lithium Hydroxide	Shaped			-50	B

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water cooled nuclear reactors.

MATERIAL
LOW MANGANESE CARBON STEEL NO. 1

NOMINAL COMPOSITION	Element	C	Mn	P	S	Si	Ti		
Percent		0.22	0.08	0.008	0.017	0.19	0.16		

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature °F	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	600	21	<0.10	70	9	Ammonium Hydroxide, Ammonia - 10 ppm	Machined finish			180	A(2000)
2	600	21	<0.10	70	9	Ammonium Hydroxide, Ammonia - 0.2 cc/l	Machined finish (inserted with oxidized specimens)			140	A(1750)
3	500	10-12	<0.10	20	9.5	Ammonium Hydroxide, Ammonia - 0.2 cc/l	Machined finish			120	A(1200)
4	600	12	<0.10	20	10	Lithium Hydroxide	Machined finish			140	A(1500)
5	500	12	<0.10	20	9.5	Ammonium Hydroxide, Ammonia - .2 cc/l	Machined finish			120	A(1200)
6	500	10	<0.10	20	9.5	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			140	A(1500)
7	500	10	<0.10	20	9.5	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			230	B(1200)
8	600	12	<0.10	20	10	Lithium Hydroxide	Machined finish (inserted with oxidized specimens)			240	B(1200)
9	500	0.5-17	<0.10	20	9.5	No Ion-X, Ammonia - 1-2 ppm	Machined finish			260	B(1100)
10	500	12	<0.10	20	9.5	Ammonium Hydroxide, Ammonia - .2 cc/l	Machined finish			200	B(1000)
11	500	23	<0.10	20	9.5	Ammonium Hydroxide	Machined finish			320	B(1000)
12	600	33	<0.10	20	7-9	No Ion-X, Ammonia - 1-2 ppm	Machined finish - steam pretreated 700°F for 25 hrs.			430	B(1000)
13	600	20	<0.10	20	9.5	Ammonia - 1-2 ppm	Machined finish			190	B(750)
14	600	20	<0.10	20	9.5	Ammonium Hydroxide, Ammonia - 1-2 ppm	Machined finish			280**	B(750)

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water cooled nuclear reactors.

*Hours of test time follow letter.
**First 200 hours at 200°F.

MATERIAL
LOW MANGANESE CARBON STEEL NO. 2

NOMINAL COMPOSITION	Element	C	Mn	P	S	Si	Ti		
Percent		0.19	0.08	0.010	0.019	0.19	0.17		

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	600	2	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 1.2 ppm	Machined finish			70	A(2500)
2	600	20	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 1.2 ppm	Machined finish			220	A(2500)
3	500-600	20	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 1.2 ppm	Machined finish (inserted with oxidized specimens)			230	A(2000)
4	500	10-12	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 2 cc/l	Machined finish			95	A(1500)
5	600	21	<0.10	10	10	Lithium Hydroxide, Ammonia - 5 ppm	Machined finish			130	A(1500)
6	600	12	<0.10	20	11	Lithium Hydroxide	Machined finish			140	A(1500)
7	500	20	<0.10	20	10	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			230	B(1200)
8	500	12	<0.10	20	9.5	Ammonium Hydroxide	Machined finish			120	A(1200)
9	500	10-21	<0.10	20-30	9.5	Ammonium Hydroxide Ammonia - 5 ppm**	Machined finish (inserted with oxidized specimens)			130	A(1200)
10	600	12	<0.10	20	11	Ammonium Hydroxide Lithium Hydroxide	Machined finish (inserted with oxidized specimens)			240	B(1200)
11	500	12	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 2 cc/l	Machined finish			200	B(1000)
12	600	21	<0.10	30	10	Lithium Hydroxide, Ammonia - 5 ppm	Machined finish (inserted with oxidized specimens)			290	C(1500)

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water cooled nuclear reactors.

*Hours of test time follow letter.
**Lithium hydroxide also added.

MATERIAL
REFERENCE CARBON STEEL

NOMINAL COMPOSITION	Element	C	Mn	P	S	Si			
Percent		0.04	0.41	0.009	0.036	0.01			

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity*
1	600	30	<0.1	D	11	Lithium Hydroxide,	Sanded, electropolished, pickled, machined			30	A(2000)
2	600	30	<0.3	500	11	Lithium Hydroxide,	Grd, machined, electropolished, pickled, as r/cvd			80*	A(2800)
3	600	30	<0.01	500	11	Lithium Hydroxide,	Sanded, electropolished, pickled, machined			35	A(2000)
4	600	30	<0.3	20	11	Lithium Hydroxide,	Grd, machined, electropolished, pickled, as r/cvd			70**	A(2000)
5	600	30	<0.2	20	7-10	Ammonium Hydroxide, Ammonia - 1.2 ppm	Sanded, electropolished, pickled			350	A(2000)
6	600	30	<0.2	500	11	Ammonium Hydroxide, Ammonia - 100 ppm	Grd, sanded, pickled, machined, as r/cvd			70	A(1500)
7	600	30	<0.2	500	11	Lithium Hydroxide,	Grd, sanded, pickled, machined, as r/cvd			85	A(1500)
8	600	12	<0.1	20	10	Lithium Hydroxide	Machined finish			140	A(1500)
9	600	12	<0.10	20	10		Machined finish (inserted with oxidized specimens)			250	B(1200)
10	600	30	<0.1	E	11	Lithium Hydroxide	Sanded, electropolished, pickled, machined			180	B(1000)
11	600	30	<0.2	20	7-10	Ammonium Hydroxide,	Sanded, electropolished, pickled			450	B(1000)
12	600	30	<0.1	40	7		Pickled			700	B(1000)
13	200-600	30	~400	Low	7-9	Ammonium Hydroxide, Ammonia - 10 ppm	Sanded, electropolished, pickled			85†	C(500)
14	200-600	30	~400	Low	7-9	Ammonium Hydroxide, Ammonia - 20 ppm	Sanded, electropolished, pickled			200†	B(500)

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water cooled nuclear reactors.

*Hours of test time follow letter.
**Frequent shutdowns.
†Heavy reddish scale.

TABULATION OF BASIC DATA

115

MATERIAL
SPECIAL CARBON STEEL NO. 3

NOMINAL COMPOSITION	Element	C	Mn	P	S	Si	Al	Ti	
Percent		0.25	0.14	0.012	0.015	0.17	0.10	0.46	

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/in ² /mo			
	Temp- erature °F	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	600	2	<0.10	20	9.5	Ammonium Hydroxide Ammonia = 1-2 ppm	Machined finish			70	A(2500)
2	600	20	<0.10	20	9.5	Ammonium Hydroxide Ammonia = 1-2 ppm	Machined finish			220	A(2500)
3	600	21	<0.10	70	9	Ammonium Hydroxide, Ammonia = 10 ppm	Machined finish (inserted with oxidized specimens)			180	A(2000)
4	600	21	<0.10	70	9	Ammonium Hydroxide	Machined finish			140	A(1750)
5	500	10-12	<0.10	20	9.5	Ammonium Hydroxide Ammonia = .2 cc/l	Machined finish			95	A(1500)
6	600	12	<0.10	20	10		Machined finish			140	A(1500)
7	500	12	<0.10	20	9.5	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			120	A(1200)
8	500	10	<0.10	20	9.5	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			130	A(1200)
9	500	10	<0.10	20	9.5	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			230	A(1200)
10	600	12	<0.10	20	10	Lithium Hydroxide	Machined finish (inserted with oxidized specimens)			240	A(1200)
11	500	12	<0.10	20	9.5	Ammonium Hydroxide Ammonia = 2 cc/l	Machined finish			200	B(1000)

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water cooled nuclear reactors.

*Hours of test time follow letter.

MATERIAL
SPECIAL CARBON STEEL NO. 4

NOMINAL COMPOSITION	Element	C	Mn	P	S	Si	Cu	Ti	
Percent		0.11	0.17	0.009	0.017	0.10	0.39	0.38	

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temperature °F	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	600	2	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 1-2 ppm	Machined finish			65	A(2750)
2	600	20	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 1-2 ppm	Machined finish			220	A(2500)
3	600	20	<0.10	20	9.5	Ammonium Hydroxide	Machined finish			230	A(2000)
4	500	10-12	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 2 cc/l	Machined finish			95	A(1500)
5	500	10	<0.10	20	10	Ammonium Hydroxide Lithium Hydroxide**	Machined finish (inserted with oxidized specimens)			130	A(1500)
6	500	12	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 2 cc/l	Machined finish			120	B(1200)
7	500	10	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 2 cc/l	Machined finish (inserted with oxidized specimens)			130	B(1200)
8	500	10-20	<0.10	20	9.5	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens) Ammonia 1-2ppm			230	B(1200)
9	600	12	<0.10	20	11	Ammonium Hydroxide Lithium Hydroxide	Machined finish (inserted with oxidized specimens)			240	B(1200)
10	500	12	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 2 cc/l	Machined finish			200	B(1000)
11	600	20	<0.10	20	10	Lithium Hydroxide Ammonia - 5 ppm	Machined finish			290	C(500)

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water cooled nuclear reactors.

*Hours of test time follow letter.
**Ammonia - 5 ppm also added.

MATERIAL
SPECIAL CARBON STEEL NO. 5

NOMINAL COMPOSITION	Element	C	Mn	P	S	Si	Cu	Ti	
Percent		0.07	0.15	0.004	0.016	0.06	0.39	0.47	

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature °F	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	600	12	<0.10	20	11	Ammonium Hydroxide	Machined finish			140	A(1500)
2	600	12	<0.10	20	11	Ammonium Hydroxide	Machined finish (inserted with			240	A(1200)

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water cooled nuclear reactors.

*Hours of test time follow letter.

MATERIAL
SPECIAL CARBON STEEL NO. 6

NOMINAL COMPOSITION	Element	C	Mn	P	S	Si	Cu	Zr	
	Percent	0.06	0.08	0.008	0.015	0.09	0.40	0.31	

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature OF	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity*
1	600	2	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 1-2 ppm	Machined finish			65	A(2750)
2	600	20	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 1-2 ppm	Machined finish			220	B(2500)
3	500-600	10-20	<0.10	20	9.5	Ammonium Hydroxide Ammonia - 1-2 ppm	Machined finish (inserted with oxidized specimens)			230	B(2000)
4	500	10-12	<0.10	20	9.5	Ammonium Hydroxide Ammonia - .2 cc/l	Machined finish			95	A(1500)
5	500-600	10	<0.10	20	9.5	Ion-X; Ammonium Hydroxide Lithium Hydroxide	Machined finish (inserted with oxidized specimens)			130	A(1500)
6	600	12	<0.10	20	11	Lithium Hydroxide	Machined finish			140	A(1500)
7	500	12	<0.10	20	9.5	Ammonium Hydroxide Ammonia - .2 cc/l	Machined finish			120	B(1200)
8	500	10	<0.10	20	9.5	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			130	A(1200)
9	500	10	<0.10	20	9.5	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			230	B(1200)
10	600	12	<0.10	20	11	Lithium Hydroxide	Machined finish (inserted with oxidized specimens)			240	B(1200)
11	500	12	<0.10	20	9.5	Ammonium Hydroxide Ammonia - .2 cc/l	Machined finish			200	B(1000)
12	600	21	<0.10	21	10	Lithium Hydroxide, Ammonia - 5 ppm	Machined finish (inserted with oxidized specimens)			290	C(500)

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water cooled nuclear reactors.

*Hours of test time follow letter.

MATERIAL
SPECIAL CARBON STEEL NO. 8

NOMINAL COMPOSITION	Element	C	Mn	P	S	Si	Cu	Va	
	Percent	0.13	1.20	0.008	0.022	0.06	0.33	0.06	

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity*
1	500	10-12	<0.10	20	9.5	Ammonium Hydroxide	Machined finish			95	A(1500)
2	500	12	<0.10	20	9.5	Ammonium Hydroxide Ammonia - .2 cc/l	Machined finish			120	A(1200)
3	500	10	<0.10	20	9.5	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			130	A(1200)
4	600	12	<0.10	20	11	Lithium Hydroxide	Machined finish			140	A(1500)
5	500	10	<0.10	20	9.5	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			230	A(1200)
6	600	12	<0.10	20	11	Lithium Hydroxide	Machined finish (inserted with oxidized specimens)			240	A(1200)
7	500	12	<0.10	20	9.5	Ammonium Hydroxide	Machined finish			200	B(1000)

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water cooled nuclear reactors.

*Hours of test time follow letter.

MATERIAL
SPECIAL CARBON STEEL NO. 9

NOMINAL COMPOSITION	Element	C%	Mn%	P%	S%	Si%	Ti		
	Percent	0.09	0.50	0.04	0.05	0.10	0.20-0.50		
	Maximum								

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temperature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	10-12	<0.10	20	9.5	Ammonium Hydroxide Ammonia - .2 cc/l	Machined finish			95	A(1500)
2	500	12	<0.10	20	9.5	Ammonium Hydroxide Ammonia - .2 cc/l	Machined finish (inserted with oxidized specimens)			120	B(1200)
3	500	10	<0.10	20	9.5	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			130	B(1200)
4	500	10	<0.10	20	9.5	Ammonium Hydroxide	Machined finish (inserted with oxidized specimens)			230	B(1200)
5	500	12	<0.10	20	9.5	Ammonium Hydroxide	Machined finish			200	B(1000)

GUIDE TO APPLICATION: Currently being investigated as a possible substitute for stainless steel in future water cooled nuclear reactors.

*Hours of test time follow letter.

TABULATION OF BASIC DATA

117

MATERIAL
A-Nickel

NOMINAL COMPOSITION	Element	C	Mn	S	Si	Cu	Fe	Ni	
	Percent	0.1	0.2	0.005	0.05	0.1	0.15	99.4	

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	30	0-1	NA	7		Machined	-5	B		
2	500	30	0-2	NA	7		Machined	-15	C		
3	500	30	0-2	NA	10	Sodium Hydroxide	Machined	+5	C		
4	500	30	0-5	NA	7		Machined	+5	B		

GUIDE TO APPLICATION: Miscellaneous material investigated. Susceptible to pitting in crevices in oxygen bearing water.

MATERIAL
Inconel

NOMINAL COMPOSITION	Element	C	Cr	Ni	Fe	Mn	Cu		
	Percent	0.15	11-17	72	6-10	1.00	0.50		

Maximum
Minimum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/cm ² /mo			
	Temp- erature °F	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60	0-1	NA	7		Machined	-5	A	-10	A
2	500	30	0-1	NA	7		Machined	-50	A	-100	B
3	500	1/60, 30	1-5	NA	7-10	Lithium Hydroxide	Machined	-5	A		
4	500	1/60, 30	D	NA	7		Machined	-5	A		
5	500	30	D	NA	10	Lithium Hydroxide	Machined	-5	A		
6	600	30	D	NA	8.5		Machined	-100	C		
7	500	1/60, 30	D	25-100	7		Machined	-5	A	-5	A
8	500	30	25	200	7		Sanded	-5	A		

GUIDE TO APPLICATION: Used as spring material in applications less than 200°F. Above this temperature intergranular attack may occur. Exact conditions which produce attack are not known, although it is thought to be due to a chromium carbide precipitate at the grain boundaries. Susceptible to pitting in crevices in oxygen bearing water.

MATERIAL
Inconel - X

NOMINAL COMPOSITION	Element	Ti	Cr	Ni	Fe				
	Percent	2.25-2.75	14-16	70	Bal				

Minimum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/cm ² /mo				
	Temp- erature °F	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change	Descaled Weight Change			
									Rate	Validity	Rate	Validity
1	500	1/60	0-1	NA	7		Machined	-10	C			
2	500	30	0-1	NA	7		Machined	-50	B			
3	500	1/60, 30	D	5-16	7-10	Lithium hydroxide for high pH	Machined	-5	A			
4	500	1/60, 20	D	50	7		Machined	-5	A			
5	500	30	25	200	7		Machined	-5	A			

GUIDE TO APPLICATION: Used as a spring material. Not subject to the limitation of Inconel. Susceptible to pitting on crevices in oxygen bearing water.

MATERIAL
Monel

NOMINAL COMPOSITION	Element	C	Ni	Mn	S	Si	Cu	Fe	
	Percent	0.1	67	0.15	0.01	0.1	30	1.4	

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature °F	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60, 30	0-5	NA	7			-50	A		
2	500	1/60	0-5	NA	10	Sodium Hydroxide		-5	A		
3	500	30	0-5	NA	10	Sodium Hydroxide		-15	B		
4	500	10	D	100	8.0-8.7			-15	C		

GUIDE TO APPLICATION: Used in applications involving continuous exposure to primary water containing small amounts of sea water due to back leakage in valves. Pitting in crevices in oxygen bearing water.

MATERIAL
K-Monel

NOMINAL COMPOSITION	Element	C	Ni	Mn	S	Si	Cu	Fe	Al
	Percent	0.15	66	0.75	0.005	0.5	29	0.9	2.75

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature °F	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60	0-1	NA	7		Machined	-50	B		
2	500	30	0-1	NA	7		Machined	-100	C		
3	500	30	0-1	NA	7		Aged	-200	C		
4	500	1/60	0-5	NA	7		Aged	-25	C		
5	500	1/60	0-5	NA	10	Sodium Hydroxide	Aged, machined	-5	A		
6	500	1/60	0-5	NA	7-10	Sodium Hydroxide for pH 10	Annealed	-5	A		
7	500	30	0-5	NA	7		Machined	-50	C		
8	500	30	0-5	NA	10	Sodium Hydroxide	Machined	-5	B		
9	500	30	0-5	NA	10	Sodium Hydroxide	Aged	-50	B		
10	500	30	25	200	7		Machined	+5	A		
11	500	1/60, 30	D	500	7		Machined	-5	B		

GUIDE TO APPLICATION: Used in applications involving continuous exposure to primary water containing small amounts of sea water due to back leakage in valves. Pitting in crevices in oxygen bearing water.

MATERIAL
Hafnium

NOMINAL COMPOSITION	Element	Zr%	N%	Ti%	Al%	Cu%	W%	Q%	Fe	Hf
	Percent	1.0	0.007	0.007	0.01	0.05	0.05	0.10	0.05-0.01	Bal

Maximum

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temperature °F	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	10	1.0	NA	10	Lithium Hydroxide	Pickled	0	B		
2	500	10	D	NA	10	Lithium Hydroxide	Pickled	-5	A		
3	500	20	30	100	7		Machined	-5	A		
4	500	20	30	100	7		Machined	0	A		
5	500	30	D	200	7		Machined	-5	A		

GUIDE TO APPLICATION: Used in applications requiring special nuclear properties in addition to superior corrosion resistance.

TABULATION OF BASIC DATA

119

MATERIAL Hard Chromium Plating	NOMINAL COMPOSITION	Element									
		Percent									

TEST CONDITIONS

	Temp- erature of	ENVIRONMENT				Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
		Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	10, 20	0	NA	10-11	Lithium Hydroxide	As plated	-5	B		
2	500	1	0.25	NA	10-11	Lithium Hydroxide	As plated	-48*	B		
3	500	2	0.25	NA	10-11	Lithium Hydroxide	As plated	-60*	B		
4	500	10	0.25	NA	10-11	Lithium Hydroxide	As plated	-84*	B		
5	500	20	0.25	NA	10-11	Lithium Hydroxide	As plated	-75*	B		
6	500	1, 2, 20	0.50	NA	10-11	Lithium Hydroxide	As plated	-90*	B		
7	500	1, 2	1.00	NA	10-11	Lithium Hydroxide	As plated	-400	B		
8	500	30	D	100	7		As plated	-5	A		

*Actual observed corrosion rates given in order to demonstrate the effect of oxygen concentration in a high pH environment and also to demonstrate the velocity effect observed at 0.25 ccO₂/ at pH 11.

GUIDE TO APPLICATION: Considered satisfactory as a bearing material. Presently, it is not normally used because of its sensitivity to environmental changes. Hard chromium plating was used extensively in the first water cooled nuclear reactor and its prototype.

MATERIAL Titanium	NOMINAL COMPOSITION	Element	C*	N*	Ti ϕ						
		Percent	0.20	0.10	99.2						

TEST CONDITIONS

	Temp- erature of	ENVIRONMENT				Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
		Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	20	D	100	8.5		Machined	-5	B		

GUIDE TO APPLICATION: Miscellaneous material investigated.

MATERIAL Zircaloy -2	NOMINAL COMPOSITION	Element	Sn	Fe	Cr	Ni	N*	Zr			
		Percent	1.2- 1.7	0.07- 0.20	0.05- 0.15	0.03- 0.08	0.01	Bal			

*Maximum

TEST CONDITIONS

	Temp- erature of	ENVIRONMENT				Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
		Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	10-20	1.0	NA	10	Lithium Hydroxide	Pickled	+10	B		
2	500	10-20	D	NA	10	Lithium Hydroxide	Pickled	+5	A		
3	500	1-2	D	NA	10.5	Lithium Hydroxide	Pickled	+10	B		
4	500	10-20	D	100	8.5		Pickled	+5	A		

GUIDE TO APPLICATION: Used in applications requiring special nuclear properties in addition to superior corrosion resistance.

MATERIAL
Zirconium Crystal Bar

NOMINAL COMPOSITION	Element	Fe [#]	C [#]	Al [#]	Ti [#]	N [#]	Mg [#]	Zr	
	Percent	0.06	0.04	0.01	0.008	0.005	0.002	Bal	

[#]Maximum

TEST CONDITIONS

	ENVIRONMENT					Cther Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo				
	Temper- ature of	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change	Descaled Weight Change			
									Rate	Validity	Rate	Validity
1	500	10	1.0	NA	10	Lithium Hydroxide	Pickled	+10	B			
2	500	1/30	2.0	NA	7		Machined	+10	B			
3	500	10	D	NA	10	Lithium Hydroxide	Pickled	+5	A			
4	500	10	D	100	8.5		Pickled	+5	A			
5	500	20	D	100	8.5		Pickled	-5	A			

GUIDE TO APPLICATION: Used in applications requiring special nuclear properties in addition to superior corrosion resistance.

MATERIAL
Special Alloy 15 Pd, 30 Cd, 55 Ag

NOMINAL COMPOSITION	Element	Pd	Cd	Ag					
	Percent	15	30	55					

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/dm ² /mo			
	Temp- erature °F	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60	0-1	NA	7		Machined	-400	C		
2	500	30	0-1	NA	7		Machined	-3000	C		
3	500	1/60	2.0	NA	7		Machined	-2000	C		
4	500	30	2.0	NA	7		Machined	-10,000	C		
5	500	1/60, 30	D	NA	7		Machined	+50	C		
6	500	1/60	D	500	7		Machined	+50	C		
7	500	30	D	500	7		Machined	-10	C		

GUIDE TO APPLICATION: Miscellaneous material investigated.

MATERIAL
Special Alloy 20 Pd, 30 Cd, 50 Ag

NOMINAL COMPOSITION	Element	Pd	Cd	Ag					
	Percent	20	30	50					

TEST CONDITIONS

	ENVIRONMENT					Other Additive	Condition of Specimen	Corrosion Rate - mg/cm ² /mo			
	Temp- erature °F	Velocity f.p.s.	Oxygen cc/kg	Hydrogen cc/kg	pH			Undescaled Weight Change		Descaled Weight Change	
								Rate	Validity	Rate	Validity
1	500	1/60	0-1	NA	7		Machined	-50	C		
2	500	30	0-1	NA	7		Machined	-2000	C		
3	500	1/60	0-2	NA	7		Machined	-2000	C		
4	500	30	0-2	NA	7		Machined	-7000	C		
5	500	1/60, 30	D	NA	7		Machined	+40	C		
6	500	1/60	D	500	7		Machined	+10	C		
7	500	30	D	500	7		Machined	+5	C		

GUIDE TO APPLICATION: Miscellaneous material investigated.

FOREWORD TO TABLE 7-3—WEAR TEST DATA*Test Conditions*

Wear factors were determined by means of two different wear test units. One unit, referred to as the piston-cylinder test rig, produces wear by means of linear reciprocating motion. The other unit, referred to as the journal-sleeve test rig, produces wear by means of rotational movement. The majority of the tests were conducted in oxygenated water containing 10 to 30 cc of oxygen (STP) per kilogram of water. The hydrogen content for wear tests in hydrogenated water varied from 200 to 500 cc (STP) per kilogram of water. For both environments initial electrical resistivity of the water was 500,000 ohm-cm or greater. Tests were normally run for 500,000 cycles. Details of the test procedures are given in chapter 5 on testing procedures.

Interpretation of Wear Factors

Wear factors for both tests were determined by measuring the weight loss per pound load per million cycles.

Most of the material combinations considered suitable for service application possessed a wear factor less than 100 mg per pound load per million cycles.

Special Notes

- (1) The martensitic stainless steels were tested in the hardened condition. For the precipitation-hardening alloys the symbol PH designates the hardened condition, and SA indicates the solution annealed condition. Ceramics, cermets, and various miscellaneous materials were tested in the as-received condition. The remaining metals and alloys were tested in the solution annealed condition. All references to chromium plating are to plating applied by an approved supplier. (See ch. 13.)
- (2) The surface finish of untested samples ranged from 8 to 16 microinch (rms).
- (3) The bearing combinations are arranged so that the entry in the "materials" column is the moving element of the wear couple unless otherwise indicated. The combinations are listed in order of increasing wear. A complete cross index of all couples can be found in the general index.

WEAR TEST DATA

Materials*	Versus	Type of Test		Additives		Temp. °F	Load (psi)	Wear Factor φ
		Piston & Cylinder	Journal & Sleeve	Hydro- gen	Oxy- gen			
AISI 304 SS or 347 SS	RT-SN Ag Brazing Alloy ***		x		x	500	10	92
**	Chromium, As Plated (.0005")	x			x	500	8	150
**	Stellite No. 6	x			x	500	8	170
	Haynes 25 (Cold Worked)	x			x	500	8	210
	Haynes No. 21 (SA)	x			x	500	8	240
	Lead	x			x	200	8	270
	S-Monel	x			x	500	8	400
	USS 18-8 W (PH)	x			x	500	8	1040
	Lead		x		x	500	10	2790
	AISI 304SS	x			x	500	8	3200
	17-4 PH (SA)	x			x	500	8	10 ⁵
	S-Monel		x		x	500	10	seized
	BT Ag Brazing Alloy ***		x		x	500	10	4
	RT-SN Ag Brazing Alloy ***		x		x	500	10	4
	Lead		x		x	500	10	4
AISI 410 SS	Stellite No. 3	x			x	500	8	16
	Stellite No. 3		x		x	500	10	140
	Stellite No. 6		x		x	500	10	145
	AISI 410 SS		x		x	200	10	290
	AISI 410 SS		x		x	500	10	380
	AISI 410 SS		x	x		500	10	145
**	Graphitar 14 (1)							

● Entry in this column is moving element of the wear couple

unless otherwise indicated.

** Employed in service

(1) No valid wear factor; however, this combination was successfully utilized.

φ Wear Factor - Milligrams per pound load per million cycles

*** Handy & Harman

WEAR TEST DATA

Materials*	Versus	Type of Test		Additives		Temp. °F	Load (psi)	Wear Factor ϕ
		Piston & Cylinder	Journal & Sleeve	Hydro- gen	Oxy- gen			
AISI 416 SS	AISI 416 SS	x			x	500	8	165
	AISI 416 SS		x	x		500	10	49
AISI 420 SS	AISI 420 SS	x			x	500	8	130
	AISI 420 SS		x		x	500	10	185
AISI 440C SS	Honed Chromium Plate (0.005") on Armco 17-4 PH		x		x	500	10	10
	AISI 440C SS	x			x	500	8	15
	AISI 440C SS		x		x	500	10	79
	AISI 440C SS		x		x	200	10	80
	AISI 440C SS		x	x		500	10	3
Armco 17-4 PH (SA)	Stellite No. 3	x			x	500	8	190
**	Honed Chromium Plate (0.005") on Armco 17-4 PH	x			x	500	8	195
	Armco 17-4 PH (PH)	x			x	500	8	440
	Armco 17-4 PH (SA)	x			x	500	8	10 ⁶
Armco 17-4 PH (PH)	Honed Chromium Plate (0.005") on Armco 17-4 PH		x		x	500	10	4
**	Chromium, As Plated (0.0005")		x		x	500	10	60
**	Honed Chromium Plate on Armco 17-4 PH (0.005")	x			x	500	8	35
**	Stellite No. 3		x		x	200	10	47
	Chrome Carbide in Ni matrix	x			x	500	8	72
**	Stellite No. 3	x			x	500	8	150

* Entry in this column is moving element of the wear couple
unless otherwise indicated.

ϕ Wear Factor - Milligrams per
pound load per million cycles.

** Employed in service.

WEAR TEST DATA

Materials*	Versus	Type of Test		Additives		Temp. °F	Load (psi)	Wear Factor
		Piston & Cylinder	Journal & Sleeve	Hydro- gen	Oxy- gen			
Armco 17-4 PH (PH) **	Chromium, Nitrided	x			x	500	8	160
**	Stellite No. 3		x		x	500	8	200
	Titanium, Nitrided	x			x	500	8	210
	Wall Colmonoy No. 6		x		x	500	10	220
**	Stellite No. 6		x		x	500	10	320
	Stellite No. 21 (SA)	x			x	500	8	340
	S-Monel	x			x	500	8	430
	Armco 17-4 PH (PH)	x			x	500	8	460
	Haynes 25 (Cold Worked)	x			x	500	8	470
	AISI 304 SS	x			x	500	8	475
**	Stellite No. 3	x		x		200	8	2
**	Honed Chromium Plate (0.005") on Armco 17-4 PH	x		x		500	8	11
	Stellite No. 21 (PH)	x		x		500	8	25
**	Stellite No. 3	x		x		500	8	25
**	Stellite No. 6		x	x			10	100
	Wall Colmonoy No. 6		x	x		500	8	236
USS 18-8 W (SA)	Stellite No. 3	x			x	500	8	31
USS 18-8 W (PH)	Chromium, As Plated(0.0005")		x		x	500	10	5
	AISI 440C		x		x	500	10	59
	Wall Colmonoy No. 6	x			x	500	8	120
	Stellite No. 3	x			x	500	8	125
	Stellite No. 3	x			x	500	8	130

* Entry in this column is moving element of the wear couple
unless otherwise indicated.

** Employed in service.

∅ Wear Factor - Milligrams per
pound load per million cycles.

WEAR TEST DATA

Materials*	Versus	Type of Test		Additives		Temp. °F	Load (psi)	Wear Factor ϕ
		Piston & Cylinder	Journal & Sleeve	Hydro- gen	Oxy- gen			
USS 18-8W (PH)	Hastelloy D	x			x	500	8	187
	Titanium, Nitrided	x			x	500	8	195
	Stellite No. 3		x		x	500	10	310
	S-Monel	x			x	500	8	340
	Haynes No. 25 (Cold Worked)	x			x	500	8	390
	USS 18-8W (PH)	x			x	500	8	470
	AISI 304 SS	x			x	500	8	880
	S-Monel		x		x	500	10	970
	Stellite No. 3	x			x	500	8	11
	Wall Colmonoy No. 6	x			x	500	8	168
	Hastelloy D	x			x	500	8	226
Stellite No. 3 **	Honed Chromium Plate (0.005") on Armco 17-4 PH	x			x	200	8	2
**	Stellite No. 3	x			x	200	8	8
**	Haynes 25 (Cold Worked)	x			x	200	8	16
	Armco 17-4 PH, Nitrided	x			x	500	8	55
	Wall Colmonoy No. 6	x			x	500	8	61
**	Stellite No. 3	x			x	500	8	71
**	Haynes 25 (Cold Worked)	x			x	500	8	77
**	Armco 17-4 PH (PH)	x			x	500	8	113
**	Stellite No. 6	x			x	500	8	120
	Stellite No. 21 (SA)	x			x	500	8	145
	USS 18-8W (PH)	x			x	500	8	220
	AISI 304 SS	x			x	500	8	250

* Entry in this column is moving element of the wear couple

unless otherwise indicated.

ϕ Wear Factor - Milligrams per
pound load per million cycles.

**Employed in service.

WEAR TEST DATA

Materials*	Versus	Type of Test		Additives		Temp. °F	Load (psi)	Wear Factor ϕ
		Piston & Cylinder	Journal & Sleeve	Hydro- gen	Oxy- gen			
Stellite No. 3	Hastelloy D	x			x	500	8	300
	Armco 17-4 PH (SA)	x			x	500	8	700
**	Stellite No. 3	x		x		200	8	1
**	Armco 17-4 PH (PH)	x		x		500	8	33
**	Stellite No. 3	x		x		500	8	34
**	Honed Chromium Plate (0.005") on Armco 17-4 PH	x		x		500	8	37
	Hastelloy D	x		x		500	8	43
	Wall Colmonoy No. 6	x		x		500	8	60
	USS 18-8W (PH)	x		x		500	8	136
Stellite No. 6 **	Stellite No. 6	x			x	500	8	27
	Wall Colmonoy No. 6	x			x	500	8	39
**	Stellite No. 3	x			x	500	8	59
**	Chromium As Plated (0.0005")	x			x	500	8	69
**	Honed Chromium Plate (0.005") on Armco 17-4 PH	x			x	500	8	74
	Stellite No. 21 (SA)	x			x	500	8	105
	USS 18-8W (PH)	x			x	500	8	155
**	Armco 17-4 PH (PH)		x		x	500	10	155
	Stellite No. 21 (PH)		x		x	500	10	165
**	Armco 17-4 PH (PH)	x			x	500	8	185
**	Honed Chromium Plate (0.005") on Armco 17-4 PH	x		x		500	8	50

* Entry in this column is moving element of the wear couple

unless otherwise indicated.

** Employed in service.

ϕ Wear Factor--Milligrams per
pound load per million cycles

WEAR TEST DATA

Materials*	Versus	Type of Test		Additives		Temp. °F	Load (psi)	Wear Factor φ
		Piston & Cylinder	Journal & Sleeve	Hydro- gen	Oxy- gen			
Stellite No. 12 **	Honed Chromium Plate (0.005") on Armco 17-4 PH	x			x	500	8	25
**	Stellite No. 3	x			x	500	8	155
**								
Stellite No. 21 (SA)	Stellite No. 6	x			x	500	8	39
**	Stellite No. 21 (SA)	x			x	500	8	51
**	Stellite No. 3	x			x	500	8	87
	Haynes 25 (Cold Worked)	x			x	500	8	95
**	Honed Chromium Plate (0.005") on Armco 17-4 PH	x			x	500	8	102
**	Chromium, As Plated(0.0005")	x			x	500	8	105
**	Stellite No. 21 (SA)		x		x	500	10	175
	USS 18-8W (PH)	x			x	500	8	200
	USS 18-8W (SA)	x			x	500	8	480
**	Stellite No. 21 (SA)	x		x		500	8	19
**	Stellite No. 21 (PH)	x			x	500	8	98
	Metamic IT-1	x			x	500	8	111
**	Stellite No. 21 (PH)	x			x	500	8	120
	Stellite No. 3	x			x	500	8	150
	USS 18-8W (PH)	x			x	500	8	160
Haynes 25 (Cold Worked)	Haynes 25 (Cold Worked)	x			x	500	8	35
**	Stellite No. 3	x			x	200	8	35
	Honed Chromium Plate (0.005") on Armco 17-4 PH	x			x	500	8	155
	Chromium, As Plated(0.0005")	x			x	500	8	155

* Entry in this column is moving element of the wear couple
unless otherwise indicated.

φ Wear Factor - Milligrams per
pound load per million cycles.

** Employed in service.

WEAR TEST DATA

Materials*	Versus	Type of Test		Additives		Temp. °F	Load (psi)	Wear Factor ϕ
		Piston & Cylinder	Journal & Sleeve	Hydro- gen	Oxy- gen			
Haynes 25 (Cold Worked) **	Stellite No. 6	x			x	500	8	160
**	Stellite No. 3	x			x	500	8	160
	Haynes 25 (Cold Worked)		x		x	500	10	650
**	Stellite No. 3	x		x		500	8	55
	Honed Chromium Plate (0.005") on Armco 17-4 PH	x		x		500	8	210
	Chromium, As Plated(0.0005")	x		x		500	8	500
	AISI 304 SS	x		x		500	8	810
Monel	Honed Chromium Plate (0.005") on Armco 17-4 PH	x			x	200	8	2
	Haynes 25 (Cold Worked)	x			x	200	8	47
KR Monel (SA)	Honed Chromium Plate (0.005") on Armco 17-4 PH	x			x	200	8	5
	Stellite No. 21 (SA)	x			x	500	8	64
	Honed Chromium Plate (0.005") on Armco 17-4 PH	x			x	500	8	135
	Stellite No. 3	x		x		500	8	22
KR Monel (PH)	Stellite No. 6	x			x	500	8	25
**	Honed Chromium Plate (0.005") on Armco 17-4 PH	x			x	500	8	81
	Stellite No. 3	x			x	500	8	170
**	Honed Chromium Plate (0.005") on Armco 17-4 PH	x		x		500	8	1
	Stellite No. 3	x		x		500	8	31

* Entry in this column is moving element of the wear couple
unless otherwise indicated.

** Employed in service.

ϕ Wear Factor - Milligrams per
pound load per million cycles.

WEAR TEST DATA

Materials*	Versus	Type of Test		Additives		Temp. °F	Load (psi)	Wear Factor φ
		Piston & Cylinder	Journal & Sleeve	Hydro- gen	Oxy- gen			
S-Monel	Armco 17-4 PH (PH)	x			x	500	8	130
	USS 18-8W (PH)	x			x	500	8	360
	AISI 304 SS	x			x	500	8	450
Wall Colmonoy No. 6	Stellite No. 6	x			x	500	8	32
	Stellite No. 3	x			x	500	8	73
	Armco 17-4 PH (PH)	x			x	500	8	99
	Stellite No. 21 (SA)	x			x	500	8	100
	Wall Colmonoy No. 6	x			x	500	8	132
	Honed Chromium Plate (0.005") on Armco 17-4 PH	x			x	500	8	235
	Wall Colmonoy No. 6		x		x	500	10	250
	Stellite No. 3		x		x	500	10	260
	AISI 440C SS	x			x	500	8	270
	Stellite No. 21 (SA)		x		x	500	10	400
Si Bronze (Everdur 1012)	AISI 304 SS	x			x	500	8	450
	Stellite No. 21 (SA)	x			x	500	8	660
	Honed Chromium Plate (0.005") on Armco 17-4 PH	x			x	500	8	830
	Honed Chromium Plate (0.005") on Armco 17-4 PH	x		x		500	8	2
	Armco 17-4 PH (PH)	x		x		500	8	3
	Stellite No. 21 (SA)	x		x		500	8	18
	Stellite No. 3	x		x		500	8	21
	AISI 304 SS	x		x		500	8	450

* Entry in this column is moving element of the wear couple unless otherwise indicated.

φ Wear Factor - Milligrams
pound load per million cycles

** Employed in service

WEAR TEST DATA

Materials*	Versus	Type of Test		Additives		Temp. °F	Load (psi)	Wear Factor ϕ
		Piston & Cylinder	Journal & Sleeve	Hydro- gen	Oxy- gen			
Honed Chromium Plate (0.005") on Armco	BT Ag Brazing Alloy ***		x		x	500	10	4
17-4 PH	Lead		x		x	500	10	4
**	Stellite No. 3		x		x	500	10	6
**	Stellite No. 3	x			x	500	8	8
**	Armco 17-4 PH (PH)	x			x	500	8	20
	Armco 17-4 PH, Nitrided	x			x	500	8	22
**	Armco 17-4 PH, (SA)	x			x	500	8	48
	Wall Colmonoy No. 6	x			x	500	8	52
	Chrome Carbide in Ni Matrix	x			x	500	8	64
	AISI 304 SS	x			x	500	8	65
**	Stellite No. 6	x			x	500	8	65
	Metamic LT-1	x			x	500	8	73
**	Stellite No. 21 (SA)	x			x	500	8	89
**	Haynes 25 (Cold Worked)	x			x	500	8	105
	Honed Chromium Plate (0.005") Armco 17-4 PH	x			x	500	8	135
	Hastelloy D	x			x	500	8	140
	RT-SN-AM Brazing Alloy ***		x		x	500	10	150
	Stellite No. 21 (SA)		x		x	500	10	155
	S-Monel		x		x	500	10	180
	Stellite No. 21 (PH)		x		x	500	10	240
	S-Monel	x			x	500	8	420
**	Stellite No. 3	x			x	500	8	1
	Si Bronze (Everdur 1012)		x	x		500	10	4
	RT-SN Ag Brazing Alloy ***		x	x		500	10	5

* Entry in this column is moving element of the wear couple
unless otherwise indicated.

ϕ Wear Factor - Milligrams per
pound load per million cycles.

** Employed in service.

*** Hardy & Harman

WEAR TEST DATA

Materials*	Versus	Type of Test		Additives		Temp. °F	Load (psi)	Wear Factor ϕ
		Piston & Cylinder	Journal & Sleeve	Hydro-Oxy- gen	gen			
Honed Chromium Plate (0.005") on Armco	BT-SN Brazing Alloy ***		x	x		500	10	5
17-4 PH **	Stellite No. 3		x	x		500	10	9
**	Armco 17-4 PH (PH)	x		x		500	8	13
	Si Bronze (Everdur 1012)	x		x		500	8	14
	Wall Colmonoy No. 6		x	x		500	10	20
**	Stellite No. 6	x		x		500	8	24
	Hastelloy D	x		x		500	8	45
	Lead		x	x		500	10	83
**	Haynes 25 (Cold Worked)	x		x		500	8	161
	S-Monel		x	x		500	10	350
Chromium, As Plated (0.0005")	Titanium, Nitrided	x			x	500	8	5
**	Stellite No. 3		x		x	500	10	17
	USS 18-8W (PH)		x		x	500	10	21
	Wall Colmonoy No. 6		x		x	500	10	21
	AISI 420 SS		x		x	500	10	21
	AISI 410 SS		x		x	500	10	25
	Stellite No. 21 (SA)		x		x	500	10	32
	Chromium, As Plated(0.0005")	x			x	500	8	34
	Armco 17-4 PH, Nitrided		x		x	500	10	40
	AISI 440C		x		x	500	10	47
	AISI 416 SS		x		x	500	10	52
**	Armco 17-4 PH (Rc 40-45)		x		x	500	10	61
**	Stellite No. 21 (PH)		x		x	500	10	80
	AISI 440C	x			x	500	8	92

* Entry in this column is moving element of the wear couple
unless otherwise indicated.

ϕ Wear Factor - Milligrams per
pound load per million cycles.

** Employed in service.

*** Handy & Harman

WEAR TEST DATA

Materials*	Versus	Type of Test		Additives		Temp. °F	Load (psi)	Wear Factor φ
		Piston & Cylinder	Journal & Sleeve	Hydro- gen	Oxy- gen			
Chromium, As Plated (0.0005")	Stellite No. 6		x		x	500	10	100
	Chromium, As Plated(0.0005")		x		x	500	10	170
	S-Monel		x		x	500	10	420
	S-Monel		x	x		500	10	2
	AISI 410 SS		x	x		500	10	3
	AISI 416 SS		x	x		500	10	5
	Hastelloy D		x	x		500	10	23
Armco 17-4 PH, Nitrided	Armco 17-4 PH, Nitrided		x		x	500	10	10
	Honed Chromium Plate (0.005") on Armco 17-4 PH		x		x	500	10	11
	Titanium, Nitrided	x			x	500	8	28
	S-Monel		x	x		500	10	7
	Graphitar 14 (1)		x		x	500		
Titanium, Nitrided	Titanium, Nitrided	x			x	500	8	43
AISI 347 SS, Nitrided	AISI 347 SS, Nitrided	x			x	500	8	0
Chromium, Nitrided	Chromium, Nitrided	x			x	500	8	0
Lead, (Sleeve)	AISI 304 SS		x		x	200	10	270
	AISI 304 SS		x		x	500	10	2790†

* Entry in this column is moving element of the wear couple
unless otherwise indicated.

φ Wear Factor - Milligrams per
pound load per million cycles.

** Employed in service.

† Lead Sleeve Badly Corroded

(1) No valid wear factor, however, this combination has been successfully
employed in bearing applications at temperatures less than 200°F.

[illegible]

Wear Factor - Milligrams
pound load per million cycles

** Employed in service

Chapter 8

RELATIVE IMPORTANCE OF DIFFERENT VARIABLES

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	Page
INTRODUCTION.....	135
MATERIAL COMPOSITION.....	135
TEMPERATURE.....	136
TIME.....	137
WATER VELOCITY.....	138
OXYGEN.....	139
HYDROGEN.....	140
EFFECT OF OTHER GASES.....	141
ELECTRICAL RESISTIVITY OF WATER.....	141
STRESS.....	142
HEAT TREATMENT.....	142
NUCLEAR IRRADIATION.....	142
SURFACE FINISH.....	143

INTRODUCTION

The data in chapter 7 presents corrosion information for various materials and environmental conditions. However, many of the variables included were not studied over a wide range because work was usually done under specific service conditions. This lack of information may make it difficult to weigh the importance of a variable. The purpose of this chapter is to give the reader a better feel for the importance of the variables covered. Most of the discussions will be based on the results given in chapter 7.* Information obtained from pilot-plant tests and reactor plant operation, where available, will also be factored into the discussion.

For the most part, the conclusions and opinions given in this chapter will be of a general nature and will encompass as many groups of alloys as possible. Specific exceptions to the generalizations made will be pointed out. Additional information on this subject is

given in an Argonne National Laboratory report¹ which covers the effect of pertinent variables on specific individual alloys rather than on groups of alloys as covered herein.

Most of the corrosion rates given in chapter 7 are based on undescaled weight change data rather than on descaled weight changes. Although the latter are considered to be more representative, the difference is important only with materials which form heavy scales, i. e., carbon steel. Therefore, for all practical purposes, the undescaled data are considered to provide a reliable basis for the discussions in this chapter.

Where it is considered applicable, the discussions which follow for each variable will contain pertinent information concerning both corrosion and wear.

MATERIAL COMPOSITION

If one attempts to make a general statement concerning the effect of composition on the corrosion resistance of materials, it becomes apparent that the specific type of corrosion must be taken into account. For instance, the suitability of various materials from the point of view of general corrosion would not necessarily apply where such forms of localized attack as stress corrosion, crevice corrosion, galvanic corrosion, or pitting corrosion might be encountered. The term "general corrosion" as applied herein refers to the uniform loss of metal by the process of corrosion. In contrast, localized corrosion involves a nonuniform loss of metal, i. e., pitting.

In this respect, a broad classification of materials investigated with respect to composi-

*Evaluations are based on actual average corrosion rates, therefore there are some apparent discrepancies between factors given in this chapter and the nominal rates in chapter 7.

tion and general corrosion resistance is shown in table 8-1.

TABLE 8-1

RELATIVE GENERAL CORROSION RESISTANCE OF MATERIALS

High	Intermediate	Low
Austenitic stainless steels	Ferritic stainless steels	Carbon steels
Cobalt-base alloys	Martensitic stainless steels	Low alloy steels
Gold	Nickel-base alloys	Aluminum-base alloys
Hafnium	Copper-base alloys	Silver-base alloys
Platinum		Organic materials in general*
Zirconium		Ceramic materials in general*
	Teflon*	

*Grouping with respect to thermal stability or solution rate.

The relative position of materials in the various groups is not substantially affected within the limits for the environments and material conditions discussed in chapter 7. For instance, if the materials listed in table 8-1 were rated in oxygen-bearing (most corrosive) and hydrogen-bearing (least corrosive) water, their relative positions would be essentially the same.

It is not possible to discuss the effect of composition per se on wear since resistance to wear is more a function of the mutual contact of materials rather than of individual compositions. For example, hardened Armco 17-4PH stainless steel possesses excellent bearing characteristics (wear factor* of 10) in combination with hard chromium plate, whereas poor bearing qualities (wear factor of 460) are obtained with a combination of Armco 17-4PH versus Armco 17-4PH steel. Although numerous materials were investigated from the point of view of wear, only a few basic materials were ultimately chosen for actual service because of further limitations imposed by corrosion, mechanical properties, and weldability. The basic materials employed are:

Stellites 1, 3, 6, 12, 19, 21, 25

Armco 17-4PH hard chromium plated

Armco 17-4PH

Armco 17-4PH nitrided†

Graphitar 14†

TEMPERATURE

Essentially all the dynamic corrosion test work was conducted at 500 or 600° F since the coolant water for nuclear reactor is normally operated between these two temperatures. Work done at lower temperatures was confined to special studies involving static autoclave tests where the determination of corrosion rate in itself was not the primary object. For instance, much of the work on crevice corrosion reported in chapter 9 was conducted at 200° F; however, in this case, evaluation was determined by the extent of localized attack (pitting and buildup of corrosion products) and the increase in torque required to move the crevice corrosion test couple. Although most of the remarks made are concerned with the effect of temperature over a limited range, unpublished data are available at lower temperatures which provide some basis for estimating the overall effect of temperature.

Generally speaking, the dynamic corrosion rate of the materials studied at 500° F is increased between 5 and 20 times when tested at 600° F, the highly corrosion resistant materials, such as the 18-8 type stainless steels, being affected the least.

A survey on low-temperature water corrosion, conducted by A. H. Roebuck,² reports information on the corrosion rate of five alloys of 18-8 type stainless steels. This work indicates that there is no significant difference in the rate of corrosion between 200° and 500° F. Tests were conducted at 190° F for 56 days in high-purity water (boiler feed water grade) with an oxygen content of 0.01 cc (STP) per kilogram of water (hereafter referred to as cc/kg) and having a pH of 8.1. The water velocity was 116 ft/sec. Corrosion rates ranged between 1.5 and 3 mg/dm²/mo. These rates are of the same order of magnitude as rates obtained at

*See App. B, Glossary, for definition.

†These materials are not used at temperatures above 200° F because they are lacking in corrosion resistance or thermal stability.

500° F at 30 ft/sec. It is not possible to correct for the difference in velocity between 30 and 116 ft/sec. A lower rate of corrosion would be expected at 30 ft/sec. However, based on the discussion which follows on the effect of velocity, this difference is expected to be very small and of no practical importance.

Although these few tests indicate little difference between 200° and 500° F, this information should be confirmed by additional work since the details of the test procedures employed are not available. On the basis of general observations made in corrosion testing, one would expect some measurable change in corrosion rate between these two temperatures.

The effect of temperature on the corrosion of zirconium has been extensively studied in static autoclave type tests using degassed water and steam at temperatures between 500° and 750° F. This work is described by Lustman and Kerze³ and is summarized in figure 8-1. The data show that the increase in corrosion of zirconium between 500 and 600° F is the same (factor of 5) as that observed for the 18-8 type stainless steels.

FIGURE 8-1. Effect of temperature on the corrosion resistance of zirconium.

In the majority of observations the wear rate is increased by a factor of 5 to 20 between tests at 200° and 500° F. This is sufficiently great to eliminate some excellent bearing combinations at the higher temperature. Ceramic materials are also excluded because of high solution rates at 500° F.

TIME

The influence of time as a variable affecting the corrosion rate of materials is well known. In most corrosion reactions involving corrosion-resistant materials, the rate decreases with time. There are numerous mechanisms which explain this observation, and the reader is referred to chapter 2 for details concerning this subject. Generally speaking, protection is afforded by the formation of a corrosion film which, with increasing time, becomes more resistant to attack than the metal in question.

The change in corrosion rate with time, for the type of materials studied, is shown in figures 8-2 and 8-3. It is interesting to note that the corrosion rates of essentially all the materials, including stainless and carbon steels, is reduced by a factor of approximately 10 during the test period between 250 and 4,700 hr. These results are of special significance in the case of carbon steel since a relatively low corrosion rate may be realized after a short term of operation in service.

FIGURE 8-2. Corrosion rate for typical structural materials.

Little can be said concerning the effect of time on corrosion rates determined by static tests since the techniques normally employed do not show measurable corrosion rates. The following figures illustrate this point. They were obtained on an 18-8 type stainless steel tested at 500° F in high-purity water (500,000

FIGURE 8-3. Corrosion of carbon steel SA 212 in water at 600° F and 30 ft/sec.

ohm-cm or better) with an oxygen content varying from 5 to 30 cc/kg.

Test period, days	Total weight gain for period indicated, mg/dm ²
30	4
60	3
120	3
180	3
240	4
330	3

These materials normally show an adherent corrosion product which is very smooth and possesses thicknesses on the order of heat-treatment temper films.

In the case of zirconium, however, measurable rates have been observed by Lustman and Kerze.³ Figure 8-1 shows that the extent of corrosion is reduced by an approximate factor of 2 during the test interval between 250 and 4,700 hr.

WATER VELOCITY

For reasons previously discussed, the effect of different water velocities was not extensively investigated since the primary interest centered on water velocities of about 30 ft/sec. Nevertheless, there is sufficient scattered information at lower limits to indicate the general effect of velocity.

In general, the corrosion rates of the materials studies are not appreciably affected by velocities ranging between 1/60 ft/sec (lowest flow studied) and 30 ft/sec (highest flow normally studied). However, it is important to

note that there is a marked difference between static and dynamic corrosion tests. Work reported by Westinghouse⁴ indicates that the static corrosion rate of stainless steel is approximately 0.3 mg/dm²/mo. Corrosion rates on the order of 5 mg/dm²/mo are obtained under comparable conditions at 1/60 and 30 ft/sec. This amounts to a twentyfold increase between static or no-flow conditions and dynamic conditions.

There are three exceptions to the above conclusions. Under certain conditions copper-nickel 70-30; K-Monel (and very likely Monel), and hard chromium plate are substantially affected by velocity.

In the presence of hydrogen, and possibly high pH conditions, there is no noticeable effect of velocity on the corrosion rate of copper-nickel 70-30 and K-Monel (Monel). However at neutral pH, with both low and high oxygen contents, the corrosion rate may increase by a factor of 2 to 4 between 1/60 and 30 ft/sec. This information was based on tests made in the range between 1 and 20 ft/sec.

The corrosion rate of hard chromium plate is heavily dependent on velocity only in waters which simultaneously contain oxygen and a high pH. A conservative extrapolation of the data indicates that the corrosion rate for hard chromium plate would be increased by a factor 8 between 1/60 and 30 ft/sec. This represents one of the most substantial effects of velocity observed within this range.

It has been concluded that the results of tests on stainless-steel specimens do not show any effect of velocity on corrosion. However, Wroughton⁵ has indicated that velocity has a significant effect on the corrosion products released in a stainless-steel recirculating system. Greater amounts of corrosion products are observed at the higher velocities, although quantitative data are not yet available. It is not believed that these observations necessarily result from an increase in corrosion rate. The observed increase in the corrosion products is considered to result from disturbance of oxide deposits (crud) produced by greater agitation and turbulence at a higher velocity.

OXYGEN

An examination of the tabulated data in chapter 7 shows that oxygen generally has very little or no effect on the corrosion rate of the materials studied under the limits investigated, namely, <0.5 to 5 cc/kg. This statement is especially true for those materials having the highest corrosion resistance, such as the 18-8 type stainless steels, and is based on tests made in out-of-pile test loops. However, indirectly, oxygen has a marked effect on the corrosion products released in a reactor or in-pile test loop. The effect of oxygen on stress corrosion is discussed in chapter 10.

Oxygen can have an appreciable effect on the water chemistry in an in-pile system, which in turn can effect the deposition characteristics of corrosion products. In the absence of sufficient hydrogen, oxygen combines with nitrogen under irradiation to form nitric acid. The formation of this acid then causes an increase in system corrosion products. It is not known whether this effect results from increased corrosion or some redistribution effect between soluble and insoluble products. The reader is referred to chapters 4 and 12, and a report by Welinsky, Cohen, and Seamon⁶ for more detailed information on this subject.

Sufficient data are not available to support a statement concerning the effect of oxygen on the corrosion rate of in-pile systems. On the basis of the results on corrosion test specimens, it is believed that the apparent increase in system corrosion products is due to deposition effects rather than to an increase in corrosion rate.

Data on out-of-pile dynamic test loops are limited to a few tests which are reported by Welinsky⁷ and Thompson.⁸ In these tests the corrosion rates are determined by chemical analysis of the spent ion-exchange resin in relation to exposure time and total surface area of the system. The Welinsky report indicates that oxygen does not affect the general corrosion rate in an 18-8 type stainless steel system. The oxygen level studied was 5 to 7 cc/kg, and it was compared to tests containing

hydrogen. The Thompson report indicated that the corrosion products which are released in a stainless steel dynamic system increase continuously with oxygen additions ranging from 1 to 6 cc/kg. The results of this work are shown in figure 8-4. This report showed that an

FIGURE 8-4. Effect of oxygen on corrosion in a dynamic loop system.

oxygen content of 5 cc/kg produced a system corrosion rate equivalent to 55 mg/dm²/mo, whereas corresponding weight changes on an 18-8 type stainless steel dynamic corrosion specimen would normally show about 5 mg/dm²/mo.

There is no definite explanation for the difference in the apparent corrosion rate of a system and the corrosion rate observed on test specimens. However, it may result from the effect of oxygen on localized corrosion. Tests made on crevice corrosion (see ch. 9) show that oxygen has a marked effect on the extent of localized attack in crevices. This form of corrosion results in the formation of relatively large amounts of corrosion product at the mouth of crevices. Therefore, since there are literally thousands of crevices in any system, the apparent increase in general corrosion rate may actually result from corrosion products formed locally at crevices. Although this explanation may account for the results reported by Thompson, there is no explanation why similar results were not obtained in other test loops. More information is needed in order to deter-

mine specifically what effect, if any, oxygen has on out-of-pile system corrosion.

Under certain specific conditions oxygen does have a marked effect on out-of-pile system corrosion products. Lembersky⁹ reports that the presence of high oxygen and high pH simultaneously, causes large quantities of chromium to be released as chromates in an out-of-pile system (also observed in in-pile system).

The difference between laboratory and system corrosion results is also highlighted by experience obtained in industry with boiler water corrosion problems, where oxygen must be controlled to limits below 0.05 cc/kg in order to minimize service failures and excessive replacement of parts. As suggested in the case of the system corrosion products, the majority of corrosion products in boiler water systems are formed primarily in areas where differences in oxygen concentration occur (similar to crevice corrosion). The importance of this type of attack is illustrated by the fact that the corrosion allowances normally specified by the ASME Code are directed toward preventing premature failures due to localized attack, such as pitting, rather than to minimize the general loss of metal from container walls.

There are three exceptions to the generalization that oxygen has little or no effect on corrosion within the limits studied. They are (1) the hardenable stainless steels, (2) copper-nickel 70-30, and (3) carbon steel.

Of special note is the effect of oxygen on the hardenable stainless steels such as USS 18-8W, Armco 17-4PH, and the martensitic varieties. These materials indicate an inverse relation between oxygen content and corrosion rate. Within the range studied, higher corrosion rates are generally obtained at the lower oxygen level. The observed corrosion rates of these materials may differ by a factor 5 to 10 when exposed to water with oxygen contents at either extreme of the range studied (range extended from <0.5 to 5 cc/kg).

The corrosion resistance of copper-nickel 70-30 is generally lowered by the presence of oxygen. Corrosion rates may increase by a

factor of 5 between the extreme oxygen concentrations studied.

The test information to date on carbon steel has not progressed to a point where an adequate statement can be made concerning the effect of oxygen. The data reported on carbon steel, particularly A-212, include many variables which prevent an adequate interpretation of the effect of oxygen. However, it is interesting to note that the corrosion rate of specimens tested at the highest oxygen concentration studied, namely, 400 cc/kg, showed corrosion rates lower than the values obtained at low oxygen concentrations, on the order of 0.5 cc/kg. The corrosion rate was reduced by a factor of 4 for comparable test periods. Since this comparison was based on one test run, it should not be completely accepted until substantiated by additional test data.

HYDROGEN

As in the case of oxygen, hydrogen additions within the limits studied have very little effect on the corrosion rate of the 18-8 type stainless steels tested in out-of-pile test loops. There is a slight inhibiting effect during the early states of corrosion; however, the magnitude of this effect is so small that it has no practical significance.

However, the introduction of hydrogen into a reactor or an in-pile test loop has a marked effect on the quantity of corrosion products released to the system. The benefits afforded by hydrogen additions are reported by Welinsky, Cohen, and Seamon.⁶ This effect is believed to result indirectly from the formation of ammonia by the reaction of hydrogen and nitrogen under irradiation and the suppression of certain undesirable side reactions. The ammonia raises the pH of the system, which, in turn, reduces the quantity of corrosion products. The effect of high pH is discussed in the next section.

The following comments are based on the data included in chapter 7.

The precipitation hardening and the hardenable martensitic stainless steels are affected by hydrogen additions. The corrosion rates of these materials in water containing low oxygen

are similar to the rates observed in water containing hydrogen. Both conditions show slightly higher corrosion rates than those observed for higher oxygen contents.

Hydrogen has a considerable inhibiting effect on the corrosion resistance of copper- and nickel-base alloys. For instance, the corrosion rate of copper-nickel 70-30 may be reduced by a factor of 50 to 200 by the addition of hydrogen. Hydrogen also has an inhibiting effect on nickel-base alloys, although the effect here is not as great as that observed for copper-base alloys.

Because of the limited information available on carbon steel, it is not possible to determine the effect of hydrogen on corrosion; however, it appears that hydrogen may have only a slight beneficial effect.

EFFECT OF OTHER GASES

The presence of small amounts of such gases as nitrogen, argon, helium, and ammonia do not appear to have a noticeable effect on the corrosion resistance of specimens tested in out-of-pile systems. Work conducted by Babcock & Wilcox⁹ showed that 200 ppm of ammonia does not affect the corrosion resistance of the materials shown in figure 8-2, in addition to beryllium-copper (4-96) and bronze. Additional unpublished work performed by Cohen¹⁰ indicates that 20 ppm of ammonia and small quantities of other gases mentioned did not adversely affect the wear characteristics of the basic materials employed for wear resistance. (Similar results were obtained with boric acid additions of approximately 1 percent.)

pH

High pH (10 to 11) has a beneficial effect in reducing the quantity of corrosion products released in an in-pile stainless steel system. Rockwell and Cohen¹¹ report that the yield of transportable corrosion products is much lower at high pH than with neutral water. It is believed that the insoluble corrosion products are more filterable at high pH. The exact reasons for the beneficial effect of high pH are not known. However, work on pH is still in progress since it holds much

promise for use in future reactors. Wroughton⁵ has indicated that high pH has a beneficial effect because it makes the crud deposits more tenacious, thereby reducing the quantity of products released to a system. Similar benefits have been obtained by high pH on out-of-pile test loops made of stainless steel and of carbon steel. As in the case of hydrogen and oxygen, the specific effect of high pH per se on the corrosion rate of stainless-steel systems is not too well understood. The conclusions which follow are based on data in chapter 7.

In many respects the inhibiting characteristics afforded by high pH are similar to the effects observed for hydrogen. The main difference is that in the case of the precipitation hardening and the hardenable martensitic stainless steels, high pH does not produce the decrease in corrosion resistance observed with additions of hydrogen. As in the case of hydrogen, high pH has a pronounced inhibiting effect on the corrosion of copper-base and nickel-base alloys. These effects are of the same order of magnitude as those described for the effect of hydrogen.

In connection with carbon steel there is a considerable difference observed in the corrosion rate between hydrogen-bearing (and neutral) water compared to high pH water. Rates in the former medium are generally 5 to 10 times greater than rates observed in the latter.

As in the case of hydrogen, high pH also has an inhibiting effect on crevice corrosion. Both hydrogen and high pH are equally effective in this respect (see chap. 9).

Only a limited amount of unpublished data¹² are available on the effect of high pH on wear. The results indicate a general effect similar to the effect of hydrogen. A 40-fold benefit was observed for AISI type 410 vs. 410 stainless steel as compared with oxygenated tests.

ELECTRICAL RESISTIVITY OF WATER

For reasons discussed in chapter 1, it was established that the electrical resistivity of the primary coolant would be limited to a minimum of 500,000 ohm-cm. Consequently, no work

was done to determine the effect of resistivity on corrosion since this limit could readily be maintained in test and in service.

In a few cases the resistivity of test waters has fallen well below this limit without showing any adverse effects.

These observations would suggest that lower resistivity waters may be acceptable in future water-cooled nuclear reactors. However, considerable work will be necessary in order to definitely establish the validity of these indications.

STRESS

Generally speaking, stress is not considered a problem with most of the materials investigated. Unpublished data by DePaul¹³ indicates that some of the materials employed in the construction of water-cooled nuclear reactors are susceptible to stress corrosion cracking under certain specific conditions. These materials are the martensitic and precipitation hardening stainless steels and cold-worked austenitic 18-8 type stainless steels.

Steels such as Armco 17-4PH and 17-7PH, USS 18-8W, and AISI 410 and 431 can fail by stress corrosion if in the fully hardened condition and stressed to levels on the order of 60,000 psi in torsion. Steels under similar conditions, but stressed in tension, are considerably less susceptible to cracking.

Austenitic 18-8 type stainless steels, which are cold-worked above 30 percent are also susceptible to cracking at torsional stress levels on the order of 20,000 psi. This problem is also minimized by tensile stress under comparable conditions. Special attention should be given to these materials (not necessarily cold-worked) when in the stressed condition and exposed to water environments containing chlorides. The reader is referred to chapter 10 for specific information on this subject.

There are many areas of stress corrosion which should be more thoroughly investigated. The statements made above are considered to be conservative in light of the limited information available. It is likely that many of the

materials mentioned could be successfully employed under high stress provided they are under confined conditions.

HEAT TREATMENT

It is generally considered that heat treatment has very little effect on the corrosion resistance of the materials studied. However, the amount of information on this subject is limited, and a more thorough investigation in the various environments under consideration may reveal substantial effects of heat treatment. For expediency most of the test work done on heat-treatable materials was performed on the materials in the heat-treated condition.

On the basis of static corrosion tests, the precipitation hardening stainless steels are not materially affected by heat treatment to the extent that they would fall in different categories. Practically speaking, if these materials are affected under dynamic water conditions, the degree must be small since the corrosion rates which are normally observed in the hardened condition (which is expected to show the least corrosion resistance) are relatively low.

The information on K-Monel indicates that the age-hardening treatment will reduce the corrosion resistance slightly in the case of neutral waters and appreciable (by an approximate factor of 10) in the case of high pH water. The importance of oxygen and hydrogen in affecting the degree of this effect should not be overlooked.

Heat treatments that involve the precipitation of chromium carbides in 18-8 type stainless steels are not considered harmful from the point of view of susceptibility to intergranular corrosion; however, they do decrease resistance to chloride stress corrosion cracking. The effects of heat treatment on these forms of corrosion are discussed in detail in chapters 9 and 10.

NUCLEAR RADIATION

Early work¹⁴ performed at the Argonne National Laboratory and current investiga-

tions by Glick,¹⁵ Galonian, Callahan, and Koenig,¹⁶ and more recently by Wroughton,¹⁷ and Brown, and Alger,¹⁸ indicate that nuclear irradiation has no material effect on corrosion resistance. These studies were and are being conducted primarily on stainless steel, carbon steel, and zirconium under irradiation and water conditions (500° F.) expected in service. A slight increase in corrosion rate has been observed in the case of carbon steel.¹⁸

From a general materials point of view, the only effect which has been noted is a slight change in the metallurgical and mechanical properties comparable to that which might be expected from a small amount of cold working. However, a recent paper by Wilson and Berggren¹⁹ suggests that more attention should be given the changes in mechanical properties resulting from nuclear irradiation.

SURFACE FINISH²⁰

Surface finishes ranging between 16 and 250 microinches (rms) did not produce any observable effects on the corrosion resistance of the 18-8 type stainless steels.

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Part C
Special Studies

Chapter 9

CREVICE CORROSION

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	Page
BACKGROUND INFORMATION.....	147
Metal-ion Concentration Cell.....	148
Oxygen Concentration Cell.....	148
Stagnant Area Corrosion.....	149
METHODS OF CONTROLLING CREVICE CORROSION.....	150
Material Composition.....	152
Oxygen Content of Water.....	155
Hydrogen Content of Water.....	157
pH of Water.....	157
Clearance Between Mating Surfaces.....	157
Relative Movement Between Mating Surfaces.....	158
Temperature.....	159
CRITICAL APPLICATIONS AFFECTED BY CREVICE CORROSION.....	159
Journal-sleeve Type Bearings.....	159
Thrust Bearing.....	161
Armatures.....	162
Springs.....	165
Rivets.....	167
Ball Bearings.....	168
Bellows.....	169
SUMMARY.....	171
APPENDIX.....	171

BACKGROUND INFORMATION

When work was first started to study the various corrosion problems that might be expected in water-cooled nuclear reactor applications, the amount of certain constituents in the water, namely, oxygen, was not definitely known. However, it was estimated that the quantity of oxygen would be on the order of 1 to 10 cc per kilogram of water (STP), (subsequently referred to as cc/kg). Consequently, many of the corrosion studies were made with water containing oxygen within this range. Most of the work on crevice corrosion reported

in this chapter was performed during early investigations under such "high" oxygen conditions (1 to 10 cc/kg).

Operational experience of the PWR and naval reactor programs show that the oxygen content of the primary water is almost immeasurable with the addition of hydrogen. The information described in this chapter shows that crevice corrosion is not normally a problem requiring special attention in systems with low oxygen contents on the order of 0.1 cc/kg. Therefore, to some extent, the material in this chapter is not directly applicable to these reactors. The main reason for including this chapter is to present all information developed on crevice corrosion which may be pertinent in a water-cooled nuclear reactor. Such information would be useful in analyzing and solving problems which may arise from accidental high oxygen water conditions in the present reactors and from consideration of future reactor water environments which may contain more oxygen.

From an engineering point of view, crevice corrosion is considered important because it can cause high torque or complete seizure in bearings and mechanical linkages in a relatively short period of time. For this reason, crevice corrosion can be a limiting factor in the choice of materials and design of components with internal moving parts. The problem is especially important if small clearances must be employed between bearing surfaces.

In the field of corrosion the term "crevice corrosion" has acquired a very general meaning which normally includes all observations of

accelerated attack observed at the junction between two metals exposed to a corrosive environment. For purposes of discussion, this form of corrosion may be divided into three main categories, all of which will be discussed in this chapter. Two of these forms of attack, the metal-ion concentration cell and the oxygen concentration cell, are very specific and can be defined in terms of known mechanisms of reaction. The third, a special case of stagnant area corrosion, is of a more general nature and does not lend itself readily to a specific definition.

Metal-ion Concentration Cell

That form of crevice corrosion which is defined as a metal-ion concentration cell results from corroding currents which arise in those regions where there is a difference in the metal-ion concentration. The extent of accelerated corrosion which occurs at these points depends primarily upon the magnitude of the corroding current, which, in turn, is related directly to the difference in the metal-ion concentration at the points in question. A schematic sketch illustrating the mechanism of this type of corrosion is shown in figure 9-1.

FIGURE 9-1. *Metal-ion cell.*

The direction of the corroding current determines the location of the accelerated corrosion products. Corrosion occurs at those points where the current leaves the metal. In this case the current travels from the metal outside of the crevice to the metal inside the crevice.

Therefore the corrosion products will form at the mouth of a crevice or at the perimeter of the contact area.

It is also apparent that this type of corrosion could be considerably minimized by continuously replacing the water in the crevice with fresh water from the outside, thus minimizing or eliminating a differential condition with respect to ion concentration. Likewise, one would expect this form of corrosion to be minimized or even eliminated by increasing the crevice gap so that sufficient flow and displacement of water could occur at the mouth of the crevice to prevent the formation of differential concentration areas.

Oxygen Concentration Cell

That form of crevice corrosion which is defined as an oxygen concentration cell results from corroding currents which arise at those points where a differential oxygen concentration occurs. As in the case of the metal-ion concentration cell, the magnitude of the corroding current is directly related to the difference in the concentration of oxygen at the point in question. A schematic sketch illustrating the mechanism of this type of corrosion is shown in figure 9-2.

FIGURE 9-2. *Oxygen concentration cell.*

This sketch shows that the corroding current travels from the low oxygen-bearing medium to the metal. Therefore, in contrast to the metal-

ion concentration cell, one would expect accelerated attack to occur at the entire interface surfaces of both materials in contact rather than at the mouth of the crevice. This form of corrosion may be controlled in the same manner as mentioned above for the metal-ion concentration cell.

Stagnant Area Corrosion

Strictly speaking, stagnant area corrosion is not normally considered a form of crevice corrosion. However, since it has been found to play an important part in the analysis of crevice corrosion problems, it is considered desirable to discuss this form of corrosion in order to indicate its importance in relation to the other forms of crevice attack and to actual design problems. Stagnant area corrosion, as specifically related to crevices, may be defined as general accelerated attack which may occur within a crevice (or any stagnant area). It results directly from the increased corrosivity of the environment, which, in turn, is a direct result of the accumulation of both soluble and insoluble corrosion products formed within the crevice. In contrast, the accelerated attack which occurs in both the ion and the oxygen concentration cells results from *differential* effects.

Since essentially no circulation of water normally occurs within crevices, it would be expected that the concentration of corrosion products would increase almost indefinitely and, thereby, produce more corrosion than would normally be expected for the same material exposed to the environment outside the crevice. For instance, if a crevice is exposed to high-purity water having a total solids content of 1 ppm, it is very possible that the water within the crevice may eventually have a total solids content 100 or 1,000 times greater than that of the surrounding environment. The corrosion resistance of the particular metal involved may be entirely inadequate in the relatively impure water as compared to the pure water. Although this form of corrosion does not depend on differential effects, the methods

of controlling this problem are essentially the same as for ion and oxygen concentration cells. The mechanism of corrosion involved in stagnant areas of all kinds is the same as that described for stagnant area corrosion in crevices. A schematic sketch of stagnant corrosion is shown in figure 9-3. Examples of stagnant area

FIGURE 9-3. Stagnant area conditions.

corrosion occurring in a ball-nut and screw are shown in figures 9-4 and 9-5. This unit was exposed in the assembled condition to oxygenated high-purity water at 200° F for 3 months. Under the conditions of this test the exposed surfaces maintained their original bright metallic luster; whereas the surfaces of metal in the stagnant area were black, indicating the formation of a thicker corrosion film. The engineering significance of such a thicker film formed in a stagnant area can only be evaluated by operational or simulated engineering type tests. This example merely serves to illustrate that corrosion can proceed at a faster rate in a stagnant area than in an area where there is movement of water. This type of attack, in applications involving moving parts with small clearances, may cause excessive wear, high torque, and even complete seizure.

The problem of crevice and stagnant area corrosion is especially aggravated by nuclear applications because of the complexity, small clearances, and limited operating forces nor-

FIGURE 9-4. *Example of stagnant area corrosion in a component.*

mally available in certain mechanical parts which must operate in water. Examples of such a mechanism are shown in figures 9-6 to 9-8.

METHODS OF CONTROLLING CREVICE CORROSION

The basic problem of crevice corrosion can best be illustrated by using a specific example. Consider a typical journal-sleeve bearing application. In this case two cobalt-base alloys, Stellite No. 6 and Stellite No. 3, operating with a diametrical clearance of approximately 0.002 in., might seize after two or three weeks of exposure to 500° F high-purity water containing relatively small amounts of oxygen. The torque normally required to overcome this seizure could be in the order of several hundred inch-pounds. Since torques of this order are not normally available in mechanically operated components, it becomes a matter of prime importance to take all possible steps in order to minimize crevice corrosion.

Examination of parts exhibiting excessive torque or complete seizure shows that the

FIGURE 9-5. *Closeup of stagnant area corrosion in a component.*

difficulties observed result from the presence of small amounts of corrosion products at the perimeters of the contact areas. This would suggest that the corrosion products formed result from a metal-ion concentration cell. The extent and the nature of the corrosion buildup normally observed in such cases is shown in figure 9-9. This figure shows essen-

FIGURE 9-6. *Illustration of complexity of components operating in high-purity water.*

tially no corrosion at the interface of the two areas in contact, with all visible corrosion limited to the perimeter of the contact area.

If two pieces of AISI type 347 stainless steel plate are placed together, as shown in figure 9-10, and subsequently exposed for a short period of time to oxygen-bearing high-purity water at 500° F, an effect similar to that shown in figures 9-11 and 9-12 will be observed.

There have been no indications that this form of crevice corrosion produces a bond between mating surfaces since tests made on

crevice corrosion plate samples do not adhere to one another and journal-sleeve bearings which have seized come apart readily when the cylinder is sectioned along the axis. Therefore, the high torque and seizure can best be explained on the basis of pressure exerted as a result of the metal-to-oxide volume change resulting from the formation of corrosion products under restraint. This form of accelerated attack normally penetrates slightly the interface of the crevice. The larger the crevice the deeper will be the band of corrosion product formed.

FIGURE 9-7. *Illustration of complexity of components operating in high-purity water.*

On the basis of the available information concerning the mechanism of crevice corrosion the following items are considered to be important: (1) material composition, (2) oxygen content of water, (3) hydrogen content of water, (4) pH of water, (5) diametrical clearance, (6) temperature, and (7) relative movement between mating surfaces.

Some of these factors aggravate crevice attack, and others are beneficial as control measures. The significance of each of the factors is discussed in the sections which follow.

Material Composition

Numerous laboratory tests were conducted to determine the effect of material composition on crevice corrosion. Approximately 25 different materials were tested in some 150 different combinations. The details of the test samples, procedures, and the results obtained are given in the appendix to this chapter and in chapter 5. The results of tests made at both 200° and 500° F are summarized in table 9-1.

All the materials studied at 500° F proved to be susceptible to crevice corrosion since all couples exhibited the characteristic corrosion

TABLE 9-1. SUSCEPTIBILITY OF VARIOUS MATERIALS TO CREVICE CORROSION

Materials		Type of attack	Numerical rating
Group designation	Investigated		
Chromium-nickel stainless steels.	AISI type 302, 304, 316, 321, 347.	Corrosion buildup..	1
Cobalt-base alloys..	Stellites Nos. 1, 3, 6, 12, 19, 21, 24.	Corrosion buildup..	1
Electroplating.....	Hard chromium plate.	Corrosion buildup..	1
Copper-base alloys..	Brass, bronze, copper-nickel (70-30).	Corrosion buildup and pitting.	2
Nickel-base alloys..	Inconel, Inconel-X, Monel.	Corrosion buildup and pitting.	3
Straight chromium stainless steels.	AISI type 410, 420, 430, 431, 440.	Corrosion buildup and pitting.	4

FIGURE 9-8. Illustration of complexity of components operating in high-purity water.

buildup and/or pitting. The extent of buildup observed at the perimeter of the contact area normally decreased with increasing corrosion resistance of the material. Certain materials, namely, the straight chromium stainless steels and high copper- and high nickel-bearing alloys, were also subject to pitting of the area

FIGURE 9-9. Journal-sleeve crevice corrosion specimen showing location and extent of crevice corrosion buildup.

in contact in addition to the peripheral buildup. It is believed that this type of pitting does not

FIGURE 9-10. *Post test appearance of plate type crevice corrosion specimen.*

result from any possible galvanic effects since it also occurs with couples where both materials are the same and where one of the materials is a plastic.

The pitting observed is usually minor in nature and is normally not objectionable except in moving parts with close clearances. Such pitting has been observed with some of the alloys investigated at temperatures as low as 200° F.

Therefore, in view of the high reliability that is required, the choice of materials for bearing applications is normally limited to those materials which do not exhibit pitting and which show the least amount of corrosion buildup. Since the major problem with crevice corrosion results from the accumulation of corrosion products within the mouth of the crevice and since all materials show this buildup to some degree, very little benefit can be afforded solely by changing materials, especially the highly corrosion resistant materials. Other

methods must be employed to minimize or eliminate this form of corrosion.

Additional tests were made on approximately 300 journal-sleeve type crevice test samples, similar to that shown in figure 9-9, in order to determine the effects of oxygen, hydrogen, pH, clearance, temperature, and relative movement. Four basic material combinations were employed for this study:

1. Armco 17-4 PH versus Armco 17-4 PH chromium plated.
2. Armco 17-4 PH chromium plated versus Stellite No. 3 and/or No. 6.
3. Stellite No. 3 or No. 6 versus Stellite No. 3 and/or No. 6.
4. AISI type 410 stainless steel versus Stellite No. 3 and/or No. 6.

The hardenable stainless steels were tested in the hardened condition, which ranged between 35 and 45 on the Rockwell C scale of hardness. Four diametrical clearances were employed for all combinations: 0.0005, 0.002,

FIGURE 9-11. Disassembled plate type crevice corrosion specimen showing buildup (4.5 $\times$).

0.005, and 0.008 in. The couples were tested under various water conditions, the details of which are given in subsequent sections. All tests were conducted in stainless steel autoclaves similar to those described in chapter 5 and 6.

Specimens were not electrically insulated from one another since galvanic corrosion was not expected to be a problem. Two stainless steel wires secured the sleeve on the journal to prevent rotation and movement along the axis. No attempt was made to center the journal within the cylinder since the corrosion products formed at the perimeter of the contact area almost invariably caused the journal to center itself. The discussions which follow are based on the above tests.

Oxygen Content of Water

Two series of tests were made to determine the effect of oxygen. One group was tested in high-purity water at 500° F with an oxygen content of 1 to 10 cc/kg. The remaining group was tested under the same conditions, except that the oxygen content was less than 0.005 cc/kg. The duration of the tests was six months, although, where seizure was observed, it normally occurred within one to three weeks of testing.

The effect of oxygen on crevice corrosion is shown in figure 9-13.

These general results indicate that the mechanism of this form of corrosion is completely

FIGURE 9-12. View of crevice corrosion buildup at corners of specimen (20 $\times$).

FIGURE 9-13. Effect of oxygen on crevice corrosion.

dependent on the presence of dissolved oxygen. In the low oxygen-bearing or degassed water, the extent of crevice corrosion observed is insignificant; whereas in the high oxygen-bearing water the extent of attack which occurs in the crevice is sufficient to cause high operational torques or complete seizure.

Tests made in the high oxygen-bearing water caused all material combinations with clearances up to and including 0.002 in. to seize within a few weeks of testing. Pitting was observed on the AISI type 410 stainless steel samples. None of the low oxygen tests seized during periods up to 6 months. In addition, the low oxygen tests did not cause pitting in AISI type 410 stainless steel.

There is limited information on the effect of oxygen content between 0.01 and 1 cc/kg. However, tests conducted with "partially degassed" water, which normally would be expected to contain oxygen in this range, strongly suggest that crevice corrosion can be equally as serious with an oxygen content of 1 cc/kg as with the higher contents studied.

From a practical point of view, crevice corrosion must be considered even in those applications where there is very little or no oxygen in the water under normal conditions. Damage may be incurred even if oxygen enters the system only for short periods on the order of a

few days or a week. This would be especially true for those applications involving close clearances and very little movement.

On the basis of a purely theoretical approach to this problem, one would expect the crevice corrosion buildup observed to result from a metal-ion concentration cell since accelerated attack is limited to the perimeter of the contact area. On the other hand it has been stated that crevice corrosion does not occur in the absence of oxygen. The tests made show that the mechanism of attack is not strictly in accordance with what would be expected, because oxygen concentration cells normally produce attack on the interface area. The true basic mechanism of crevice corrosion which occurs in oxygen-bearing high-purity water is not known with certainty and requires further study.

Hydrogen Content of Water

Tests in hydrogenated water were conducted under conditions similar to those described above except that they contained about 500 cc/kg of hydrogen and from 0.5 to 1 cc/kg of oxygen. Only limited information is available on the effect of hydrogen on crevice corrosion. However, there is sufficient data to indicate that hydrogen plays an important role in the control of crevice corrosion by minimizing the adverse effects of oxygen. These preliminary tests show that crevice corrosion is virtually eliminated even in the worst combination of materials and clearances studies, e. g., AISI type 410 stainless steel with a 0.0005 in. clearance.

On the basis of the corrosion inhibition afforded by hydrogen on the general corrosion of materials, one would expect that a concentration of hydrogen on the order of 25 to 50 cc/kg would provide adequate protection against crevice corrosion. However, additional work will be required in order to verify this inference.

pH of Water

A limited number of tests were also directed toward determining the effect of high pH (10 to 11) on crevice corrosion. These tests were made under conditions similar to those em-

ployed for the oxygenated water tests, except that the pH of the water was raised to 11 by the addition of lithium hydroxide at the start of the test. Although the pH normally decreased with test time, it seldom went below 10 during the test period.

The results of these tests indicate that high pH appears to have an inhibiting effect similar to that observed for hydrogen additions.

Relatively speaking, only exploratory work has been done in high pH media as compared to oxygenated, degassed, and hydrogenated solutions. Therefore, any statements made concerning high pH should be substantiated by additional tests before such information is actually employed in a given application.

Clearance Between Mating Surfaces

Clearance is one of the most important factors controlling the extent of damage resulting from crevice corrosion applications where restraint can be developed by the formation of corrosion products within the mouth of a crevice, e. g., between a journal and sleeve. Clearance is also important in nonrestraint types of bearings since it can govern the degree of washing in the crevice, thereby making it possible to minimize attack. Any modifications in design which would provide for circulation of water between the crevice and adjacent environment would tend to minimize or eliminate the problem.

As previously discussed, the diametrical clearances investigated were 0.0005, 0.002, 0.005, and 0.008 in. Samples were evaluated by examination for freedom of movement or for seizure and by the torque required to produce movement in those couples which did seize. In practically all cases where seizure occurred, it appeared after 1 to 3 weeks of testing. Tests on specimens which did not seize were continued for 6 months.

All the material combinations studied (with the exception of the AISI type 410 stainless steel couples) generally showed similar results with respect to the susceptibility to seizure and to the torques required to overcome seiz-

ure. The average torques as a function of clearance were essentially the same irrespective of material composition. These results are shown in figure 9-14 (see also fig. 9-13).

FIGURE 9-14. Effect of temperature on crevice corrosion.

The data indicate that little or no difficulty would be expected in journal-sleeve type bearings and linkages made up of highly corrosion resistant materials, providing the diametrical clearances were maintained at 0.005 in. or larger. Further tests utilizing couples made up of AISI type 410 stainless steel, which is of intermediate corrosion resistance (see chap. 7) indicate that for comparable conditions seizure will occur at the larger clearances and higher torque will be required to impart movement to the journal. More specific information is not available on the AISI type 410 stainless steel since it was not extensively investigated for bearing applications. However, on the basis of general corrosion data, it is reasonable to assume that all the straight chromium stainless steels will react in a similar manner.

Engineering considerations do not always permit so generous a clearance in bearings, particularly where alignment and shock resistance are important considerations. Most of the journal-sleeve applications in the water-cooled reactor required clearances on the order of 0.002 in. Therefore, because of design considerations, the problem of crevice corrosion

cannot always be solved by providing adequate clearances. Nevertheless, where possible, every advantage should be taken of the benefits afforded by employing such large clearances. Where smaller clearances are mandatory, they may be employed providing that alternate provisions are made to minimize crevice corrosion.

Relative Movement Between Mating Surfaces

Based on the mechanisms presented for the various forms of crevice corrosion, one could justifiably predict that the degree of movement expected in a given component would play an important part in influencing this type of corrosion. The advantages that can be obtained by movement of a part are similar in many respects to the advantages obtained by providing a larger clearance. Movement provides a means for the partial or complete replacement of water within the crevice. In the case of movement, this replacement is more positive and can be effected more completely than is possible by relying on large clearances.

Only a limited amount of work has been done to determine the benefits to be obtained by prescribed movements under specific conditions. Most of this work was done on production valves and prototype mechanical linkages simulating designs under consideration. The limited information from these tests indicate that freedom from seizure or excessive torque requirements can be obtained in a journal-sleeve application with a diametrical clearance of 0.002 in. (tested in oxygenated water at 500° F), provided the unit is operated at least once every week. This interval can be extended for more favorable environmental conditions. The success or failure in such an application will be determined by the degree of movement. Obviously, movement involving complete and frequent replacement of the water within the crevice would minimize the crevice corrosion problem.

The extent of movement required for a given application under specific conditions must be determined by actual tests on production or prototype units since the problem of crevice

corrosion is too complicated to permit such a determination for a particular design solely on the basis of laboratory test results. Extreme caution should be observed in those applications where the diametrical clearance of moving parts is less than 0.002 in.

stainless steels are considered to be a critical problem even at this relatively low temperature. On the other hand, at 500° F all material combinations would have to be considered from the point of view of crevice corrosion.

FIGURE 9-15. Post test appearance of crevice corrosion specimens tested at 200° F.

Temperature

Temperature has a marked effect on crevice corrosion. The results of comparative tests made at 200° and 500° F are shown by the curve in figure 9-14. The marked difference in appearance between samples tested at the two temperatures is illustrated in figures 9-15 and 9-16. The extent of buildup observed on samples tested at 200° F, with the exception of AISI 410 stainless steel (first sample shown), was merely a discoloration with no measurable thickness. However, all the samples tested at 500° F, and the AISI 410 stainless steel tested at 200° F, showed heavy corrosion buildup.

These results show that for material combinations such as those numbered 1, 2, and 3 in the section on Material Composition, crevice corrosion is not considered to be a problem requiring special attention at 200° F. In contrast to this generalization, the straight chromium

CRITICAL APPLICATIONS AFFECTED BY CREVICE CORROSION

Journal-Sleeve Type Bearings

Close fitting journal-sleeve type bearing applications and linkages are considered to be among the most important applications affected by crevice corrosion. In this case high operating torque, or complete seizure, results from the radial restraint developed by the expansion associated with metal to a metal-oxide formation (corrosion buildup) which expands radially within the crevice. For purposes of discussion, such applications will be referred to as "restraint type" bearings.

It is important to note that malfunction in this type of application under adverse conditions can occur in a relatively short period of time, i. e., from a few days to a week; whereas most of the other operational problems discussed

FIGURE 9-16. *Post test appearance of crevice corrosion specimens tested at 500° F*

FIGURE 9-17. *Pitting on AISI type 410 stainless-steel journal.*

herein are affected only from a long-range point of view.

The order of magnitude of the torque required to overcome seizure in restraint bearings has already been discussed. However, in connection with the occurrence of pitting resulting from crevice corrosion, a typical test was conducted under conditions simulating those of service for a valve containing a journal-sleeve type stem and guide. In this test the stem,

made of AISI type 410 stainless steel, was operated against a Stellite No. 1 sleeve, with a diametrical clearance of 0.008 in. The test was conducted at 500° F in water with an oxygen content of 0.5 to 3 cc/kg. The valve was operated for 4 hrs every week, and the total duration of the test was 6 weeks. The pitting observed on the AISI type 410 stem is shown in figures 9-17 and 9-18. The pits ob-

served had an average diameter of 0.002 in. and an average depth of 0.005 in.

FIGURE 9-18. *Magnified view of pitting on AISI type 410 stainless-steel journal.*

Thrust Bearing

Because of the limited restraint that can be developed by crevice corrosion in thrust bearings, this is considered to be the one application which is least affected by this type of corrosion. Crevice corrosion buildup at the perimeter of the contact area is not normally detrimental because of the large amount of axial play usually present in this type of bearing. A small amount of pitting can also be tolerated in most designs since the corrosion products can readily be washed away during operation. Furthermore, loss of bearing area due to slight pitting is of no real consequence. It is realized, however, that excessive pitting may interfere with successful operation of any type of bearing.

Ultimately, each case of crevice corrosion must be evaluated in terms of the specific design and existing operational and material problems. The Kingsbury type thrust bearing shown in figures 9-19 and 9-20 illustrates this

FIGURE 9-19. *Shoes employed in Kingsbury thrust bearings.*

FIGURE 9-20. *Runner employed in Kingsbury thrust bearings.*

case. Figure 9-19 shows the stationary shoes, and figure 9-20 shows the rotating runner.

The radial lines shown in the runner represent areas where crevice corrosion occurred during several shutdown periods. If the bearing had been idled only once and allowed to remain immobile for a period of sufficient dura-

tion for crevice corrosion to occur, the radial lines would correspond to the positions of the shoes, with no evidence of overlapping. The close proximity of the radial lines results from the shoes coming to rest at different positions after several shutdowns.

FIGURE 9-21. Effect of crevice corrosion on magnetic applications.

This type of bearing application permits the use of materials having corrosion rates higher than those normally required for journal-sleeve and other restraint-type bearing applications. A small loss of material from the bearing members, provided it is uniform, should not adversely affect the operational characteristics of this type bearing since it would not affect the clearance.

Armatures

The activation of mechanical parts by magnetic control is another application where crevice corrosion is important. The adverse affects

of crevice corrosion in this case are shown schematically in figure 9-21.

With this sort of arrangement, it can be seen that both corrosion buildup and pitting could increase the airgap between the armature and the coils to the point where the magnetic field will

FIGURE 9-22. AISI type 410 stainless steel armature protected on contact surface by 0.003-in. chromium plate.

be interrupted and the mechanism will be released at some value below the calculated magnetic holding force.

Because of its magnetic properties, AISI type 410 stainless steel is a desirable material for the construction of armatures. It also possesses a fair degree of general corrosion resistance (see chap. 7). However, as previously indicated, this material is considered to be quite susceptible to crevice corrosion buildup and pitting. In applications where this material is employed, the surfaces in contact

FIGURE 9-23. *Pitting observed on AISI type 410 stainless-steel magnetic inserts.*

between the coils and the armature can be protected by electroplating with a suitable material. A review of the various platings that can be considered shows hard chromium plate to be the most satisfactory material, even though it is normally considered to be porous. Figure 9-22 shows an armature made of AISI type 410 stainless steel protected by 0.003 in. of hard chromium plate on the surface in contact.

This unit was exposed to 200° F. oxygenated water for a period of approximately 3 months and showed no evidence of accelerated attack on the plated section but considerable corrosion on the unplated portions of the armature. The extent of pitting which can be expected to occur under comparable conditions on unplated AISI type 410 stainless steel (and very likely all the straight chromium stainless steels) armatures is shown in figures 9-23 and 9-24.

The armature shown in figure 9-22 is made entirely of AISI type 410 stainless steel, whereas the one shown in figure 9-23 has two circular poles made of the same material in an armature body made of AISI type 304 stainless steel. This difference is not important in illustrating the point in question. Pitting can be observed in several localized areas on both poles shown in figure 9-23. A photomicrograph of the pitted area (fig. 9-24) indicates the extent of pitting.

In the interest of conserving space, some work has been done with gold-plated silicon steel. In this case, because of the extremely poor corrosion resistance of the silicon steel, the entire armature required plating. This approach has not been utilized to any extent because of difficulties experienced in gold plating, e. g., blister formation during hydrogen relief heat treatment. A minimum thickness of 0.003 in. was originally used for corrosion

FIGURE 9-24. Photomicrograph through pitting observed on AISI type 410 stainless-steel magnetic inserts. (a) 250 $\times$
(b) 100 $\times$.

protection by gold plating. Although this thickness was employed, experimental test data show that 0.0003 in. would provide

adequate corrosion protection. However, because of the critical nature of the application, an extremely conservative safety factor was

FIGURE 9-25. Magnified view of end turn of spring showing partial protection by chromium plate.

employed, which will undoubtedly be reduced if gold plating is employed in future designs.

Springs

Applications involving certain types of springs can also be seriously affected by crevice corrosion. Here crevice corrosion can materially affect the operational characteristics of helical springs, where the crevice involved is that formed between the flat ends of the last turns of a plane ground spring and its supporting structure. Corrosion buildup, as such, produces no harmful effects. However, in the case of the nickel-base alloys Inconel and Inconel-X, pitting and other forms of localized attack can occur at the interface.

Of considerable importance is the observation that intergranular corrosion may occur on those

surfaces of Inconel springs that are within the crevice, whereas this attack will not occur on exposed surfaces. Figure 9-25 illustrates the nature of this intergranular attack as it occurs in the crevice formed by the supporting coil of the spring. The localized attack observed in this case probably results from a stagnant area effect rather than from a concentration cell effect. In one case, intergranular attack has been observed on Inconel-X at 500° F.

The exact conditions under which intergranular corrosion will or will not take place with the alloys in question are not known. It has been suggested by the International Nickel Co., Inc., that the mechanism of attack is similar to that which takes place in the austenitic stainless steels due to the precipitation of chromium carbides at the grain boundaries. This may account for the relative insensitivity

FIGURE 9-26. Magnified view of end turn of spring showing partial protection by chromium plate.

to attack of Inconel-X (columbium-bearing Inconel) as compared to Inconel. In view of the fact that Inconel-X does possess desirable spring properties and in view of the limited number of spring materials which are available, efforts were made to eliminate the possible occurrence of intergranular corrosion in the crevice. Laboratory tests and service experience have shown that adequate protection of this material can be afforded by electroplating the flat ends of the spring which form the crevice with approximately 0.0005 in. of hard chromium plate. Although such a plate is normally considered to be too porous for corrosion protection, experience has shown that it will adequately protect the part in question against intergranular attack in the crevice.

Figures 9-26 to 9-28 illustrate the degree of protection which can be afforded by chromium plating.

In relation to what has already been said concerning crevice corrosion in springs, there is one other problem that warrants some discussion. This concerns the use of spring housings where stagnant area effects could conceivably promote more severe attack on the metal than might normally be expected in the nonstagnant environment. In such cases it has been found advantageous to provide several holes or openings in the housing, thereby promoting some circulation of water and minimizing stagnant area effects. Figure 9-29 illustrates accelerated general corrosion in crevices, demonstrating the stagnant area effect on supporting spring coils.

FIGURE 9-27. Magnified view of end turn of spring showing nearly complete protection by chromium plate.

Rivets

The use of rivets must also be considered from the point of view of crevice corrosion. As in the case of springs, the problems associated with rivets are directly related to the particular materials involved. If the 18-8 type stainless steels did not work-harden, this group could be employed satisfactorily for rivets, and crevice corrosion would not be a problem. In most rivet applications for corrosion-resistant service, AISI type 410 stainless steel is employed because of its nonwork-hardening properties. As indicated earlier, this material is susceptible to pitting in crevices. In addition, tests have also shown that accelerated attack of this metal may also result from the stagnant area effect. Figure 9-30 shows the extent of attack observed

in an AISI type 410 stainless steel rivet after several months of exposure to water at both 200° and 500° F.

This figure shows a penetration rate along the axis of the rivet of approximately 0.070 in. per year at both temperatures. It also shows no visible attack on the riveted structures which were made of an 18-8 type stainless steel. These results show that the use of this material, or one similar in composition, would not be considered satisfactory for rivet applications. The solution to this problem involved the choice of a more corrosion-resistant material, Carpenter No. 10 (a modified austenitic chrome-nickel steel) which possesses good non work-hardening characteristics and is not susceptible to pitting or stagnant area corrosion in crevices.

FIGURE 9-28. Magnified view of end turn of spring showing complete protection by chromium plating.

Ball Bearings

Crevice corrosion has not presented a problem with ball bearings as applied in the first water-cooled nuclear reactor and its prototype. In these applications highly corrosion resistant materials, such as the Stellites and Armco 17-4PH, are employed, and the operating temperatures are on the order of 300° F.

Although specific information is not available concerning crevice corrosion in ball bearings at 500° F, the experience with other types of bearings with similar materials at elevated temperatures indicates that this type of corrosion would not be expected to be a problem. However, because of the possibility in this application of the combined action of crevice and stagnant area corrosion, it is recommended

that the subject be investigated prior to use of ball bearings at elevated temperatures.

In connection with the possible use of materials with lower corrosion resistance, tests made on experimental ball bearings composed of straight chromium stainless steels show that this form of attack can be a limiting factor in such applications. Figure 9-31 illustrates the difference in appearance of two ball bearings made up completely of martensitic stainless steels and exposed to high-purity oxygenated water for a period of one week at 200° and 500° F. It is interesting to note that at 200° F no discoloration resulted from exposure to the test water and the metal retained its original metallic luster. The ball-bearing tests at 500° F, however, showed a dark thin adherent film.

FIGURE 9-29. Accelerated general corrosion in a crevice, illustrating the stagnant area effect.

TABLE 9-2. CREVICE CORROSION IN BALL BEARINGS

	At 200° F	At 500° F
Post-test change in clearance (radial).	-0.0002 in.	-0.0004 in.
Post-test change in clearance (axial).	-0.0006 in.	-0.0001 in.
Breakaway torque.	4 in.-oz.	110 in.-oz.

Bearing components:	Materials
Balls.....	AISI type 440 SS
Inner race.....	AISI type 440 SS
Outer race.....	AISI type 440 SS
Retainer.....	AISI type 431 SS

These were not operated during the test in order to simulate a stagnant area condition within the bearings. Table 9-2 shows the changes

that were observed in the breakaway torque and radial clearances at the two temperatures.

The breakaway torque of the ball bearing tested at 500° F was 25 times greater than the breakaway torque for the bearing tested at the lower temperature. Radial and axial clearances were materially reduced in both cases. The results of these preliminary tests indicate that crevice corrosion might be a major consideration in ball-bearing applications involving the straight chromium stainless steels or other materials which have a poor resistance to crevice corrosion.

Bellows

Crevice corrosion can be an important consideration in determining the feasibility of certain types of bellows-designs. In many

FIGURE 9-30. Effect of crevice corrosion on AISI type 410 stainless steel rivet applications.

FIGURE 9-31. Effect of crevice corrosion on ball bearings.

cases bellows are made up of relatively thin pressure-containing material, ranging in thickness from 0.005 to 0.010 in. The thin wall imposes definite restrictions from the point of view of crevice corrosion because of the increased possibility of penetration resulting from localized attack.

Many bellows designs contain numerous crevices since the convolutions are normally joined by brazing or welding. The problem is further complicated by the fact that many thin-walled pressure-containing bellows are enclosed in housings or rings for reinforcement

of the bellows. This condition is very conducive to the formation of the stagnant areas in which accelerated attack of either a general or a localized nature may occur.

Apart from a materials consideration, the operational characteristics of bellows may be adversely affected by crevice corrosion as a direct result of the buildup of corrosion products within the crevices formed between convolution joints. Here the buildup may interfere with movement of the bellows during compression.

The complexity of bellows and their variety of design make it difficult to discuss general methods of solving crevice corrosion problems. In many cases, even where the specific conditions are known and well defined, it has been found that laboratory-type test data offer very little practical information concerning the suitability of a given type of bellows with a given material or set of conditions. Experience has shown that the most satisfactory approach to the evaluation of bellows is to test them under actual or simulated service conditions.

SUMMARY

The mechanism of crevice corrosion and controlling factors has been discussed. Crevice corrosion is not considered to be a problem in systems where the oxygen content of the water is on the order of 0.1 cc/kg or in high pH or hydrogen-bearing water. At higher concentrations of oxygen (in the absence of high pH or hydrogen additions), certain precautions must be taken in order to ensure successful operation. This type of corrosion is not expected to be a problem in crevice joints, such as socket welds or flange joints. It can be extremely important in bearings and mechanical linkages, especially where clearances less than 0.002 in. are involved. This form of corrosion can be controlled by (1) maintaining low oxygen levels, (2) adding hydrogen to the water, (3) raising the pH of the water, (4) providing adequate clearances in bearings and linkages, (5) periodic movement, and (6) choosing proper materials.

APPENDIX

Contact Corrosion on Various Material Combinations

Considerable attention has been given to the corrosion problems associated with metals in contact with one another under simulated reactor conditions. The accelerated corrosion which may result normally occurs at the areas in contact where there is very little or no movement between the water in the interface and the surrounding water. The confinement of water within the crevice leads to an increase in the conductivity of the water and/or depletes the oxygen in the water. Both these conditions aggravate galvanic, oxygen and ion concentration cell corrosion.

Preliminary results have been obtained on about 140 different material combinations simulating the various contacts to be found in the reactor. Tests were made at 200° F (in a dynamic loop) and 500° F (in static autoclaves). Both tests were made in oxygenated water. Specimens were lapped and polished with fine aluminum abrasive paper to give a finish of about 2 microinches (rms). All hardenable materials were treated to maximum hardness. The area of contact, in most cases, was 2 cm².

The results of microscopic examination on the tested surfaces in contact are shown in the attached tables. In general, the surfaces in contact all showed a narrow continuous ridge of corrosion product at the perimeter of the contact area. The ridges were, for the most part, several mils wide and the heights varied from a few tenths of a mil (referred to as "slight buildup") to a few mils (referred to as "heavy buildup"). The pitting observed on contact surfaces was of a minor nature, most of which could easily be overlooked with the naked eye. The pits usually averaged about two per square centimeter of contact surface. In size, the pits measured a few mils in diameter and depth. Although the extent of pitting observed is not considered serious from an operational point of view, it is reasonable to predict pits will increase in size and num-

ber with continued exposure. Unless otherwise indicated, contact and other surfaces showed good general corrosion resistance.

A summary of the results indicates:

1. Essentially all the couples tested at 200 or 500° F showed a narrow ridge of corrosion product at the perimeter of the contact area.

2. In general, most of the couples exposed to 200° F water retained their original metallic appearance; couples at 500° F were all darkened owing to the formation of a thicker oxide film. Exceptions to this generalization were the nickel and copper alloys, which showed the dark film at 200° F.

3. Pitting was observed on Inconel and Monel samples tested at 200° F; whereas, similar material couples at 500° F did not show pitting. (There is no explanation for this observation, except that the high temperature tests may have contained less oxygen.)

4. The pitting observed at 200° F was limited to the AISI type 400 stainless steels and to nickel, copper, and their high alloys.

5. There is insufficient data to correlate the occurrence of pitting with the type of mating material; however, it appears that the type of mating material has no effect on the occurrence of pitting.

COUPLE INDEX

Material	Couple No.	
	200° F	500° F
SS 304-----	68-----	16, 23, 27, 31, 36, 40, 42
Armco 17-7PH--	93-----	
USS 18-8W-----	48, 55, 70, 74, 77, 78, 79, 80, 81, 82, 83, 88, 121	10, 13, 17, 18, 25, 27, 30, 37, 43F, 43D
SS 347-----	68, 73, 84, 85, 86, 87, 88, 89, 90, 91, 92, 101, 107, 108, 115, 127	12, 15, 17, 21, 28, 34, 40, 41, 43C, 43B
Armco 17-4PH--	44, 50, 64, 77, 85, 93, 94, 95, 96, 97, 99, 103, 111, 119	19, 26, 30, 31, 41, 43, 43E
Z-rolled 347-----		3
Z-rolled 304-----	124-----	

COUPLE INDEX—Continued

Material	Couple No.	
	200° F	500° F
Teflon impreg- nated with asbestos	-----	32
SS 304 chrome plated	59, 60, 61, 62, 82, 90, 95, 125, 126	5
USS 18-8W chrome plated	122-----	43A
SS 347 chrome plated	123, 124-----	1, 2, 3, 32
Armco 17-4 chrome plated	-----	4
Armco 17-4PH nitrided-----	120, 129, 130, 131	6, 7, 8, 9
USS 18-8W nitrided-----	-----	10, 12, 14, 16, 20, 22, 35, 43G
SS 420-----	98, 99, 100, 101, 109	
SS 440C-----	111, 112, 113, 114, 115, 116, 128	
SS 410-----	49, 56, 58, 71, 102, 103, 104, 106, 108, 117, 127, 128, 132	43B
SS 440C chrome plated	131-----	7
Aluminum bronze	47, 55, 56-----	
Copper-----	105, 106, 107-----	
Phosphorus bronze	70, 71, 72-----	
Silicon bronze--	48, 49, 69-----	
Wall Colmonoy 6 on SS 347	57, 58, 74, 75-----	
Inconel-X-----	60, 66, 67, 76, 81, 89	11, 21, 22, 23, 25, 29, 38
K-Monel-----	-----	19, 24
KR-Monel-----	44, 45, 46, 50-----	
Mumetal-----	87, 105-----	
Nickel-----	73-----	34, 43C
Refractaloy 26--	125-----	4
Haynes alloy 25--	45, 47, 57, 62, 63, 64, 65, 69, 72, 76, 78, 86, 109, 110, 113, 129, 132	8, 20, 24, 28, 29, 36, 37, 39, 43, 43E, 43F, 43G, 43A

COUPLE INDEX—Continued

Material	Couple No.	
	200° F	500° F
Refractaloy 120	126	5
Stellite 3	46, 51, 52, 53, 54, 59, 63, 67, 75, 80, 91, 97, 98, 102, 110, 112, 123	2, 14, 18, 38, 39, 43D
Stellite 6	66, 79, 84, 96, 100, 104, 114, 122	1, 11, 13, 15, 33, 35, 42
Vascoloy-Ramet 171	118	

COUPLE INDEX—Continued

Material	Couple No.	
	200° F	500° F
Graphitar 14	61, 65, 83, 92, 94, 116, 117, 130	9
Permo #511	51	
Permo #11	53	
Permo #K-75	52	
Permo #116	54	
Tantung G	118, 119, 121	

RESULTS ON PRELIMINARY CONTACT CORROSION TESTS

Couple No.	Materials in contact	500° F corrosion remarks	
		14-day test	44-day test
*1	SS 347 chrome plated	Moderate buildup	Heavy buildup, deposit on contact surface
	Stellite 6	Very slight buildup	Moderate buildup, deposit on contact surface
*2	Stellite 3	Slight buildup	Moderate buildup, deposit on contact surface
	SS 347 chrome plated	Same	Heavy buildup, deposit on contact surface
*3	Z-rolled SS 347	Slight buildup	Moderate buildup, sample cracked
	SS 347 chrome plated	Moderate buildup	Heavy buildup
*4	Refractaloy 26	Very slight buildup	Heavy buildup
	Armco 17-4PH chrome plated	Moderate buildup	Same
*5	Refractaloy 120	Slight buildup	Slight buildup
	SS 304 chrome plated	Same	Moderate buildup
6	Armco 17-4PH nitrided	Heavy buildup	
	Armco 17-4PH nitrided	Same	
*7	SS 440C chrome plated	Moderate buildup	
	Armco 17-4PH nitrided	Same	

See footnotes on p. 185.

RESULTS ON PRELIMINARY CONTACT CORROSION TESTS—Continued

Couple No.	Materials in contact	500° F corrosion remarks	
		14-day test	44-day test
8	Armco 17-4PH nitrided	Moderate buildup	
	Haynes alloy 25	Same	
9	Graphitar 14	Moderate buildup	
	Armco 17-4PH nitrided	Heavy buildup	
10	USS 18-8W	Moderate buildup, slight deposit on contact surface	Moderate buildup
	USS 18-8W nitrided	Same	Slight buildup, corner of case badly corroded
11	Inconel-X	Very slight buildup	Very slight buildup, mostly discoloration
	Stellite 6	Same	Same
12	SS 347	Moderate buildup	Moderate buildup
	USS 18-8W nitrided	Heavy buildup, slight deposit on surface	Heavy buildup
13	Stellite 6	Moderate buildup	Moderate buildup
	USS 18-8W	Same	Slight buildup
14	USS 18-8W	Moderate buildup, corner of case badly corroded	Heavy buildup, corner of case badly attacked
	Stellite 3	Slight buildup	Slight buildup
15	SS 347	Slight buildup	Slight buildup
	Stellite 6	Discoloration on contact edge	Moderate buildup
16	SS 304	Moderate buildup	Moderate buildup
	USS 18-8W nitrided	Moderate buildup, corner of case badly corroded	Moderate buildup, corner of case badly corroded
17	SS 347	Heavy buildup	Moderate buildup
	USS 18-8W	Moderate buildup	Moderate buildup
18	USS 18-8W	Moderate buildup	Moderate buildup
	Stellite 3	Very slight buildup, mostly discoloration	Very slight buildup, mostly discoloration

RESULTS ON PRELIMINARY CONTACT CORROSION TESTS—Continued

Couple No.	Materials in contact	500° F corrosion remarks	
		14-day test	44-day test
19	K-Monel	Moderate buildup	Very slight buildup
	Armco 17-4PH	Slight buildup	Slight buildup
20	USS 18-8W nitrided	Slight buildup, corner of case badly corroded	Slight buildup, corner of case badly corroded
	Haynes alloy 25	Slight buildup	Slight buildup
21	SS 347	Slight buildup	Slight buildup
	Inconel-X	Very slight buildup	Slight buildup
22	USS 18-8W nitrided	Moderate buildup	Moderate buildup
	Inconel-X	Same	Moderate buildup
23	Inconel-X	Slight buildup	Slight buildup
	SS 304	Moderate buildup	Moderate buildup
24	K-Monel	Slight buildup	Slight buildup, green corrosion product in stamped number
	Haynes alloy 25	Very little buildup, mostly discoloration	Very slight buildup
25	USS 18-8W	Slight buildup	Slight buildup
	Inconel-X	Same	Same
26	Armco 17-4PH	Very slight buildup, considerable force required to separate couple, large patches of bare metal on contact surface	Moderate buildup, couple not stuck
	Armco 17-4PH	Same	Same
27	SS 304	Moderate buildup	Moderate buildup
	USS 18-8W	Same	Same
28	Haynes alloy 25	Moderate buildup	Very slight buildup
	SS 347	Same	Same
29	Inconel-X	Slight buildup	Very slight buildup
	Haynes alloy 25	Same	Same

RESULTS ON PRELIMINARY CONTACT CORROSION TESTS—Continued

Couple No.	Materials in contact	500° F corrosion remarks	
		14-day test	44-day test
30	USS 18-8W	Moderate buildup, couple stuck, large patch of bare metal	Slight buildup, couple very lightly stuck
	Armco 17-4PH	Slight buildup, numerous small patches of bare metal	Same
31	Armco 17-4PH	Slight buildup	Moderate buildup
	SS 304	Same	Same
*32	Teflon impregnated with asbestos	Maintained original appearance, surface was oily	
	SS 347 chrome plated	No buildup on surface	
33	Stellite 6	27-day test: moderate buildup	
	Stellite 6	Same	
34	Nickel	7-day test: severe pitting along outer edge of contact surface	37-day test: severe pitting along outer edge of contact surface
	SS 347	Very slight buildup, mostly discoloration	Slight buildup
35	USS 18-8W nitrided	Moderate buildup	Heavy buildup
	Stellite 6	Same	Moderate buildup
36	Haynes alloy 25	Moderate buildup	Slight buildup
	SS 304	Same	Moderate buildup
37	USS 18-8W	Slight buildup	Moderate buildup
	Haynes alloy 25	Same	Very slight buildup
38	Inconel-X	Very little buildup, mostly discoloration	Very slight buildup
	Stellite 3	Slight buildup	Same
39	Haynes alloy 25	Slight buildup	Slight buildup
	Stellite 3	Same	Same
40	SS 347	Moderate buildup	Moderate buildup
	SS 304	Same	Same

RESULTS ON PRELIMINARY CONTACT CORROSION TESTS—Continued

Couple No.	Materials in contact	500° F corrosion remarks	
		14-day test	44-day test
41	SS 347	Moderate buildup	Moderate buildup
	Armco 17-4PH	Same	Same
42	SS 304	Moderate buildup	Heavy buildup
	Stellite 6	Same	Same
43	Haynes alloy 25	Moderate buildup	Slight buildup
	Armco 17-4PH	Same	Same
*43A	Haynes alloy 25	27-day test: moderate buildup	
	USS 18-8W chrome plated	Same	
†43B	SS 410	34-day test: heavy buildup, pitting on contact surface	
	SS 347	Heavy buildup	
†43C	SS 347	34-day test: heavy buildup	
	Nickel	Heavy buildup, pitting on contact surface	
†43D	USS 18-8W	34-day test: Moderate buildup	
	Stellite 3	Slight buildup, black spots on contact surface	
†43E	Armco 17-4PH	34-day test: moderate buildup	
	Haynes alloy 25	Same	
†43F	USS 18-8W	34-day test: moderate buildup	
	Haynes alloy 25	Slight buildup	
†43G	USS 18-8W nitrided	34-day test. heavy buildup	
	Haynes alloy 25	Slight buildup	
44	KR-Monel	Slight buildup; mostly discoloration, pitting on contact surface	
	Armco 17-4PH	Slight buildup	

RESULTS ON PRELIMINARY CONTACT CORROSION TESTS—Continued

Couple No.	Materials in contact	500° F corrosion remarks	
		14-day test	44-day test
45	KR-Monel	Slight buildup	
	Haynes alloy 25	Slight buildup, mostly discoloration	
46	KR-Monel	Slight buildup, pitting on contact surface	
	Stellite 3	Slight buildup, mostly discoloration	
47	Aluminum bronze	Slight buildup, possible pitting on contact surface	
	Haynes alloy 25	Slight buildup, mostly discoloration	
48	Silicon bronze	Moderate buildup	
	USS 18-8W	Slight buildup	
49	Silicon bronze	Moderate buildup, pitting on contact surface	
	SS 410	Heavy buildup	
50	KR-Monel	Slight buildup, heavy pitting on contact surface.	
	Armco 17-4PH	Slight buildup, mostly discoloration	
51	Stellite 3	Slight buildup, mostly discoloration	
	Permo 511	Same	
52	Stellite 3	Slight buildup, mostly discoloration	
	Permo K-75	Same	
53	Stellite 3	Slight buildup, mostly discoloration	
	Permo 11	Slight buildup, pitting on contact surface	
54	Stellite 3	Slight buildup, mostly discoloration	
	Permo 116	Slight buildup, mostly discoloration, pitting on contact surface	
55	Aluminum bronze	Moderate buildup, pitting on contact surface	
	USS 18-8W	Slight buildup, mostly discoloration	

RESULTS ON PRELIMINARY CONTACT CORROSION TESTS—Continued

Couple No.	Materials in contact	500° F corrosion remarks	
		14-day test	44-day test
56	Aluminum bronze	Moderate buildup, possible signs of pitting on contact surface	
	SS 410	Heavy buildup, pitting on contact surface	
57	Wall Colmonoy 6 on SS 347	Slight buildup §	
	Haynes alloy 25	Slight buildup, mostly discoloration	
58	Wall Colmonoy 6 on SS 347	Slight buildup §	
	SS 410	Moderate buildup	
*59	SS 304 chrome plated	Slight buildup, mostly discoloration	
	Stellite 3	Same	
*60	SS 304 chrome plated	Slight buildup, mostly discoloration	
	Inconel-X	Slight buildup, signs of possible pitting on contact surface	
*61	SS 304 chrome plated	Slight buildup, mostly discoloration	
	Graphitar 14	Very slight buildup	
*62	Haynes alloy 25	Slight buildup, mostly discoloration	
	SS 304 chrome plated	Slight buildup	
63	Haynes alloy 25	Slight buildup, mostly discoloration	
	Stellite 3	Same	
64	Haynes alloy 25	Slight buildup, mostly discoloration	
	Armco 17-4PH	Same	
65	Haynes alloy 25	Slight buildup, mostly discoloration	
	Graphitar 14	Same	
66	Inconel-X	Slight buildup, mostly discoloration, pitting on contact surface	
	Stellite 6	Slight buildup, mostly discoloration	

RESULTS ON PRELIMINARY CONTACT CORROSION TESTS—Continued

Couple No.	Materials in contact	500° F corrosion remarks	
		14-day test	44-day test
67	Inconel-X	Slight buildup, mostly discoloration, signs of pitting	
	Stellite 3	Slight buildup, mostly discoloration	
68	SS 347	Moderate buildup	
	SS 304	Slight buildup	
69	Silicone bronze	Moderate buildup, pitting on contact surface	
	Haynes alloy 25	Slight buildup, mostly discoloration	
70	Phosphorus bronze	Moderate buildup, pitting on contact surface	
	USS 18-8W	Slight buildup, mostly discoloration	
71	Phosphorus bronze	Moderate buildup, pitting on contact surface	
	SS 410	Moderate buildup	
72	Phosphorus bronze	Moderate buildup, pitting on contact surface	
	Haynes alloy 25	Slight buildup, mostly discoloration	
73	Nickel	Moderate buildup, heavy pitting on contact surface	
	SS 347	Moderate buildup	
74	Wall Colmonoy 6 on SS 347	Slight buildup, mostly discoloration §	
	USS 18-8W	Same	
75	Wall Colmonoy 6 on SS 347	Slight buildup, mostly discoloration §	
	Stellite 3	Slight buildup	
76	Inconel-X	Slight buildup, pitting on contact surface	
	Haynes alloy 25	Slight buildup, mostly discoloration	

RESULTS ON PRELIMINARY CONTACT CORROSION TESTS—Continued

Couple No.	Materials in contact	500° F corrosion remarks	
		14-day test	44-day test
77	USS 18-8W	Moderate buildup	
	Armco 17-4PH	Same	
78	USS 18-8W	Moderate buildup	
	Haynes alloy 25	Slight buildup	
79	USS 18-8W	Slight buildup, mostly discoloration	
	Stellite 6	Same	
80	USS 18-8W	Slight buildup	
	Stellite 3	Slight buildup, mostly discoloration	
81	USS 18-8W	Moderate buildup	
	Inconel-X	Slight buildup, pitting on contact surface	
82	USS 18-8W	Moderate buildup	
	SS 304 chrome plated	Slight buildup	
83	USS 18-8W	Slight buildup, mostly discoloration	
	Graphitar 14	Slight buildup	
84	SS 347	Moderate buildup	
	Stellite 6	Same	
85	SS 347	Slight buildup, mostly discoloration	
	Armco 17-4PH	Same	
86	SS 347	Moderate buildup	
	Haynes alloy 25	Slight buildup, mostly discoloration	
87	Mumetal	Slight buildup	
	SS 347	Same	
88	SS 347	Slight buildup, mostly discoloration	
	USS 18-8W	Same	

RESULTS ON PRELIMINARY CONTACT CORROSION TESTS—Continued

Couple No.	Materials in contact	500° F corrosion remarks	
		14-day test	44-day test
89	SS 347	Slight buildup, mostly discoloration	
	Inconel-X	Slight buildup, possible pitting on contact surface	
*90	SS 347	Slight buildup, mostly discoloration	
	SS 304 chrome plated	Same	
91	SS 347	Moderate buildup	
	Stellite 3	Slight buildup, mostly discoloration	
92	SS 347	Slight buildup, mostly discoloration	
	Graphitar 14	Slight buildup, deposit on contact surface	
93	Armco 17-4PH	Slight buildup, mostly discoloration	
	Armco 17-7PH	Same	
94	Armco 17-4PH	Slight buildup, mostly discoloration	
	Graphitar 14	Slight buildup	
*95	Armco 17-4PH	Slight buildup	
	SS 304 chrome plated	Same	
96	Armco 17-4PH	Slight buildup	
	Stellite 6	Slight buildup, mostly discoloration	
97	Armco 17-4PH	Moderate buildup	
	Stellite 3	Slight buildup, mostly discoloration	
98	SS 420	Heavy buildup, pitting on contact surface.	
	Stellite 3	Slight buildup	
99	SS 420	Moderate buildup, pitting on contact surface	
	Armco 17-4 PH	Slight buildup	

RESULTS ON PRELIMINARY CONTACT CORROSION TESTS—Continued

Couple No.	Materials in contact	500° F corrosion remarks	
		14-day test	44-day test
100	SS 420	Heavy buildup, pitting on contact surface	
	Stellite 6	Slight buildup, mostly discoloration	
101	SS 420	Heavy buildup, contact surface pitted	
	SS 347	Moderate buildup	
102	SS 410	Heavy buildup, pitting on contact surface.	
	Stellite 3	Slight buildup	
103	SS 410	Moderate buildup, pitting on contact surface	
	Armco 17-4PH	Moderate buildup	
104	SS 410	Moderate buildup, pitting on contact surface	
	Stellite 6	Slight buildup, mostly discoloration	
105	Mumetal	Slight buildup, mostly discoloration	
	Copper	Slight buildup, pitting on contact surface	
106	Copper	Moderate buildup, pitting on contact surface	
	SS 410	Heavy buildup, pitting on contact surface	
107	Copper	Slight buildup, pitting on contact surface	
	SS 347	Slight buildup, mostly discoloration	
108	SS 347	Slight buildup	
	SS 410	Moderate buildup, pitting on contact surface	
109	SS 420	Heavy buildup	
	Haynes alloy 25	Slight buildup, mostly discoloration	

RESULTS ON PRELIMINARY CONTACT CORROSION TESTS—Continued

Couple No.	Materials in contact	500° F corrosion remarks	
		14-day test	44-day test
110	Stellite 3	Slight buildup, mostly discoloration	
	Haynes alloy 25	Same	
111	SS 440C	Heavy buildup, signs of pitting on contact surface	
	Armco 17-4PH	Moderate buildup	
112	SS 440C	Moderate buildup	
	Stellite 3	Slight buildup, mostly discoloration	
113	SS 440C	Heavy buildup, signs of pitting on contact surface	
	Haynes alloy 25	Slight buildup, mostly discoloration	
114	SS 440C	Moderate buildup, pitting on contact surface	
	Stellite 6	Slight buildup, mostly discoloration	
115	SS 440C	Heavy buildup, possible signs of pitting	
	SS 347	Slight buildup	
116	SS 440C	Very slight buildup, pitting on contact surface	
	Graphitar 14	Moderate buildup	
117	SS 410	Slight buildup, pitting on contact surface	
	Graphitar 14	Slight buildup, possible pitting on contact surface	
118	Tantung G	Slight buildup, mostly discoloration	
	Vascolloy-Ramet 171	Same	
119	Tantung G	Slight buildup	
	Armco 17-4PH	Same	
1120	Armco 17-4PH nitrided	Heavy buildup	
	Armco 17-4PH nitrided	Same	

RESULTS ON PRELIMINARY CONTACT CORROSION TESTS—Continued

Couple No.	Materials in contact	500° F corrosion remarks	
		14-day test	44-day test
121	Tantung G	Slight buildup, mostly discoloration	
	USS 18-8W	Same	
*¶ 122	SS 332 chrome plated	Slight buildup, mostly discoloration	46-day test: slight buildup, mostly discoloration
	Stellite 6	Same	Same
*¶ 123	SS 347 chrome plated	Discoloration on contact edge	46-day test: moderate buildup
	Stellite 3	Same	Slight buildup, mostly discoloration
*¶ 124	SS 347 chrome plated	No corrosion observed	46-day test: moderate buildup
	Z-rolled SS 304	Same	Slight buildup
*¶ 125	SS 304 chrome plated	No corrosion observed	Slight buildup
	Refractaloy 26	Same	Same
*¶ 126	SS 304 chrome plated	No corrosion observed	46-day test: slight buildup, mostly discoloration
	Refractaloy 120	Same	Same
¶ 127	SS 410	7-day test: slight buildup	
	SS 347	Slight buildup, mostly discoloration	
128	SS 410	Heavy buildup	
	SS 440 C	Same	
¶ 129	Armco 17-4PH nitrided	Heavy buildup	
	Haynes alloy 25	Slight buildup	
¶ 130	Graphitar 14	Heavy buildup	
	Armco 17-4PH nitrided	Same	
*¶ 131	440C chrome plated	slight buildup	
	Armco 17-4PH nitrided	Heavy buildup	
132	SS 410	Slight buildup, pitting on contact surface	
	Haynes alloy 25	Slight buildup, mostly discoloration	

*The thickness of the chromium plate was 5 mils.

†Each material in the couple was exposed to 200° F oxygenated water for 7 days to provide an oxide coating, after which, the samples were coupled with the pretreatment oxide and tested for 34 days.

‡Each sample in the couple was exposed to 500° F oxygenated water for

41 days to provide an oxide coating, after which, the samples were coupled with the pretreatment oxide and tested for 34 days.

§Owing to the porosity of Wall Colmonoy 6 samples, it was difficult to determine whether pitting had occurred.

¶Conducted in static autoclave tests.

Chapter 10

STRESS CORROSION

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Section I		Section II	
	Page		Page
INTRODUCTION.....	187	LABORATORY TESTS.....	191
GENERAL PREVENTIVE MEASURES.....	188	Apparatus and Procedures.....	191
DETAILS ON EFFECTS OF VARIABLES AND CON- TROL MEASURES.....	188	Tests in Primary Water Systems.....	192
Austenitic Stainless Steels in High-Purity Water.....	188	Tests in Secondary Steam-Water Systems.....	196
Austenitic Stainless Steels in Chloride- Bearing Water.....	188	AUXILIARY BOILER EXPERIENCE.....	211
Ferritic and Martensitic Stainless Steels.....	190	STRESS CORROSION FAILURES IN MODEL HEAT EXCHANGERS.....	214
Precipitation-Hardening Stainless Steels.....	191	INDUSTRIAL EXPERIENCE.....	219
Nickel-Base Alloys.....	191		
Other Materials.....	191		

SECTION I—ENGINEERING CONSIDERATIONS

INTRODUCTION

Stress corrosion is that type of corrosive attack which occurs through the combined action of stress and a corrosive environment. The stress can be applied or residual, but it is always a tensile stress. The aggressiveness of the corrosive environment required to cause cracking may vary for different materials. The environment may be exceedingly mild, producing little or no corrosive attack in the absence of stress. However, the same environment may cause localized attack (cracks) with the same material in the stressed condition. In very corrosive environments cracking may occur in the same material at much lower stress levels.

Stress corrosion attack takes the form of cracks which grow slowly or rapidly, depending on environmental conditions. The cracks

may be intergranular, transgranular, or a combination of both.

Many factors affect the occurrence and rate of stress corrosion. Among these are the stress level, the nature of the corrosive agent, the time and temperature of exposure, the structure of the material, the amount of plastic strain, the behavior of protective films on the material, and perhaps others. These points are discussed in the published literature. For a more thorough study of the subject, the reader is referred to selected references listed at the end of the chapter, particularly the following: (1) the general problem, references 1 to 6; (2) ferritic steels, references 5, and 7 to 18; (3) nickel-base alloys, references 4, 6, and 19; (4) austenitic stainless steels, references 20 to 29; and (5) stress corrosion theories, references 30 to 35.

Stress corrosion can be caused by two corrosive media in nuclear powerplants. One is the high-purity water in the primary coolant system of water-cooled nuclear reactors. The other is the boiler water in the secondary steam generation system. In addition, the action of these waters can vary according to whether or not a material is exposed in the liquid phase or the vapor phase.

GENERAL PREVENTIVE MEASURES

Except for a few specialty items, such as materials of spring temper, stress corrosion is not known to be a problem in primary water systems. The few problems that do exist apparently can be circumvented without much difficulty by the proper selection of materials and their heat treatments.

The main stress corrosion problem has come about through the use of austenitic stainless steels in the secondary steam generation system. The boiler water in the secondary system can contain chlorides, and most stress corrosion failures of austenitic stainless steels have been associated with chloride-bearing environments.

An obvious method of overcoming the stress corrosion problem would be to construct the secondary system of conventional boiler materials, i. e., ferritic steels. However, if stainless steels are used for the primary system, a transition from austenitic to ferritic steels between the primary and secondary systems would introduce complicated design and fabrication problems.

Much can be accomplished toward the reduction or elimination of stress corrosion in austenitic stainless steels by the use of annealed steels, stabilized steels, and stress relief treatments and by keeping design and operating stresses as low as possible. But these alone are not always enough. Positive control can be realized only by employing special means to inactivate the corrosiveness of the boiler water.

It appears that stress corrosion of austenitic grades of stainless steel can be effectively

inhibited in the liquid phase of ordinary boiler waters by an alkaline-phosphate water treatment similar to that used in conventional naval boilers. However, this treatment is not effective in the steam phase, and it is here that more extreme methods of control must be exercised.

The most critical areas in the steam phase are those in which the equipment is subjected to intermittent wetting and drying. This can come about above the water level by splashing, carryover, etc. Nevertheless highly critical areas can also exist below the water level. Zones which are especially vulnerable exist in crevices formed by tube joints and under corrosion deposits, wherein local hot spots can develop and the water can flash to steam. The intermittent wetting and drying leads to the concentration of boiler water constituents (and chlorides), thereby creating a local aggressive medium in an otherwise mild environment.

Experiments have demonstrated that both chloride and oxygen must be present for stress corrosion of austenitic stainless steels to occur in boiler environments. Keeping the chloride content at a very low average level is helpful, but is not foolproof under conditions where local concentration can occur. Therefore, the most effective guard against stress corrosion in the secondary system is to keep the oxygen at the lowest possible level. The use of oxygen scavengers may be necessary.

DETAILS ON EFFECTS OF VARIABLES AND CONTROL MEASURES

Austenitic Stainless Steels in High-purity Water

The stress corrosion behavior of austenitic stainless steels in primary waters has not been explored as extensively as might be desired. However, the evidence shows that stress corrosion cracking is not a problem in the major structural components of primary systems. Such components would be fabricated from mill-annealed material, and stresses from fabrication and service, even if beyond the yield strength, should not cause stress corrosion.

On the other hand, heavy cold working of these steels induces susceptibility to stress corro-

sion in primary waters, particularly oxygen-bearing waters. On this basis, austenitic stainless steels are not recommended for use as springs or any other specialty item in which the material is to be strengthened by intentional cold working. In some applications, such as bolts a small amount (10 percent) of cold working can be tolerated.

Austenitic Stainless Steels in Chloride-bearing Water

The stress corrosion behavior of austenitic stainless steels in secondary steam-water environments is a considerably more critical problem, mainly because of the quantities of chlorides which can be encountered in steam generation systems. This is especially true in naval boilers, where the feed water is cooled with sea water, which usually causes contamination by condenser leakage.

The austenitic stainless steels as a class appear to be susceptible to stress corrosion cracking in high-temperature chloride water environments. Some compositions are found to be more resistant than others. AISI types 304, 316, and 347 are considered to be among the more susceptible alloys. However, insufficient work has been done to enable listing the numerous alloys in a reliable order of relative resistance.

Stress corrosion is characterized by cracking of a predominantly transgranular nature, but intergranular failures have also been observed. Sensitivity to intergranular corrosion is not necessary for transgranular stress corrosion to occur. However, sensitized alloys can fail by stress corrosion cracks following an intergranular path.

Transgranular stress corrosion cracks can vary in appearance from single, relatively straight cracks to highly branched, fingerlike crack networks. Stress corrosion cracks usually start at corrosion pits, but it cannot be concluded that all environments leading to corrosion pits will also ultimately lead to stress corrosion cracks.

Stabilization of the austenite by a moderate increase of nickel content (such as in AISI

types 305 and 316) does not prevent stress corrosion, although it probably does increase resistance to cracking.

Austenitic chromium-manganese steel is considered to be as susceptible to cracking as the austenitic chromium-nickel grades.

The section thickness has no noticeable effect on susceptibility to cracking.

Applied stresses as low as 5,000 psi can cause stress corrosion of annealed steel under ideal conditions. Residual stresses from tube rolling, cold forming, welding, and even cleaning with emery cloth may be sufficient to cause failure in environments conducive to stress corrosion.

The temperature of the environment does not have to be high. Information from laboratory and pilot-plant tests and other industrial sources would indicate that stress corrosion can occur at temperatures as low as the boiling point of water, and probably even lower. Although stress corrosion increases with temperature, quantitative data are not available.

Stress corrosion can occur rapidly under highly conducive conditions. Specimens have been observed to fail within 20 min at 500° F (plus heating and cooling time).

Stress corrosion of austenitic stainless steels can occur in uninhibited water with a moderately low chloride content. Specimens immersed in oxygen-bearing water with 300 ppm chloride are readily cracked. Similar tests in chloride-free water did not result in cracks. The region below 300 ppm chloride has not been explored sufficiently to determine whether or not some threshold level exists (other than zero) below which stress corrosion will not occur with specimens exposed in the liquid phase.

The stress corrosion of austenitic stainless steels submerged in chloride-bearing waters of practical interest apparently can be prevented by alkaline-phosphate water treatment, provided the steels are in the mill-annealed condition at the time of fabrication and provided sensitization does not occur from welding or operating temperatures. Tests of AISI type 304 steel indicate that sensitization of unstabilized alloys can lead to failure by inter-

granular stress corrosion cracking in low oxygen alkaline-phosphate treated water, except possibly when the chloride content is kept very low.

Austenitic stainless steels exposed in the steam phase of chloride-bearing water and intermittently wetted (in tests, by inversion of the pressure vessel) are susceptible to stress corrosion cracking at very low chloride contents. Cracks were produced readily under these circumstances with water containing as little as 1 ppm chloride.

It is not known whether the extreme sensitivity to cracking in the steam phase is due to some reactive characteristic of the vapor not present in the water or to a concentration of the water constituents through the alternate wetting and drying process. However, the evidence favors the latter explanation. One test in the vapor without intermittent wetting did not result in cracks.

Alkaline-phosphate water treatment does not inhibit the stress corrosion of austenitic stainless steels in the steam phase of secondary system waters.

Oxygen is a strong accelerator of stress corrosion of austenitic stainless steels in hot-water environments. In fact, the evidence indicates that some oxygen is necessary for stress corrosion to occur. The necessary amount is small. It is believed that maintenance of oxygen at some value below 1 ppm* (probably 0.5 ppm in critical areas) will provide reasonable assurance against stress corrosion failures at chloride levels likely to be encountered in steam generation equipment.

The maintenance of low oxygen might not be an entirely satisfactory method of preventing intergranular stress corrosion in unstabilized sensitized steel, such as AISI type 304. However, no problem of this sort is anticipated with stabilized steel, such as AISI type 347.

Inhibitors offer some promise for the control of stress corrosion in the vapor phase. It is

*Although the standard practice in this handbook is to express oxygen as cubic centimeters per kilogram of water (STP) or cc/kg, because of its common usage in boiler water technology, parts per million or ppm was retained in this chapter.

probable that any successful inhibitor will have oxygen scavenging characteristics. Sulfite treatment has shown considerable promise.

There is some indication that stress corrosion of austenitic stainless steel may be controlled by suitable galvanic couples, however, this aspect has not been explored sufficiently to be of practical use at this time.

The tests of the austenitic stainless steels, covered in section II, were conducted for the most part under severe stress and environmental conditions. This was done purposely to detect susceptibility to stress corrosion within reasonable testing times. Thus, the high percentage of test specimen failures does not, in itself, indicate that service failures will occur in epidemic proportions. The principal value of the tests was to point to the need for extreme caution in the design and operation of equipment in which austenitic stainless steels are used in contact with high-temperature waters, and especially the steam phase of such waters. Much can be accomplished by proper design and by operation of equipment within safe limits. The use of annealed steels, stress relief treatments, stabilized grades, low operational stresses, low chloride levels, low oxygen levels, and proper corrosion inhibitors are all important steps toward the elimination of stress corrosion hazards.

Ferritic and Martensitic Stainless Steels

The ferritic stainless steels and the martensitic stainless steels at low hardness levels probably are immune to stress corrosion cracking in the high-temperature water environments associated with primary and secondary systems. This conclusion is based on limited tests which did not include studies of processing variables such as welding or cold rolling.

The martensitic stainless steels heat treated to high hardness levels (probably above Rockwell C-30) are susceptible to cracking, as demonstrated by the failure of coil springs in primary waters. Judging from published work of other investigators, the hardened steels

apparently fail because of sensitivity to hydrogen embrittlement.

Precipitation-hardening Stainless Steels

Limited tests of precipitation-hardened stainless steels indicate susceptibility to stress corrosion in high-temperature waters similar to, and perhaps greater than, the austenitic stainless steels. The precipitation-hardened steels are not suitable for springs in primary waters.

Nickel-base Alloys

Miscellaneous tests of the nickel-base alloys

listed in table 9 indicate immunity to stress corrosion cracking in primary and secondary water environments. The only failures observed were those of alloys I and K in 550° F. sea water (20,000 ppm chloride). Alloy J is indicated as a suitable spring material for exposure to primary waters.

Other Materials

Limited tests of carbon steel, titanium, copper-nickel 90-10 and copper-nickel 70-30 did not reveal stress corrosion cracking in environments which would have led to cracking of austenitic stainless steels.

SECTION II—SPECIAL INVESTIGATIONS AND SERVICE EXPERIENCE

LABORATORY TESTS

Numerous laboratory tests have been conducted to help define the conditions under which stress corrosion cracking will or will not occur in high-temperature waters. Most of the tests were conducted on the austenitic stainless steels, especially AISI types 304 and 347. However, limited data were gathered on other materials as well.

The data presented below are arranged, insofar as possible, to illustrate the effects of the several variables associated with conditions likely to exist in primary coolant systems and secondary steam-water systems of water-cooled nuclear reactors.

Apparatus and Procedures

The laboratory stress corrosion tests are conducted at elevated temperatures in stainless steel pressure vessels. Two basic test systems are used. One is a hydraulic loop, which is a semi-closed system through which high-temperature water can be circulated past the corrosion specimens. Circulation is provided by a stainless steel "canned rotor" pump.

The second system utilizes autoclaves to contain the specimens. Such a vessel can be

used either for static exposure or for dynamic exposure by utilizing some form of external drive to rotate the specimens in the water. The liquid level is usually maintained at one-half to two-thirds full, and the specimens are exposed in either the steam phase or the water phase, or both alternately.

Waters of known composition, including gas content, are used as corrosive media. It should be pointed out that the composition of these media can change during the course of some of the experiments, particularly in the case of the autoclave tests where the volume of the water is relatively small and is not replenished continuously. Composition changes have been noted especially in regard to the oxygen content since the oxygen is sometimes scavenged by reaction with the specimens or with the pressure vessel itself.

The majority of the tests have been made with specimens basically similar to those shown in figure 10-1.

The U-bend specimens were used to determine susceptibility to stress corrosion under severe stress conditions. The simple beam specimens were used for tests at lower stress levels, especially when the stress level was of interest as a variable under study.

Other specimens and special environments were used in some cases. These are described, as necessary, along with the corresponding test results.

FIGURE 10-1. Basic stress corrosion specimens used in the majority of the laboratory tests.

Tests in Primary Water Systems

GENERAL

Primary coolant waters are characterized by their relatively high purity. The high-purity water used in the following experiments is defined as water having a total solids content of less than 1 ppm and a resistivity of at least 500,000 ohm-cm. Such water is prepared by distillation and deionization. A gas of interest (usually oxygen) is added in most cases.

So far, annealed austenitic stainless steels have been used exclusively for the construction of the main elements of primary coolant systems. Although these materials are not likely to stress-corrode in primary waters (except possibly under very special circumstances) specialty items, such as springs, present a more difficult problem. Much of the experimental work which follows has been directed toward the selection of suitable spring materials.

AUSTENITIC STAINLESS STEELS

Numerous tests in primary waters have been made with simple beam specimens made of

austenitic stainless steels. Four conditions of treatment have been considered: (1) annealed, (2) cold worked, (3) cold worked and annealed, and (4) sensitized 2 hr at 1,200° F. The results of these tests are summarized in table 10-1.

It is noteworthy that the two AISI type 304 specimens not cold worked prior to annealing and stressing did not crack when tested at 500° F. In contrast, over half of those cold worked, annealed and stressed did crack when tested at 600° F in oxygen-bearing water. The 600° F tests in hydrogen-bearing water (with less than 0.5 ppm oxygen) did not result in failure.

The effects of the many variables that might influence the stress corrosion behavior of austenitic stainless steels in primary waters have certainly not been explored as extensively as might be desired. However, it is believed that no particular difficulties will arise in actual equipment as long as fabrication is limited to hot rolled-annealed steels. On the other hand, there is sufficient evidence to indicate that austenitic steels should not be used for springs in primary waters because the spring temper material is obtained by intentional heavy cold working.

There remains the possibility that stress corrosion failure might occur in unexpected cases. At least one interesting case has been observed. Leaks developed in two sections of ¼-in. AISI type 347 stainless-steel tubing installed at orifice meters in a hydraulic test loop. The tubing apparently was obtained in the mill-annealed condition but was worked by severe cold bending during fabrication of the loop. Installation was in an area where the tubing could have been exposed to water vapor as well as to the water itself.

Failure developed after the loop had been operated 1,550 hr at 600° F and 4,200 hr at 500° F. At various times the water in the system had been degassed or had contained either 1 to 5 or 20 to 30 ml of oxygen per kilogram of water (STP) (cc/kg). A typical cross section of the failed tubing is shown in figure 10-2. Similar tubes on other loops have not failed, and the reason for this particular casualty has not been determined.

TABLE 10-1

AUTOCLAVE STRESS CORROSION TESTS IN PRIMARY WATERS WITH SIMPLE BEAM SPECIMENS
OF AISI AUSTENITIC STAINLESS STEELS

Water conditions			AISI type	Condition	Stress, psi	Test time, days	Stress corrosion cracks
Temp., ° F	Gas content	Velocity,* ft/sec					
500	5-10 ppm O ₂ -----	0	302	Annealed-----	10,000	90	No
500	do-----	0	302	do-----	30,000	90	No
500	do-----	0	302	do-----	† > YP	90	No
500	do-----	0	302	Sensitized 2 hr, 1,200° F--	10,000	90	No
500	do-----	0	302	do-----	30,000	90	No
500	do-----	0	302	do-----	† > YP	90	No
500	0.5-4.6 ml/liter O ₂ -----	11	304	Annealed-----	30,400	30	No
500	20-30 ml/liter O ₂ -----	11	304	do-----	30,400	120	No
600	5-10 ppm O ₂ -----	0	304	Cold worked 10%, annealed.	30,000	74	Yes
600	do-----	0	304	do-----	50,000	74	Yes
600	do-----	0	304	Cold worked 50%, annealed.	30,000	74	Yes
600	do-----	0	304	do-----	50,000	74	No
600	do-----	0	304	Cold worked 10%-----	60,000	74	Yes
600	do-----	0	304	do-----	80,000	74	Yes
600	do-----	0	304	Cold worked 20%-----	70,000	30	No
600	do-----	0	304	do-----	90,000	74	Yes
600	do-----	0	304	Cold worked 30%-----	95,000	30	Yes
600	do-----	0	304	do-----	110,000	30	No
600	do-----	0	304	Cold worked 40%-----	110,000	30	No
600	do-----	0	304	do-----	125,000	30	Yes
600	do-----	0	304	Cold worked 50%-----	130,000	30	No
600	do-----	0	304	do-----	150,000	30	No
600	200 ml/liter H ₂ -----	0	304	Cold worked 10%-----	60,000	38	No
600	do-----	0	304	do-----	80,000	38	No
600	do-----	0	304	Cold worked 20%-----	70,000	38	No
600	do-----	0	304	do-----	90,000	38	No
600	do-----	0	304	Cold worked 30%-----	95,000	38	(‡)
600	do-----	0	304	do-----	110,000	38	(‡)
600	do-----	0	304	Cold worked 40%-----	110,000	38	No
600	do-----	0	304	do-----	125,000	38	(‡)
600	do-----	0	304	Cold worked 50%-----	130,000	38	No
600	do-----	0	304	do-----	150,000	38	No
500	0.5-4.6 ml/liter O ₂ -----	11	310	Annealed-----	29,800	30	No
500	20-30 ml/liter O ₂ -----	11	310	do-----	29,800	120	No
500	0.5-4.6 ml/liter O ₂ -----	11	316	do-----	28,300	30	No
500	20-30 ml/liter O ₂ -----	11	316	do-----	28,300	120	No
500	0.5-4.6 ml/liter O ₂ -----	11	347	do-----	31,500	30	No
500	20-30 ml/liter O ₂ -----	11	347	do-----	31,500	120	No
600	Degassed §-----	25	347	do-----	¶22,400	34	No

*Water velocity obtained by rotation of specimen in water or circulation of water past specimen.

§Degassed means air purged by boiling autoclave before sealing.

‡Slight defect parallel to direction of stress; apparently associated with a rolling seam; doubtful if associated with stress corrosion.

¶Loaded in direct tension.

†Yield point.

Returning again to autoclave tests of simple beam specimens, three proprietary austenitic stainless steels have been exposed in primary waters without stress corrosion damage. Each

primarily for spring applications. Results with simple beam specimens, both notched and unnotched, are listed in table 10-2. It is obvious that alloy F is unsuitable for the intended

FIGURE 10-2. Stress corrosion cracks in a type 347 steel tube from a hydraulic test loop ($\times 7$).

of these was in the mill-annealed condition. The test conditions were as follows, and the compositions of the alloys were as listed in table 10-9.

<i>Environment</i>	<i>Exposure</i>
500° F water with 0.7 to 7 ppm O ₂	Alloy A, 28,300 psi, 30 days
	Alloy B, 28,700 psi, 30 days
500° F water with 35 ppm O ₂	Alloy A, 28,300 psi, 120 days
	Alloy C, 35,000 psi, 90 days

PRECIPITATION HARDENING STAINLESS STEELS

The stress corrosion properties of the precipitation-hardening stainless steels were evaluated

application. In addition, tests of actual springs, described in a subsequent section, indicated the unsuitability of alloys G and H, despite the lack of stress corrosion in the simple beam specimens.

The compositions of the three alloys are indicated in table 10-9. A photograph of the alloy F specimens tested at 600° F is shown in figure 10-3.

OTHER MATERIALS

Martensitic stainless steels, nickel-base alloys, and copper-nickel alloys were also tested. All the tests made use of simple beam specimens loaded in bending or of tension specimens loaded in direct stress. All the tests were negative, either because of inherent resistance

to stress corrosion or because of the relatively low level of applied stress.

The lack of stress corrosion cracks in the martensitic stainless steels should not be interpreted to indicate immunity to cracks under all conditions. The unsuitability of these materials at spring temper hardnesses and high stresses is demonstrated in a subsequent section dealing with tests of actual springs.

The results of the specimen tests are recorded in table 10-3. The compositions of alloys I, J, K, Q, and R are given in table 10-9.

TESTS OF SPRINGS

Numerous tests of coil springs have been made under static and dynamic load conditions. A summary of these tests is given in table 10-4. Additional comments regarding the data follow:

1. AISI type 304: Increasing the amount of cold work from 60 to 90 percent increases the degree of cracking.

2. AISI type 304: The anneal at 2,100° F before cold working results in more severe cracking than the anneal at 1,950° F.

3. The martensitic and precipitation-hardening stainless steels appear to have failed by hydrogen embrittlement at the high hardness levels required for springs.

4. Alloy I: Although this alloy did not crack in the tests, the manufacturer does not recommend its use for springs in 500° F water because of the possible danger of intergranular corrosion. Alloy J is preferred because of its immunity to intergranular corrosion.

The seriousness of spring cracking is illustrated by figure 10-4, which shows the extent of

FIGURE 10-3. Simple beam specimens of a precipitation-hardened stainless steel (alloy F) tested in 600° F aerated primary water.

TABLE 10-2.

AUTOCLAVE STRESS CORROSION TESTS IN PRIMARY WATERS WITH SIMPLE BEAM SPECIMEN
OF PRECIPITATION-HARDENING STAINLESS STEELS

Alloy*	Rockwell C hardness	Type of specimen	Water temp., °F	Oxygen content	Stress, psi	Test time, days	Number of specs.	Stress corrosion cracks
F	43	Plain -----	500	0.5-4.6 ml/liter -----	58, 600	30	1	No
F	43	do -----	500	20-30 ml/liter -----	58, 600	120	1	No
F	42-45	do -----	600	5-10 ppm -----	30, 000	15	1	No
F	42-45	do -----	600	do -----	70, 000	15	2	1-Yes, 1-?
F	42-45	do -----	600	do -----	140, 000	15	2	2-Yes
F	42-45	Notched -----	600	do -----	30, 000	15	1	yes
F	42-45	do -----	600	do -----	70, 000	15	2	2-yes
F	42-45	do -----	600	do -----	140, 000	15	2	2-yes
F	42-45	do -----	600	do -----	200, 000	15	1	Yes
G	42	Plain -----	500	0.5-4.6 ml/liter -----	60, 800	30	1	No
G	42	do -----	500	20-30 ml/liter -----	60, 800	120	1	No
H	38	do -----	500	0.5-4.6 ml/liter -----	58, 300	30	1	No
H	38	do -----	500	20-30 ml/liter -----	58, 300	60	1	No

*Compositions given in table 10-9.

failure encountered in the AISI type 420 springs exposed to 600° F degassed water for 34 days.

FIGURE 10-4. Type 420 steel springs after exposure to 600° F degassed primary water.

Tests in Secondary Steam-Water Systems

GENERAL

In contrast to primary coolant water, an important characteristic of water in a secondary system is the presence of chlorides. It has been known for a number of years that austenitic stainless steels are susceptible to stress corrosion cracking in chloride-bearing environments. The preponderance of industrial failures has occurred in environments where chlorides were known or suspected to have been present. It is also known that oxygen plays an important role in the stress corrosion of austenitic steels in high-temperature water.

There is no reason to believe that the actual mechanism of the stress corrosion process in the water phase is any different from that in the steam phase. However, alternate wetting and drying of parts in the steam phase can cause concentration of constituents present in the water. Such behaviour is similar to the concentration of constituents in crevices of heat-transfer equipment, such as at tube-header joints. Other important characteristics of a two-phase system include the unequal distribution of any gases present and the possible ineffectiveness of corrosion inhibitors in controlling corrosion in both the water and steam phases.

For these reasons the stress corrosion behavior of a material in a given steam-water system depends on whether exposure is to the liquid or vapor. Accordingly, it is convenient to separate the water- and steam-phase tests in presenting the following data from corrosion tests carried out in laboratory autoclaves.

WATER-PHASE TESTS

EFFECT OF CHLORIDE LEVEL IN UNTREATED WATER

Very few tests were made in plain chloride-bearing waters for two reasons: (1) the sec-

TABLE 10-3

AUTOCLAVE STRESS CORROSION TESTS IN PRIMARY WATERS WITH SPECIMENS OF MARTENSITIC STAINLESS STEELS, NICKEL-BASE ALLOYS, AND COPPER-NICKEL ALLOYS

[All results were negative (no cracks)]

Environment	Alloy*	Stress, psi	Test time, days
600° F degassed water, velocity 29 ft/sec.....	Type 420†.....	20,000	30
	Type 440†C.....	20,000	30
	Nickel.....	20,000	30
	Alloy I.....	20,000	30
	Alloy K.....	20,000	30
600° F degassed water, velocity 25 ft/sec.....	Type 420†.....	51,000	34
	Type 440C†.....	51,000	34
	Nickel.....	23,200	34
	Alloy I.....	26,900	34
	Alloy K.....	24,600	34
500° F water, 0.5-4.6 ml/liter O ₂ , velocity 11 ft/sec.....	Alloy J.....	40,600	30
500° F water, 20-30 ml/liter O ₂ , velocity 11 ft/sec.....	Alloy Q.....	18,400	60
	Alloy R.....	21,600	60

*Compositions and treatments of lettered alloys are given in table 10-9.
†Oil quenched from 1,850° F, tempered 1 hr at 650° F.

ondary system waters to be used in service were mostly to be alkaline-phosphate treated, and (2) water-phase problems did not prove to be as serious as steam-phase problems. Thus, there was no systematic study of chloride level in untreated waters.

The few available data on untreated waters are listed in table 10-5. In a very rough way, these data illustrate the expected increase in cracking susceptibility with increase in chloride level and temperature. The data also point to the importance of oxygen in the stress corrosion process.

EFFECT OF WATER COMPOSITION IN ALKALINE-PHOSPHATE TREATED WATERS

In contrast to the limited data on untreated waters, a great number of tests have been conducted with stainless steel specimens submerged in alkaline-phosphate treated waters. These tests have explored such variables as chloride level, oxygen content, temperature, time, pH, and material composition. Typical data, which illustrate the results obtained over a range of environmental conditions, are presented in table 10-6 for stainless steels in the annealed condition prior to stressing.

The only positive cases of stress corrosion damage recorded in table 10-6 occurred to the first three specimens listed under the 530 ppm chloride tests. These specimens were exposed in the water phase during most of the test period. However, they were also exposed to the steam phase for brief intervals when the autoclave was inverted to wet down specimens being treated simultaneously in the steam phase. An oxygen-saturated environment was used in the tests, and, since high oxygen is known to have an accelerating effect on stress corrosion, it is possible that the cracking was associated with the steam phase. In any case, similar vessel inversion tests did not lead to cracking in environments with lower, more realistic oxygen levels.

There have been 2 or 3 other isolated cases of cracking with specimens submerged in alkaline-phosphate-treated water. These cases have not been included in table 10-6 since there is a lack of complete information regarding the tests. Either the test environments have not been defined adequately or the cracks are very minor and not definitely established as having been caused by stress corrosion.

TABLE 4

AUTOCLAVE STRESS CORROSION TESTS IN PRIMARY WATERS OF COIL SPRINGS UNDER STATIC AND DYNAMIC LOADS

Water		Alloy	Condition of alloy	Type of applied stress, torsion, psi	Test time, days	Cracked
Temp., ° F.	O ₂ content, ppm					
500	Degassed*	AISI 302	Cold worked to spring temper	Static: 80,000	30	No
500	5-10	AISI 304	Annealed	Static: beyond yield	21	No
500	5-10	AISI 304	Annealed, cold worked 60%	Static: 20,000	21	Yes
500	5-10	AISI 304	Annealed, cold worked 90%	do	21	Yes
500	5-10	AISI 304	Annealed 1,950° F, cold worked 60%	Static: 60,000	21	Yes
500	5-10	AISI 304	Annealed 1,950° F, cold worked 90%	do	21	Yes
500	5-10	AISI 304	Annealed 2,100° F, cold worked 60%	do	21	Yes
500	5-10	AISI 304	Annealed 2,100° F, cold worked 90%	do	21	Yes
500	5-10	AISI 304	Annealed 1,950° F, cold worked 60%	Dynamic: 0-60,000 at 120 cpm.	21	Yes
500	5-10	AISI 304	Annealed 1,950° F, cold worked 90%	do	21	Yes
500	5-10	AISI 304	Annealed 2,100° F, cold worked 60%	do	21	Yes
500	5-10	AISI 304	Annealed 2,100° F, cold worked 90%	do	21	Yes
500	5-10	AISI 410	Hardened, spring temper	Static: 60,000	21	Yes
600	Degassed*	AISI 420	do	Static: 96,000	34	Yes
500	5-10	AISI 431	do	Static: 60,000	21	Yes
500	5-10	Alloy F†	do	do	21	Yes
500	5-10	Alloy G†	do	do	21	Yes
500	5-10	Alloy H†	do	do	21	Yes
500	5-10	(‡)	do	do	21	(§)
500	Degassed*	Alloy I¶	Spring temper	Static: 49,000	30	No
500	5-10	Alloy I¶	do	Static: 70,000	90	No
500	5-10	Alloy J¶	do	do	90	No

*Degassed by boiling autoclave before sealing.

†Precipitation-hardening stainless steel (see table 10-9 for composition).

‡Colbat-base alloy: per cent composition 40 Co, 20 Cr, 15 Ni, 7 Mo, 2Mn, 0.04 Be, 0.15 C, remainder Fe.

§Cracks developed, but cause doubtful; possibility of seams.

¶Nickel-base alloy (see table 9 for composition).

The data in table 10-6 strongly indicate that an alkaline-phosphate water treatment can successfully inhibit the stress corrosion of austenitic stainless steels in any secondary water likely to be encountered under practical circumstances. The inhibiting action would extend even to those waters which are known to contain sufficient chloride and oxygen to cause stress corrosion cracking in the absence of the alkaline-phosphate treatment. This con-

clusion is applicable only to the case of steels submerged in the water. The conclusion is also applicable only to steels in the mill-annealed condition at the time of their fabrication, a condition which would be almost universally applicable in the case of secondary systems.

Sensitized Steels

There is one important exception to the inhibiting action in alkaline-phosphate-treated waters. The exception is susceptibility to in-

TABLE 10-5

AUTOCLAVE STRESS CORROSION TESTS OF AUSTENITIC STAINLESS STEEL SPECIMENS
SUBMERGED IN UNTREATED WATERS WITH VARIOUS CHLORIDE CONTENTS*

Medium	Cl, ppm	O ₂ content	Temp, ° F	Time, days	Stress corrosion cracks AISI type			
					304	310	316	347
Natural sea water	20,000 ±	Aerated	550	15	Yes	Yes	Yes	Yes
Do	20,000 ±	do	350	30	Yes	No	No	Yes
Do	20,000 ±	do	120	45				No
Distilled water + NaCl†	300	Degassed	500	14		No		No
Do	300	15-35 ml/liter	500	4	Yes			Yes
Dilute sea water†	80	Degassed	470	25				No
Distilled water	0	0.5-4.5 ml/liter	500	30	No	No	No	No
Do	0	20-30 ml/liter	500	120	No	No	No	No

*Single specimen tests; steels annealed before stressing.

†These tests were with U-bends in static water. All other tests were

with simple beam specimens, stressed in bending to $\frac{1}{2}$ the tensile strength, and tested at a water velocity of 10 to 11 ft/sec.

tergranular stress corrosion following intergranular sensitization of the steel, especially from welding operations. (The usual stress corrosion cracking of austenitic stainless steel follows a predominantly transgranular path, but sensitization can lead to intergranular stress corrosion in some environments.) The tests described in table 10-7 were conducted to check on this point. The data indicate that sensitized AISI type 304 steel can fail by intergranular stress cracking in low oxygen alkaline-phosphate-treated water, except possibly when the chloride content is kept very low.

MISCELLANEOUS MATERIALS

A variety of single-specimen water-immersion tests have been made on miscellaneous materials other than the austenitic stainless-steel types. These data are presented in Tables 10-8 and 10-9.

STEAM-PHASE TESTS

EFFECT OF INTERMITTENT WETTING (TILT TEST)

Exposure of austenitic stainless steels in the steam phase of high-temperature chloride-bearing waters does not, in itself, appear to lead to stress corrosion cracking. However, cracking does seem to be a serious problem where intermittent wetting and drying can occur, such as by splashing, by water carry-

over, by a rise and fall of water level, by penetration of water through deposits and evaporation from hot surfaces, by startup and shutdown operation, and by periodic flashing to steam of water which enters crevice areas of heat-transfer equipment. It is believed that the most important characteristic of these alternate wetting and drying situations is the concentration of water-soluble constituents on the surface of the metal. The problem is especially acute because alkaline-phosphate water treatment does not seem to possess inhibiting characteristics outside the water phase.

Most of the steam-phase tests conducted in laboratory autoclaves were carried out with cycles of intermittent wetting. This was done by mounting the specimens above the water level, in the steam phase, and then wetting the specimens periodically by inverting the autoclave. The procedure has become known as a "tilt test."

EFFECT OF WATER COMPOSITION (ALKALINE-PHOSPHATE TREATED WATERS)

Austenitic Stainless Steels: Wetted Twice Daily

Table 10-10 presents the conditions and results of intermittent-wetting steam-phase tests on austenitic type stainless steels in the annealed

TABLE 10-6

AUTOClave STRESS CORROSION TESTS OF AISI TYPE AUSTENITIC STAINLESS STEEL U-BEND SPECIMENS SUBMERGED IN VARIOUS ALKALINE-PHOSPHATE TREATED WATERS*

Cl, ppm	Nominal O ₂ , † ppm	AISI type	Days of test in water with pH of—†			Total days in test	Temp., ° F	Number of specs.	Stress corrosion cracks
			10.6	11.0	11.3				
High §	Degassed	347	14			14	500	2	No
High ¶	do	347			14	14	500	2	No
553	Saturated	347	15			15	467	2	No
553	30	347	7			7	500	3	No
553	0.1–0.7	347	30			30	467	2	No
553	0.06	347	7			7	500	3	No
553	Degassed	347	15			15	467	4	No
550	0.05–0.5	304	7		55	62	500	40	No
550	0.05–0.5	347	7	24	51	82	500	50	No
530	Saturated	304	15			15	500	1	Yes**
530	do	305	15			15	500	1	Yes**
530	do	347	15			15	500	1	Yes**
530	do	304			15	15	500	1	No
530	do	347			15	15	500	1	No
530	Aerated	304	90			90	500	1	No
530	do	347	90			90	500	2	No
530	Degassed	347	14			14	470	1	No
500	do	347	15			15	467	1	No
400	do	347	15			15	467	1	No
350	<1.0	347	15			15	500	2	No
350	Degassed	347	15			15	467	1	No
336	Aerated	347			30	30	500	2	No
336	Degassed	347			30	30	470	1	No
336	do	347			30	30	500	2	No
300	do	347	15			15	467	1	No
200	0.05–0.5	304	21	9	35	65	500	40	No
200	0.05–0.5	347	21	53	31	105	500	50	No
150	Degassed	347	15			15	467	1	No
100	<1.0	347	15			15	500	2	No
50	0.05–0.5	304	35		43	78	500	40	No
50	0.05–0.5	347	49	39	52	140	500	50	No
10	0.05–0.5	304	33		83	116	500	40	No
10	0.05–0.5	347	42		74	116	500	50	No
2	0.05–0.5	304	36		67	103	500	40	No
2	0.05–0.5	347	59	14	66	139	500	50	No
1	200	347	15			15	500	2	No
1	30	347	15			15	500	2	No
Total								495	Yes, 3 No, 492

*Steels annealed before stressing.

†"Degassed" means oxygen removed by boiling and venting autoclave. "Aerated" means no attempt was made to remove air before sealing autoclave. "Saturated" means oxygen was bubbled through autoclave before sealing. Actual or calculated oxygen contents are given where data are available.

‡Water compositions were: pH—10.6, 50 ppm PO₄; pH—11.0, 120 ppm PO₄; and pH—11.3, 200 ppm PO₄.

§Exact chloride unknown. High chloride obtained by boiling off to full saturation a solution originally containing 530 ppm Cl, 50 ppm PO₄, and 10.6 pH.

¶Exact chloride unknown. High chloride obtained by boiling off to full saturation a solution originally containing 336 ppm Cl, 200 ppm PO₄, and 11.3 pH.

**Vessel was inverted momentarily twice each day, thus exposing the specimens to the vapor phase for short periods (see text).

TABLE 10-7

AUTOCLAVE STRESS CORROSION TESTS OF SENSITIZED TYPE 304 STAINLESS STEEL U-BEND SPECIMENS SUBMERGED IN 500° F ALKALINE-PHOSPHATE TREATED WATERS CONTAINING 0.05-0.5 PPM OXYGEN

Time sensitized at 1,200° F, hr	Cl, ppm	Days of test in water with pH of—*			Total days in test	Number of specimens tested	Number of specimens with intergranular cracks
		10.6	11.0	11.3			
1-----	550	7	-----	-----	7	10	10
1-----	200	21	9	35	65	10	2
1-----	50	7	-----	35	42	10	10
1-----	10	33	-----	69	102	10	None
1-----	2	36	-----	67	103	10	None
2-----	550	-----	-----	40	40	4	4
2-----	550	-----	-----	28	28	10	6
2-----	50	-----	-----	29	29	10	None

*Water compositions were: pH—10.6, 50 ppm PO₄; pH—11.0, 120 ppm PO₄; and pH—11.3, 200 ppm PO₄.

condition prior to stressing. The principal variables were the oxygen and chloride contents. Practically all these tests were made with a vessel tilting time of several seconds twice each day.

A rough plot of the data in table 10-10 is presented in figure 10-5. This plot was prepared with no attempt to differentiate between alloys (AISI types 304, 305, 316, and 347); temperatures (467° F and 500° F); and testing times (1 to 30 days). Also, it was prepared with the following estimates of oxygen content when the actual content was not known:

Saturated----- 200 ppm
 Aerated----- 35 ppm
 Under 1.0----- 0.6 ppm
 Degassed----- 0.3 ppm
 Where range is given. Average

Figure 10-5 represents, in a rough way, the relation believed to exist between the chloride and oxygen contents and stress corrosion cracking in the steam phase. It appears that both oxygen and chloride must be present to some extent if stress corrosion is to occur. The dividing line between safe and unsafe compositions has certainly not been well defined. Indeed, it is doubtful that a definite division

TABLE 10-8

AUTOCLAVE STRESS CORROSION TESTS OF SINGLE SPECIMENS OF MISCELLANEOUS MATERIALS SUBMERGED IN TREATED AND UNTREATED CHLORIDE-BEARING WATERS

Type of water	Cl, ppm	O ₂ content	Temp., ° F	Time, days	Alloys stress corroded*	Alloys not stress corroded*
Natural sea water-----	20000 ±	Aerated-----	550	24	B, C, F, G, H, I, K.	J, L, P, Q, R.
	20000 ±	do-----	350	45	F, G-----	A, B, C, H, I, J, K, L, P, Q, R.
	20000 ±	do-----	120	45	-----	B, C, F, G, J, K, L, P, Q, R.
Alkaline-phosphate treated water (pH—10.6 PO ₄ —50 ppm).	530	Saturated-----	500	15	-----	K, M, N.
	530	Aerated-----	500	15	E-----	D, K, L, O.

*See table 10-9 for compositions.

TABLE 10-9
COMPOSITION AND HEAT TREATMENT OF MATERIALS IN TABLE 10-8

Alloy	C	Mn	Si	Cr	Ni	Mo	Cb	Cu	Ti	Fe	Al	Others	Heat treatment†
SPECIAL AUSTENITIC STAINLESS STEELS													
A*	0.08	1.45	0.49	17.45	14.00	2.87	0.36	3.14	0.22	Bal.			2,250° F, ½ hr, WQ, 1,300° F, 5 hr, AC
B†	0.07	0.75	1.00	20.00	29.00	2.00		3.00		do			Mill annealed
C‡	0.09-0.10	1.52-1.76	0.38-0.72	15.28-16.62	25.34-26.25	5.34-6.35				do			Cast, annealed
D*	0.10	1.33	0.76	16.26	25.51	6.35				do			Annealed at 2,160° F, WQ
E*	0.11	14.56	0.44	14.93	0.96					do		N, 0.18	Mill annealed
PRECIPITATION-HARDENING STAINLESS STEELS													
F*	0.05	0.59	0.35	16.58	4.29			3.89		Bal.			Hardened 950° F, 2 hr
G*	0.08	0.56	0.72	17.16	6.92	0.31				do	1.02		Hardened 1,400° F, 2 hr AC, 950° F, 2 hr
H*	0.07	0.54	0.54	16.58	6.78			0.11	0.48	do	0.19		Hardened 1,000° F, 2 hr
NICKEL-BASE ALLOYS													
I§	0.15 max.	1.00 max.	0.50 max.	12.0-15.0	75.00 min.			0.50 max.		9.00 max.			Mill annealed
J§	0.08 max.	0.30-1.00	0.50 max.	14.0-16.0	70.00 min.		0.70-1.20	0.20 max.	2.25-2.75	5.0-9.0	0.40-1.00		Solution treated, aged
K§	0.30 max.	2.00 max.	0.50 max.	63.0-70.0				Bal.		2.50 max.	0.50 max.		Cold rolled, special
L§	0.15 max.			15.5-17.5	Bal.	16.0-18.0				4.5-7.0		W, 3.75-5.25	Mill annealed
M†	0.01	0.20	0.15		99.50			0.02		0.05			Tubing, probably annealed.
N*	0.01	0.30	0.11		99.02			0.02	0.058	0.08	0.066	Zr, 0.27 Mg, 0.038	Do.
OTHER MATERIALS													
O§	0.08-0.13	0.30-0.50								Bal.			Hot rolled
P*	0.24	0.07							Bal.	0.13		N, 0.002	Cold rolled, 50%
Q*		0.32			Bal.			87.08		1.76			Cold rolled, hard
R*		0.74			do			68.10		0.31			Mill annealed

*Actual composition of test material.

†Nominal composition.

‡Actual range of test materials.

§Specification range.

¶"WQ" denotes water quenched; "AC," air cooled.

could be established without precise definition of alloy, treatment, time, temperature, stress, frequency of intermittent wetting, and perhaps other factors. However, it does appear that the maintenance of oxygen at some value below 1 ppm (perhaps 0.5 ppm in critical areas) will provide reasonable assurance against

stress corrosion failures at chloride levels likely to be encountered in steam generation equipment.

Austenitic Stainless Steels: Special Wetting Cycles.

The tests described in the previous section were conducted with an arbitrarily standardized

TABLE 10-10

AUTOCCLAVE STRESS CORROSION TILT TESTS (INTERMITTENT WETTING) OF AISI TYPE AUSTENITIC STAINLESS STEEL U-BEND SPECIMENS MOUNTED IN THE STEAM PHASE OF VARIOUS WATERS WITH 50 PPM PO_4 AND 10.6 pH*†

Cl, ppm	Nominal O_2 , ‡ ppm	Temp., ° F	AISI type	Days in test	Number of specs.	Stress corrosion cracks
553	200	500	347	1	2	Yes
553	200	500	347	2	3	Yes
553	42	500	347	15	2	Yes
553	30	500	347	15	4	Yes
553	28	500	347	15	2	Yes
553	14	500	347	15	2	Yes
553	0.01-2.5	467	347	7	3	No
553	0.01-2.2	467	347	7	3	No
553	<1.0	500	347	2	1	No
553	<1.0	500	347	15	4	Yes, 2; no, 2
553	0.09-0.7	467	347	30	2	No
553	0.01-0.14	467	347	7	3	No
553	0.02-0.05	467	347	120	1	No
553	Degassed	467	347	15	4	Yes, 1; no, 3
530	Saturated§	500	304	15	1	Yes
530	do§	500	347	15	1	Yes
530	do	500	304	15	4	Yes
530	do	500	305	15	1	Yes
530	do	500	316	15	1	Yes
530	do	500	347	15	3	Yes
530	Aerated	500	347	15	1	Yes
350	42	500	347	15	2	Yes
350	<1.0	500	347	15	4	Yes, 2; no, 2
315	0.95-3.0	467	347	7	3	Yes, 2; no, 1
100	42	500	347	15	2	Yes
100	<1.0	500	347	15	4	No
10	42	500	347	15	1	Yes
10	<1.0	500	347	15	4	Yes, 2; no, 2
3½	30	500	304	15	1	Yes
3½	30	500	347	15	1	Yes
1	200	500	347	15	2	Yes
1	30	500	347	15	2	Yes
1	0.02-0.04	500	347	7	3	No
Nil	Saturated	500	304	30	1	No
Nil	do	500	347	30	1	No
Nil	Degassed	500	304	30	1	No
Nil	do	500	347	30	1	No

*Steels annealed before stressing.

†The intermittent wetting was done in most cases by inverting the pressure vessel for several seconds twice each day.

‡"Degassed" means oxygen removed by boiling and venting autoclave. "Aerated" means no attempt was made to remove air before sealing

autoclave. "Saturated" means oxygen was bubbled through autoclave before sealing. Actual or calculated oxygen contents are given where data are available.

§pH: 11.2.

vessel tilting cycle producing momentary wetting twice each day. In contrast, the following experiments were conducted to determine the effects of more frequent vessel tilting. These effects were of interest not only in relation to

specimens mounted in the steam phase but also in relation to specimens mounted in the water phase and exposed to the steam phase when the autoclave was inverted. At the same time, the tests provided additional information on

the effect of water composition, sensitization of the steel, and surface conditioning of the material as related to boiler startup conditions.

All tests were made with U-bend specimens. Results are summarized below.

FIGURE 10-5. Approximate relation between chloride and oxygen content of alkaline-phosphate treated boiler water and susceptibility to stress corrosion of austenitic stainless steels exposed to the steam phase with intermittent wetting. Numbers denote number of specimens. Curve is based on observations made under specific conditions, therefore is not intended for general use.

Test 1 was conducted for ninety 3-minute vessel tilting cycles with chemically deoxygenated alkaline-phosphate-treated water. The experiment was carried out as follows: Specimens were mounted in both the lower and upper portions of the vessel. Dry sodium sulfite was added to effect subsequent deoxidation. The vessel was sealed, evacuated, and purged with helium. The vessel then was half filled with degassed water and heated to 500° F. The apparatus was allowed to stand for 12 hr to obtain complete chemical deoxidation before the start of the tilting cycles.

Actual water analyses were:

	At start	At finish
Chloride, ppm-----	550	Not reported
Oxygen, ppm-----	0.000	0.000
Excess sulfite, ppm-----	2	3
PO ₄ , ppm-----	48	48.5
pH-----	10.4	10.4

The results of test 1 are recorded in table 11. The lack of cracks was not unexpected in view of the absence of oxygen.

Test 2 was conducted under conditions designed to simulate boiler startup. U-bend specimens were mounted in both the water and steam phases. Some of the specimens were annealed (before stressing), some were sensitized, and some were both sensitized and preconditioned by 7 days' exposure in 500° F water of 11.3 pH, 200 ppm PO₄, 10 ppm SO₃, no chloride, and no oxygen.

The autoclave was charged with water of 11.3 pH, 200 ppm PO₄, 1 ppm oxygen, and no chloride. The sealed vessel was heated to 500° F and then tilted on a cycle of 1 min every 2 hr. After 16 hr (8 cycles), the oxygen was scavenged chemically by adding 10 ppm sulfite in excess, and then 200 ppm chloride ion was introduced. The cycling was continued, with specimens examined after various periods of exposure.

The results of the test are shown in table 10-12. It is noteworthy that the few stress corrosion failures were restricted to the sensitized type 304 specimens which were exposed principally in the vapor phase and that these failures were all intergranular.

Test 3 was conducted to study the effect of a cyclic addition and removal of oxygen from 500° F boiler water containing 200 ppm chloride, 200 ppm phosphate, and 11.3 pH. The test was started with 10 ppm excess sulfite ion to insure the absence of oxygen. After 7 days oxygen was injected to a concentration of 1 ppm, and the test was continued for an additional day. The oxygen then was removed by adding excess sulfite. This type of oxygenation-deoxygenation cycle was repeated about every 8 days during the life of the test.

In other respects the test was similar to test 2. U-bend specimens, prepared in various ways,

TABLE 10-11

SPECIAL AUTOCLAVE TILT TEST 1: AUSTENITIC STAINLESS STEEL U-BEND SPECIMENS TESTED IN CHEMICALLY DEOXIDIZED ALKALINE-PHOSPHATE TREATED WATER*

(Tilt cycle: 1 min upright, 2 min inverted, total test time 4½ hr)

AISI type†	Treatment	Specimen location at start‡	Time per cycle		Number of cycles	Number of specs.	Stress corrosion cracks
			Water, min	Steam, min			
304	Annealed	Water	1	2	90	1	None
304	do	Steam	2	1	90	1	None
304	Sensitized§	do	2	1	90	1	None
347	Annealed	Water	1	2	90	1	None
347	do	Steam	2	1	90	1	None
347	Sensitized§	Water	1	2	90	1	None

*Cl, 550 ppm; PO₄, 48 ppm; excess SO₃, 2 to 3 ppm; oxygen, 0.000 ppm; pH, 10.4; temperature, 500° F.

†Type 304 had 0.063 percent carbon.

‡Type 347 had 0.061 percent carbon and 0.79 percent columbium.

§Sensitized 2 hr at 1,200° F.

¶Specimens exposed in this location for 12 hr prior to start of tilting cycles.

were mounted in the upper and lower portions of the autoclave. The pressure vessel was inverted for 1 min every 2 hr. The results of the test are indicated in table 10-13. The lone failure occurred in a sensitized specimen by a mixture of transgranular and intergranular cracking.

Test 4 was conducted with oxygen-free 500° F boiler water containing 200 ppm chloride, 200 ppm phosphate, and 11.3 pH. Freedom from oxygen was obtained by maintaining sulfite ion at 25 to 50 ppm. The specimens were U-bends of AISI type 304 steel which had been sensitized and preconditioned (see tests 2 and 3 for details). These were mounted in both the water and steam phases. The autoclave was tilted for 1 min out of every 6 min.

The vessel was opened after 725 tilt cycles (total time, 72 hr). An analysis showed sulfite ion to be present. No specimen cracks were detected. The test was continued to 1,674 cycles (total time, 167 hr). No sulfite could be detected at that time, and all specimens showed intergranular attack. The experiment demonstrated the ease with which intergranular attack could be produced in stressed sensitized AISI type 304 steel exposed with intermittent wetting to low oxygen boiler water steam.

Test 5 was conducted to obtain information on the speed with which stress corrosion cracks could be produced in an intermittent tilting test. U-bend specimens were prepared from annealed AISI types 304 and 347 steels. These were exposed in both the water and steam phases of an autoclave half filled with water containing 550 ppm chloride, 50 ppm phosphate, 7 ppm oxygen, and 10.6 pH. The vessel was heated, tilted 5 times in 4-min cycles, and then cooled. The total test time was 20 min, plus heating and cooling time.

Three tilting schedules were tried, with results as shown in table 10-14. It is of interest that the specimens which started and finished in the steam phase cracked in all cases. This indicated that the exposure to the steam during the heating and cooling of the vessel contributed to the cracking of the specimens in addition to the exposure during the 20 min of vessel tilting. The test also demonstrated the brief time needed to crack the specimens under conditions highly conducive to stress corrosion damage.

MISCELLANEOUS MATERIALS WETTED TWICE DAILY

A number of miscellaneous materials were tested in the steam phase of alkaline-phosphate-treated waters, with wetting twice daily by

TABLE 10-12

SPECIAL AUTOCLAVE TILT TEST 2: AUSTENITIC STAINLESS STEEL U-BEND SPECIMENS TESTED UNDER SIMULATED BOILER START-UP CONDITIONS IN ALKALINE-PHOSPHATE TREATED WATER*

(Tilt cycle: 119 min upright, 1 min inverted)

AISI type	Treatment	Specimen location at start	Time per cycle		Number of cycles†	Total time, days	Number of specs.	Type of stress corrosion cracks
			Water, min	Steam, min				
304	Annealed.....	Water.....	119	1	94	8	1	None
304	do.....	do.....	119	1	349	29	1	None
304	Sensitized‡.....	do.....	119	1	349	29	1	None
304	Sensitized, preconditioned‡ §.....	do.....	119	1	255	21	2	None
304	Annealed.....	Steam.....	1	119	349	29	1	None
304	Sensitized‡.....	do.....	1	119	94	8	1	Intergranular
304	do.....	do.....	1	119	281	23	1	Do.
304	Sensitized, preconditioned‡ §.....	do.....	1	119	68	6	3	Intergranular in 1 specimen
304	do‡ §.....	do.....	1	119	187	16	2	Intergranular in 1 specimen
347	Annealed.....	Water.....	119	1	136	11	1	None
347	do.....	do.....	119	1	485	40	2	None
347	Sensitized, preconditioned‡ §.....	do.....	119	1	136	11	1	None
347	do‡ §.....	do.....	119	1	230	19	1	None
347	do‡ §.....	do.....	119	1	485	40	1	None
347	Annealed.....	Steam.....	1	119	136	11	2	None
347	do.....	do.....	1	119	485	40	1	None
347	Sensitized, preconditioned‡ §.....	do.....	1	119	136	11	1	None
347	do‡ §.....	do.....	1	119	230	19	1	None
347	do‡ §.....	do.....	1	119	485	40	1	None

*Original water had pH 11.3; PO₄, 200 ppm; oxygen, 1 ppm; and no chloride. After 16 hr, oxygen was removed with 10 ppm SO₂ in excess, and 200 ppm chloride was added.

‡Sensitized 2 hr at 1,200° F in helium.

§Preconditioned 7 days in 500° F water with pH, 11.3; PO₄, 200 ppm; SO₂, 10 ppm; no chloride; and no oxygen.

†Includes initial 8 cycles in water containing 1 ppm oxygen and no chloride.

inversion of the autoclave. The available data are presented in table 10-15. For the most part, the test conditions were such that austenitic stainless steels would have stress corroded.

SPECIAL TUBE-JOINT CREVICE TESTS

The extreme sensitivity of some materials to stress corrosion in the steam phase, with intermittent wetting, led to the belief that these same materials would be subject to failure in tube-joint crevices of heat-exchanger equipment. It was believed that tube rolling and/or welding could be the source of the stress. It was also believed that the thermal gradient across the tube walls of heat exchangers would be sufficient in many cases to cause steaming of any water

entering the tube-tube sheet crevice. This action, together with startups and shutdowns, would produce intermittent contact with water and steam and would lead to concentration of water constituents in the crevice areas. This action was studied in the apparatus shown in figure 10-6.

Simulated tube-joint experiments did demonstrate that water constituents tend to concentrate in the joint crevices. However, X-ray analyses usually failed to reveal sodium chloride in the deposits, probably because the X-ray technique was not sensitive below a level of several percent. A photograph of a typical deposit is shown in figure 10-7.

TABLE 10-13

SPECIAL AUTOCLAVE TILT TEST 3: AUSTENITIC STAINLESS STEEL U-BEND SPECIMENS TESTED IN 500° F BOILER WATER WITH CYCLIC ADDITION AND REMOVAL OF OXYGEN*

(Oxygen cycle: deoxygenated 7 days, oxygenated 1 day; tilt cycle: 119 min upright, 1 min inverted)

AISI type	Treatment	Specimen location at start	Tilting cycles			Number of oxygen cycles	Total time, days	Number of specimens	Type of stress corrosion cracks
			Time per cycle		Number of cycles				
			Water, min	Steam, min					
304	Sensitized, preconditioned†	Steam	1	119	272	3	23	2	None
347	Annealed	Water	119	1	665	7	55	3	None
347	Sensitized, preconditioned†	do	119	1	665	7	55	3	None
347	Annealed	Steam	1	119	665	7	55	3	None
347	Sensitized, preconditioned†	do	1	119	393	4	33	2	None, 1; transgranular and intergranular, 1
347	do†	do	1	119	665	7	55	1	None

*Basic water had Cl, 200 ppm; PO₄, 200 ppm; and pH, 11.3. Oxygenated by injection of gas to produce 1 ppm oxygen. Deoxygenated by addition of 10 ppm excess SO₂.

†Sensitized 2 hr at 1,200° F in helium, then preconditioned 7 days in 500° F water with pH, 11.3; PO₄, 200 ppm; SO₂, 10 ppm; no chloride; and no oxygen.

TABLE 10-14

SPECIAL AUTOCLAVE TILT TEST 5: AUSTENITIC STAINLESS STEEL U-BEND SPECIMENS TESTED IN STEAM AND WATER PHASES OF 500° F WATER CONTAINING 550 PPM CHLORIDE, 50 PPM PHOSPHATE, 7 PPM OXYGEN, AND 10.6 pH

AISI type*	Specimen location at start	Tilting cycles			Total cycling time, † min	Stress corrosion cracks
		Time per cycle		Number of cycles		
		Water, min	Steam, min			
304	Water	1	3	5	20	No
304	Steam	3	1	5	20	Yes
347	Water	1	3	5	20	No
347	Steam	3	1	5	20	Yes
304	Water	2	2	5	20	Yes
304	Steam	2	2	5	20	Yes
347	Water	2	2	5	20	Yes
347	Steam	2	2	5	20	Yes
304	Water	3	1	5	20	No
304	Steam	1	3	5	20	Yes
347	Water	3	1	5	20	No
347	Steam	1	3	5	20	Yes

*Annealed before stressing.

†Time of heating and cooling vessel not included.

TABLE 10-15

AUTOCLAVE STRESS CORROSION TILT TESTS (INTERMITTENT WETTING) OF SINGLE U-BEND SPECIMENS OF MISCELLANEOUS MATERIALS MOUNTED IN THE STEAM PHASE OF 500° F ALKALINE-PHOSPHATE TREATED WATER CONTAINING 530 PPM CHLORIDE, 50 PPM PHOSPHATE, AND 10.6 pH*

O ₂ content†	Alloys stress corroded‡	Alloys not stress corroded‡
Saturated	D, E, § F	Type 410, type 430, I, J, K, L, M, N, O
Aerated	D, E	K, L, O
Degassed		Type 410, I, J, K, O

*Compositions of coded alloys are as shown in table 10-9. (Tilt cycle: Momentarily, twice daily, for 15 days)

†“Degassed” means oxygen removed by boiling and venting autoclave. “Aerated” means no attempt was made to remove air before sealing autoclave. “Saturated” means oxygen was bubbled through autoclave before sealing.

‡See table 10-9.

§pH—11.2.

FIGURE 10-6. Basic elements of special tube-joint crevice test apparatus.

MISCELLANEOUS EXPERIMENTS

Except as otherwise indicated, the miscellaneous experiments described below were conducted under the following conditions:

Exposure: steam phase, wetted by vessel inversion twice daily.

Test time: 15 days, average.

Water: 530 ppm Cl, 50 ppm PO₄, 10.6 pH, and aerated (no attempt made to remove gases before sealing of autoclave).

Temperature: 500° F.

Material: AISI types 304 and 347 austenitic stainless steel, annealed before stressing.

EFFECTS OF STRESS LEVEL

Specimens of 1/16-in.-thick strip were annealed by suspending them from wires, heating to 1,750° F, and air cooling. Then they were cleaned by a chemical method. This procedure was followed to produce strips with a minimum of residual internal stresses. The specimens so obtained were carefully inserted in a simple beam jig and stressed to 0, 5000, 15,000, 30,000, 40,000, and 50,000 psi. Exposure in the autoclave produced stress corrosion cracks in all

FIGURE 10-7. Crevice deposit in a tube joint tested in an alkaline-phosphate treated chloride-bearing water.

specimens except the one without stress. The test demonstrated the probable lack of a practical threshold stress below which failure will not occur in the steam phase.

EFFECTS OF TUBE ROLLING, TUBE WELDING, AND SURFACE PREPARATION

Experiments have shown that residual stresses produced by rolling and/or welding in the fabrication of tube-tube sheet joints are sufficient to cause failure. In fact, 1/2-in.-diameter tubes with 40- to 50-mil wall thickness were expanded 1 to 3 mils and used successfully in lieu of U-bend specimens in numerous autoclave experiments.

There were indications in at least one experiment that the cleaning of annealed specimens with emery cloth produced sufficient residual surface stresses to result in stress corrosion without the presence of applied stress.

EFFECTS OF MATERIAL THICKNESS

Simultaneous tests of U-bend specimens ranging in thickness from 0.062 to 0.41 in. revealed no difference in stress corrosion sensitivity over a 15-day exposure period.

CONCENTRATION OF WATER CONSTITUENTS IN INTERMITTENT WETTING TESTS

In the autoclave experiments described in this chapter, the vessels were one-half to two-thirds filled with water. Temperature surveys conducted in a few of the vessels revealed that with 500° F water the steam was slightly superheated. The maximum observed superheat was about 30° F, and the minimum was as little as 1° F.

A special autoclave experiment was designed to show if exposure of specimens in the steam phase, with intermittent wetting by vessel inversion, would lead to concentration of water constituents on the specimens. Specimens of a porous stainless steel filter medium were mounted in the steam phase of a typical autoclave. The volume of the pores in the specimens was known. After 15 days' exposure, with wetting twice daily, the chlorides were leached from the specimens and analyzed quantitatively. It was found that the chloride content in the pores of the specimens was 4 to 8 times the chloride content in an equivalent volume of the test water. Thus it is known that, when a material in the steam phase is intermittently wetted, the water constituents concentrate on the specimen.

EFFECTS OF GALVANIC COUPLES

Testing in boiling 42 percent $MgCl_2$ solution has indicated some promise in the use of galvanic couples to control stress corrosion of austenitic stainless steel. The tests have been made with AISI type 347 steel U-bend specimens coupled in two ways: (1) attachment to a

coupon of a dissimilar metal and (2) plating of the legs of the U-bend but leaving the apex of the bend unplated. Results of such tests are shown in table 10-16. Cracks can be prevented in some cases, and in other cases cracking can be delayed.

TABLE 10-16

TESTS OF GALVANICALLY COUPLED TYPE 347 STEEL U-BEND SPECIMENS IN BOILING 42 PERCENT $MgCl_2$ SOLUTION

Other metal	Type of couple	Area ratio, coupled metal to type 347	Exposure time, hr	Stress corrosion cracks in type 347
None			2	Yes
Nickel	Coupon*	1.3	17	Yes
Do	do. *	1.3	111	Yes
Do	do. *	2.5	24	Yes
Do	do. *	6.0	24	Yes
Do	Plate. †	1.3	60	Yes
Do	do. †	1.3	810	No
Do	do. †	3.5	92	No
Copper	Coupon*	2.0	1,000	No
Do	do. *	2.2	27	No
Do	(‡)		24	No

*Coupon attached to U-bend.

†Legs of U-bend electroplated; apex of bend not plated.

‡Coupon of copper inserted in solution without contact with U-bend. Some copper dissolved in solution, and a part plated out on U-bend.

A few similar tests were made in autoclaves on plated U-bend specimens mounted in the steam phase of a synthetic boiler water. The interest here was to determine if protection would be obtained in an environment which would be expected to have low electrical conductivity. Only very limited data are available, but it would appear that chemical nickel plating, which produces a nickel-phosphorus alloy coating, might offer some chance of success. The results of the test are given in table 10-17.

EFFECTS OF INHIBITORS AND OXYGEN SCAVENGERS

The ineffectiveness of alkaline-phosphate water treatment in preventing stress corrosion of austenitic stainless steels in the steam phase led to numerous autoclave "tilt" tests with

TABLE 10-17

AUTOCLAVE STRESS CORROSION TILT TESTS (INTERMITTENT WETTING) OF PLATED AUSTENITIC STAINLESS STEEL U-BEND SPECIMENS MOUNTED IN THE STEAM PHASE OF 500° F WATER WITH 553 PPM CHLORIDE, 50 PPM PHOSPHATE, AND 10.6 pH

(Test time: 15 days; tilt cycle: momentarily, twice daily)

U-bend, AISI type	Type of plating	Location of plating on U-bend	Area ratio, plating to bare metal	Oxygen in water, ppm	Stress corrosion cracks
347	Electroplated copper	Legs	3.5	200	Yes
347	Electroless copper	do	2.0	200	Yes
347	do	All over		200	Yes
347	Electroplated nickel	Legs	3.5	42	Yes
347	Electroless nickel	All over		42	No
304	do	(*)	100	42	No
304	do	All over		42	No

*Plated all over, then stripped in small area on apex of bend.

other inhibitors. Tannin, chromate, and octadecylamine (a film forming amine) were tried. None of these was found to be effective.

Tests have also been made with oxygen scavengers added to the autoclaves since it has been postulated that stress corrosion will not occur in the absence of this gas. Both hydrazine and sodium sulfite were tried. The results appear quite promising, especially in the case of the sodium sulfite additions. Stress corrosion cracks occurred only in a minority of cases with sulfite, under conditions which otherwise would have caused consistent and severe cracking.

The results with sulfite additions were somewhat inconsistent. These inconsistencies are probably related to a delay in complete scavenging of oxygen in the steam when the sulfite is added to the water. Attempts to hasten the reaction with copper and cobalt catalysts have not been successful in eliminating inconsistent results in the autoclave tests.

GENERAL OBSERVATIONS

Types of Cracks

Stress corrosion cracks in annealed austenitic stainless steels are predominantly transgranular. The cracks may vary in appearance from single, relatively straight cracks to highly branched, fingerlike crack networks. Typical examples

are illustrated in figures 10-8 and 10-9. It is possible that the straight, single cracks are those which are produced under conditions causing rapid crack development, whereas the branched cracks are produced under milder circumstances.

The transgranular crack network type is easy to recognize in austenitic stainless steels as

FIGURE 10-8. Example of a single relatively straight transgranular stress corrosion crack in an austenitic stainless steel ($\times 250$).

FIGURE 10-9. Example of a highly branched network of transgranular stress corrosion cracks in an austenitic stainless steel ($\times 500$).

having been caused by stress corrosion. The straight single cracks are less easy to diagnose, because they appear much like fatigue cracks. The diagnosis of the cause of such a crack requires knowledge of the type of stress and corrosive environment leading to failure. The acceleration of stress corrosion by cyclic fatigue stresses is also a distinct possibility. In fact, corrosion fatigue can be considered as a special case of stress corrosion, the main difference being that stresses are cyclic in the former case and static in the latter.

Stress corrosion in sensitized stainless steels may follow an intergranular path. Intergranular attack would usually be found locally in heat affected zones near welds, although it could occur generally in stainless equipment operated at sensitizing temperatures. Differentiation between ordinary intergranular corrosion and intergranular stress corrosion probably would require a supplementary corrosion study in the environment to determine whether stress was necessary for failure to develop. An example of intergranular stress corrosion is illustrated in figure 10-10.

FIGURE 10-10. Example of intergranular stress corrosion cracks in a sensitized type 304 austenitic stainless steel ($\times 100$).

Relation of Pitting and Cracking

It has been observed that stress corrosion cracks in austenitic stainless steels nearly always start at macroscopic corrosion pits on the surface of the specimen. It is possible that pitting is a necessary initial step in the development of cracks. However, there is no evidence to indicate that all environments leading to corrosion pits will also ultimately lead to stress corrosion. In fact, it has been observed that, although all cracks may start at pits, there are usually fewer cracks in specimens having more numerous pits.

AUXILIARY BOILER EXPERIENCE

The laboratory tests described in the previous section indicated that austenitic stainless steels are especially vulnerable to stress corrosion in the steam phase of secondary systems where intermittent wetting might occur. Of particular concern are tube-header joints of heat-transfer equipment since water entering

the joint crevices might flash to steam and cause concentration of the solids dissolved in the water. The laboratory tests also indicate that control of the stress corrosion might be accomplished by (1) prevention of steaming in the crevices, (2) elimination of chlorides, or (3) elimination of oxygen.

Verification of these points under practical circumstances was provided by service and laboratory runs of some small stainless steel boilers. These units were fire-tube boilers intended for auxiliary services aboard non-magnetic minesweepers. The boilers were made of welded AISI type 304 steel. Normal operation was at 260° F and 35 psi. The combustion gas temperature in the "hot end" header was between 1,700 and 1,800° F. The maximum metal temperature of the header in the hot end was 440° F as determined by measurement.

Critical crevice areas were located in three places. These were (1) the joints between the tubes and headers, (2) the joint between the combustion tube and one of the headers, which joint was welded with a backing ring on the water side, and (3) the joints between the headers and shell. A typical longitudinal section through a tube-header joint is shown in figure 10-11.

One of these boilers was steamed on a test stand with alkaline-phosphate-treated water and no special deaeration. The unit was steamed 1,008 hr with water containing 530 ppm chloride and then an additional 295 hr with water containing 1,775 ppm chloride. Tube-header joints were removed for examination after the initial 1,008 hr. In addition, samples of the tube-header joints, the combustion tube-header joint, and the header-shell joints were obtained after the full run of 1,303 hr. Stress corrosion cracks were found in all cases.

Typical examples of tube-header joint cracks are shown in figures 10-11 and 10-12. All in all, 48 tube-header joint sections were examined. Of these, 26 had tube-wall cracks, 14 had header cracks, and 5 had weld cracks. Some of the tube cracks penetrated the entire wall, although no malfunctioning from leaks had been observed during operation of the boiler.

FIGURE 10-11. Stress corrosion cracks in a tube-header joint from a type 304 steel auxiliary boiler, longitudinal section ($\times 5$).

Metallographic inspection revealed that the cracks were predominantly transgranular. All occurred within $\frac{1}{4}$ in. of welds. All cracks originated from the water side in crevice areas. No cracks were observed at joints which had no crevices.

FIGURE 10-12. *Stress corrosion cracks origination from the crevice of a tube-header joint from a type 304 steel auxiliary boiler, transverse section ($\times 10$).*

These observations led to the sampling of tube joints from four similar boilers which had been steamed aboard ship for about 1,000 hr.

Stress corrosion damage was observed in all these joints. Stress corrosion cracks were also found in the tube joints of an AISI type 304 steel hot-water heater which had been removed from shipboard service because of leaks after 2,000 hr of operation. This heater was a fire-tube unit operated at a water discharge temperature of 190° F.

A second AISI type 304 steel auxiliary boiler was operated on a test stand to determine the effects of modified tube-joint designs. The boiler was steamed for a total of 1,574 hr with alkaline-phosphate-treated water of 2.5 to 3.5 epm alkalinity, with no special deaeration. The chloride level was 530 ppm during the first 1,048 hr, and 1,775 ppm during the final 526 hr. Table 10-18 describes the various tube joints and the operating times at which inspections were made.

Joint designs 1 through 5 all showed severe stress corrosion cracking. From this it was concluded that deep J-welds and tube rolling were not satisfactory because crevices were not entirely eliminated from the tube-header joints. Joint design 6 was completely free of cracks, and this demonstrated the effectiveness of keeping water out of the crevices by welding from the water side of the joint. Joint 7 likewise produced no stress corrosion cracks. This experimental joint was of interest because it demonstrated that the presence of boiler water in the crevice was not harmful, provided the water was not allowed to boil.

A third boiler of standard design was operated on a test stand to determine the effect of eliminating chlorides from the water. The boiler was operated for 1,013 hr. The initial feed water was passed through an ion exchanger to reduce chlorides to about 0.1 ppm. A closed system was used, with the boiler water maintained at less than 10 micromhos during the entire operating period. Subsequent examination of the tube joints revealed freedom from stress corrosion cracks.

TABLE 10-18

DESCRIPTION OF SPECIAL TUBE JOINTS
TESTED IN TYPE 304 STEEL AUXILIARY
FIRE TUBE BOILER

Joint design No.	Description of joint	Operating time when examined, hr.
1	Standard boiler design; header beveled 45° to half thickness, welded from fire side-----	1048
2	J-welded from fire side to near full depth of header-----	1048
3	Same as 2, except type 316 tubes-----	1048
4	Tube rolled to contact, J-welded from fire side to half depth of header, then rerolled lightly-----	1048
5	Tube rolled 3 mils on radius beyond contact, then J-welded from fire side to half depth of header-----	1048
6	Fillet welded on water side, and small J-weld on fire side-----	1048; 1574
7	Same as 1, except tube was plugged to prevent gas circulation and ends were water cooled to prevent steaming of boiler water in joint crevice--	1574

Finally, a fourth boiler of standard design was tested to determine the benefits to be obtained through oxygen control. This boiler was operated 3,000 hr with alkaline-phosphate treatment, 2.5 to 3.5 epm alkalinity, and 530 ppm chloride. In addition, the system was scavenged of oxygen by maintaining a minimum of 100 ppm sulfite, added as sodium sulfite. Examination of tube joints from this boiler revealed no evidence of stress corrosion.

STRESS CORROSION FAILURES IN MODEL HEAT EXCHANGERS

Tests of scale-model heat exchangers were made primarily to obtain heat-transfer data and to establish design criteria. Although many of these units performed without failure, others failed by cracking during test. The cracking was identified as stress corrosion in only two

cases. In a third case there was a possibility that cracking was initiated by stress corrosion. Other failures occurred in which cracking started on surfaces in contact with liquid metals (Hg, Na, or NaK). Laboratory experiments failed to show any indications that either of these liquid metals causes stress corrosion^{36 37} in several types of austenitic stainless steels.

One of the units in which stress corrosion occurred consisted of a two-tube evaporator

FIGURE 10-13. Construction of two-tube model evaporator. Radial cracking occurred in the heavy tube sheet on the water side, and tube failure occurred in the third fluid region.

constructed as shown in figure 10-13. This unit was made entirely of AISI type 304 stainless steel. The tube arrangement is shown in figure 10-14 with part of the shell removed. Actually, the tubes shown between the inner tube sheets were of a duplex tube construction, with helium as a third fluid occupying grooved spaces between the duplex tubes and between the tube sheets at each end of the unit. During test, heating was accomplished by circulating NaK through the tubes, and steam was produced at 467° F (500 psi). The testing schedule consisted of 2,500 thermal cycles followed by 2 weeks at steady state.³⁸ The composition of the water in this steam generator was maintained within the following limits: chlorides, 462 to 602 ppm; phosphates, 50 to 60 ppm; and pH, 10.6 to 10.7.

Subsequent examination³⁹ revealed that extensive transgranular cracking had occurred on the inside surface of the shell (water-steam side) and also on the water-steam side of the

FIGURE 10-14. Photograph of tube and tube sheet arrangement in two-tube evaporator.

FIGURE 10-15. Radial cracks on water side of tube sheet in two-tube model evaporator ($\times 4$).

tube sheet at the hot end. In neither case did the cracks penetrate to any great extent. In the shell the penetration was about 0.010 in., whereas in the tube sheet, penetration was about one-fourth in. Cracks in the tube sheet were radial from the tube holes as shown in figure 10-15. Definite proof was obtained of chloride concentration in the annulus between the tubes

and tube sheet. A deposit removed from this area was analyzed and showed the presence of 1 percent chlorides.⁴⁰ This type of concentration is believed to be caused by boiling within a crevice where a thermal gradient exists.

In addition to the cracks in the shell and tube sheet, others were found in the inner tubes of the helium manifold at the hot end (fig. 10-16).

FIGURE 10-16. Cracked tube from third fluid zone of two-tube model evaporator.

This cracking was very severe and upon microscopic examination it was found to be intergranular in nature (fig. 10-17).

The presence of large quantities of rust in the manifold indicated that moisture had been present at some time during the test.

The other model unit that was stress corroded consisted of a nine-tube superheater, constructed as shown in figure 10-18. This, too, was made of AISI type 304 stainless steel. After 48 hr of operation the shell failed by extensive cracking around support brackets welded to the shell. The shell was replaced with a new one carefully tested to make certain that no cracks were present. After several weeks of operation the second shell failed, although this time free floating supports had replaced the welded brackets. The largest crack was pegged, and a patch plate was welded over the cracked

area. Extensive cracking was noted in the vicinity of the patch plate after several more weeks of operation. An increase in the pressure of the third fluid at this time indicated a leak between it and the steam. When the unit was cut open for detailed examination, a thin white deposit was found on the steam side of the shell. The deposit was present in quantities so small that a satisfactory sample for analysis could not be obtained. However, it is believed to have consisted of salts concentrated from carry over in the steam. The steam superheated in this unit was generated from water containing 40 ppm chlorides.

A detailed examination³⁹ revealed cracking in the shell to be typical of stress corrosion cracking (fig. 10-19).

The microstructure has many strain lines, indicating that the shell had been plastically

FIGURE 10-17. Intergranular cracking in type 304 tube shown in figure 10-18.

deformed and that a high state of stress existed. Cracks were also found in several of the baffle plates, and all three tie rods were broken. One tie rod was sectioned in several places. Cracks were found in each section. Cracks in the shell, baffle plates, and tie rods were identified as stress corrosion cracks. The leak from the steam side to the third fluid was found to have resulted from a crack in a seal weld at the end of one of the tubes. The cause of this failure could not be determined.

Severe and extensive cracking occurred in a third model unit. This unit was a steam generator, the construction of which has been

described by Trocki and Nelson.⁴¹ Cracks were found in an AISI type 347 tube sheet separating NaK from Hg and in two AISI type 347 tubes also separating NaK from Hg. Since cracking occurred in the hottest portion of the heat exchanger subjected to water slugging and did not start from the water side, it was felt that it was caused by thermal stresses.⁴² There was, however, some possibility that this cracking might have been at least partly caused by stress corrosion. The tubes separating the water from the mercury were made of SA280 steel (nominal composition: .015 percent C, 0.65 percent Cr and 0.55 percent Mo). An increase of pressure on the third fluid, mercury, after 10,600 hr indicated a leak from the water side. The unit was shut down and drained in a matter of hours. Subsequent examination⁴³ showed perforation of the SA280 tubes by pitting, permitting water to enter the mercury system. However, the time during which the stainless-steel tubes and tube sheet were exposed to water was short. It is doubtful that the severe extensive cracking could have been

FIGURE 10-18. Schematic drawing showing constructional features of nine-tube model superheater.

FIGURE 10-19. *Typical cracks in shell of nine-tube superheater ($\times 140$).*

caused by stress corrosion in the short time of exposure to water.

INDUSTRIAL EXPERIENCE

Failures in industrial equipment from stress corrosion have occurred in several of the alloys that were tested and discussed in a previous section. Some of these failures are reviewed and commented upon in this section.

Hardenable Stainless Steels

Most of the reported stress corrosion failures in this class of steels have occurred in media other than hot water and steam. Failures have

been numerous in the petroleum industry, particularly where hydrogen sulfide has been encountered.¹⁴ One known exception was the failure of AISI type 403 compressor blades;¹⁵ this was attributed to the presence of moisture. In this case, the cracking was intergranular in nature and did not appear until after a considerable amount of operation. Cracking was associated with a small amount of surface corrosion. Johnson¹⁴ suggested that cracking was caused by nascent hydrogen generated at the surface. These failures occurred in the lower temperature stages and were, therefore, not directly comparable to conditions in water-cooled nuclear reactors. However, they were of considerable interest because the importance

of proper heat treatment was demonstrated. No additional failures were encountered after the adoption of a stress relieving heat treatment at 950° F.

Nathorst²³ has described intergranular stress corrosion cracks in steam turbine blades made of martensitic stainless steel. However, no mention was made of heat treatment and the specific alloy.

Valve trim made of AISI type 410 stainless steel does not appear to be susceptible to stress corrosion in the steam systems when the alloy is properly heat treated and excessively high operating stresses are not imposed.⁴⁵ If proper heat treatment is not used on such parts constructed of martensitic stainless steels, the combination of operating stresses superimposed on high residual stresses may render these materials susceptible to stress corrosion cracking when exposed to a corrosive medium.

In media other than moist air or steam, but much more corrosive, the importance of proper heat treatment has been demonstrated by laboratory experiments. The length of time required for failure in 1-1 HCl plus 1.0 percent SeO₂ was materially increased by tempering AISI type 403 at 1,050° F. Furthermore, failures were eliminated by this treatment when the applied stress did not exceed 75,000 psi.¹⁵ Similar results have been obtained with several hardenable stainless steels using a corroding medium⁴⁶ consisting of 0.5 percent CH₃COOH periodically saturated with H₂S.

Of direct interest in connection with nuclear power plants is the experience in another service with a small waste heat boiler constructed entirely of AISI type 430 stainless steel. This boiler has been operating satisfactorily at about 350° F for approximately 2 years without failure.⁴⁷

Nickel-base Alloys

As previously pointed out, nickel-base alloys are relatively free from stress corrosion cracking except in certain specific media. Two cases are known in which failure of nickel-base alloys was attributed to stress corrosion cracking under

conditions similar to those encountered in nuclear power plants. Both these failures occurred in a material corresponding to alloy I of table 10-9, one in steam and the other in hot water.⁴⁸ The component that failed in steam was a spring that had been in service 4 years at a temperature of 750° F under a stress of 77,000 psi. Cracking was intergranular in nature.

The failure in hot water occurred in the tubes of a heat exchanger.⁴⁸ The function of this heat exchanger was to maintain constant steam temperature in a steam line bypassing a portion of the steam through the unit. It was so operated that steam passed through vertical tubes surrounded by water. Stress corrosion occurred as intergranular cracks originating on the water side of the tubes within a sludge on the bottom tube sheet. An investigation of the failed tubes attributed the failure, at least partially, to the presence of a continuous intergranular precipitate. DePaul,⁴⁹ in discussing intergranular attack in this alloy in high-temperature water, states that such attack can be minimized considerably if small amounts of columbium are present.

Austenitic Stainless Steels

It appears that stress corrosion failures in austenitic stainless steels were first recognized as such in the petroleum industry. Dixon⁵⁰ described failures in heat exchanger and condenser tubes and also in the linings of pressure vessels. Some failures originating on the product side have been attributed to chlorides in crude oils either as emulsified brines or as organic chlorides. Others originating on the water side in heat exchanger and condenser tubes have been attributed to soluble chlorides.

Failures in austenitic stainless steels have been reported in a wide variety of equipment ranging from coffee urns to heavy industrial equipment. In most cases, chlorides have been considered as the principal offenders. Other corrosive media have also been considered responsible for certain failures. Nathorst²³ describes a number of industrial failures in-

volving many corrosive media, several of which contained chlorides. He also points out that in some cases trouble can be eliminated by reducing stresses either by design changes or by stress relief.

Of particular interest in connection with nuclear power plants are failures from stress corrosion in which either water or steam was the corrosive medium. Several of these have been discussed in the literature. The more pertinent ones are reviewed here. Davis⁵¹ described the failure of a stainless steel (type 304) turbocompressor through stress corrosion of two rotors. Failure by transgranular cracking occurred after 3 months of service. The unit was used to compress steam which was subsequently condensed. The condensate contained less than 0.5 ppm total solids. However, chlorides were present in the raw water to the extent of about 20 ppm and were also found in a nonmetallic deposit on the failed parts. Failure was attributed to concentration of chlorides, which were presumed to have entered the compressor in the medium of finely divided particles of water.

Another case described by Davis⁵² occurred in the tubes of a heat exchanger. Normal temperature on the process side was 350° to 380° F, and in emergencies this could reach 500° F. The outside surfaces of the tubes were exposed to cooling water with a chloride content of 110 to 420 ppm. Examination showed that the tubes were cracked from the water side. The cracks had originated under a nonmetallic deposit on the underside of the tubes. This deposit may have permitted concentration of chlorides on the metal surface and at the same time caused a rise in temperature. The stresses were believed to be caused by the forming operation. This conclusion was reached when the cracks, which in the original specimen were just barely visible, opened one thirty-second in. when the pipe was sectioned.

Davis⁵² also noted another failure in which conditions favorable to concentration existed. This occurred in a vapor-heated steam generator after only 90 hr of service. It was believed that a small vapor space existed in the shell

directly under the upper tube sheet. A heavy deposit of a nonmetallic substance was found in this area, and transgranular cracks originated on the water side. Water analysis showed only 13.5 ppm chlorides.

Additional failures have occurred in vertical tubular heat exchangers where the cooling water was low in chlorides, but the existence of a vapor space under the upper tube sheet was probable. Even though boiling on tube surfaces may not have occurred, it is probable that fluctuations in water level and turbulence afforded opportunity for the concentration of chlorides.

Collins⁵³ has described failures in vertical condensers where vapor spaces actually existed under the upper tube sheet. This resulted in concentration under nonmetallic deposits. He also pointed out two design changes and one operational change that corrected the condition. Each of these was in the direction that reduced the tendency for concentration.

Three small waste heat boilers described by Collins⁵³ are of particular interest because they provided another means of concentration. These boilers were constructed of AISI type 316 stainless steel, all of the same basic design. Two of these boilers failed from stress corrosion originating in a crevice between a backing strip and the weld joining the top tube sheet to the top flange. The other boiler failed from stress corrosion originating in crevices between the tubes and the lower tube sheet. The condition was materially improved in a rebuilt boiler by the elimination of crevices where concentration could occur.

Another interesting series of failures was described by Nathorst.²³ He reported the failure of 25 steam-jacketed boilers made by one manufacturer.

The failure record of these vessels illustrated the variations in service life that can occur in presumably identical components. No mention was made of the chloride concentration in the steam. However, the fact that low-pressure steam was condensed on the inner boiler suggests the possibility of concentration.

The distribution of service life is shown below.

Number of boilers cracked	Approximate service life, years
3-----	1
4-----	2
10-----	3
2-----	4
2-----	5
3-----	7
1-----	9

Conclusions From Auxiliary Boiler Experience, Industrial Experience, and Model Heat Exchangers

A study of available stress corrosion data on service and simulated service equipment leads to a general confirmation of the conclusions reached from the laboratory tests. The main contributions of the laboratory tests were (1) a closer definition of the conditions causing stress corrosion in high-temperature waters and (2) a demonstration of the importance of oxygen in the stress corrosion process in chloride-bearing waters.

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Chapter 11

INTERGRANULAR CORROSION

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INTRODUCTION.....	Page 225
ENGINEERING IMPORTANCE.....	225
MECHANISM AND CONTROL.....	226
WORK DONE ON UNSTABILIZED STEELS.....	227

INTRODUCTION

Stainless steel AISI type 347 was generally chosen as the main material of construction for water-cooled reactors because it offered the maximum degree of corrosion resistance for the intended environment. This stainless steel is less susceptible to a specific type of localized corrosion, known as "intergranular corrosion," than any of the other commonly employed stainless steels. It is classified as a "stabilized" stainless steel because an element (niobium) is added to the metal to prevent intergranular attack. Similar stainless steels that do not contain stabilizing elements are classified as "unstabilized" grades. Until recently there was no information available concerning the susceptibility of unstabilized stainless steels to intergranular attack in high-purity water at temperatures on the order of 600° F. Therefore, the unstabilized grades of stainless steel, such as AISI type 304, were not initially employed.

As the project progressed toward the completion of the prototype reactor, it became apparent that the use of an unstabilized grade such as AISI type 304 would be highly advantageous. There were two advantages to using AISI type 304 in place of type 347. First the AISI type 347 stainless steel contained the element ni-

obium, which was a critical element during this period. Secondly, because of the overall urgency of the project, procurement time for purchasing materials was vitally important. Unstabilized stainless steels can be delivered in relatively short periods of time compared to the stabilized grades.

It was realized that before the stabilized grade could be replaced by the unstabilized grade many factors would have to be investigated in order to determine whether or not the unstabilized grade of stainless steel would be susceptible to intergranular attack under the expected service conditions.

The work described in this chapter showed that an unstabilized steel such as AISI type 304 could be employed as a replacement for type 347 without danger of intergranular corrosion.

ENGINEERING IMPORTANCE

Intergranular corrosion may be defined as the selective attack occurring at the grain boundary of a metal or alloy exposed to a corrosive environment. Specific details concerning the various proposed mechanisms and methods for controlling the problem are described in many text books and industrial publications. An excellent discussion of intergranular corrosion in stainless steels is given in the ASTM Special Technical Publication No. 93 entitled "Symposium on Evaluation Tests for Stainless Steels." This chapter will deal only with the highlights of the mechanism and the control of the problem.

When an unstabilized chromium-nickel stainless steel such as AISI type 304 is exposed to temperatures ranging between 800° and 1,500° F, a preferential chemical reaction takes place between the carbon existing at the grain boundary and the chromium in the adjacent grains which results in the formation of a discontinuous precipitate at the grain boundary. This precipitate is chromium carbide. Chromium carbides form predominately at the grain boundary because most of the excess carbon (not soluble in austenite grains) is located at the grain boundary. When this type of precipitation occurs, the steel is said to be "sensitized," or in a condition which may be susceptible to intergranular attack. These carbides are dissolved only by solution annealing followed by rapid cooling through the 800° to 1,500° F range.

From an engineering point of view this reaction is important since almost any piece of metal which is welded will be exposed to temperatures in this range for a time interval which varies with both the thickness of the metal being welded and the method of cooling. It is also important in that precipitation may occur during annealing or stress-relieving operations.

From a structural point of view intergranular corrosion is important primarily because it produces embrittlement, which thereby reduces the shock resistance and mechanical strength of the member. This type of corrosion is not readily detected by visual inspection because only an extremely small amount of metal (at the grain boundary) is subject to accelerated corrosion. Since it is not readily observed it often leads to catastrophic failures. Therefore, every effort should be made to determine the susceptibility of a material to intergranular attack under the specific material and environmental conditions expected in service.

MECHANISM AND CONTROL

The simplest explanation for the susceptibility of the 18-8 chromium-nickel stainless steel to intergranular corrosion is that the corrosion

resistance of the chromium carbide precipitate formed during sensitization is considerably less than that of the alloy grains. Another mechanism commonly accepted is that accelerated attack occurs at the grain boundary because of the variation in the composition of chromium between the metal grains and the surface layer of the metal grains immediately adjacent to the grain boundary. Depletion of chromium occurs at this point because of the chromium carbide precipitate which forms at the grain boundary. It is further postulated that galvanic corrosion occurs at the point where the difference in composition exists.

There are many controlling factors that affect the degree of intergranular corrosion which occurs under a given set of conditions. The most important of these is heat treatment. Obviously, if a metal is not exposed to temperatures within the sensitizing range, the chromium carbide precipitate will not form at the grain boundary. Another important factor is the carbon content of the steel. The quantity of chromium carbide precipitate varies directly with carbon content. Of lesser importance are grain size and ferrite and nitrogen content.

Grain size may affect intergranular corrosion in that it controls the concentration of the precipitate formed at the grain boundary. In small grain size alloys the precipitate will be finely dispersed, whereas with large grains the precipitate will be more concentrated. This is due primarily to the differences in grain boundary interfacial area.

Ferrite affects this form of corrosion in that austenite grain boundaries immediately adjacent to ferrite grains are lower in carbon content. This difference exists because carbon is more soluble in the ferrite than in the austenite grains. Thus the carbon dissolved by the ferrite reduces the carbon available for precipitation at the grain boundary of the austenite grains and thereby effects a control on the extent of precipitation.

Nitrogen is important in that it affects the equilibrium between austenite and ferrite, i. e., high nitrogen reduces the ferrite content of the steel.

Although chemical composition can materially affect intergranular corrosion, a discussion on the effects of chromium and nickel content is considered to be beyond the scope of this chapter.

Several general rules for avoiding intergranular attack have evolved from the use of unstabilized stainless steels in industry. For instance; it is generally accepted that intergranular corrosion is not a problem with steels in which the carbon content is equal to or less than 0.03 percent. As indicated previously, the thickness of the material to be welded or heat treated can materially affect the degree of precipitation that occurs during exposure to the sensitization temperature range. In this connection the Allegheny Ludlum Steel Corp. recommends that for unstabilized stainless steels to be welded, the specific maximum allowable carbon content should be governed by the thickness of the metal. A report entitled "Evaluation of 0.03 Percent Maximum Carbon Types 304 and 316 Compared to Types 347 and 318" states that it soon became apparent, when the carbon content of alloys falling within the type 304 stainless steel range was maintained at some low level, the susceptibility to intergranular corrosion was reduced. The reduction in susceptibility was of such a magnitude that sections up to $\frac{1}{2}$ in. thick could be safely welded if the carbon content was maintained at 0.06 percent maximum; $\frac{3}{4}$ in. thick at 0.05 percent maximum; and 1 in. thick at 0.04 percent maximum. If 0.03 percent maximum carbon type 304 was used, it could be safely welded and stress relieved for 2 hr in the sensitizing temperature range, 800° to 1,500° F, without danger of becoming susceptible to intergranular corrosion.

The precipitate formed at the grain boundary may be dissolved by a solution anneal followed by rapid cooling through the sensitizing range (800° to 1,500° F). This heat treatment illuminates the undesirable aspects of sensitization since the precipitate no longer exists at the grain boundary. In many applications, especially in welding, solution annealing is not practical or possible.

WORK DONE ON UNSTABILIZED STEELS

Although there was considerable experience and information on the susceptibility of unstabilized 18-8 type stainless steels to intergranular attack in various environments and under many different conditions, this information could not be used to predict its susceptibility under the expected service conditions for the water-cooled nuclear reactor. Specific corrosion tests in high-purity water were necessary to make this determination.

Preliminary tests were conducted in high-purity water at 500° F by Leggett and Thomas.¹ These tests indicated that AISI type 304 stainless steel, sensitized by exposure to 1,200° F for 2 hr and subsequently corrosion tested in high-purity water at 500° F for 173 days, is not susceptible to intergranular corrosion.

A more detailed study² was made in which various heat treatments and carbon contents were investigated as the principle variables. In this study special heats of an 18-8 type stainless steel were made with carbon contents ranging from 0.03 to 0.25 percent. The main reason for investigating carbon contents in excess of 0.08 percent (upper limit of AISI type 304 stainless steel) was to study the effect of high carbon contents which might be obtained on the surface of a steel that had been accidentally carburized. Three different heat treatments were investigated. These treatments were chosen to simulate all likely exposures that would be expected in normal fabricating operations.

Briefly they consisted of: (1) solution annealing, (2) sensitizing at 1,200° F for 2 hr, and (3) sensitizing at 1,200° F for 48 hr. For most applications the heat treatment for 2 hr would be sufficient to simulate exposures expected during fabrication. The 48-hr treatment applies only to relatively large pieces of equipment that had very slow cooling rates.

Four different corrosive environments were studied. They were (1) oxygenated water at 600° F (neutral pH), (2) oxygenated water at 640° F (neutral pH), (3) oxygenated water at high pH, and (4) oxygenated water at low pH.

TABLE 11-1
SUMMARY DATA ON THE SUSCEPTIBILITY OF AUSTENITIC STAINLESS STEELS TO
INTERGRANULAR CORROSION*

Material conditions studied †		Corrosion test conditions §	Duration of tests	Results
Carbon contents studied, percent	Heat treatment ‡			
0.03 0.10 0.15 0.25	Each group of specimens for a given carbon content (9) contained 1 sample from each of the 3 heats which were heat treated as follows: 1. Solution annealed at 1,900° F 2. Sensitized at 1,200° F for 2 hr 3. Sensitized at 1,200° F for 48 hr	All specimens were tested under the following conditions: 1. Oxygenated water at 600° F, neutral pH 2. Oxygenated water at 640° F, neutral pH 3. Partially oxygenated water at 600° F, pH 10-11 4. Partially oxygenated water at 600° F, pH 3-4	Conditions (1), (2) and (3) were tested for 4 months. Condition (4) was tested for 2 months.	None of the specimens tested under condition (1), (2), or (3) showed evidence of intergranular attack. Condition (4) showed intergranular attacks on sensitized steels at the higher carbon contents. ¶

*Based on unpublished work.²

†15 different heats were employed in which there were 3 heats for each carbon content studied. The percentage range in compositions was as follows: carbon, 0.03 to 0.25; chromium, 17.3 to 22.2; nickel, 7.6 to 10.9; manganese, 0.45 to 1.3; and silicon, 0.25 to 0.85.

‡All specimens were air cooled following heat treatment, and the oxide film was removed with abrasive paper.

§Water employed for testing has a specific resistance of 500,000 ohms-cm prior to additions and testing. The oxygen content of conditions (1) and (2) was 10 to 30 cc/kg of water at temperature and of (3) and (4) was 1 to 5 cc/kg. The range of pH given was maintained throughout the test.

¶Intergranular attack was observed in the three specimens shown below.

Carbon, percent	Heat treatment	Depth of attack
0.20	Condition (3)	2 grains
0.25	Condition (2)	4 grains
0.25	Condition (2)	2 grains

Test condition (1) was considered to be the most aggressive normal environment which could exist, and (2) applied only in one piece of equipment which contained immersion heaters. Condition (3) represented possible short-term exposures. Condition (4) was included for information only and is not expected to occur in service.

Tests were made on the type of specimen shown in figure 6-3, chapter 6. The specimens were tested in stainless-steel autoclaves similar to those described in chapter 5. Details of the test conditions and the results obtained are shown in table 11-1.

These results show that intergranular corrosion should not normally be expected to occur in unstabilized steels exposed to conditions (1), (2), or (3). However, it also indicates that

intergranular corrosion should be considered very carefully where materials are exposed to low pH conditions. Since condition (4) was not expected to occur in the present reactor systems, it was considered satisfactory to employ AISI type 304 as a substitute for AISI type 347 without the requirement for heat treatment to dissolve precipitated chromium carbides.

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Chapter 12

CORROSION PRODUCTS IN RECIRCULATING SYSTEMS

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	Page
INTRODUCTION.....	229
PROPERTIES OF SYSTEM CORROSION PRODUCTS..	230
Physical and Chemical Properties.....	230
DEPOSITION OF SYSTEM CORROSION PRODUCTS..	231
Observations of Deposition Tests.....	231
Deposition.....	233
Unirradiated Studies.....	235
REMOVAL OF SYSTEM CORROSION PRODUCTS....	236
Purification Systems.....	236
Removal by Chemical Techniques.....	237
DETAILED SUMMARY.....	237

INTRODUCTION

As indicated in chapter 1, the major point of departure of the nuclear power plant from conventional systems is the presence of a radioactive flux produced by the nuclear fuel employed.

The possible radiation hazards to operating personnel in such a system makes it mandatory that the primary components of the reactor be hermetically sealed as much as is practically possible. Because of this requirement, the corrosion products formed cannot be removed by continuous blowdown as practiced in conventional boiler water installations. Consequently corrosion products must be kept to a minimum by other less conventional means. Corrosion products in a system present three major problems:

1. Fouling of heat transfer by corrosion products (crud*).
2. Accumulation of insolubles on moving parts in such quantity as to impair the operations of these parts.

*"Crud" is a term developed in laboratory usage for insoluble corrosion products formed and circulated in the primary systems of pressurized water reactors and test loops.

3. Control of radioactivity at levels low enough to permit accessibility for maintenance.

Certain corrosion products present in the primary system become highly radioactive when circulated through the reactor core. The influence of corrosion products on fouling and activity level is considered to be more of a problem than the structural damage produced by corrosion. Corrosion rates that are negligible by industrial and military standards are considered to be extremely important in nuclear applications from the standpoint of radioactivity. For example, a corrosion rate of 10 mg/dm²/mo, which is representative for a stainless steel water-cooled nuclear reactor represents only 0.001 in. of penetration in 16 years. Nevertheless, this represents about an ounce of corrosion product introduced into the system for every day of operation. The quantity of circulating corrosion products is maintained at a tolerable level by three methods, an ion exchanger, a mechanical filter, and the addition of hydrogen (in the presence of radioactive flux).

On the basis of reactor operating experience and observations made on in-pile and out-of-pile test loops, the following variables are considered important in affecting the deposition of corrosion products in radioactive systems: (1) presence of radioactive flux, (2) amount of corrosion product formed, (3) pH of the system, and (4) presence of oxygen in the system water.

Present methods of control include the following: (1) maintenance of basic pH, (2) maintenance of dissolved hydrogen in the system water, (3) purification, and (4) choice of cor-

rosion-resistant materials (this item has no practical bearing on the reactors which are constructed primarily of stainless steel; it could be important in reactors involving such materials as carbon steel).

PROPERTIES OF SYSTEM CORROSION PRODUCTS

Physical and Chemical Properties

Corrosion products originate at the surfaces of materials in contact with the primary coolant. Since water-cooled nuclear reactor systems are constructed mainly of an 18-8 type stainless steel, the corrosion products contain the elements found in these steels, i. e., iron, chromium, nickel, silicon, and carbon. However, consideration must also be given to other materials which have been used for special applications in the primary system of the reactor. It is not possible to assign exact percentage values, but table 12-1 presents a list of typical materials that are employed and the approximate percentage of the total area occupied by these materials.

TABLE 12-1

MATERIALS USED IN THE PRIMARY SYSTEM AND TYPICAL PERCENTAGES OF THE TOTAL SURFACE¹

Material	Typical percentage of total surface
AISI type 304 or 347	>75
Armco 17-4PH	<10
Monel	<5
Inconel	<5
AISI type 410	<1
Hard chromium plate	<1
Stellited surfaces	<1
Inconel-X	<1

Corrosion rates for the primary system materials are low (less than 0.0001 in. per year).¹ As a result the concentrations of corrosion products observed in the primary coolant as solubles and insolubles (crud) are relatively low. The actual concentration is dependent on such factors as the chemical properties of the primary coolant and the nature of plant operation. In general, the crud level (weight of insoluble cor-

TABLE 12-2

TYPICAL SPECTROGRAPHIC ANALYSIS OF IMPURITIES PRESENT IN PRIMARY COOLANT WATER

Element	ppm
Aluminum	0.01
Calcium	0.03
Chromium	0.005
Copper	0.004
Iron	0.37
Magnesium	0.002
Manganese	0.009
Nickel	0.01
Niobium	0.06
Silicon	0.007
Sodium	0.05
Tantalum	<0.03
Zirconium	0.01

TABLE 12-3

CRUD ANALYSES²

CHEMICAL ANALYSIS

	Relative values		
	Iron	Chromium	Nickel
Theoretical for AISI type 347	1.00	0.230-0.275	0.122-0.174
Spread in 5 crud samples taken at various times	1.00	0.40-0.143	0.143-0.157

SPECTROGRAPHIC ANALYSIS

Assumed oxide form	
Fe ₃ O ₄	93.0
Cr ₂ O ₃	0.42
NiO	5.6
MnO	0.23
CoO	0.43
Nb ₂ O ₅	0.01
CuO	0.03
SiO ₂	0.06
Al ₂ O ₃	0.10
MgO	0.10

rosion products per unit weight of water) of the primary coolant is less than 1 ppm. Typical spectrographic analyses for the metallic elements present when the system is operated with a demineralizer, filter, and the addition of hydrogen are given in table 12-2. These elements are present primarily as insolubles. Chemical and spectrographic analyses of crud vary. Other typical analyses are given in table 12-3. These corrosion products were observed by optical microscopy and electron microscope techniques to determine the size and

structure of the products formed. A particle size distribution by optical microscopy techniques showed crud taken from the stainless steel system to have a mean diameter of 0.5μ . Electron microscope techniques showed an ultimate particle size distribution frequency, highly skewed in the less than 0.2μ diameter range.

When formed during hot pressurized operations, crud is normally a black, crystalline, magnetic material having a spinel type structure and good filtering properties. On the other hand, when crud is formed during cold or warm-up operations, reddish residues with varying percentages of ferric oxide and less filterable properties are observed.²

Radiochemical Properties

Induced radioactivities are produced as a result of recirculating the primary coolant and its constituents through the reactor core during critical operation. The bulk of the activity in the primary coolant is short lived, with a level largely dependent on the nuclear power level. When deaerated charging water is used in a typical reactor, the gross primary coolant (gamma) radioactivity, 15 min after sampling and during normal conditions, reaches a maximum of 0.3 microcurie* per milliliter at 100 percent power. Owing to the induced radioactivity of certain elements, a higher value could result if a higher crud level were present, but this would be a transitory condition. If nondeaerated charging water is used, the argon can add 0.5 microcurie to the maximum level, should the filling and charging water be saturated at standard conditions. The long lived specific activities of crud (determined after 120 hr) have not exceeded 8 microcuries/mg.¹

The predominant radioactive species identified in pressurized-water reactor primary coolant samples are shown in table 12-4. The short-lived activities decay to levels that are insignificant within a few minutes after reactor shutdown. Therefore, access to the shielded reactor compartment is controlled by the longer lived activity from those impurities present in the water or deposited on the walls

*One microcurie is equal to 3.7×10^4 dis/sec.

TABLE 12-4

TYPICAL RADIOCHEMISTRY OF COOLANT³

Element	Half-life	Radiation level, microcuries/ml	Source
N16	7.3 sec	100	O16 in H ₂ O.
N17	4.1 sec	(*)	O17 in H ₂ O.
K38	7.7 min	5×10^{-2}	(?).
A41	1.8 hr	4×10^{-2}	Air in H ₂ O.
F18	1.9 hr	4×10^{-2}	(?).
Mn56	2.6 hr	0.5×10^{-2}	Steel.
Na24	15 hr	1×10^{-3}	Na in H ₂ O.
Co60	5.3 yr	2.5×10^{-5}	Steel.
Fe59	45 days	1.1×10^{-5}	Steel.
Ta182	111 days	0.6×10^{-5}	Steel.

*800 neutrons/cm²/sec.

of piping and system components. One operating loop has shown that the activity level in the primary water 15 min after reactor shutdown is generally in the range of 0.05 to 0.1 microcurie per milliliter of water, with radiation near the piping varying from 2 to 200 mr/hr, depending upon the location of measurement.³ One of the factors causing variations in the water activity is the variable concentration of insoluble corrosion products present in the system, a condition that is apparently caused by the alternate storing and releasing of these products in the system due to hydraulic and other effects.

DEPOSITION OF SYSTEM CORROSION PRODUCTS

Observations of Deposition Tests

One of the possible consequences of corrosion in a water-cooled reactor was pointed out by a PWR reactor fuel assembly irradiation experiment.⁴ The object of this experiment was to subject a large test fuel subassembly to irradiation under reactor conditions in order to observe the effects of irradiation. Reactor coolant conditions were simulated by means of a loop shown schematically in figure 12-1.

In this test the zirconium was undamaged. However, corrosion products from the stainless-

FIGURE 12-1. Schematic diagram of stainless-steel test loop with bypass purification system.

steel loop deposited on the heat-transfer surfaces of the in-pile subassembly in sufficient amounts to seriously affect heat transfer. Representative photographs of the subassembly are shown in figures 12-2 through 12-5. This preferential deposition (fouling) on in-pile fuel element specimens has continued to appear in several subsequent loop tests.⁵

A characteristic noted in all of these tests has been the gradual increase in pressure drop with an accompanying decrease in flow across the test sections during operation. It was found that these gradual changes could be alleviated by increasing the coolant pH to about 10 with lithium or potassium hydroxide.

During the more than 2 years of operation of other reactor loops and systems, several other fuel subassemblies have been withdrawn periodically and inspected. It has been found that serious fouling of the fuel element surfaces can be prevented. Under favorable reactor plant conditions, uniform dull black coatings have been found on the outside and inside ends of the subassemblies, the flow channels have been clear; and the fuel elements hold small, almost negligible, amounts of deposited products.⁶

The only positive evidence of fouling in such systems was observed on throttling valves such as that shown in figures 12-6 and 12-7. When fouling of this type occurs, it is characterized by decreasing flow and can be alleviated by periodically closing and opening the fouled valve.

FIGURE 12-2. PWR reactor experimental fuel rod bundle before irradiation in an in-pile loop.

FIGURE 12-3. PWR reactor experimental fuel rod bundle after removal from in-pile loop.

Attempts have been made to correlate some automatic valve failures⁷ and control rod drive mechanism malfunctions with crud deposition.⁸ In all cases observed, it has been shown that while crud may have contributed to faulty operation of these components, other factors probably were the predominant cause for malfunctioning.

During the performance of out-of-pile corrosion tests, some general observations were made with regard to crud circulation and deposition. These are listed for comparison with in-pile test and reactor experiences discussed above.

1. Crud concentrations in the water of stainless steel loops are generally below 1 ppm.⁹
2. Crud deposits uniformly on all surface areas with a tendency for heavier deposition in low-velocity areas.
3. Preferential deposition is observed on throttling valves, as shown in figure 12-7.

Deposition

To obtain a more complete knowledge of the mechanism of crud deposition, studies were performed in which water containing stainless steel corrosion products was subjected to irradiation and magnetic and chemical forces in an effort to produce deposition.

Simulated In-Pile Tests

Initial simulated in-pile experiments were performed in a hot pressurized loop. Water containing stainless steel corrosion products was circulated past a thin zirconium sheet which was irradiated by a deuteron beam from a cyclotron.¹⁰ It was observed in these experiments that fouling of the water side of the zirconium sheet occurs during exposure to a deuteron beam with neutral water in the loop. Experiments using the cyclotron as an irradiation source were discontinued in favor of a Van de Graaff electron accelerator at this point in the investigations.

The irradiation tests with the Van de Graaff apparatus were performed with crud deliber-

FIGURE 12-4. Views of individual rods from PWR fuel rod bundle. Note crud deposits on rod surface (4 $\times$).

ately added to the loop. These products were kept in suspension in the loop water by periodically vibrating the system following additions of crud to the loop. The length of experiments was generally 36 to 48 hr, and the rate of energy dissipation in the water was approximately 30 times that experienced in the pressurized-water reactor. The following conclusions were drawn from these tests:

1. Deposition occurs on the flow channels in the irradiated areas and downstream for a distance corresponding to about 0.1 sec after irradiation.
2. Deposition is not appreciably affected by heat transfer in either direction between the metal and the water.

FIGURE 12-5. Preferential deposition observed on a throttling valve removed from a reactor loop.

FIGURE 12-6. Preferential deposition observed on throttling valve removed from stainless-steel test loop.

3. Deposition is increased by low pH solutions and inhibited by high pH solutions (fig. 12-8). The most effective bases for inhibiting deposition are those which remain highly dissociated and give a high pH at elevated temperatures. From this, it appears that deposition is at least an implicit function of

hydrogen-ion concentration at the operating temperature.

4. Deposition in low pH solutions is decreased by high salt concentration.

Some of these results are illustrated in figure 12-8.

Unirradiated Studies

Heat-transfer experiments in unirradiated systems demonstrated that heat-transfer surfaces are fouled (with accompanying drop in heat-transfer rate) under the simultaneous conditions of low pH and high oxygen concentration.^{11 12} Addition of hydrogen during a fouled condition apparently causes a simultaneous elimination of oxygen from the water and a release of crud from the heat-transfer surfaces, resulting in an increase in heat-transfer coefficient. No decrease in heat-transfer coefficient was observed when the pH was maintained at 10.5 and dissolved gases were held at a minimum by recirculation through the pressurizer which was vented intermittently.

In connection with contemplated heat-transfer and cleaning studies on fouled surfaces, investigations were directed toward the possi-

pH 6

pH 11 (LiOH)

FIGURE 12-7. Photograph of Van de Graaff target specimens showing effect of pH on deposition of crud on irradiated zirconium surfaces in a circulating water system. Loop 500° F, 1500 psi, flow of 8.7 ft/sec. Tested 45 hr with no ion exchanger. Zirconium 9 mils thick; crud added to system. Van de Graaff: 2-new beam, 100 microamperes.

bility of effecting controlled deposition of crud on a given test section geometry. The deposition mechanism utilized was cataphoresis, the migration of suspended or colloidal particles in a liquid due to the effect of a potential applied between immersed electrodes. It was found that deposition of magnetite can be effected on a positively charged zircaloy rod. A reversal in polarity results in no deposition.¹³

REMOVAL OF SYSTEMS CORROSION PRODUCTS

Purification Systems

A typical purification system consists of a bypass demineralizer and a mechanical filter.

In general, these purification systems have performed satisfactorily in their ability to remove the transported corrosion products. Apart from flow rate considerations, the demineralizer is much more effective than the hydraulic service system filter. The demineralizer is over 99 per cent efficient in removing nongaseous solubles and from 89 to 99 percent efficient in removing crud.¹⁴ The sintered stainless steel mechanical filter, having a 20 μ pore size, is effective in removing 60 to 80 percent of the crud and its associated long-lived activities¹ but is only effective in removing from 15 to 40 percent of the total water activity which is attributed mainly to short-lived soluble activities.

The demineralizer is very efficient with regard to corrosion-product removal but suffers from thermal instability at system temperatures. Therefore, heat exchangers are required for cooling the influent. Development of a high temperature resin would eliminate this problem.¹⁵

The mechanical filters in pressurized-water reactor systems have shown very inconsistent and generally unsatisfactory operating characteristics. During low-temperature operation, they show rapid pressure drop increases which result in the need for frequent backflushing. The backflushing operation results in more complex operating procedures, excessive use of water, and a disposal problem with backflush water. Despite the difficulties associated with the mechanical filters, the overall efficiency of the purification system was satisfactory mainly because of the filtering characteristics of the demineralizer.

The disposal of the highly radioactive concentrated products from spent ion-exchange resin and the backflush water from the filters presents difficult handling problems. These problems are for the most part associated with the exposure of personnel to radiation.

Removal by Chemical Techniques

Considerable effort was expended toward investigating corrective measures for fouling by chemical techniques. The results were generally unsuccessful since the effective chemical reagents were not compatible with the materials present in the system.^{9, 16} The most satisfactory reagents for dissolving crud for cleaning purposes include: (1) hydrochloric acid, (2) sulfuric acid, (3) a mixture of chromic and nitric acids, and (4) oxalic acid followed by nitric acid. These were studied in various concentrations and with various inhibitors, but in all cases the degree of their attack on system materials was considered prohibitive. In addition to dissolving agents, dispersing and suspending agents were also investigated. These were ineffective in removing crud deposits, although the system corrosion rates remained low.

Cleaning by ultrasonic techniques was considered; however, preliminary observations do not appear promising.

DETAILED SUMMARY

Corrosion products appear as solubles and insolubles (crud) which are transported in the primary coolant, with the insolubles contributing the major percentage by weight. The crud in stainless steel systems appears as a magnetic oxide consisting mainly of iron and some chromium and nickel. It tends to settle out on the walls of the system and is resuspended by changes in plant operating conditions, e. g., addition of oxygen or higher velocities.

The bulk of the radioactivity observed in the primary coolant is short lived, and its level is dependent largely on the reactor power level. The accessibility of the primary system for maintenance purposes is dependent on the induced activities present at various time intervals after critical operation.

These observations have been made with regard to fouling:¹¹

1. Although the corrosion rates of AISI type 304 and 347 stainless steel are low by ordinary standards, sufficient soluble and insoluble corrosion products are present in the water to cause problems of fouling and high radioactivity level in the primary loops of water-cooled nuclear power plants.

2. In-pile experiments indicate that corrosion products deposit preferentially on fuel element surfaces of the in-pile subassemblies, whereas the out-of-pile subassembly surfaces remained relatively clean. In all these cases the pH of the water was about neutral.

3. Measures have been developed and demonstrated for preventing fouling in reactor loops. The use of dissolved hydrogen in the water in the presence of irradiation suppresses free detectable oxygen; pH is maintained at approximately 7.5 to 9.3. Crud suspension in water increases rapidly on occasion, usually during start-up.

4. Zirconium surfaces irradiated by an electron beam become fouled with crud at pH 6 to 6.5 but not at pH 10 to 11.

5. In unirradiated systems, heat-transfer surfaces become fouled (with an accompanying drop in heat-transfer rate) when low pH (5 to 6) and high oxygen (5 cc/kg) concentrations occur simultaneously. The addition of hydrogen during fouled condition (high oxygen and low pH) caused the elimination of oxygen, a rise in pH, and a release of crud from the heat-transfer surfaces.

In order to meet accessibility requirements and to maintain a minimum concentration of corrosion products in the primary system, a purification system is employed. The typical water-cooled nuclear reactor purification system consists of a sintered stainless steel mechanical filter and a demineralizer. The mechanical filter is effective in removing crud transported to it but much less effective in reducing the total nongaseous short lived activity. The demineralizer is very effective in its function as a demineralizer and a crud filter.

There are presently no completely satisfactory means for removing crud deposited in present reactor systems.

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Chapter 13

APPLICATION CONSIDERATIONS OF WEAR

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	Page
INTRODUCTION.....	239
Material Relationships.....	239
Basis of Conclusions.....	240
DISCUSSION AND INTERPRETATION OF WEAR	
DATA IN CHAPTER 7.....	241
The Wear Factor.....	241
Factors Influencing Wear.....	242
DISCUSSION OF SUPPLEMENTARY DATA.....	245
Typical Problems Arising in Simulated	
Component Testing.....	245
Ball-bearing Tests.....	246
Claddings and Hard Facings.....	250
PRACTICAL CONSIDERATIONS IN CHOOSING MA-	
TERIALS.....	251
Design.....	251
Manufacturing and Processing.....	252
Nonmetallic Materials Investigated.....	256
Martensitic Stainless Steels.....	256
Environmental Considerations.....	257
Introduction of Possible Lubricants.....	257
Special Considerations.....	257
Areas of Future Research.....	258

INTRODUCTION

The choice of water as the moderator and coolant for present commercial and naval nuclear reactors and the incorporation into the design of many complex mechanisms operating in contact with primary water presented new and practically uninvestigated problems to be solved in the field of wear. The major complicating factors were the absence of effective lubrication, high temperatures, and the possibilities of radiation damage.

Early experience with component tests indicated that materials considered satisfactory by the designer on the basis of corrosion resistance (such as the austenitic stainless steels) suffered immediate seizure or at best erratic short-term operation in service. This difficulty was ob-

served not only in antifriction bearings and linkages but also in such seemingly light service items as nuts and bolts.

It was also apparent that conventional bearing materials such as the babbitts would not satisfy the demands of service in the novel high-temperature high-purity water environment. The choice of materials could be resolved only after careful evaluation of both corrosion resistance and wear resistance.

What was then required was a program to screen and evaluate all likely wear combinations in order to provide the designer with a body of information from which he could draw with some assurance of successful operation.

Material Relationships

The bulk of information resulting from the basic wear test program involves material relationships, i. e., the relative performance of materials in combination. Subsequent experience with components in test and in service have either verified or slightly modified the original findings. The section entitled "Practical Considerations in Choosing Materials" is a summation of the findings of the basic tests and subsequent experience.

Early in the program conventional soft, yielding bearing materials were found to be susceptible to severe corrosive attack in oxygenated high-purity water at 500° F. Consequently, they were unsatisfactory for reactor application. The highly corrosion resistant materials that remained for consideration in wear applications were generally hard, ranging from Rockwell C 30 to Rockwell C 60.

From this point the efforts in selecting and developing materials were directed toward two major goals: (1) the determination of optimum

bearing combinations from among the hard corrosion-resistant materials and (2) the development of composites utilizing the softer, flowing materials embedded in a hard matrix, i. e., Teflon-impregnated stainless steel and silver bearing compacts.

The hard, corrosion-resistant materials were tested in simulated reactor environments. The standard tests for this phase of the program were of the piston-cylinder and sleeve-journal types. The equipment and methods of testing are described in chapter 5. The results of these tests were sufficiently reproducible and indicative that the ranking of materials combinations shown in chapter 7 could be formulated.

Development of the composite materials for wear applications was carried out largely by the Armour Research Foundation. The program of investigation and the materials studied are described in the outline which follows:

1. Development of hard intermetallic or metalloid structures on the surfaces of corrosion-resistant metals.

Titanium nitride

Carbon-nitride case development on titanium

Chromium nitride

Metal boride cases

2. Development of hard intermetallic or metalloid structures through powder metallurgy or solid-state reactions.

Copper-nickel-graphite

Cobalt-chromium-carbon

3. Utilization of liquid or low melting, low shear strength materials as lubricants.

Tin-chromium composites

Gold in a high melting corrosion-resistant metal skeleton

Utilization of silicones as lubricants infiltrated into porous metal bodies

Many of the experimental bearing materials show promise and may be selected for future reactors. However to date, bearing materials in use are those available commercially.

The first or screening phase of investigation was considered essentially closed with the successful operation of the Arco prototype

reactor. This conclusively demonstrated the availability of a group of materials that could perform successfully in the wear application of an operating nuclear reactor.

The second phase of wear investigation called for a more detailed evaluation of successful wear combinations with the intent of improving performance. Problems of geometry and high unit bearing pressures could now be more thoroughly studied in detail and maximum operating loads determined. Uninvestigated problems, such as the effect of wear particles on wear rates, could be studied. Concurrent with these investigations the evaluation of new bearing materials could continue.

Included among the second-phase investigations are wear and friction studies conducted by Dewees. These investigations are presently in progress. A partial tabulation of the results of these tests is given in table 13-6.

This chapter includes wear data that are not sufficiently extensive to warrant tabular presentation in chapter 7. Such information supplements the tables and broadens their utility by correlating with them the knowledge gained from simulated component tests and actual plant experience. Among these data are results of test programs on ball bearings showing effects on wear of such variables as load and speed.

Basis of Conclusions

Some of the information made available during the course of basic wear programs was immediately incorporated into mechanism design, or it served as criteria for modifications. Concern was naturally felt at what might be considered undue extrapolation, and with the successful operation of the prototype reactor at the Naval Reactor Testing Facility at Arco, Idaho, more emphasis was shifted to the testing of simulated components such as ball bearings, mechanical linkages, and lead screws.

As might be expected, some discrepancies arose from the comparison of the performance of materials in basic wear tests and in component tests. These were due to the introduc-

tion of such new variables as geometry, severity and method of loading, continuity of operation, and varied chemical environments. However, these new data do not show any instances in which a material proposed as acceptable, on the basis of either piston-cylinder or sleeve-journal wear tests, later proved unsatisfactory.

On the other hand, some material combinations that were not strongly recommended as a result of the basic wear tests proved usable with design modifications directed toward utilizing desirable qualities other than wear resistance. A material representative of such treatment is Armco 17-4 PH stainless steel. Here, by the expedient of utilizing a relatively wide bearing surface, the combination 17-4PH vs. 17-4PH (wear factor 460) was "successfully" employed. The galled appearance of the wear track was in keeping with the high wear factor. The use of these materials in a closely confined bearing application would have resulted in erratic short-time operation at best. Thus severity of application is an important factor in choosing material combinations.

The consequence of component failure may also be the determining factor in the choice of a material. Parts that are inaccessible or that may require complete shutdown in the event of failure must possess the highest integrity even at the risk of becoming unduly costly. On the other hand, readily replaceable components may be so located that fair or borderline combinations can be tolerated.

It is intended that the data presented will assist in orienting the reader in the field of water-lubricated bearings. As a whole, they describe an area of materials choice which, to date, has proved to be compatible with the requirements for operation in a water-moderated nuclear reactor.

DISCUSSION AND INTERPRETATION OF WEAR DATA IN CHAPTER 7

The Wear Factor

The necessity of establishing a uniform means of evaluating the relative merit or performance of materials combinations became evident early

in the wear test program. Preliminary tests were run to determine what measurements would be significant in the evaluation of wear. In addition, methods for compiling and presenting the data were established so that the information would be of use to the design engineer. The following dimensional standards were adopted: Linear dimensions were measured to the nearest 0.00001 in., and weights were recorded to the nearest 0.1 mg. Early test data showed that weight change was one of the most sensitive and most reproducible measures of wear. In fact there were only a few cases, involving porous materials which absorbed water and soft materials which wiped or flowed under load, where dimensional measurements were of greater significance. By taking these measurements plus hardness and surface roughness data in microinches (rms), it was found that the test results could be described satisfactorily. Early tests further proved, within the limit of the loads employed, that the amount of wear was directly proportional to the number of cycles of operation, disregarding the possibility of an initial wear-in period of relatively short duration.

An examination of these variables led to the introduction by Westphal and Glatter¹ of the wear factor. This factor has the units of milligrams weight loss per pound load per million cycles. The duration of tests was approximately 500,000 cycles; at 120 cycles/min it required three days to perform a test. The information shown below includes data taken from a representative piston-cylinder test conducted at 500° F in oxygenated water.

Test No. 1796

Materials 17-4 PH vs. Haynes 21, SA

Hardness Rockwell C scale:

17-4PH.....	43
Haynes 21, SA.....	30
Number of cycles.....	500,000
Load, psi.....	8.0
Dimension change, in.:	
Piston (O. D.).....	-0.0062
Cylinder (I. D.).....	+0.0028
Weight change:	
Piston.....	-0.2813
Cylinder.....	-0.1692

Test No. 1796—Continued

Surface finish, microinches (rms):		
	Start of test	End of test
Piston.....	9	28
Cylinder.....	15	50
Wear factor, Mg Wt. loss/lb load/10 ⁶ cycles....		300

Remarks: surface is bright, scored.

The wear factor permits a relative ranking of material combinations in table 7-3, chapter 7. This table includes the data obtained by means of piston-cylinder and journal-sleeve tests. Generally speaking, those couples having a wear factor in oxygenated water of 100 mg or less per pound load per million cycles were agreed to show wear resistance satisfactory for bearing applications in a water-cooled reactor. Combinations showing greater wear factors were critically reviewed and sometimes used in the event that they possessed other desirable factors.

In evaluating the wear factors, it should be remembered that they represent the results of a standardized series of tests in which the primary emphasis was placed on covering a wide range of materials rather than attempting to investigate the effects of variations in environment or configuration. The wear factor, then, is not an absolute measure of wear but rather it provides a useful method of ranking material combinations as to wear properties. It is also apparent from even a cursory inspection of the table that the role of the material in the wear couple, i. e., stationary or movable member, may alter the wear factor.

In addition, the wear factor for any one combination of materials may be found to vary, depending upon the type of test employed. For example, it may be observed that, for a given combination of materials, the journal-sleeve wear factor differs from the corresponding piston-cylinder factor. However, it has been observed that for rotating tests the relative ranking of wear combinations follows that established for wear test using reciprocating motion.

Owing to the relatively short exposure time (approximately 70 hr) the full effects of service life exposure to the water environment are not apparent. The problem of corrosion affect-

ing the observed weight changes was not of concern in the early screening phase owing to the choice of materials tested. These materials developed a thin closely adherent corrosion product of negligible weight.

It is unfortunate that basic tests cannot simulate all problems in operating mechanisms. Such factors as poor mechanical design and type of operation can completely mask desirable wear properties. Hence the results of simulated component tests that indicate a lack of correlation with the results of basic tests should be reviewed critically. This method of checking has been used successfully in the case of ball bearings to locate design flaws. Furthermore, it has been observed in industry that continuous tests which simulate service life in all respects except that of intermittent operation do not always predict the operating life of the mechanism, since factors depending on time, such as film formation and dissipation of heat, are impossible to duplicate in continuously operated or accelerated tests.

Factors Influencing Wear

HARDNESS

If the problem of wear is approached with the aim of utilizing a hard material yielding friable wear products for both members of the wear couple, generally, the higher hardness would be accompanied by improved wear performance. To illustrate the wear factor for fully hardened material, Armco 17-4PH (R_c 45) in combination with Stellite No. 3 gives a wear factor of 115 but when the material is in the solution-annealed condition, (R_c 32) the wear factor rises to 700 (see table 13-1). Hardness, however, does not always have a consistent effect on wear.² Nitrided surfaces, chromium plate, and cobalt-base alloys have respectively decreasing hardness corresponding to decreasing wear resistance. However, contradicting examples can be cited, for instance, Armco 17-4PH vs. Stellite No. 3 (R_c 54 to 60) has a wear factor almost three times greater than Armco 17-4PH vs. Stellite No. 6 (R_c 40 to 46) (items 41 and 24 in table 13-1). In the case of USS 18-8W vs. Stellite No. 3 it was found

TABLE 13-1

PARTIAL SUMMARY OF PISTON-CYLINDER
WEAR TESTS(All tests performed at 500° F in water; radial loading
at 8 psi; first-named item is the piston)

Materials combinations*	Mg. wt. loss per lb. load per million cycles	
	Oxygen- ated water	Hydro- genated water
1. Nitrided AISI type 347 SS/ nitrided AISI type 347 SS	0	-----
2. Nitrided chrome plate/nitrided chromium	0	-----
3. As-plated chrome/nitrided ti- tanium	5	-----
4. Metamic LT-1/nitrided Armco 17-4PH	7	-----
5. Honed chrome plate/Stellite No. 3	8	1
6. AISI type 440-C SS/AISI type 440-C SS	15	-----
7. AISI type 410 SS/Stellite No. 3	16	-----
8. Honed chrome plate/Kenta- nium K-151	16	-----
9. Honed chrome plate/Armco 17- 4PH	20	13
10. Honed chrome plate/nitrided Armco 17-4PH	22	-----
11. Stellite No. 1/AISI type 440-C SS	23	-----
12. Stellite No. 12/honed chrome plate	25	-----
13. Stellite No. 6/Stellite No. 6	27	-----
14. Nitrided Armco 17-4PH/ni- trided titanium	28	-----
15. US steel 18-8 W (SA)/Stellite No. 3	31	-----
16. Wall Colmonoy No. 6/Stellite No. 6	32	-----
17. As-plated chromium/as-plated chromium	34	-----
18. Armco 17-4PH/honed chro- mium plate	35	11
19. Haynes No. 21 (SA)/Stellite No. 6	39	-----
20. Carboloy 608 (chrome carbide)/ honed chromium plate	41	-----
21. Haynes No. 21 (SA)/Haynes No. 21 (SA)	51	19
22. Stellite No. 3/honed chrome plate	55	-----
23. Stellite No. 3/wall Colmonoy No. 6	61	60
24. Armco 17-4PH/Stellite No. 6	62	-----
25. Honed chrome plate/Stellite No. 6	65	24
26. Stellite No. 3/Stellite No. 3	71	34

Materials combinations*	Mg. wt. loss per lb. load per million cycles	
	Oxygen- ated water	Hydro- genated water
27. Armco 17-4PH/Carboloy 608 (chrome carbide)	72	-----
28. Metamic LT-1/Metamic LT-1	76	-----
29. Stellite No. 3/Haynes No. 25 (CW)	77	47
30. KR-Monel/honed chrome plate	81	1
31. Stellite No. 1/Stellite No. 6	88	-----
32. Haynes No. 21 (PH)/Haynes No. 21 (SA)	98	-----
33. Haynes No. 21(SA)/honed chrome plate	102	28
34. Honed chromium plate/Haynes No. 25 (CW)	105	-----
35. Stellite No. 3/Armco 17-4PH	115	33
36. Haynes No. 21 (PH)/Haynes No. 21 (PH)	120	-----
37. US steel 18-8 W/Stellite No. 3	130	11
38. Honed chrome plate/honed chrome plate	135	-----
39. Honed chrome plate/Hastel- loy D	140	45
40. AISI type 304 SS/as-plated chromium	150	-----
41. Armco 17-4PH/Stellite No. 3	150	25
42. KR-Monel/Stellite No. 3	170	31
43. Stellite No. 3/Hastelloy D	300	43
44. Armco 17-4PH/Armco 17-4PH	460	-----
45. Silicon bronze/Haynes No. 21 (SA)	660	18
46. Stellite No. 3-Armco 17-4 (SA)	700	-----
47. Silicon bronze-honed chrome plate	830	2
48. AISI type 304 SS/AISI type 304 SS	3,200	-----

**"SA" indicates solution annealed; "PH," precipitation hardened;
and "CW," cold worked.

that by heat treating the type W material to maximum hardness (R_c 42 to 45) the combination displayed its highest wear factor, 130. However, when the hardness was reduced just a few points, the wear factor was reduced to 31.

Another material which does not conform to the popular conception that materials with higher hardness experience less wear is the cobalt-base alloy Stellite No. 21. This material when run in combination with itself resulted in the least wear when both elements were solution-annealed, more wear when one element was hardened, and most wear when both elements were hardened.

CORROSION

An appreciation of the effect of corrosion on wear may be obtained by comparing the wear factors listed in table 7-1 and in chapter 7. The results in the column marked hydrogen were obtained from a number of tests that were similar to oxygenated tests in every respect, except that a partial pressure of hydrogen was substituted for oxygen.

In almost every case, a substantial reduction in wear factor was noted. The greatest change took place with those materials most susceptible to oxidation. Everdur No. 1012 (silicon bronze) vs. chrome plate, for example, produced the low wear factor of 2 in hydrogenated water and the extremely high factor of 830 in oxygenated water. An 88 percent reduction in wear was observed for the KR-Monel vs. chrome-plate combination. In contrast, the combinations of cobalt-base alloys, presumably because they are more oxidation resistant, did not show improvements of this magnitude. Here improvement, in terms of the wear factors, ranged from a few percent up to a maximum of 50 percent.

These materials which perform well in hydrogen include many of the conventional bearing materials of industry. The advantages that could be realized by employing these readily available materials is obvious since cost would be lower and manufacturing problems would be reduced. However, such bearings would be extremely sensitive to unfavorable environmental changes.

ENVIRONMENTAL CONSIDERATIONS

The environmental effects noted in the basic tests were limited to two temperatures (200 and 500° F) and two additives (oxygen and hydrogen). A small number of tests were conducted in lithium hydroxide, and these results are indicated in table 13-2.

A fine black powder (mostly magnetite) was commonly observed on autoclave and specimen surfaces after hydrogenated tests. This was in contrast to the heavier red deposit (mostly hematite) found after oxygenated tests; post-test examinations showed vessel surfaces to be

TABLE 13-2

SUMMARY OF JOURNAL-SLEEVE WEAR TESTS
IN LiOH

(All tests performed in 500° F. water; radial loading at 10 psi; pH 10; first item is journal)

Materials combinations*		Mg. wt. loss per lb. load per mil- lion cycles
1. APCP on 17-4PH (0.0005 in.)/Armco 17-4PH		5
2. AISI type 410 SS/AISI type 410 SS		9
3. Honed chromium plate on Armco 17-4PH/Stellite No. 3		14
4. Stellite No. 6/Stellite No. 6		18
5. APCP on 17-4PH (0.0005 in.)/Stellite No. 6		31
6. APCP on 17-4PH (0.005 in.)/Haynes 21 (SA)		45
7. Stellite No. 1 (on 347 SS)/Stellite No. 3		47
8. Honed chromium plate on Armco 17-4PH/Stellite No. 3		50
9. US steel 18-8 W/Stellite No. 3		70
10. 17-4PH/Stellite No. 3		72
11. Haynes 21 on AISI type 347 SS/Haynes 21 (SA)		72
12. Stellite No. 6 hard facing on AISI type 304 SS/Haynes 21 (SA)		78
13. Honed chromium plate on Armco 17-4PH/Armco 17-4PH		113
14. APCP on Armco 17-4PH (0.005 in.)/Haynes 25		125

*"aped" indicates as-plated chromium plate; "PH," precipitation hardened and "SA," solution annealed.

extremely clean and pH measurements to be less acid in the hydrogenated water.

TEMPERATURE

Tests were conducted at the two temperatures roughly corresponding to reactor operating temperatures. The bulk of the data is at either 200 to 500° F. Although the 300° F difference of temperature is relatively small, marked differences in wear were observed.

These temperature effects were so pronounced that whole bodies of material, such as the carbon-graphites and ceramics, which proved excellent in pump bearing investigations designed for operations in 200° F water, were ruled out at 500° F. Exposure to water at the 500° F temperature promotes the leaching out of the bonding agent leaving a rough skeletal surface.¹

DISCUSSION OF SUPPLEMENTARY DATA

The data included in chapter 7 are limited to those that can be readily tabulated; however, there are considerable additional data gained from specific studies and operating experience that tend to further validate and extend the usefulness of the basic wear information. Included in the supplementary data are items of information that developed during specific investigations which have broader significance and may possibly indicate the direction of future wear and friction testing.

The supplementary data presented here summarize, to a great extent, ball-bearing investigations, simulated component tests, and actual plant operating experience. In the course of acquiring this information many new testing techniques were developed. A specific example of such a development is the torque sensing device used for the testing of ball bearings, lead screw-ball nut, and lead screw-roller nut combinations.

The observations presented here are necessarily more specific than those presented in chapter 7. Trends observed during the basic wear tests were investigated in more detail and, where possible, evaluated. For example, additional work was directed toward a more comprehensive understanding of the effect of operating temperature, chemical environment, load, and time in service.

In keeping with this policy the effects of chemical environment were studied in more detail than the basic wear program would permit. As various environments were proposed for nuclear reactor operation, it became necessary to duplicate such anticipated environments in simulated service testing.

To simulate the high-purity, high-temperature water present in a water-moderated nuclear reactor, it was necessary to construct and operate flow systems or loops (see ch. 5). Through the use of these loops, the chemical additives were constantly replenished throughout the duration of each test. Chemical sampling of the fluid was conducted on schedule in order to maintain water chemistry. By using autoclaves and other special vessels, the temperatures and pressures necessary to simulate reactor conditions were readily obtainable.

Table 13-3 is a comparison between conditions that existed for the basic wear tests and those maintained for ball-bearing tests. This comparison is used since the ball-bearing test environments might be considered representative of the simulated component tests insofar as coolant chemistry is concerned.

Typical Problems Arising in Simulated Component Testing

Throughout the tests of prototype components, problems which proved to be character-

TABLE 13-3
SUMMARY OF TEST CONDITIONS

Type of test	Additive			Additive conc., cc/kg	Load, lb	Temp., ° F	Speed, cycles/min	Resistivity of water, ohm-cm
	O ₂	H ₂	LiOH					
Piston-cylinder	X			5-30	3 and 8	200; 500	120	\$ > 500,000
		X		200-400	3 and 8	200; 500	120	\$ > 500,000
Journal-sleeve	X			5-30	10	200; 500	120	\$ > 500,000
		X		200-400	10	200; 500	120	\$ > 500,000
Ball bearing*	X			1-3	1-10%†	200; 500	10-160	> 500,000
		X		90-110	1-10%†	200; 500	10-160	> 500,000
			X	(‡)	1-10%†	200; 500	130	¶ > 500,000

*Ball-bearing tests are in continuously circulating systems.

†Sufficient LiOH added to maintain pH 10.5 to 11.5.

‡Ball-bearing loads are per cent rated load as determined from "New Departure Handbook," vol. II, 20th ed.

§Resistivity of charging water.

¶LiOH was added to water of this initial purity.

istic of the mechanisms tested were recurrent. For this reason, special studies were frequently necessary to eliminate the objectionable characteristics.

In the basic wear tests of the piston-cylinder or sleeve-journal types, it was possible to adopt standard procedures that were followed in all tests of that type; however, in the simulated component tests, each test or type of test required tailormade procedures. The major considerations in planning simulated service tests are not only that the environment be controllable and that it duplicate the reactor environment but also that the test specimen be observed in such a manner that its motions, loads, and materials duplicate those of actual service. In the course of these investigations, problems of testing techniques arose that required solutions which could not be found in the literature.

The outstanding differences between the basic tests and simulated component tests were that basic tests operated in static or nonflow systems and that water chemistry for basic tests was known only at the start and end of testing; whereas the simulated component tests had a programed sampling procedure as mentioned above.

Perhaps the outstanding difficulty with early ball-bearing investigations was the lack of knowledge of the frictional torques developed by bearings in operation. The ball-bearing tests were operated in a solid water system with temperatures up to 500° F, water pressure to 2,000 psig, and with gaseous additives. Excessive leakage could not be tolerated. With these requirements in mind, a torque sensing element or "torque tube" was developed. The torque problems encountered in lead screws closely paralleled those encountered in the investigation of ball bearings. Therefore, the development of the torque sensing tube provided a most effective evaluating device for both tests.

Torque sensing units are extensions of the motor drive shaft. Torques developed in the bearing and transmitted through the shaft tend to restrain the rotation of the shaft. These

restraining forces twist and displace a thin-walled annular section of the torque tube. The minute deflections thus produced vary the resistance of electrical strain gages, resulting in a low electromotive force that is amplified so that a continuous tape record can be obtained by means of a pen recording oscillograph. Figure 13-1 illustrates a torque sensing element developed for 200 to 400° F water applications at 1,000 psig pressure.

One of the problems encountered in the development of this device was the need for pressure seals. The system wiring was brought out of the pressurized vessel through the torque tube shaft. Another problem was that of cooling the strain gages so that they operated at temperatures lower than 375° F while the tests were operating at 500 F.

Ball-Bearing Tests

Ball bearings as a group were among the most exhaustively investigated single items in the reactor system. Investigations were conducted with radial loads and thrust loads, at high speed and low speed, with continuous rotation, intermittent service, and vibratory motion.

In normal lubricated service, ball-bearing failure can be attributed in large measure to fatigue failure. However, for the ball bearings tested during the development stages of the water-moderated nuclear reactor, fatigue was not critical since design life was shorter than the expected fatigue life in hot-water service. As a result, new criteria were established for the determination of nominal failures. These criteria involved increases in radial and axial looseness as well as weight loss. The looseness that could be tolerated in the system was dictated by the rigid alignment requirements of the control mechanism, and the weight loss, to a great extent, by the amount of wear and corrosion products that could be tolerated in the primary coolant.

Several ball-bearing test rigs described in chapter 5 are used in investigations designed to show specific effects of variables on ball-bearing wear and to proof-test these items. Among

FIGURE 13-1. Torque sensing element used in ball-bearing tests.

these investigations, as previously indicated; were such determinations as the effect of chemical environment, load, temperature, speed of rotation, time in operation, and proposed lubricants. In addition, work is currently being done to evaluate the effectiveness of hard facings and claddings. The results of these investigations are presented below.

CHEMICAL ADDITIVES

Various chemical additives were proposed in

the course of development. As indicated before, these additives were introduced to produce high pH environments, to decrease crud formation, to provide lubricity, and to lower the corrosion rate of the various alloys being investigated.

During these investigations the variables studied were the effects of oxygen content, hydrogen content, and pH of the water. Table 13-4 is a summarization of some representative control conditions for the several media.

TABLE 13-4
CHEMICAL ADDITIVES TO BALL-BEARING TESTS

Additive	Additive conc., cc/kg	Water to which addition is made		Oxygen residual, cc/kg
		pH	Resistivity, ohm-cm	
O ₂ -----	1-3-----	6.5-7.5	>500,000	Not determined
H ₂ -----	90-110-----	6.5-7.5	>500,000	<0.05
LiOH-----	(*)-----	10.5-11.5	†>500,000	<0.05
Degassed H ₂ O-----	None-----	6.5-7.5	>500,000	<0.05

*LiOH added to provide pH in the 10.5 to 11.5 range.

†LiOH added to water of this initial purity.

Specific conclusions based upon these studies are limited considerably by the small number of tests conducted in the lithium hydroxide and degassed environments. However, valid generalizations can be drawn for oxygenated and hydrogenated tests. Wear observed in a hydrogenated environment is generally one tenth of that observed in oxygen. In addition, on the basis of few data, there are indications that wear in degassed water may closely approximate that observed in hydrogen. The fourth additive, lithium hydroxide, did not appear to improve significantly (for such materials as the cobalt-base alloys and 17-4PH) upon the wear observed in oxygenated tests. It should be pointed out, however, that the hardenable martensitic stainless steels of the AISI 400 series were included in these tests, and it was for these materials that lithium hydroxide was found to improve the wear factors in basic wear tests (see ch. 8).

Figure 13-2 illustrates a typical comparison between the two tests, one conducted in hydrogenated water and the other in oxygenated water. As indicated, the hydrogenated environment reduced the wear by very nearly a factor 10.

EFFECTS OF TEMPERATURE

Ranking high in importance among the specific ball-bearing investigations was a study directed toward the determination of the effects of temperature on ball-bearing wear. Since the bulk of the bearing tests were conducted at either 200 or 500° F, the nature of the wear-temperature relation within this range was speculative until tests were initiated to provide data points in the interval between 200° and 500° F. Limited data were thus obtained for the intermediate temperatures in both oxygenated and hydrogenated water. These data, as shown by figure 13-3, suggest that the wear-temperature relation in the 200 to 500° F range³ is not linear and that a point of inflection is located at some point between 300 and 400° F. Further investigation will be necessary in order to verify this relation. However, a

FIGURE 13-2. Curves showing the relative wear of ball bearings tested in 200° F water with hydrogen (●) and oxygen (△) additions.

comparison of wear at the extremes of temperature for the tests conducted at 200° and 500° F indicated that it is reasonable to expect the wear observed at 500° F to be approximately 10 times as great as that at 200° F.

EFFECTS OF LOAD

Load investigations conducted in oxygenated and hydrogenated environments include various ball-bearing sizes and designs.⁴ On the basis of these tests, wear for ball bearings has been determined as a linear function of load and of the following general form:

$$W = ml + b$$

FIGURE 13-3. Curve showing wear-temperature relation.

where W = a particular measure of wear, i. e., weight loss, increase in radial looseness, or increase in axial looseness

m = slope

l = load in pounds

b = a constant

It is necessary to determine the slope experimentally for each bearing design and size and for each environment. This relation is shown by figure 13-4.

EFFECTS OF VELOCITY

In the sleeve bearing tests of the basic wear series, the angular velocity was set at 120 rpm since this velocity was considered to be low enough to preclude the formation of an effective hydrodynamic film. Thus contact between the materials under observation was assured, giving an indication of wear under the most adverse operating conditions. Tests conducted with ball bearings⁵ indicated that for a given number of total revolutions the wear decreased exponentially as angular velocity increased.

ANGULAR CONTACT BEARINGS—SIZE 203
THRUST LOADS

Test	Percent load	Pounds load bearing
□-1303	1	8
○-1300	3	26
△-1301-1304	5	44
□-1302	10	87

FIGURE 13-4. Curve showing wear-load relation.

FIGURE 13-5. Curve showing wear-velocity relation.

This is shown by figure 13-5 for angular velocities ranging from 10 to 130 rpm. However, this

result may be masked to some extent by corrosion since for an equal number of cycles the 10-rpm test was in the 200° F water environment 13 times as long as the (130 rpm) test with which it was compared.

RELATION BETWEEN TIME IN SERVICE AND WEAR

Throughout the investigation of prototype components, including latching mechanism, lead screw-roller nut, lead screw-ball nut, and ball-bearing tests, where periodic observations were necessary, the specimens were observed and measured after each of several periods of operation. In this manner a continuous record of wear vs. time in service was established. Upon examination of data, wear was found to be a linear function of time of operation. There are several instances where a break-in period is indicated, but such a period is usually of sufficiently short duration to permit the overall relation to be considered linear.

VIBRATION

Investigations of vibrations to simulate ship-board applications were carried out early in the development program. Previous industrial and military experience indicated that fretting might be troublesome in mechanisms subjected to standing vibrations from pumps and propellers. However, examination of components after 2 years of operation failed to reveal fretting as a problem requiring special attention. Nevertheless, fretting should always be considered in applications involving relative slip in critical areas.

INTRODUCTION OF POSSIBLE LUBRICANTS

From the beginning of the development of the first water-cooled and -moderated nuclear reactor, it was apparent that the lack of any but the boundary lubrication provided by the water environment would be a major obstacle to design personnel. Various proposed lubricants were investigated, as were several plating materials designed to reduce wear and friction.

However, as previously explained, no lubricant was found to be compatible with the primary system. Nevertheless, there is presently under investigation a group of water-soluble lubricants which show definite promise in reducing wear and frictional torque. Several important factors remain to be investigated: their effect on heat-transfer rates, their stability when exposed to radioactive flux, and their long-term stability at elevated temperatures. The concentration of one water-soluble additive has been tentatively optimized in ball-bearing tests at about 0.2 percent added to deionized water with about 5 cc oxygen per kilogram and initial electrical resistivity in excess of 500,000 ohm-cm.

In an endeavor to determine the effectiveness of additives in this amount, a ball-bearing test was initiated where the bearings operated in oxygenated and deionized water until a predetermined torque level was reached. At this time water-soluble lubricant sufficient to provide the optimum concentration was injected into the pressure vessel. The result was a 50 percent reduction in torque compared to the value recorded prior to addition of the lubricant. Development of such a lubricant suitable for use in a reactor system might prove quite useful.

Another lubricant investigated is a colloidal dispersion of amorphous graphite in isopropyl alcohol. However, this material tends to "squeeze out" of ball bearings and become ineffective. The major applications of this lubricant are discussed in chapter 14.

Claddings and Hard Facings

The cobalt-base alloys are considered the most promising materials studied in the ball-bearing wear test program. They are desirable not only from the standpoint of wear alone but also from the standpoint of corrosion resistance. However, there were some indications that their application might possibly be restricted because of their relatively low shock resistance. As a result Stellite No. 1 was deposited on a relatively soft backup material such as AISI type 304 stainless steel so

that the composite might retain the excellent wear resistance of the cobalt-base alloys plus the added shock resistance provided by the type 304 backup. The facing of Stellite No. 1 on AISI type 304 provides a metallurgical bond that shows good stability against corrosive attack. One of the applications where Stellite facing has been outstanding is in ball-bearing races. Of the materials considered for this application, Stellite No. 1 has shown the most promise as a facing material, running against balls of Stellite No. 3 or 19.

PRACTICAL CONSIDERATIONS IN CHOOSING MATERIALS

Standardized basic wear studies, component tests, and final acceptance proof tests have yielded a body of information which gives insight into the continuing problem of effecting maximum integrity and efficiency of operation. The wear problem is not simply one of materials choice and cannot be considered apart from mutually interacting factors relating to the particular application in mind. Considerations such as accessibility for repair and consequences of failure illustrate the designers problem. Should the component be inaccessible during plant operation or should the consequences of failure be severe then only materials rated excellent by wear test standards would be considered for the application. On the other hand readily accessible items that could fail without serious consequences may be manufactured from materials rated only fair on the basis of performance in wear tests. Thus it becomes highly important that the wear properties of promising materials be investigated in the several water environments so that the designer will be more adequately equipped to meet the many wear problems arising in a pressurized-water reactor system.

Design

For convenience the design factors of interest for wear applications can be broken down somewhat arbitrarily into clearances, load, velocity, and geometry.

CLEARANCES

Clearances change upon heating; therefore it is necessary that thermal expansion be considered when determining bearing clearances. This dimension cannot be optimized, however, without also considering crevice corrosion. Tests and experience at 200° F have shown some material combinations to require clearances as great as 0.005 in. Westphal and Glatter¹ observed that clearances of 0.008 in. were sufficient to permit all material combinations observed in the journal-sleeve test jig at 500° F to operate satisfactorily for 500,000 revolutions. These clearances are cited as examples but are not to be considered as recommendations. Even the most satisfactory bearing materials can be adversely affected by improper choice of clearance. Therefore, in designing parts for bearing applications it is desirable to check carefully such factors as differential expansion, crevice corrosion (see chap. 9), and frequency of operation.

LOAD

Early designs were limited, to some extent, by the geometrical requirements for wide bearing areas and correspondingly small contact pressures. This necessitated an increase in the size of moving parts and unduly large components. The situation assumes greater importance when the space limitations aboard a naval vessel are considered. In addition, the wear and corrosion occurring over this increased area release a greater quantity of wear particles into the primary coolant stream.

The tendency for even the best material combinations to seize made it imperative, as mentioned above, to keep loads to a minimum. In ball-bearing tests the loads imposed ranged between 1 and 10 percent of the rated load under normal lubricated conditions.⁶ Results of load investigations are discussed in the portion of this chapter dealing with ball-bearing tests.

VELOCITY

Relative velocity between moving parts can involve the removal, pickup, and redistribution

of wear particles. Thus the type of motion and the exact velocities are very often the governing factors in the selection of wear couples for a particular application. Type of motion must be considered. An examination of the differences between rotating journal-sleeve and reciprocating piston-cylinder tests illustrates the fact that performance is dependent on the type of motion, i. e., reciprocating or rotational. The degree of slip attributable to lack of conformity between parts is also a factor here. Furthermore, should an application include inoperative periods followed by a sudden need for movement, crevice corrosion could prove to be a serious consideration.

GEOMETRY

Considerations of geometry may frequently mean the difference between successful operation and immediate seizure of parts. Perhaps the most striking effect of geometry is illustrated in the case of ball bearings where stress levels can be regulated by controlling such geometrical factors as ball and race conformities, angle of contact and width of wear track. The usefulness of many materials may well be reestablished in some cases on the basis of studies directed toward optimizing a bearing geometry for water-lubricated service. Experience has shown that many objectionable wear problems can be overcome by redesign based upon geometrical considerations.

Manufacturing and Processing

Although the design factors discussed here are fundamental to the successful operation of moving bearing parts in the high-temperature water environment, strict adherence to manufacturing and processing specifications are necessary to establish the acceptability of finished parts. Here the importance of adequate quality control manifests itself. Readily observable features such as weights, measurements, and surface roughness can be examined with standard measuring devices, but such operations as cladding and plating are largely based on the integrity and competence of vendors who have been duly qualified by test to perform the operations satisfactorily.

SURFACE ROUGHNESS

Surface roughness of materials in contact can affect the wear resistance and galling tendencies of the combination. It may be observed generally that, if the thin lubricating water film available at elevated temperatures is to be utilized, surface asperities must be kept small (2 to 5 microinches (rms) would be desirable, if practical). In the interest of reproducibility and uniformity of the real contact area, a requirement of 8 microinches (rms) surface roughness, or better, was established for all wear specimens. However, it was found that there are exceptions to this generalization. Upon testing certain materials, particularly the austenitic stainless steels, specimens prepared with this order of roughness galled and seized immediately under load. In subsequent testing sandblasting of the bearing surfaces enabled other specimens of the same combination to operate, although with admittedly high wear. Thus, it is apparent that superfine surface finishes are no overall guarantee of good wear properties, particularly for the austenitic stainless steels. It is believed that the interrupted surface produced by sandblasting prevents the propagation of minute asperity welds into large-scale galling.

One such example may be seen in table 13-1. As-plated chromium vs. as-plated chromium with a surface roughness of 30 to 40 microinches (rms) shows the low wear factor of 34, whereas the same materials combination with honed surfaces (1 microinch, rms) has a much higher wear factor of 135.

When it is necessary to use dissimilar mating materials differing greatly in hardness, it is important that the harder of the two have a good finish. Otherwise wear is accelerated by a continuous cutting or "milling" action on the softer material or by excessive loading of the rough surface followed by abrasive wear.

CASE HARDENING

Case hardening provides a hard, wear-resistant bearing surface. Examination of table 13-2 shows that nitrided surfaces head the list. These materials have shown the greatest wear

FIGURE 13-6. (a) Enlarged view of a worn area of a nitrided 17-4PH ball-bearing raceway after 1,000,000 cycles of operation. The pattern is typical of fatigue-type failure. (b) View of the bearing illustrated in (a) showing the width of the wear path relative to the width of the raceway.

resisting and antigalling characteristics of all the materials observed. Unfortunately, nitrided chromium and nitrided titanium alone in this group have sufficient corrosion resistance in high-temperature water to be even considered for application. Thus the consideration of wear factor alone is not sufficient for acceptance since the duration of the wear tests is only 72 hr and the effects of long-term corrosion damage are not reflected. Among these effects are pitting of materials and the buildup of products which might occur and collect under static conditions.

Nonuniform susceptibility to corrosive attack has been reported in long-term corrosion tests of nitrided specimens (see ch. 7). However, it is significant that the more consistently corrosion resistant specimens were prepared under laboratory conditions. Extensive investigation of nitrided specimens has not revealed a reasonable explanation for this erratic behavior, but investigations are continuing in an attempt to obtain a more reproducible case.

PLATING

A survey of the data in chapter 7 shows chromium plating second only to nitrided surfaces in general wear performance. Hard, smooth, electro-deposited surfaces were prepared on several base materials as a method for reducing wear.

In the absence of a suitable nondestructive physical test for evaluating the quality of the chromium plate, an attempt was made to assure the quality by limiting the source of plating to approved suppliers. The suppliers who sought approval submitted standard chromium-plated piston samples (0.0005 in. plate thickness) which were tested in the piston-cylinder unit against cylinders made of AISI type 304 stainless steel, 17-4PH, USS 18-8W or Monel. Specimens were tested under loads of 3 and 25 lb applied radially. The lighter loading was used as a measure of wear, and the heavier loading as a measure of adherence. It was observed that plating suppliers are consistent in the quality of their product, whether good or bad. Of the 24 suppliers who submitted test

samples for qualification, only 7 produced a satisfactory plate.

Figure 13-7 shows the appearance of specimens which gave satisfactory performance. Under heavy loading minor scuffing of the chromium was observed on the soft base material (AISI type 304) only. Figure 13-8 shows the post-test appearance of samples that were unsatisfactory. Here general scoring and scuffing has taken place indicating poor adherence of the plate.

Of the platings suggested, only hard industrial chromium plate was investigated extensively and ultimately employed in operating mechanisms. Typical of the benefit which may be derived from the use of chromium plate is a comparison involving the high wear factor of 460 obtained for Armco 17-4PH stainless steel run against itself and the wear factor of 20 observed when one member was plated. This should not be interpreted to mean that plating can in any way substitute for good design and workmanship. For a typical application, such as threaded connections, plating will not prevent seizure if such conditions as wire edges, torn metal, burrs, or bad thread contours exist. These defects are often present in stainless steel machined parts.

Certain other precautions must be kept in mind in making use of chromium plate as a wearing surface to prevent scuffing. Sharp corners are to be avoided since these promote the formation of nodules during plating operations. Such nodules present considerable difficulty in removal without chipping. Corners may also result in the formation of points of highly concentrated stress, which promote flaking or spalling. By using corners with a 0.030 in. or larger radius, this difficulty was alleviated.

The chromium qualification program revealed an apparent relation between base material and the chromium plating. The base materials ranged in hardness from approximately Rockwell B 85 (type 304 stainless steel) to Rockwell C 45 (17-4PH), and it was noted that the harder the base material the heavier the load that could be withstood by the chro-

FIGURE 13-7. Post-test appearance of approved chromium-plated specimens submitted for qualification testing.

FIGURE 13-8. Post-test appearance of unsatisfactory chromium-plated specimens submitted for qualification testing.

mium plate. In addition, it was found that a heavy plate (0.005 in. or more) when honed to give a good surface finish (8 microinches (rms) or better) will not only give longer service but will withstand heavier loads than a thin (0.0005 in.) unfinished plate.

Tests conducted under conditions that are unlikely in normal reactor operation have indicated that chromium plating is severely attacked in a flowing high-temperature water environment when high pH and dissolved oxygen are present simultaneously (see chaps. 7 and 8). Therefore if water control is relaxed in a flowing system and high pH and oxygen occur simultaneously, the use of chromium plating should be closely examined. The limiting factors in the use of chromium plate are the simultaneous occurrence of high temperature, fluid flow, high pH, and the presence of oxygen in the system.⁷

Should the intended application be of such a nature that one or more of these objections can be eliminated, the use of chromium plate becomes more feasible. A presently approved

application involves the use of chromium plating for threaded joints. Here, where fluid velocity is negligible, plating can be used to aid in assembly and disassembly of parts that are required to operate infrequently, and then under light loads.

Other electrically deposited platings were investigated to a limited extent. Piston-cylinder tests of gold plating and silver plating yielded inconclusive results. Gold plating smeared and deformed and silver plating broke down under test conditions. However, under conditions of pure impact or battering, gold plating, apparently owing to its high ductility, performed very well. Electro-deposited lead and indium performed unsatisfactorily in both hydrogenated and oxygenated environments, peeling off in the former and wearing and corroding on the latter.⁸

Exploratory tests of electrodeposited rhodium indicated a lack of adherence. Patches of the rhodium plate were removed from both piston halves when run under light load against a cylinder of AISI type 347 stainless steel.

Chromizing was investigated to a limited extent. This is a process in which chromium diffuses into a base material and forms a layer or "case" either of high chromium stainless steel or chromium carbide embedded in a high chromium alloy matrix depending on the composition of the base alloy. Poor test results were attributed to a lack of case depth. A chrome carbon steel such as SAE 52100 presumably could develop a deep case.⁸ Improved processing methods have renewed interest in chromizing, and an investigation is presently in progress to reevaluate the wear and corrosion resistance of materials prepared in this manner.

CLADDING AND HARD FACING

In general, the cobalt-base alloy materials rank third in wear tests, behind nitrided and chromium plated materials. However, since the two materials that rank ahead of them are restricted in use, the cobalt-base alloys emerge as the outstanding "usable" group of materials from the standpoint of wear. Extensive use is being made of this fact in the hard facing of wear surfaces for reactor applications. They have shown excellent performance in such applications as ball-bearing races, valve stems and seats, and sliders.

Although the process holds great promise, there are problems to be considered. Hard facing is often more expensive than the industrial hard chromium plating it replaces in some applications. Also there is the possibility of distorting the clad parts as by thermal expansion and contraction. In addition the use of claddings may require the redesign of parts to avoid complicated geometries.

Currently, the most extensively used overlay materials are Stellite No. 1, No. 6, and No. 12. With the No. 6 alloy, greater shock resistance is gained at the expense of hardness. If hardness is the prime consideration, Stellite No. 12 is used in the intermediate range; for extreme wear, requiring very little shock resistance and higher hardness than Stellite No. 12 offers, Stellite No. 1 is occasionally used.

Nonmetallic Materials Investigated

A large number of nonmetallic materials were tested, mostly as sleeve bearings against metallic journals. Among these were carbon-graphite compacts, ceramics, and plastic materials. None performed with complete success in water at 500° F. Physical properties of plastics changed under these conditions. The other two groups of materials generally exhibited rapid abrasive wear. This was attributed to the leaching out of the bonding agents, leaving a rough skeletal structure on the surface.¹ An intermediate material, Metamic LT-1, which is a cermet consisting of chromium and alumina, exhibited excellent wear and corrosion resistance when run in combination with an abrasion-resistant mating material (a nitrided porous chromium compact developed by Armour). Such a combination is shown as item 4 in table 13-1. Against mating materials with slightly less abrasion resistance, the wear factor was found to be high.⁸

Although breaking down at the higher temperatures, the ceramic materials ranked high among the bearing materials investigated for 200° F service. A list of such materials indicating wear properties is shown in table 13-5.⁹ The only sintered carbide found acceptable at 500° F, again with respect to corrosion considerations, was Carboloy No. 608 which is chromium carbide bonded with nickel. However, with the stringent requirements for reactor use, only Graphitar 14 (which might be considered representative of nonmetallic materials) is permitted for use to date. This material can be used only under compressive loading conditions, with an intimate metal backup at temperatures less than 200° F.

Teflon coatings on Armco 17-4PH were evaluated since this material ranks high in antigalling characteristics. Good results obtained in earlier tests were not reproducible, indicating adherence to be variable.⁸

Martensitic Stainless Steels

Excellent wear resistance was found with straight chromium stainless steels as compared with nickel-chromium stainless alloys, but the

former were unacceptable for use in oxygenated water because of crevice corrosion. The nickel-chromium stainless steels are well known for their susceptibility to seizure and galling. Of this class of steels only the age-hardening grades are usable for wear purposes to even a limited degree.

Environmental Considerations

The reactor designer is confronted with an environment established primarily for nuclear rather than wear considerations. Even such a mechanism as a ball nut-lead screw, reliable in normal service, develops severe operating problems. Torques are unpredictable, and excessive wear promotes erratic performance.

The complicating factors encountered in environmental considerations are temperature, pressure, and coolant chemistry. Although these items were discussed in the presentation of ball-bearing test results, they may be briefly summarized as follows:

The wear-temperature relation in the 200 to 500° F interval does not appear to be linear. However, wear at 500° F exceeds wear at 200° F by an approximate factor of 10 in both oxygenated and hydrogenated environments. Fluid pressure was not investigated as a variable, rather it became contingent upon the operating temperature. For all tests the pressure was maintained above saturation pressure for the temperature so that the system remained liquid. The only chemical additives to the coolant that were studied in sufficient detail for evaluation were oxygen and hydrogen. It was shown that wear was generally lower in hydrogenated water by an approximate factor of 5. Wear in other water environments, such as high pH (LiOH and NH_3), degassed, and low pH (H_2BO_3), was not investigated sufficiently to permit conclusive evaluation.

Introduction of Possible Lubricants

The various lubricants investigated in basic tests and ball-bearing tests have been discussed. In review, there are no compatible lubricants presently available. Encouraging preliminary

results have been obtained for a water-soluble lubricant now being investigated (see the section entitled "Discussion of Supplementary Data"). Various other lubricants were proposed, and although none of the solid lubricants were employed in an operating nuclear reactor, several were considered during the screening phase. Among these were molybdenum disulfide, litharge, pure lead, plastilube, and mica. These proposals met with varying degrees of success.

Special Considerations

Certain other factors are also of considerable interest. Some of these have their counterpart in industrial experience but are modified by the stringent ground rules for nuclear power plants.

Corrosion, as related to wear, is considered widely as a superimposed effect. The problems most frequently encountered involve crevice corrosion, pitting, and general corrosion stress corrosion.

Crevice Corrosion.—Crevice corrosion is discussed briefly in this chapter and is presented in detail in chapter 9. It is sufficient to say that crevice corrosion buildup can materially affect the operational characteristics of components. It has been found to be good practice to examine all close-fit bearing parts in order to eliminate or redesign all regions favorable to crevice attack.

Pitting Corrosion.—Pitting corrosion could result in very serious wear problems if an improper choice of materials were made. Materials such as the martensitic stainless steels which show a tendency to pit in most environments of interest are not recommended for wear purposes. Pitting can develop in the wear path and serve as incipient points of failure.

General Corrosion.—General corrosion should be considered for bearing materials since the designer must be ever mindful that the crud level (see Glossary) is of fundamental importance to efficient operation. Although the corrosion rates given, when translated into inches of penetration per year, seem to be insignificant, these corrosion rates do not take wear into

account. Here there is a continuous wearing away of any protective film which might form and a constant replenishment of this film. The corrosion reaction on the bearing surface is confined to the steep initial portion of the corrosion curve (see fig. 8-2, ch. 8); so the amount of corrosion products liberated to the system would be out of proportion to the actual area involved.

Stress Corrosion.—Although it has not been considered as a serious problem among the materials that have been chosen for wear applications to date, the possibility of stress corrosion must always be considered in the choice of bearing materials. Chapter 10 covers in detail the stress corrosion problem in reactor applications.

Areas of Future Research

Perhaps the most urgent need for further investigation lies in the field of basic development to provide adequate design criteria for improved mechanisms. Investigations of materials under high unit stresses (as in ball bearings) should be included in this area. Effort might well be directed toward the investigation of more long-range basic problems associated with environmental effects and design limitations of acceptable materials based on wear, galling, friction coefficient, temperature, and water chemistry.

There are indications¹⁰ that critical stresses may exist for material combinations which, if exceeded, can lead to a marked increase in the

amount of wear products. If such critical pressures can be determined for materials of interest, the designer may then limit his loads and control load surface geometries in the light of this information.

The mechanisms contributing to wear and friction in primary water environments are not reliably known. Physical surface phenomena associated with friction in a water media containing varying concentrations of dissolved gases is a region of investigation that could be directed toward a basic understanding of wear and friction for materials of interest that could be incorporated at the design level.

In addition, investigation might well be directed toward the determination of the effect of wear particle accumulation on friction and wear factors in standardized tests. This would provide a means of more accurately predicting performance for design variations from wear test specimens.

The possible investigations indicated above are for the most part material considerations. However, tests have shown that there are materials and processes that perform satisfactorily when prepared under laboratory conditions but are not acceptable when prepared commercially. Therefore investigations directed toward the removal of objectionable commercial practices and the development of a compatible product by commercially feasible methods could make available entire groups of materials for wear applications. The nitriding process remains, to a large extent, in this class.

FOREWORD TO TABLES 13-5b AND 13-5c

The results shown in tables 13-5b and 13-5c were reported by Wepfer and Cattabiani.⁹ The sequence of testing observed in the 2¼-in. diameter journal bearing tests (table 13-5b) and the 1½-in. bearing tests (table 13-5c) is given below:

Table 13-5b: 2¼-in.-diameter journal:

The bearing testing sequence was as follows:

1. With the unit assembled and at 200° F the journal was rotated at 3,600 rpm and a unidirectional load was applied at a rate of 25 psi per hour until 72 psi was reached. The test was continued for 24 hr at 72 psi.

2. As above, but at 1,800 rpm.

3. As above, but at 900 rpm.

4. A stop-start test was run at 900 rpm and 25 psi. The cycle was 15 sec off and 45 sec on. The test continued for 1,000 cycles.

Table 13-5c: 1½-in.-diameter journal:

The bearing testing sequence was as follows:

1. Speed, 3,600 rpm constant.
2. The loading schedule used was 200 hr of test at each of the following loads: 20, 40, 60, and 80 psi based on projected bearing area.

TABLE 13-5A

RESULTS ON MORE FAVORABLE MATERIAL COMBINATIONS: THRUST BEARING TESTS*

<i>Bearing shoe</i>	<i>Thrust runner</i>	<i>Remarks</i>
Stellite No. 3.....	Stellite Star J.....	Ran 200 hr; 500 start-stop cycles; burnished; no visible wear
Stellite No. 6.....	Tungsten carbide (Carboloy 55B).....	Ran 500 hr; 500 start-stop cycles; burnished; no visible wear
Stellite No. 6.....	Copper graphalloy.....	Ran 150 hr at 1,800 rpm; 200 hr at 3,600 rpm; 500 start-stop cycles; slight scratches on shoes
Stellite No. 12.....	Silver graphalloy.....	Ran 200 hr; 500 start-stop cycles; shoes slightly scratched
Aluminum oxide (cold pressed)...	Tungsten carbide (Carboloy 55B).....	Ran 220 hr; 500 start-stop cycles; shoes burnished; no visible wear
Aluminum oxide (cold pressed)...	Aluminum oxide (cold pressed).....	Ran 140 hr at 3,600 rpm; 1,000 start-stop cycles; no visible wear
Aluminum oxide (cold pressed)...	Bonded aluminum oxide.....	Ran 318 hr; 500 start-stop cycles; no visible wear

*All tests at 21 psi load and 1,800 rpm unless otherwise noted. Tested in high-purity oxygenated water at 200° F and 40 psi pressure.

TABLE 13-5B

RESULTS ON MORE FAVORABLE MATERIAL COMBINATIONS: 2¼-IN. DIAMETER JOURNAL BEARING TESTS*

<i>Bearing</i>	<i>Journal</i>	<i>Diametral clearance (cold), in.</i>	<i>Load, psi</i>	<i>Remarks</i>
Boron carbide.....	Tungsten carbide (Firthite H-13)	0.0043	72	Tested 10 hr; no wear or corrosion; journal polished
Boron carbide.....	Tungsten carbide (Firthite T-66)	.003	72	Tested 44 hr; no failure
Aluminum oxide (cold pressed)	Tungsten carbide (Firthite T-66)	.003	72	Tested 72 hr; no failure
Boron carbide with titanium boride addition	Tungsten carbide (Firthite T-66)	.003	72	Do.
Boron carbide.....	Stellite Star J.....	.003	72	Do.
Aluminum oxide (hot pressed)	Stellite Star J.....	.003	72-125	Tested 72 hr; no failure; 600 start-stop cycles
Silver-lead.....	Tungsten carbide (Firthite H-13)	.003	72-125	Tested 195 hr; 1,410 start-stop cycles; failed when loaded to 125 psi
Carbon graphite.....	Armco 17-4PH, malcomized	.0035	72-125	Tested 196 hr; 1,400 start-stop cycles; loaded to failure at 175 psi
Boron carbide with titanium boride addition	Tungsten carbide (Firthite H-13)	.003	72	Tested 301 hr; no wear; bearing and journal highly polished
Aluminum oxide (cold pressed)	Tungsten carbide (Firthite H-13)	.003	72	Tested 78 hr; no failure
Aluminum oxide (hot pressed)	Tungsten carbide (Firthite H-13)	.003	72	Tested 101 hr; no failure

*All tests in 200° F water. Results of the test were reported by Wepfer and Cattabiani. The bearing testing sequence was as follows: (1) With the unit assembled and at 200° F, the journal was rotated at 3,600 rpm, and a unidirectional load was applied at a rate of 25 psi per

hour until 72 psi was reached. The test was continued for 24 hr at 72 psi. (2) Same as (1) but at 1,800 rpm. (3) Same as (1) but at 900 rpm. (4) A stop-start test was run at 900 rpm and 25 psi. The cycle was 15 sec off and 45 sec on. The test continued for 1,000 cycles.

TABLE 13-5c

RESULTS ON MORE FAVORABLE MATERIAL COMBINATIONS: 1½-IN. DIAMETER JOURNAL BEARING TESTS*

<i>Bearing</i>	<i>Journal</i>	<i>Diametral clearance (cold), in.</i>	<i>Load, psi</i>	<i>Remarks</i>
Graphitar 14-----	Chrome-plated stainless steel	0.0025	20, 40, 60, 80	No wear; polishing
Tungsten carbide (Firthite H-13)	Tungsten carbide (Firthite T-66)	.0024	20, 40, 60, 80	No wear; very light score; contact and static corrosion
Graphitar 14-----	Titanium carbide (Firthite T-77)	.0018	10, 20, 40, 60, 80	No wear; polish
Graphitar 14-----	Stellite No. 12-----	.0023	20, 40, 60, 80	0.0001 in. wear; light score; carbon trace
Graphitar 14-----	Stellite No. 1-----	.0027	20, 40, 60, 80	0.0002 in. wear; medium score
Graphitar 14-----	Stellite 98M2-----	.0025	20, 40, 60	Do.
Titanium carbide (Firthite T-77)	Titanium carbide (Firthite T-77)	.0029	10, 20, 40, 60	Do.
Titanium carbide-----	Tungsten carbide (Firthite T-66)	.0024	10, 20, 40, 60	0.0002 in. wear; rusting
Graphitar 14-----	USS 18-8W, malcomized--	.0020	20, 40, 60, 75	0.0005 in. wear; contact corrosion; slight scoring

*All tests conducted in 200° F oxygenated water of greater than 500,000 ohm-cm initial resistivity; pH 6.5 to 7.5; ambient pressure, 1,500 psig. The results were reported by Wepfer and Cattabiani. The bearing

testing sequence was as follows: (1) Speed, 3,600 rpm constant. (2) The loading schedule used was 200 hr of test at each of the following loads: 20, 40, 60, and 80 psi, based on projected bearing areas.

TABLE 13-6

ROOM-TEMPERATURE WEAR AND FRICTION DATA TESTS CONDUCTED IN WATER*

(Data obtained by Dewees using pendulum slide machine)

<i>Rider</i>	<i>Disk</i>	<i>Friction coefficient</i>		<i>Wear factor</i>
		<i>Minimum</i>	<i>Maximum</i>	
AISI type 304 (70 R _b)-----	Stellite No. 3 (55 R _c)-----	0.47	0.68	16
	Haynes 25 (50 R _c)-----	.45	.72	8
	Armco 17-4PH (36 R _c)-----	.45	.70	†64
	Armco 17-4PH (43 R _c)-----	.48	.73	64
	Chromium, as-plated, on AISI type 410-----	.35	.4	2,000
	Chromium, old, stoned, plated on AISI type 410.	.55	.68	16
Armco 17-4PH (35 R _c)-----	Stellite No. 3 (55 R _c)-----	.35	.67	8
	Haynes 25 (38 R _c)-----	.37	.73	‡500
	Haynes 25 (50 R _c)-----	.37	.64	\$32
	Armco 17-4PH (36 R _c)-----	.46	.72	‡32,000
	Armco 17-4PH (43 R _c)-----	.48	.74	‡1,000
	Chromium, as-plated, on AISI type 410-----	.40	.61	500
	Chromium, new, stoned, plated on AISI type 410.	.39	.57	16
	Chromium, old, stoned, plated on AISI type 410.	.37	.58	8
Armco 17-4PH (43 R _c)-----	Kentanium 151 (72 R _c)-----	.42	.78	64
	Stellite No. 3 (55 R _c)-----	.49	.78	32
	Haynes 25 (38 R _c)-----	.37	.71	‡2,000
	Haynes 25 (50 R _c)-----	.38	.73	64
	Armco 17-4PH (36 R _c)-----	.38	.78	†16,000

TABLE 13-6—Continued

Rider	Disk	Friction coefficient		Wear factor
		Minimum	Maximum	
Stellite No. 3 (46 R _c)	Armco 17-4PH (43 R _c)	0.47	0.66	‡64
	Chromium, as-plated, on AISI 410	.39	.71	16,000
	Chromium, old, stoned, plated on AISI 410	.59	.71	32
	Kentanium 151 (72 R _c)	.46	.64	64
	Stellite No. 3 (55 R _c)	.34	.67	32
	Chromium, as-plated, on AISI type 410	.27	.46	64
	Chromium, new, stoned, plated on AISI type 410	.37	.55	32
	Chromium, old, stoned, plated on AISI type 410	.35	.48	16
Haynes 25 (46 R _c)	Kentanium 151 (72 R _c)	.37	.62	32
	Stellite No. 3 (55 R _c)	.41	.55	16
	Haynes 25 (38 R _c)	.45	.57	8
	Haynes 25 (50 R _c)	.31	.5	§16
	Chromium, as-plated, on AISI type 410	.26	.41	125
	Chromium, new, stoned, plated on AISI type 410	.4	.61	32
	Chromium, old, stoned, plated on type 410	.29	.52	16
	Kentanium 151 (72 R _c)	.26	.65	8
Chromium plate (honed) on 17-4PH	Chromium, as-plated, on AISI type 410	.34	.67	64
	Chromium, old, stoned, on AISI type 410	.41	.63	64
Inconel-X (28 R _c)	Stellite No. 3 (55 R _c)	.36	.58	16
	Haynes 25 (38 R _c)	.5	.8	‡32,000
	Haynes 25 (50 R _c)	.38	.59	§32
	Armco 17-4PH (36 R _c)	.4	.74	(‡)
	Chromium, as-plated, on AISI type 410	.35	.59	-----
	Chromium, new, stoned, plated on AISI type 410	.27	.57	16
	Chromium, old, stoned, plated on AISI type 410	.27	.45	32
	Kentanium 151 (72 R _c)	.35	.48	16

*Loads, 2.6, 10, and 40 lb; Hertz stress, 1,200 to 5,000 psi; maximum velocity, 0.5 in./sec.

§Poor compatibility—roughness measurements.

‡Bad compatibility—roughness measurements.

‡Bad compatibility—roughness measurements and photomicrographs.

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Chapter 14

MANUFACTURING PROCEDURES AFFECTING CORROSION AND WEAR

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	Page
INTRODUCTION.....	263
GENERAL CLEANLINESS.....	263
MACHINING, GRINDING, AND POLISHING.....	266
GRIT AND VAPOR BLASTING.....	266
LUBRICATION.....	266
ACID CLEANING.....	267
INITIAL CLEANING.....	270
DEGREASING.....	270
WATER EMPLOYED FOR CLEANING.....	270
DRYING.....	271
PREPARATION FOR STORAGE AND SHIPMENT.....	271

INTRODUCTION

There are many procedures performed during fabrication, assembly, and cleaning which can adversely affect a component or one of its parts (in the following discussion components and parts are also referred to as items) from the point of view of corrosion and wear. For reasons pointed out in chapter 1, it is considered extremely necessary to minimize all difficulties which might arise in components which would involve the removal or the replacement of items.

It is the purpose of this chapter to discuss those procedures which past experience has shown to be areas requiring special attention.

Forms of contamination such as metal chips and turnings, metal dust and abrasives from grinding, loose weld spatter, loose scale, and other foreign particles may lodge between bearing surfaces or between parts operated with extremely small clearances, thereby causing excessive wear or complete seizure. Particles may also lodge in small orifices or other restrictions which could block control lines or prevent valves from seating properly. Improper mechanical and chemical cleaning may result in

surface contamination which causes rusting, rough surfaces, and accelerated corrosive attack, which may occur during cleaning or when the item is put into service. Also, lubricating oils and greases present as contaminants may decompose under service conditions and, in the case of chloride- and sulfur-bearing cutting oils, may cause either accelerated general corrosion or localized attack on critical surfaces. Apart from their effect on corrosion, small amounts of oil or grease not removed from areas to be welded may alter the composition of weld metal, thereby possibly decreasing its strength, or induce porosity or cracking in the weld. These forms of contamination may also have an appreciable effect on wear. Localized corrosion on bearing surfaces can also increase the operating torque or even cause complete seizure.

GENERAL CLEANLINESS

The general cleanliness of components maintained during fabrication and installation is considered to be one of the important aspects affecting the integrity of the plant. Although it is not possible to define adequately the extent of cleanliness required for such a system, the desired degree of cleanliness may be obtained by defining the specific procedures to be employed in cleaning items. This approach has been very helpful from the point of view of inspection and quality control, since specific procedures for cleaning can be defined precisely for contractual arrangements.

For purposes of discussion, reference to surface contamination made herein is defined as any foreign material which is present as an

inclusion or adherent to an item. Any foreign material which cannot be removed from a surface by flushing with water and/or grease solvent is considered to be surface contamination. Items such as burs, weld spatter, scale, slag inclusions, and adherent rust are considered to be forms of surface contamination.

In contrast, dirt is defined as any foreign matter on the surface of an item which can be removed by wiping or flushing with water and/or grease solvent. Included in this category would be such things as normal atmospheric dirt, machine shop metal dust, abrasive materials used in grinding, polishing, and grit blasting, and loose corrosion products formed in the item or in some other component and transported to the item in question.

One of the prime requisites in obtaining clean components is by the use of a "clean area" for carrying out all pertinent fabrication, assembly, and test operations. Depending on the nature of the job and the facilities available, a clean area ideally consists of a complete enclosure with tight-fitting windows and doors in which conditions of cleanliness are maintained at a desired level by supplying the area with filtered air, periodic cleaning and by minimizing contamination from outside shop areas. Basically, the clean area is considered to be one which is free of dirt and debris, the cleanliness of which is maintained comparable to that normally found in business offices or homes. In certain cases practical considerations may limit a clean area to a temporary canvas tent which completely encloses the component. In those cases where an enclosure does not adequately prevent outside contamination, the area or the tent may be maintained under a slight positive pressure with clean air blowers. With respect to the cleanliness of air, freedom from oil is considered more important than freedom from water. In those instances where only a small amount of work is required and it is not considered practical to provide a clean area, it may be possible to perform these operations in

shop areas if shop dirt-producing operations are temporarily suspended.

It is especially important in dealing with complex internal parts, which are not accessible for cleaning, that exposure to a general shop area atmosphere be kept to an absolute minimum. Obviously such exposures will be unavoidable occasionally, at least for short periods of time. However, good judgment should be used on the part of the quality control engineer and the job foreman in order to minimize contamination during the exposure. During assembly all openings not in use should be maintained closed. This may be accomplished by the use of the various types of temporary seals shown in figure 14-1.

FIGURE 14-1. Examples of temporary seals used to protect internal areas of components during fabrication.

When grinding and welding operations are being carried out on a component in such a position that they may contaminate the completed portion of the component, the vessel should be positioned so as to minimize these forms of contamination. For example, during grinding, the vessel can be placed in such a

FIGURE 14-2. Debris filtered from the reactor coolant after completion of construction.

manner that particles will fall outside the vessel rather than into the vessel. A vacuum hose may be employed to remove fine airborne particles. It is realized that some particles will enter a component handled under these conditions; however, a thorough flushing with water upon completion of the item will generally remove most of these particles. In certain cases, especially in large components, some operations may necessitate the use of special shoe coverings, coveralls, and gloves by working personnel in order to maintain cleanliness. It is desirable that coveralls and smocks worn by shop personnel have no front pockets. Items such as pencils, pens, rulers, and coins may fall into

components while work is being performed. Despite the precautions which are taken during the construction of a reactor system, some debris is always obtained during the initial cleanout filtering treatment. An example of the size and quantity of the debris obtained is shown in figure 14-2. The dried material weighed approximately 3 gm. and consisted of glass insulation, slag, weld spatter, cloth, paper, asbestos, and wood. This amount of material is not considered alarming in view of the magnitude of the construction job involved in the primary coolant system. Nevertheless, every precaution should be taken to minimize these forms of debris as much as is practically possible.

MACHINING, GRINDING, AND POLISHING

Under ordinary circumstances the use of conventional tool steels for machining does not contaminate the surface of chromium-nickel stainless steel items. In certain cases, however, the use of conventional tool steels is not recommended. The straight chromium stainless steels, Armco 17-4 PH, and 17-7PH have occasionally shown contamination resulting from iron pickup. If the extent of contamination observed is considered objectionable, then consideration should be given to the use of carbide cutting tools in order to minimize the problem.

Prepared surfaces should be machined to solid metal, free of all slag, scale, spatter, and surface inclusion. Unless otherwise required, as in the case of bearing surfaces, the surface finish on internal parts exposed to the primary coolant normally ranged between 63 and 125 microinches (rms).

Experience has shown that the use of silica abrasive papers or grinding wheels generally results in contamination of stainless steels in such a manner as to produce localized rust spots. Every effort should be made to prevent or minimize the contact of stainless steels with silica. For this reason, only aluminum oxide or silicon carbide abrasives are recommended for grinding or polishing. For the same reason, silicious bonding materials should not be employed in grinding wheels. Only resin- or rubber-bonded wheels are considered satisfactory. Carbide tools should be employed for filing and deburring operations in order to avoid iron contamination.

GRIT AND VAPOR BLASTING

For the same reasons mentioned above, it is not desirable to employ silica as a grit or vapor blasting material. At one time it was considered that alumina or silicon carbide grit could be used on stainless steel without any adverse effects; however, experience has shown that even the so-called pure grades of these materials can occasionally cause surface con-

tamination. Consequently, where grit blasting is required, it is followed by acid pickling in order to remove any contamination pickup from the process. In certain cases, it may be possible to use alumina or silicon carbide (but not silica) grit without subsequent acid cleaning. This can be done by means of a grit qualification test which involves blasting sample pieces of stainless steel with the particular batch of grit in question and subsequently exposing the samples to an environment which will reveal contamination. This test is performed by immersing the blasted samples in a tank of hot water (150° F) saturated with oxygen. Contamination from blasting usually can be detected in 6 hr. If this grit qualification test does not reveal any contamination on the test samples, the grit may be employed for the purpose at hand without subsequent acid cleaning. It is desirable, however, not to recirculate the grit in such cases.

The size of the blasting material employed was approximately 100 mesh for air blasting and 230 mesh for vapor blasting. These particle sizes do not materially affect the finish of items normally possessing a surface finish between 63 and 125 rms.

LUBRICATION

Careful consideration is given to the choice of a lubricant in those applications where it cannot be completely removed from the item following its use, e. g., threaded joints and pipe-expanding operations. Lubricants retained in such crevices may decompose under service conditions and form highly corrosive products. In addition lubricants may introduce into the system constituents which are undesirable from a nuclear point of view. The remarks made herein do not refer to lubricants used in machining or other applications where the lubricant can subsequently be completely removed. In this connection, it is not safe to assume that lubricants can be effectively removed from crevices and joints by washing with water or by degreasing.

The lubricants normally employed for applications where possible exposure to primary water exists are graphite-alcohol mixtures, high-purity water, and straight hydrocarbon oils (consisting only of hydrogen, oxygen, and carbon) where only traces of the oil are expected to be retained.

Graphite-alcohol mixtures are limited to use in threaded joints where antigalling is required only during assembly, testing, and installation. Graphite will react with water slowly under service conditions to form carbon dioxide; consequently it should not be used in applications requiring antigalling properties after exposure to service conditions. In time the graphite will be depleted owing to oxidation. Materials having inherent antigalling characteristics should be used in those applications where it is desirable to minimize galling of items intended for removal after exposure to service conditions.

Water or straight hydrocarbon oils have been successfully used in tube and pipe expanding operations. Although every effort should be made to eliminate the entrapment of the oil, traces of oil are not considered detrimental provided they do not interfere with the production of sound welds.

ACID CLEANING

Acid cleaning is generally considered undesirable as a standard fabrication procedure because of the many difficulties which can arise owing to misapplication and improper handling during pickling operations. It is realized that in many cases acid cleaning affords a considerable advantage; however, the possible consequences of mishaps very often outweigh its advantages. In those instances where acid cleaning is considered necessary, the following procedures and precautions will be helpful in minimizing the dangers normally associated with this process.

The acid cleaning procedures normally employed for the various materials concerned are shown in table 14-1.

It should be noted that the standard nitric-hydrofluoric acid pickle (treatment A) is not

recommended for use with the stabilized stainless steels in the sensitized or welded condition. Cases have been observed where intergranular corrosion has occurred on welded AISI type 347 items during normal pickling operations with the above acids. Similarly, this type of attack may also be expected on welded nonstabilized 18-8 type stainless steel such as AISI type 304. In order to insure against intergranular attack, the hydrochloric acid pickle (treatment B) should be employed. Although this solution will produce a matte appearance, it does not cause intergranular corrosion.

Special consideration is given to the hardenable stainless steels, such as AISI type 410 and Armco 17-4PH, and 17-7PH in the hardened condition since stress corrosion cracking may occur after relatively short periods of exposure to pickling acids. In those cases where it is necessary to pickle such materials in the hardened condition, it is recommended that tests be made to determine if stress cracking can occur under the specific conditions which are being considered for both the material and the acid.

A few cases have been observed where both Inconel and Inconel-X showed intergranular corrosion which resulted from pickling in hot solutions of nitric-hydrofluoric and nitric acid. Therefore, careful consideration is given to the exposure of these materials to such corrosive environments.

Organic and inorganic (metals excluded) items are not normally subjected to the liquids employed for pickling various metals since the porosity of many of these materials makes acid removal difficult. Materials such as asbestos, graphite, bonded metal carbides, and alumina bodies can be adversely affected because of their porosity. Likewise extreme care is taken in pickling porous metal filter plate materials.

Special attention should be given to the pickling of small-diameter tubing since the restricted movement of acid within the tube may accelerate corrosion or cause localized pitting. In such cases it is desirable to replace the acid in the tube at least once every 5 min during the operation. This may be done by

TABLE 14-1
ACID CLEANING PROCEDURES EMPLOYED WITH VARIOUS MATERIALS

Materials	Acid treatment	Conditions
AISI type 304 ELC AISI type 304 AISI type 308 AISI type 309 AISI type 316 AISI type 347 AISI type 321 Armco 17-4PH Armco 17-7PH Haynes Stellite (1, 3, 6, 21, 25) Hard chromium plate	A	Nitric acid (1.42 sp. gr.)-- 150 parts by volume Hydrofluoric acid (60%)-- 15 parts by volume Water----- 835 parts by volume Temperature of solution-- 120° to 130° F Time of immersion----- 15 min
AISI type 304 ELC AISI type 304 AISI type 308 AISI type 309 AISI type 316 AISI type 347 AISI type 321 Armco 17-4PH Armco 17-7PH	Welded or exposed to temperatures in the carbide precipitation range. "A" treatment may be used if the parts are given a solution anneal by heating to 1,900° F and water quenching prior to pickling.	B Hydrochloric acid (1.2 sp. gr.)-- 50 parts by volume Water----- 50 parts by volume Temperature of solution-- 130° to 150° F Time of immersion----- 15 min [NOTE.—In some cases a black deposit will result from this bath. It can be removed by dipping the part in nitric acid (1.42 sp. gr.) room temperature.]
AISI type 410	C	Same as "A" above except that the time of immersion is 5 min
Inconel Inconel-X	D	Same as "A" above except that the temperature is between 70° and 100° F
Monel K-Monel KR-Monel Nickel	E	Sulfuric acid (1.83 sp. gr.)-- 95 parts by volume Water----- 1,000 parts by volume Sodium nitrate (crude)--- ½ lb per gallon Common salt (NaCl)----- 1 lb per gallon Temperature of solution-- 180° to 190° F Time of immersion----- 30 min
Copper Copper-nickel 70-30 Brass Bronze	F	Sulfuric acid (1.83 sp. gr.)-- 70 parts by volume Sodium dichromate----- 2 percent by weight Water----- 1,000 parts by volume Temperature of solution-- 100° to 125° F Time of immersion----- 30 min
Carbon and low alloy steel	G	Hydrochloric acid----- 11 parts by volume Water----- 89 parts by volume Rodine #60----- 0.3 to 0.5 (by weight) Temperature of solution-- 120° to 150° F Time of immersion----- 10 to 20 min

raising the tubes out of the acid in such a manner that the acid is adequately drained. In addition, immersion should be done in a manner that will prevent the formation of air pockets.

Although it is considered undesirable to pickle items containing crevices, circumstances occasionally dictate the need for acid cleaning. When acid cleaning must be used on items with crevices, there are a number of precautions that are taken in order to minimize the type of damage which may result from pickling.

Pickling of units or parts with crevices requires special attention in order to minimize entrapment of acid or to ensure complete removal of acid from crevices. Entrapment of acid in crevices can be minimized considerably by wetting and filling the crevices with water prior to exposure to acid. Under these conditions acid can only reach the inside of the crevice by diffusion, which will be very slight because of the short exposure time. Following the pickling operation, crevice-bearing items are immersed in distilled water between 150° and 200° F for a period not less than 6 hr. At the end of this period the item is drained and litmus paper is placed immediately adjacent to the mouth of crevices in order to detect the presence of any residual acid. If the litmus paper shows a change in color indicating acid the immersion treatment is repeated.

In addition to crevices, the bearing surfaces of a unit may also require special attention during pickling. Experience has shown that the pickling procedures recommended in table 14-1 do not adversely affect the surface finish properties of the Stellites and industrial hard chromium plate. Bearing surfaces made of AISI type 410 stainless steel should be masked off during acid treatment since the finish on such parts can be substantially changed. In such cases adequate protection has been afforded to bearing surfaces by masking with liquid neoprene paint. This preparation can be removed with toluol, xylol, or acetone following the completion of the pickling operation.

Because of the toxicity of acid fumes, pickling baths are covered with wooden or rubberized

steel exhaust hoods. In most cases the baths can best be heated by the use of stainless steel immersion heaters. Some means of agitation of the solution or the part being cleaned should be provided. Where large quantities of nitric-hydrofluoric acid solutions are used, the containers may be made of carborundum brick supported by a steel tank with $\frac{1}{4}$ in. of rubber or neoprene covering both the inside and the outside of the brick. Large quantities of the sulphuric acid solution can best be handled in lead-lined steel tanks or in acid-resisting brick lined tanks covered with asphalt or Bitumastic paint. Where small volumes of both acid solutions are used infrequently, stainless steel or glass equipment is used.

The information discussed so far has been in connection with the use of acid cleaning during fabrication of individual items or complete units. The use of acid cleaning for these operations has not created any serious problems since, as a matter of policy, acid cleaning has been avoided wherever possible. However, there is one area of considerable practical importance where the exposure of components to pickling solutions cannot be readily avoided.

This problem is in connection with the possible adverse effects of uranium fuel-element ruptures in a water-cooled nuclear reactor. Such a failure could increase the radioactivity level in the reactor water to a level higher than that which was anticipated in initially determining the thickness of shielding required during the design stage.

Since the greatest portion of insoluble solids in the primary system is deposited on the container walls, it is difficult to remove this material by simply flushing the system. A preliminary analysis of the problem indicates that acid cleaning is the only feasible method of decontaminating the primary system in the event that it should be required as a result of fuel-element rupture. The problems associated with such an undertaking are extremely complex and beyond the scope of this handbook. The problem is considered to be twofold: (1) finding an acid which will decontaminate and not have any adverse effects on materials, and

(2) the physical and mechanical problem in circulating the solution and subsequently removing it completely from all areas. Initial studies have indicated that, for one reason or another, none of the standard solutions shown in table 14-1 are completely satisfactory. Consequently, work is presently in progress to find a suitable acid or combination of acids which could be circulated through the reactor for purpose of decontamination and which would not have any adverse effects on the materials or the components in the system. Consideration is being given to the use of citric acid. However, there is insufficient information on this subject to date to warrant a discussion at this time.

INITIAL CLEANING

The cleaning operations normally employed can be divided into two main categories. The first phase consists of initial cleaning procedures on individual items following final machining or fabrication. These involve the removal of heavy grease and dirt, followed by scrubbing with a suitable soap and water and a hard bristle brush or by steam cleaning. The second phase of cleaning consists of a degreasing operation which is usually performed on individual fabricated items prior to assembly in order to remove traces of oil not removed during initial cleaning and/or oil picked up from handling.

DEGREASING

The solvents normally employed for degreasing are acetone, inhibited trichlorethylene, inhibited perchlorethylene, and alcohol. Depending on the size and complexity of the part being cleaned, degreasing is carried out by vapor degreasing, immersion in hot or cold solvent, or by swabbing with a clean cloth moistened with the solvent. The last traces of grease can best be removed by a combination of exposure to the solvent together with vigorous rubbing with a clean cloth. This is especially true with the use of cold solvent.

Since it is not always possible to remove liquids entrapped in crevices, the choice of a particular solvent is very important. All the solvents mentioned above decompose under service conditions. The chloride-bearing solvents can be extremely corrosive even at slightly elevated temperatures. Consequently, these types of solvents are not used on parts containing crevices. In such cases acetone or alcohol can be employed since they are very volatile, leave little or no residue, and their decomposition products are considered to have no adverse effect on corrosion or wear. It is desirable to rinse degreased items with water before the solvent has dried. The purpose of this rinse is to "mechanically" wash off the last traces of solvent which is laden with oil. Clean solvent is also used for this operation. This will minimize the slight amount of residue which is occasionally observed on degreased items.

WATER EMPLOYED FOR CLEANING

The purity of water employed in cleaning operations is considered to be important with regard to the ultimate cleanliness of the unit. Waters with a high solids content can leave harmful deposits on the surface of a metal after drying has occurred. In many cases, depending on the specific chemistry of the water, deposits remaining after drying will not redissolve when subsequently washed in water. This is attributed to the formation of insoluble carbonates resulting from the direct exposure of water residues to the air. Such deposits are considered harmful for two reasons. First, and uppermost in importance, they may introduce certain elements into the primary coolant which are detrimental from a nuclear point of view. Second, they could affect the corrosivity of the primary coolant if present in large quantities.

It is realized that these remarks do not have a significant bearing in those applications where the total internal area of a component is small. However, it should be pointed out that some components, such as the main heat exchangers may occupy a large fraction of the total primary

plant area. Therefore, improper handling of this one component could grossly affect initial plant operating conditions. In addition, the cumulative effect of numerous small components cannot be overlooked.

Consequently, although tap water is employed for many initial cleaning operations, the items are rinsed with high-purity water before the tap water is allowed to dry.

The quality of high-purity water considered satisfactory for cleaning operations is defined as distilled or demineralized water with a maximum total solids content (soluble and insoluble) of 10 ppm, and a pH between 6 and 8.

DRYING

Drying is considered essential in those cases where a component or any part thereof will rust when exposed to water or high humidity during fabrication, storage, and shipment and in those applications where water must be removed in order to adequately perform leak tests. Units and parts which will not rust under these conditions are normally dried by draining and air drying, drying with hot air blowers or by wiping with clean cloths in those cases where all surfaces are accessible. Small amounts of moisture which may be retained by employing such procedures do not adversely affect the unit or the system in which it is installed. However, units and parts which are expected to rust under these conditions are thoroughly dried. The following two procedures have been successfully employed where absolute dryness is required. One method involves oven drying and the other utilizes vacuum techniques.

Oven drying is normally carried out by placing the item in an oven maintained at a temperature between 250° and 300° F. Inlet and outlet pipes or suitable hose attachments are provided on the unit so that it can be flushed with an inert gas (−40° dewpoint), such as nitrogen. After the unit has reached the temperature of the oven, sufficient gas is introduced into the unit to completely replace the moisture-laden air. Following the completion of the flushing operation, the oven is turned off, and the unit is

allowed to remain sealed for 8 hr, after which a dewpoint reading is taken on the gas in the unit to determine the extent of dryness. If the dewpoint of the gas in the unit is equal to or less than −40° F, the unit is considered dry. If the dewpoint is above −40° F, additional drying is employed until the desired degree of dryness is obtained.

Vacuum drying is normally carried out by evacuation of the unit, or a container in which the unit is placed, to a pressure of 0.1 mm. An acetone-dry ice cold trap is incorporated into the system in order to detect small quantities of moisture. In order to insure adequate removal there should be no water in the trap at a pressure of 0.1 mm.

Occasionally, freezing of the water may occur during evacuation, especially in units with complex internal parts. In such cases, freezing is eliminated by providing heat to the vessel during the evacuation. The absence of frozen water is determined by allowing the unit to remain at the vacuum pressure for 30 min after the vacuum pumps have been disconnected from the unit. If the pressure does not rise during this period, there is good assurance that ice is not present. The cold trap may also be used to detect freezing.

PREPARATION FOR STORAGE AND SHIPMENT

In order to maintain the degree of cleanliness desired in cleaned components, it is necessary that they be adequately protected during storage and shipment. For this purpose many regulations have been established to cover the various types of components involved and the service for which they are intended. In most cases, the preparation for storage is the same as for shipment. The preparations are subdivided into three major categories: (1) components sealed in metal containers, (2) components sealed in moisture-vapor-proof envelopes, and (3) large components having a few openings which can readily be sealed off with expandable plugs.

The air in packaged items made of materials which will not rust when exposed to water or the atmosphere, e. g., 18-8 type stainless steels, is not purged with an inert gas. However, packaged items made of materials which will rust, e. g., carbon steel, are purged and maintained at 10 psig.

Large components having an internal surface that cannot be closed off completely by simply

FIGURE 14-3. *Expandable plug employed for sealing components.*

sealing a few openings are packaged in metal containers with rubber gasket seals. When required these containers are normally purged with nitrogen having a dewpoint of -40°F or lower. The purging operation can be carried out effectively by pressurizing the container to about 10 psig with the inert gas and venting to atmospheric pressure for at least four complete cycles. The containers are not maintained above atmospheric pressure unless the materials in the components are susceptible to rusting under humid conditions.

Small components and spare parts having openings which cannot be completely closed off by sealing are normally packaged in polyethylene envelopes made of sheet material having a minimum thickness of 0.004 in. The excess air in these bags is evacuated either manually or mechanically prior to complete heat sealing. It is very important that special attention be given to the handling of components sealed in this manner since the envelopes can be ruptured if not packed properly. Therefore, adequate cushioning should be provided during the final packing operation.*

Large components with internal surfaces that can readily be sealed from the outside by plugging several openings are sealed by means of expandable rubber plugs. By this method the component itself forms a part of the moisture vapor-proof barrier, with the complete sealing being effected by the use of plugs on all external openings. The type plug employed is shown schematically in figure 14-3. Basically it consists of a solid rubber disk about one-fourth to one-half in. in thickness, which when compressed between two metal plates expands in diameter and seals the opening. When required components sealed with expanded plugs are purged in the same manner described above for component packaging in metal containers. As previously indicated, only those components containing parts that would rust in the atmosphere are purged and pressurized.

All items are packed in accordance with requirements consistent with the following Government specifications:

Specification	Gross weight, lb
PPP-B-601 or NN-B-621	<200
NN-B-621	≥ 200 and <500
MIL-C-3769	≥ 500 and <3000
JAN-P-104	>3000

*More recently this procedure has been adopted for components which were originally packaged in metal containers.

Appendix A

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Appendix B

GLOSSARY OF TERMS

- activity, long-lived** Radioactive elements possessing a long half life (on the order of days or years).
- activity, residual** The radioactivity in primary systems remaining after shutdown of a nuclear reactor.
- activity, short-lived** Radioactive elements possessing a short half life (on the order of seconds or minutes).
- alkali-phosphate treatment** Chemical treatment of boiler feed water for the purpose of reducing corrosion and deposition. The treatment involves approximately 50 ppm of phosphate (as PO_4^{3-}) and sufficient alkali to raise the pH to 10.5. These are nominal figures and vary slightly depending on the application.
- ANL** Argonne National Laboratory, Chicago, Ill.
- anode** The electrode of an electrolytic cell at which oxidation occurs. In corrosion processes it is an area that is usually corroded.
- ASME Code** American Society of Mechanical Engineers Boiler and Pressure Vessel Code.
- asperities** High points or irregularities that exist even on finely finished surfaces. These play a major role in friction and wear.
- ASTM** American Society for Testing Materials.
- blowdown** The process by which the total solids content of boiler water is maintained at a tolerable level. Quantities of boiler water with high solids are periodically replaced with makeup water containing a low solids content.
- BMI** Battelle Memorial Institute, Columbus, Ohio.
- boiler water** The water employed in boilers which provides steam to operate the turbines. It is normally treated (see alkali-phosphate treatment) to inhibit corrosion and to minimize deposits.
- buildup, crevice corrosion** Accelerated localized attack observed at the perimeter of a contact area resulting from crevice corrosion.
- cathode** The electrode of an electrolytic cell at which reduction occurs. In corrosion processes it is the area that is usually not corroded.
- carbon steel** Steels which do not contain alloying elements and whose properties are determined by the carbon content, e. g., ASTM A212.
- caustic embrittlement** Stress corrosion cracking of carbon steel which is observed in boiler waters treated with alkali.
- cc/kg** Cubic centimeters of gas per kilogram of water (STP).
- clean area** Area employed for the final fabrication, assembly, and cleaning of primary components.
- The degree of cleanliness comparable to that generally observed in homes and offices.
- contact corrosion** See buildup, crevice corrosion.
- coolant, primary** In the pressurized-water nuclear reactor the (radioactive) coolant fluid which comes directly in contact with the reactor core and extracts heat which is later transferred to the secondary system through the main steam generators.
- coolant, secondary** In the pressurized-water nuclear reactor, the (nonradioactive) coolant fluid which removes heat directly from the main steam generators and which forms steam to drive the turbines.
- core** The central part of a nuclear reactor which contains the uranium or other fissionable elements and where fission heat is released. The primary source of heat in the nuclear reactor.
- corrosion** The transfer of atoms in a metal from the metallic to the ionic state. In aqueous solutions it involves the formation of soluble and insoluble compounds of the metal being corroded.
- corrosion fatigue** Accelerated localized corrosive attack which causes cracking to occur in areas where a metal is subjected to cyclic stresses.
- crevice (contact) corrosion** See buildup, crevice corrosion.
- crud** The insoluble corrosion products formed in the primary coolant of water-cooled nuclear reactors.
- crud level** The quantity of crud per unit volume of the primary coolant. It is normally expressed as parts per million (ppm).
- Crud probe** A device inserted directly into the primary coolant system for the purpose of collecting sample quantities of crud.
- curie** The quantity of a radioactive species decaying at a rate of 3.7×10^{10} disintegrations per second. It is also defined as 3.7×10^{10} gamma or beta disintegrations per second.
- decontamination (for radioactivity)** The process employed to reduce the activity resulting from radioactive deposits in components or a system to a tolerable level. Mechanical and chemical cleaning methods are employed.
- degassed water** Low oxygen-bearing water employed for corrosion tests to simulate low oxygen conditions in the reactor. The oxygen content for degassed water was normally 0.05 to 0.1 cc/kg.
- demineralized water** High-purity water obtained by the use of ion exchangers.

- descaling (corrosion specimens)** A procedure of removing corrosion products from the surface of a corrosion test specimen. It is employed to obtain weight-change measurements of the amount of metal converted to oxide during exposure to a corrosive environment.
- dynamic test loop** An apparatus which provides circulation of a test water past specimens under controlled water chemistry, velocity, and temperature.
- erosion-corrosion** The loss of metal resulting from the combined action of corrosion and erosion.
- feed water** Term employed in boiler water technology to signify the relatively pure water which is condensed from the steam in the turbine and which is fed back to the main system.
- fretting corrosion** Accelerated attack of metal which occurs at the interface between two surfaces in contact and is directly attributable to the presence of vibrations which produce slip between adjacent surfaces.
- fuel element** Individual segments of a core containing the fissionable material.
- galvanic corrosion** Accelerated corrosive attack occurring at the point of contact between two dissimilar metals, resulting from the difference in electrical potentials produced by the two metals in contact.
- general corrosion** The uniform loss of metal as a result of corrosive attack.
- half life** The time required for the number of radioactive nuclei of a given kind, or for their activity, to decay to half their initial value. The time is independent of the radioactivity present.
- high-purity water** Arbitrarily defined as water having a minimum resistivity of 500,000 ohms-cm, with a total solids content of less than 2 ppm and a pH ranging between 6 and 8.
- hot spots (radioactive)** Accumulations of radioactive particles within the primary system, requiring protective shielding for plant operating personnel.
- hydrogen embrittlement** Loss in ductility of a metal or alloy resulting from the adsorption of nascent hydrogen.
- hydrogenated water** Test water used to determine the effect of dissolved hydrogen on corrosion and wear in a simulated reactor environment. This water is prepared by adding known amounts of hydrogen to degassed water (see degassed water).
- induced radioactivity** That radioactivity which is induced in a material as a result of exposure to radiation emanating from the core.
- in-pile tests** See out-of-pile test.
- intercrystalline cracking** See intergranular cracking.
- intergranular (intercrystalline) cracking** Cracking which occurs at the boundaries between the grains of a metal (see transgranular cracking).
- intergranular corrosion** A special form of localized corrosion in which accelerated corrosive attack occurs only at the grain boundary of a metal.
- ion exchanger** A unit employed to purify water. The water is circulated through a column containing a resin or mixture of resins. These resins replace foreign ions (anions and cations) in the water with hydrogen and hydroxyl ions, which, in turn, combine to form water.
- KAPL** Knolls Atomic Power Laboratory, Schenectady, N. Y. This installation is operated by the General Electric Co. for the Atomic Energy Commission.
- Kirkendall experiment** Experiments conducted to determine the corrosion behavior of iron in high-temperature water, e. g., diffusion of iron ions through the oxide film.
- localized corrosion** Nonuniform loss of metal as a result of corrosive attack, e. g., pitting.
- loop** See dynamic test loop.
- low alloy steel** Steels which possess special properties that are developed by the addition of alloying elements, e. g., ASTM A213.
- low oxygen water** Test water employed to simulate conditions where low oxygen-bearing water was expected in service. Normally ranged between 0.1 and 1.0 cc/kg.
- mechanical filter** Filter employed to remove insoluble corrosion products from the primary coolant system. It consisted of numerous porous stainless-steel filter units having a pore size of 20 μ .
- MDM** Term employed to represent the corrosion rate of a material, milligrams of metal corroded per square decimeter per month.
- microcurie** One-millionth of a curie (see curie).
- mil** In linear measure, 1 mil equals one one-thousandth of an inch (0.001 inch).
- NaK** Designation employed to signify a mixture of sodium and potassium.
- NEES** United States Naval Engineering Experiment Station, Annapolis, Md.
- NRTF** Naval Reactor Test Facility, Arco, Idaho. This installation is operated by Westinghouse Electric Corp. for the Atomic Energy Commission.
- oxygenated water** Test water employed to simulate conditions where high oxygen-bearing water was expected in service. Normally ranged between 1 and 30 cc/kg.
- out-of-pile test** Term employed to differentiate between tests conducted under reactor radiation conditions (in-pile-tests) and those performed without radiation (out-of-pile tests).
- pressurized-water reactor** Another term employed for water-cooled nuclear reactor.
- precipitation-hardening stainless steel** Stainless steels which are hardened by a constituent precipitating from an alloy during a specific heat treatment.
- primary coolant** See coolant, primary.
- radioactivity** The spontaneous emanation of electromagnetic waves and/or particles resulting from natural or induced nuclear instability or excitation.

- reference water** Water intended to simulate, for test purposes, the coolant in the primary system of a water-cooled nuclear reactor (usually without the presence of radioactive flux).
- restraint type bearings** Bearing such as sleeve and journal where corrosion products in the annulus exert a radial force that restrains relative movement of the members. This force may produce increased torque or result in seizure.
- rms** Root mean square, i. e., the square root of the arithmetic average of the squares of a group of numbers.
- sensitization (chromium carbide)** Exposure of an unstabilized austenitic stainless steel to temperatures which will cause the precipitation of chromium carbide at the grain boundaries. The material is thus rendered susceptible to intergranular attack in certain environments.
- simulated component tests** Tests conducted on a mechanism simulating a reactor component under conditions approximating those in service.
- stainless steels** Stainless steels are divided into three broad categories, the austenitic, ferritic, and martensitic types. The austenitic stainless steels generally refer to the 18 chromium-8, nickel type, e. g., AISI type 304 or 347. The ferritic stainless steels generally contain 12 percent or more of chromium and are not hardenable by heat treatment, e. g., AISI type 405 or 430. The martensitic stainless steels generally contain 12 percent or more of chromium and are hardenable by heat treatment, e. g., AISI type 410 or 420.
- stress corrosion** Accelerated localized corrosive attack which causes cracking to occur in highly stressed areas of a metal.
- structural materials (main)** The main materials used in the fabrication of pressure-containing parts of the primary system.
- surface contamination** Arbitrarily defined as any foreign material that is present as an inclusion or adherent to a surface; e. g., any foreign material which cannot be removed from a surface by flushing with water and/or grease solvent is considered to be surface contamination.
- thermal shield** Barrier surrounding the core for the purpose of absorbing radiation (principally neutrons) which would otherwise overheat the pressure vessel walls.
- transcrystalline cracking** See transgranular cracking.
- transgranular (transcrystalline) cracking** Cracking that occurs through the grains of a metal (see intergranular cracking).
- transported corrosion products** Insoluble corrosion products deposited at certain locations other than those where the products were initially formed.
- treated boiler water** Boiler feed water that has been treated with alkali and phosphate to inhibit corrosion and deposition (see alkali-phosphate treatment).
- U. S. P.** United States Pharmacopoeia.
- validity factors** Method for representing the overall significance of corrosion rates given in the Handbook. This factor represents the weighted importance of consistency of results, number of samples, and duration of test.
- WAPD** Westinghouse Atomic Power Division, Bettis Plant, Pittsburgh, Pa. This plant is operated by the Westinghouse Electric Corp. for the Atomic Energy Commission.
- wear factor** A numerical method of ranking materials by wear resistance. The factor varies directly with wear.

INDEX

- Abrasives,
 - application of, 264-266
 - alumina grit, 265
 - rubber and resin binders, 265
 - silicon carbide grit, 265
 - grinding and polishing, 266
 - grit and vapor blasting, 266
 - grit materials, 265
 - silica grit, contamination by, 266
 - test for contamination, 266
- Abrasive wear, 27, 28
- Accumulated wear particles; effect on wear, 258
- Acetone for degreasing, 270
- Acid pickling, 269
- Acid cleaning, 267-269
 - fumes, toxicity of, 270
- Activation energies, diffusion controlled process, 14-16
- Activity, residual primary system, 236-237
- Adhesive wear, related to
 - distance traveled, 28
 - load, 29
- Adsorbed gases, effect on friction, 25
- Age hardening, effect on corrosion resistance, 141, 142
- Alcohol, for degreasing, 270
- Alkaline-phosphate treatment, effect on chloride stress corrosion, 199-202, 220-221
- Alnico 6, static corrosion classification, 98
- Alumina, fused, static corrosion classification, 99
- Alumina bodies, static corrosion classification, 99
- Aluminum bronze, static corrosion classification, 98
- Ammonia,
 - analysis for, 55
 - formation of, 32
- Analysis for,
 - chlorides (ASTM Method D-512), 55
 - corrosion products, chemical and spectrographic size determination,
 - iron, 55
 - oxygen (Blacet-Leighton Method), 55
 - phosphates, 55
- Annealing, role in stress corrosion, 188, 194
- Anodic reactors, 13-15, 17
- Apparatus, wear test,
 - journal-sleeve (rotating), 67-68
 - split piston-cylinder (reciprocating), 65
- Application of materials, *see* Choosing materials
- Armature, effect of crevice corrosion, 162-165
- Armco iron, static corrosion classification, 98
- Armco 17-4 PH and 17-7 PH, *see* stainless steels
- Asbestos (gasket material), static corrosion classification, 98
- Asperites,
 - cold welding of, 23
 - deformation, 22, 23
 - local temperature at, 23
 - mechanical interlocking of, 23
 - theory, 23
 - welding of, 23
- Austenite, stabilized, effect on
 - intergranular corrosion, 220-221, 226-227
 - stress corrosion, 220-221
- Autoclave tests, *see* Corrosion tests, static, *see* ball bearing tests
- Bacharach alloy, static corrosion classification, 97
- Back-flush water, by-pass filter, 237
- Baked phenolic resin, static corrosion classification, 100
- Balances, analytical, 56-57
- Ball bearing tests, 246-251
 - break-in period, 250
 - chemical additives, 247
 - claddings and hard facings on races, 251
 - criteria for evaluation, 246
 - effect of chemical additives, 247
 - of load, 248-249
 - of service life, 250
 - of temperature, 248
 - lubricants studied, 250, 257
 - results of high pH tests, 247
 - summary of environmental consideration, 257
 - summary of test conditions, 245
 - typical test rigs, 246
- Ball bearing torques, frictional, measurement of, 246
- Ball bearings, effect of crevice corrosion on, 168-169
 - axial clearance, 169, 246
 - operating torque, 168-169
 - periodic movement, 150-159
 - radial clearance, 169, 246
- Basic friction theory, 22
- Basic materials used in reactor, 6-7, 95-97
- Basic wear tests,
 - effect of
 - corrosion, 28, 244
 - environment, 244
 - hardness, 242-243
 - hydrogen, dissolved, 119, 243
 - oxygen, dissolved, 244, 248
 - service life exposure, 242
 - temperature, 244
 - factors influencing wear, 242-244
 - material relationships, 239
 - screening tests, 240
 - summary of piston-cylinder tests, 243

- Beam specimens, for stress corrosion tests, 194
- Bearing combinations,
 - effect of water chemistry, 122-133
 - type of motion, 122-133
- Bearing materials,
 - (see specific materials), 122-133
 - ranking of by wear factor, 122-133
- Bearing surfaces, pickling of, 267
- Bearings, restraint type, 159-162
- Bellows, effect of crevice corrosion, 169-171
- Beryllium-copper (4-96), static corrosion classification, 99
- Blacet-Leighton gas analysis apparatus, 55
- Boiler, steam, (pressurizing), 48
 - oxygen control to prevent corrosion, 212
 - standard, effect of chloride elimination, 212
 - stress corrosion in, 211-214
- Boiler water,
 - phosphate additives to, 212, 214
- Brass, static corrosion classification, 98
- Brazing alloys, use in bearings,
 - BT-AG vs. AISI 304, 122
 - BT-AG vs. chromium plate (honed), 130
 - BT-SN vs. chromium plate (honed), 131
 - RT-SN vs. AISI 304, 122
 - RT-SN vs. chromium plate (honed), 130
 - RT-SN-AM vs. chromium plate (honed), 130
- Build-up, crevice corrosion, 147-150
- Cadmium, static corrosion classification, 99
- Canned motor pumps, in corrosion test loops, 47
- Carbide cutting tools, 265
- Carbon, effect on intergranular corrosion, 226-227
- Carbon and low alloy steels, for structural materials, 6-9
- Carbon steel,
 - descaling corrosion test specimens, 57-58
 - disadvantages of, 6
 - future outlook for, 7
 - incentives for use of, 6
 - present status of, 7
 - start-up procedure for corrosion test loops, 51-54
- Carnegie hi-tensile steel, static corrosion classification, 98
- Carpenter 18-5, static corrosion classification, 97
- Carpenter 20, dynamic corrosion data, 109
 - use in rivets, 167
- Case hardening, considerations for wear, 252
- Cataphoresis, 236
- Cathodic and anodic reactions, 12-15
- Cathodic reactions, depolarized by oxygen, 17
- Ceco 100, static corrosion classification, 98
- Ceramics, static corrosion classification, 99, 100
- Chemical additives,
 - ball bearing tests, 247
- Chloride-bearing water, *see* Stress Corrosion
- Choosing materials, considerations in, 251, 4
 - application, 75
 - bearing clearances, 251
- Choosing materials, considerations in—Continued
 - case hardening, 252
 - clearances, 251
 - corrosion,
 - erosion, 93
 - fatigue, 93
 - fretting, 93
 - galvanic, 83-86
 - intergranular, 92-93
 - localized, 80-83
 - stress, 86-92
 - geometry, 252
 - load, 251
 - manufacturing and processing, 252
 - plating, 254
 - surface roughness, 252
 - velocity, 251-252
 - wear, 250
- Chromates, as inhibitor, 210
- Chromium, effect on
 - general corrosion, 18
 - intergranular corrosion, 226-227
- Chromium carbide in nickel matrix, static corrosion classification, 99
 - use in bearings,
 - vs. Armco 17-4 PH, 119
 - vs. chrome carbide, 133
 - vs. chromium plate (honed), 130, 133
 - vs. titanium, nitrided, 133
- Chromium plate (as plated),
 - use in bearings,
 - vs. AISI 304, 122
 - vs. AISI 410, 131, 132
 - vs. AISI 416, 131, 132
 - vs. AISI 420, 131
 - vs. AISI 440-C, 131
 - vs. Armco 17-4 PH (nitrided), 131
 - vs. Armco 17-4 PH, 123, 131
 - vs. chromium plate (as plated), 131, 132
 - vs. Hastelloy D, 132
 - vs. Haynes 25 (CW), 127, 128
 - vs. S-Monel, 132
 - vs. Stellite No. 3, 131
 - vs. Stellite No. 6, 126, 132
 - vs. Stellite No. 21, 127, 131
 - vs. Titanium (nitrided), 131
 - vs. USS 18-8 W, 125, 131
 - vs. Wall colmonoy No. 6, 131
- Chromium plate,
 - attack in oxygen-bearing high pH water, 255
 - static corrosion classification, plated on
 - AISI 347, 98
 - Armco 17-4 PH, 98
 - USS 18-8, 98
 - qualification test for vendors, 254
 - relationship with base metal hardness, 254
 - thickness normally employed, 254-255

- Chromium plate (hard, honed),
 - use in bearings,
 - vs. AISU 304, 130
 - vs. AISI 440 C, 123
 - vs. Armco 17-4 PH, 123, 124, 130, 131
 - vs. Armco 17-4 PH (nitrided), 130, 131, 132
 - vs. brazing alloy BT AG, 130
 - vs. brazing alloy, BT-SN, 130, 131
 - vs. brazing alloy, RT-SN-AM, 130
 - vs. brazing alloy, RT-SN, 130
 - vs. chromium carbide in Ni matrix, 130
 - vs. chromium plate (honed), 130
 - vs. chromium plate (nitrided), 132
 - vs. Everdur 1012 (silicon bronze), 129, 130, 131
 - vs. Graphitar 14, 133
 - vs. Hastelloy D, 130, 131
 - vs. Haynes 25, 127, 128, 130, 131
 - vs. KR Monel, 128
 - vs. lead, 124, 125, 133
 - vs. Metamic Lt-1, 130
 - vs. Monel, 128
 - vs. S-Monel, 130, 131
 - vs. Stellite No. 3, 125, 126, 130, 131
 - vs. Stellite No. 6, 126, 130, 131
 - vs. Stellite No. 12, 127
 - vs. Stellite No. 21, 127, 130
 - vs. Wall Colmonoy No. 6, 129, 130, 131
- Chromized 2½% silicon steel, static corrosion classification, 99
- Chromized Hipernik, static corrosion classification, 99
- Chromizing, 256
- Chromoco tool steel, static corrosion classification, 98
- Cimet, static corrosion classification, 98
- Circuits, dynamic corrosion, 46-50
- Citric acid, for cleaning, 270
- Claddings and hard facings, ball bearing raceways, 250, 251
- Clean area, cleanliness required, 263, 265
- Cleaning,
 - general, 263, 265, 267-271
 - acids, limitations and procedures, 267-270
 - autoclaves (static), 41-43
 - chemical, primary system, 237
 - parts with crevices, precautions, 269
 - test specimens, 56, 57
 - ultrasonic, 237
 - water employed for, 270-271
- Cleanliness, in
 - assembly operations, 265
 - grinding, 264
 - welding, 264
- Clearances in bearings, 251
- Cobalt, static corrosion classification, 99
- Cobalt (electrolytic), static corrosion classification, 99
- Cobalt-base alloys,
 - dynamic corrosion data, 101, 105, 109
 - static corrosion classification, 97
- Coefficient of diffusion, determination, 13-16
- Coefficient of friction,
 - destruction and maintenance of surface layers, 25-26
 - effect of adsorbed gases, 22, 26
 - chemical and physical reactions, 26
 - contaminant films, 25
 - corrosion, 26
 - mechanical and metallurgical factors, 27
 - film formation, 26
 - general, 24-27
 - gross reactions, 26
 - hydroxide formation, 26
 - influence of interface materials, 24-25
 - interface materials in contact, 24
 - modifying environmental effects, 26
 - nature of surface layers, 25
 - oxide replenishment, 26
- Cold welding of asperities, 23
- Cold working, effect on stress corrosion, 189, 208-209
- Colmonoy 4, static corrosion classification, 98
- Colmonoy 5, static corrosion classification, 98
- Colmonoy 6, static corrosion classification, 98
- Colmonoy Graphalloy 5, static corrosion classification, 99
- Columbium (niobium), static corrosion classification, 99
 - importance in intergranular corrosion, 225
- Component tests, simulated, problems, 245-246
- Components, storage and shipment, 271-272
- Composition of materials, effect on
 - crevice corrosion, 152-155
 - general corrosion, 135-136
 - wear, 239-241, 252-257
- Contact (bearing) area, 22-23
- Contact corrosion, *see* Crevice Corrosion
- Contact of interface materials, 24
- Contact pressure,
 - in wear applications, 258
- Containers for pickling solutions, 269
- Contaminant films, effect on coefficient of friction, 26
- Contamination,
 - fission products, 229-231
 - forms of, 268
 - resulting from iron pick-up, 266
 - surface, definition of, 263-264
- Contributing organizations, 9-10
- Coolant, choice of, 3
- Cooling system, *see* Primary System
- Copper,
 - static corrosion classification, 98
- Copper alloys, static corrosion classification, 98
- Copper-base alloys,
 - dynamic corrosion data, 33, 109
 - effect of dissolved hydrogen on corrosion resistance, 140-141
 - static corrosion classification, 98
 - susceptibility to crevice corrosion, 153-155
- Corrosion classification, static, of all materials investigated, 97-100
- Corrosion in crevices, *see* Crevice Corrosion

- Corrosion (*see specific type*), definition of, 11
 - effect in basic wear tests, 242
 - on friction surfaces, 26, 28
 - on systems, 95-96
 - films, 15-16
 - general, 75-80, 11-12
 - inhibitors, *see* Inhibitors
 - iron, 13-16
 - main reactions (nuclear systems), 32
- Corrosion fatigue, 211
- Corrosion film study
 - binocular microscope, 56
 - X-ray diffraction, 56
- Corrosion products, 229-238
- Corrosion rate
 - determined by hydrogen effusion, 13-16
 - effect of occluded hydrogen, 16
 - dissolved hydrogen, 17
 - dissolved oxygen, 17
 - heat treatment, 142
 - localized attack, 80-83
 - pH, 16-17
 - time, 80-83
 - velocity, 18, 138
 - increase in dynamic systems, 18
 - interpretation of dynamic corrosion tests, 101
 - interpretation of static corrosion classification, 96-97
 - significance of, 76-80
 - stainless steel, 6-7, 136, 137-142, 102, 109
- Corrosion specimens, preparation of, 56
- Corrosion tests, dynamic
 - copper base alloys, 101, 106
 - corrosion rates, interpretation of, 101
 - description of, 41-64
 - description of specimens, 55-56
 - description of test circuits, 41-51
 - iron-base alloys, 101, 106, 110-116
 - loops, test, dynamic, 46-51
 - semi-static, 44-46
 - miscellaneous metals and alloys, 101
 - nickel-base alloys, 101, 117-118
 - principal additives to, 101
 - specimen arrangement, 48, 50
 - specimen holder, 48-50
 - surface finish of samples, 101
 - test conditions, 101
 - validity factors, 101
 - weight changes in, 101
- Corrosion tests, evaluation of, 56-60, 63-64
- Corrosion tests, static,
 - classification on the basis of, 96-100
 - general, 41-60
 - significance of,
 - ceramics and allied materials, 99-100
 - cobalt-base alloys, 97
 - copper-base alloys, 98
 - iron-base alloys, 98
- Corrosion tests, static—Continued
 - significance of—Continued
 - miscellaneous alloys and elements, 98-99
 - nickel-base alloys, 98
 - plastics, 100
 - special stainless steels, 97
 - stainless steels, 97
 - special,
 - corrosion fatigue, 63
 - crevice, 61
 - galvanic, 60-61
 - heat transfer, 63
 - stress, 61
- Corrosive wear, 28, 29
- Cracking (*see* Stress Corrosion, Fatigue Corrosion, Fretting Corrosion, Intergranular Corrosion)
- Crane special alloy, static corrosion classification, 97
- Crevice corrosion,
 - corrosion built-up in, 147-152
 - definition of, 147-150
 - effect of,
 - clearance, 157-158
 - hydrogen, 157
 - material composition, 152-155
 - oxygen, 155-157
 - pH, 157
 - periodic movement, 158
 - temperature, 159
 - wear, 257
 - engineering importance of, 187-191
 - metal-ion cell in, 14
 - occurrence in,
 - armatures, 162-165
 - ball bearings, 168-169
 - bellows, 169-171
 - journal-sleeve bearing, 159-160
 - rivets, 167
 - springs, 165-166
 - oxygen cell in, 148-149
 - pitting in, 147-150, 165
 - prevention by electroplating, 162-165
 - stagnant area effect in, 149
 - test specimens for,
 - journal-sleeve, 80-83
 - plate-type, 81
- Crevices,
 - entrapment of pickling fluids, 269
 - in stress corrosion, 188
- Critical contact pressure, 258
- Croloy, dynamic corrosion data,
 - 1/4, 112
 - 2/4, 113
- Crud, 229
- Cupro-nickel (70-30)
 - dynamic corrosion data, 106
 - effect of velocity on corrosion, 138

- Deburring procedures, 266
- Degreasing,
 autoclaves (static), 41
 general, 270
 parts with crevices, precautions, 270
 solvents,
 acetone, 270
 alcohol, 270
 perchloroethylene, inhibited, 270
 trichloroethylene, inhibited, 270
 test specimens, 56
 vapor, 270
- Demineralized water, quality for cleaning, 271
- Demineralizer,
 see Ion Exchangers
 see Deionization
 thermal stability of resins, 237
- Deposition,
 see Carbon Steel Crud and Stainless Steel Crud
- Deuteron beam, used in crud experiments, 233
- Dew point, reference for drying of components, 271
- Diffusion coefficients, techniques for determining, 14-15
- Diffusion controlled process,
 experiments of Bloom and Krufeld, 19
- Dirt, definition of, 264
- Dirt-free work area—clean area, 264
- Discaloy 24, static corrosion classification, 98
- Dissociation of water—*see* Water Chemistry
- Dissolved hydrogen, effect on corrosion rate, 17
- Dissolved oxygen,
 effect on corrosion rate, 17, 139, 140
- Distilled water,
 quality for cleaning, 271
- Drying,
 by oven and vacuum, 271
 related to dew point, 271
- Duraloy, static corrosion classification, 98
- Duranickel, static corrosion classification, 98
- Duration of dynamic corrosion loop test, 80
- Duration of static autoclave corrosion test, 76
- Durimet 20, static corrosion classification, 97
- Duriron, static corrosion classification, 98
- Dynamic corrosion tests, *see* Corrosion Tests, Dynamic
- Dynamic test loops, *see* Corrosion Tests, Dynamic
- Electrical resistivity of water,
 effect on,
 corrosion resistance, 141-142
 crevice corrosion, 141-142
 galvanic corrosion, 141-142
- Electrodeposition, *see* Plating
- Electroplating, *see* Plating
- Electroplating for,
 crevice corrosion protection, 162-165
- Energies, activation, for diffusion controlled process, 13-16
- Equilibria, metal-water
 copper, nickel, iron, 13
- Equilibrium constants, metal-water reaction, 13
- Evaluation of corrosion tests, 95-96, 101
- Evaluation of wear,
 by wear factor, 241-242
 by weight change, 241-242
- Expandable rubber plugs, for sealing, 271-272
- Expanded tubes, effect on stress corrosion, 208, 209
- Fatigue corrosion,
 general, 93
- Fatigue, surface, in wear, 28, 29
- Fatty acid lubricants, 26
- Ferrite, effect on intergranular corrosion, 226-227
- Ferritic stainless steels
 hydrogen embrittlement in, 190
 susceptibility to stress corrosion, 190
- Ferrous hydroxide, formation of, 13-16
- Filing of metals, procedures for, 266
- Films,
 formation on friction surfaces, 26
 study of,
 binocular microscope, 56
 hydrodynamic, 239
 X-ray diffraction, 56
- Filter sintered stainless steel, 236
- Finish, surface, of corrosion test specimens, 56
- Firetube boilers, stress corrosion in, 212
- Fissionable product contamination, 229, 231-233
- Flow control, in dynamic corrosion test loops, 46
- Flow pressure, plastic, 23
- Flow section, Venturi, 40-46
- Force, Friction, *see* Friction Force
- Formation of,
 magnetite, 13-16
- Fouling,
 by corrosion products, 231-237
 influence on activity level, 230-231
- Frank alloy (Ge 12, Au 88) static corrosion classification, 99
- Friction, coefficient of, *see* Coefficient of Friction
- Friction force,
 ploughing force as a contributor, 23
 related to actual contact area, 28
 related to applied load, 28
 related to nature of materials, 28
 related to velocity, 28
- Friction Theory, basic, 22
- Fuel element ruptures, consequences of, 268
- Fumes, acid, toxicity of in pickling, 267
- Future research, areas of wear and friction, 258
- Galvanic corrosion,
 for protection in stress corrosion, 190, 209
 importance of, 83
 test methods for, 85-86
 test samples for, 85-86
- Gas analysis by Blacet-Leighton, method, 54-55
- Gases, adsorbed, effect on friction, 24-25

- Gases, effect on systems, 139-141
- General Electric Magnet Alloy (Pt 77, Co 23), static corrosion classification, 99
- Geometry, general considerations for wear applications, 252
- Glass (silica), static corrosion classification, 100
- Glatzer, J. and Westphal, R. C., basic wear tests, 241
- Gold, static corrosion classification, 98
- Gold plating, 255
- Gotalota Chrome, static corrosion classification, 98
- Grain size, effect on intergranular corrosion, 226-227
- Graphalloy, static corrosion classification, babbitt, 100
copper, 100
gold, 100
- Graphitar, 14,
static corrosion classification, 99
use in bearings,
vs. Armco 17-4 PH (nitrided), 132
vs. chromium plate (honed), 133
- Graphite-alcohol lubricant, 266
- Grease, removal of, 226
- Grinding operations, cleanliness of, 263-265
- Grinding wheels, *see* Abrasives, 265
- Grit blasting, 265
followed by acid pickling, 265
grits employed, 265
grit qualification test, 265
- Gross area of contact, 23
- Hafnium,
static corrosion classification, 99
dynamic corrosion data, 118
- Handbook, purpose of, 3,
scope of, 3-4
- Hard chromium plate, *see* Chromium Plate
- Hard facing and cladding, 252, 256
- Hardened steels, hydrogen embrittlement in, 190
- Hardening (work hardening), effect on friction, 27
- Hardness, effects in basic wear tests, 242
- Hastelloy, A, B, C and D, static corrosion classification, 98
use in bearings,
vs. chromium (as plated), 132
vs. chromium plate (honed), 130, 131
vs. USS 18-8 W, 125
vs. Stellite No. 3, 125, 126
- Haynes 21, use in bearings,
vs. AISI type 304 stainless steel, 122
- Haynes 25,
(cold worked) use in bearings,
vs. AISI 304, 122, 128
vs. Armco 17-4 PH, 127, 128
vs. chromium (honed), 127, 128, 130, 131
vs. Haynes 25, 127, 128
vs. Monel, 128
vs. Stellite No. 3, 125, 127, 128
vs. Stellite No. 6, 128
- Haynes 25—Continued
(cold worked) use in bearings—Continued
vs. Stellite No. 21, 128
vs. USS 18-8 W, 125
dynamic corrosion data, 109
static corrosion classification, 97
- Haynes Multimet, (nitrided), static corrosion classification, 99
- Haynes 98 M2, static corrosion classification, 97
- Heat affected zones, stress corrosion in, 211
- Heat exchangers, stress corrosion failures, in 214-221
- Heat transfer,
deposition of corrosion products, 231-232, 235-236
effect of hydrogen in crudded system, 235-236
variables causing decrease, 231-232, 235-236
- Heat treatment,
effect on corrosion of materials, 142
hydrogen embrittlement, 191
intergranular corrosion, 225-228
role in stress corrosion, 188, 190
- Heaters, electric, in test loops, 41, 42
- Helical springs, stress corrosion of, 89
- Hevimet, static corrosion classification, 99
- High pH,
effect on ball bearing wear, 248
effect on corrosion, 16-17
results of basic wear tests, 25
- High purity water,
definition of, 7
present research on, 8-9
quality of, for cleaning, 269
stress corrosion in, 192
use in boilers, 9
- Hiperco 27, static corrosion classification, 99
- Hiperco 35, static corrosion classification, 99
- Hot rolled steels, fabrication limits for stress corrosion considerations, 194
- Hot spots,
frictional, 23
- Hydrazine, as oxygen scavenger, 210
- Hydrogen
analysis for, by Blacet-Leighton method, 55
dissolved,
effect on
bearing characteristics, 140-141
corrosion resistance, 12-13, 97, 244
corrosion resistance of copper base alloys and nickel base alloys, 140
crevice corrosion, 157
heat transfer in crudded system, 235
systems, 140
- Hydrogen embrittlement,
dependence on heat treatment, 190-191, 195
dependence on stress, 195
effect on precipitation hardening steels, 191
ferritic steels, 190-191
martensitic stainless steel, 190-191
media occurring in, 190-191

- Hydrogen oils for lubricants, 266
- Hydrogenated water,
 - in wear tests, 121
- Illium G, static corrosion classification, 98
- Illium R, static corrosion classification, 98
- Incolloy, static corrosion classification, 98
- Inconel,
 - dynamic corrosion data, 117
 - intergranular attack in crevice corrosion, 165-166
 - static corrosion classification, 98
- Inconel X, *see* Inconel
- Indium plating,
 - static corrosion classification, 99
 - wear applications, 255
- Industrial failures of austenitic stainless steel components, 220-222
- Industrial failures due to stress corrosion, 219-222
- Industrial uses of high purity water, 9
- Inhibitors,
 - anodic, dissolved salts, 17
 - effects on stress corrosion, 209-210
 - vapor phase, role in stress corrosion, 199-205
- In-pile tests,
 - corrosion products observed, 233-235
 - early investigations, 231-233
 - heat transfer, 232
- Integrity of plant, cleanliness, 263-264
- Intergranular attack (*see* specific materials)
 - Inconel, 165-166
 - Inconel X (alloy J), 195
- Intergranular corrosion (*see* specific alloy)
- Intergranular failures due to stress corrosion, 189
- Intermetallic or metalloid structures developed as bearing materials, 240
- Invar, static corrosion classification, 98
- Ion exchangers, in corrosion test loops, 46
 - lithium hydroxide regenerated, 237
 - thermal instability, 237
- Iron,
 - analysis for, 55
- Iron-base alloys,
 - dynamic corrosion data, 109-116
 - static corrosion classification, 98
- Iron corrosion, mechanism of, 13-16
- Iron pick-up contamination, 266
- Iron-water system, thermodynamic data for, 13, 4
- Irradiation,
 - effect on corrosion, 231-232
- Jeliff 1000, static corrosion classification, 99
- Joints, threaded lubrication of, 265-266
- Journal-sleeve bearings, crevice corrosion in, 159-160
- Karbate A, static corrosion classification, 100
- Karbate C, static corrosion classification, 100
- Kel-F, static corrosion classification, 100
- K-Monel,
 - dynamic corrosion data, 118
 - effect of water velocity on corrosion, 138
- Kovar, static corrosion classification, 98
- KR Monel,
 - use in bearings,
 - vs. chromium plate (honed), 128
 - vs. Stellite No. 3, 128
 - vs. Stellite No. 6, 128
 - vs. Stellite No. 21, 128
- Lead,
 - static corrosion classification, 99
 - use in bearings,
 - vs. AISI 304, 122, 132, 133
 - vs. chromium plate (honed), 130, 131, 132
- Lead plating, 255
- Leaded bronze, static corrosion classification, 98
- Linear motion wear test apparatus, 65-67
- Lithium hydroxide (high pH), *see* Corrosion Rate and Tests
- Load,
 - considerations for wear applications, 248-249, 251
 - external, effect on friction, 27
- Localized attack, *see* Crevice Corrosion, Erosion Corrosion, Fatigue Corrosion, Fretting Corrosion, Galvanic Corrosion, Intergranular Corrosion, Stress Corrosion
- Loop, *see* Corrosion Tests, Dynamic
- Lubricants, extreme pressure, 26
 - fatty acid, 26
 - graphite-alcohol (Neolube), 266
 - hydrocarbon oils, straight, 226
 - in threaded joints, 226
 - low melting point, 240
 - low shear strength, 240
 - use for ball bearing application, 250, 257
 - water soluble, 250
- Magnesium,
 - static corrosion classification, 99
- Mallory 1000, static corrosion classification, 99
- Manufacturing and processing, general consideration for wear, 251, 252
- Martensitic stainless steel (*see* specific steel)
- Materials, consideration in choosing, 4
- Materials Outlook, present and future, 7
- Mechanical and metallurgical factors affecting friction,
 - external load, 27
 - velocity, 27
 - work hardening, 27
- Mechanical history, effect on stress corrosion, 188
- Metal oxides, free energies of formation, 13
- Metal-water equilibria,
 - copper, nickel, iron, 13
- Metallloid structure developed as bearing material, 240

- Metamic LT-1,
 - static corrosion classification, 99
 - use in bearings,
 - vs. Armco 17-4 PH (nitrided), 133
 - vs. chromium plate (honed), 130
 - vs. Metamic LT-1, 133
 - vs. Stellite No. 3, 133
 - vs. Stellite No. 21 (PH), 127
- Mica (natural and glass bonded), static corrosion classification, 100
- Microscope, electron, 230
- Microscopic examination,
 - preparation of specimens for, 58-60
- Mill annealed condition, as related to stress corrosion, 188
- Miscellaneous alloys, static corrosion classification, 98-99
- Molecules, polar, on friction surfaces, 26
- Molybdenum, static corrosion classification, 99
- Moly-sulfide, static corrosion classification, 99
- Monel,
 - carbon graphite, static corrosion classification, 98
 - corrosion resistance of, effects of water velocity, 138
 - dynamic corrosion data, 118
 - high nickel, static corrosion classification, 98
 - K-Monel, static corrosion classification, 98
 - S-Monel,
 - static corrosion classification, 98
 - use in bearings,
 - vs. Armco 17-4 PH (nitrided), 132
 - vs. chromium plate (honed), 128
 - vs. Haynes 25, 128
- Natural-circulation loop, 47
- Neoprene paint, masking parts in pickling operation, 267
- Nesslerization, in ammonia analysis, 55
- Nichrome, static corrosion classification, 98
- Nickel,
 - A-nickel,
 - dynamic corrosion data, 117
 - static corrosion classification, 98
 - E-nickel,
 - effect on intergranular corrosion, 227
 - static corrosion classification, 98
 - L-nickel,
 - static corrosion classification, 98
- Nickel-base alloys,
 - dissolved hydrogen on corrosion resistance, 141
 - in dynamic corrosion data, 101, 117-118
 - static corrosion classification, 98
 - stress corrosion,
 - conclusions on, 220
 - failures in, 220
 - immunity from, 220
 - occurrence in, 220
 - prevention in, 220
 - susceptibility to crevice corrosion, 152-155
- Nickel-moly (L), static corrosion classification, 98
- Nickel Nitralloy, nitrided, static corrosion classification, 99
- Ni-Resist, static corrosion classification, 98
- Niobium, see Columbium
- Nitric acid,
 - formation of, 33
- Nitriding (*see* specific alloy), 254, 258
- Nitrogen, effect on intergranular corrosion, 226
- Nonmetallic materials investigated for wear, 256
- Nuclear irradiation, effect on corrosion resistance, 142-143
- Nuclear power plants, choice of materials for, 4-9
- Nuclear reactions, 33
- Nusite, static corrosion classification, 98
- Octadecylamine, as oxygen scavenger, 210
- Oils, hydrocarbon (*see* Lubricants)
- Ontario tool steel, 98
- Organic materials,
 - excluded from primary system, 12
 - see* Feflon
 - Orthophenanthroline in colorimetric analysis of, 55
- Out-of-pile tests, 235-236
- Oven drying (*see* Vacuum Drying)
- Oxidation of mild steel, following parabolic law, 14
- Oxidation resistance, effect of alloying constituents 18-19
- Oxide film, erosion of, 15-16
- Oxide replenishment on friction surface, 26
- Oxides, metal, free energies of formation, 13-16
- Oxygen
 - analysis for,
 - ASTM method, 55
 - Blacet-Leighton method, 55
 - dissolved,
 - effects on,
 - ball bearing wear, 245
 - corrosion resistance of materials, 139-140
 - crevice corrosion, 155-157
 - systems, 139-140
 - role in stress corrosion, 190
- Oxygenated water,
 - in corrosion tests, 55
 - in wear tests, 121
- Oxygen-free, boiler water, 189-190
- Oxygen level,
 - required for stress corrosion protection, 190
- Oxygen scavengers, 210
- Packing specifications, 270-271
- Parabolic law, in oxidation of mild steel, 14, 20
- Particle size, crud,
 - optical microscopy, 230
- Pendulum slide test,
 - procedures, 68-70
 - specimens used, 68-70
- Perchloroethylene, inhibited for degreasing, 270

- pH (*see* Corrosion)
 effects on corrosion rate, 16-17
 effect on crevice corrosion, 157
 effects on systems, 141
- Phosphates, analysis for, 55
- Phosphor bronze, static corrosion classification, 98
- Pickling, acid (*see* Cleaning, Acids),
 acids employed, 267
 agitation of, 267
 containers for, 267
 entrapment of fluids in crevices, 267
 of bearing surfaces, 267
 of small-diameter tubing, 267
 precautions, 267
 protection of bearing surfaces, 267
 toxicity of acid fumes, 267
- Piston-cylinder wear tests apparatus, 65
 description of specimen, 65-66
 operating conditions for, 66
 partial summary of basic wear tests, 243
 representative data from, 241
- Pitting (*see* Corrosion)
 adverse effects of, 75
 as related to stress corrosion, 189, 211
 in bearings, 257
 in crevice corrosion, 147-150, 165
- Plastics (*see* Teflon), static corrosion classification, 100
- Plastic flow pressure, 23
- Plastic strain, effect on stress corrosion, 187, 189, 208-209
- Plating,
 chromium, 254-256
 crevice corrosion protection, 162-165
 for wear applications, 254-256
 gold, 255
 indium, 255
 lead, 255
 nickel, 209
 qualification tests for vendors, 254
 relationship with base metal hardness, 254
 rhodium, 255
 silver, 255
 stress corrosion protection, 209
- Platinum, static corrosion classification, 99
- Plexiglass, static corrosion classification, 100
- Ploughing force, contributing to friction force, 23, 28
- Polar molecules on friction surfaces, 26
- Polyethylene, static corrosion classification, 100
- Polyethylene envelopes for storage and shipment, 272
- Protection of bearing surfaces during pickling, 269
- Protection films, role in stress corrosion, 187
- Pump bearing materials, 259-261
- Purification system, 236-237
 efficiency of mechanical filter and demineralizer, 236-237
- Quartz, static corrosion classification, 100
- Radiation,
 species predominant in corrosion products, 230-231
 tracers, Kirkendall experiments, 14
- Radioactivity, induced in,
 secondary system, 4
- Ranking of bearing materials by wear factor, 241-242
- Rate of corrosion (*see* Corrosion)
- Reactor conditions, simulated in test loops, 245-246
- Reagents for dissolving crud,
 chromic-nitric acid mixture, 237
 hydrochloric acid, 237
 oxalic acid followed by nitric acid, 237
 sulfuric acid, 237
- Reciprocating motion, in wear tests, 121
- Refractalloy 26, static corrosion classification, 98
- Refractalloy 80, static corrosion classification, 97
- Refractalloy 120, static corrosion classification, 97
- Relative areas, study of galvanic corrosion, 83-86
- Relative general corrosion resistance of materials, 136
- Removal of primary system corrosion products, 236-237
- Research, future areas of, 258, 7, 8, 9
- Residual activity in the primary system, 231
- Resin bonded grinding wheels (*see* Abrasives), 266
- Resistance to oxidation,
 effect of alloying constituents, 18-19
 resistivity of test water, 54
- Restraint bearings, 161-162
- Rexalloy, static corrosion classification, 97
- Rhenium, static corrosion classification, 99
- Rhodium, static corrosion classification, 99
- Rivets,
 effect of crevice corrosion, 167
- Rotating motion wear test apparatus, 67-68
- Roughness, surface, *see also* roughness, 24
- Rubber bonded grinding wheels (*see* Abrasives), 266
- Rubber plugs, for sealing components, 271-272
- Rulon, static corrosion classification, 100
- Rupture disk, safety device in pressurized systems, 43, 46
- Safety devices, in corrosion test loops, 46
- Safety valves, in corrosion test loops, 46
- Salts, dissolved, as anodic inhibitors, 17
- Schikorr's equation, 19
- Scale, corrosion, need for research in, 19
- Scaling of,
 iron in air, 19
 iron in oxygen, 19
- Scope, of subject handbook, 3-4
- Screening tests, basic wear test type, 240-244
- Seals, temporary, 264
- Secondary system,
 stress corrosion tests in, 196-211
- Semistatic test systems, 44-46
- Sensitization,
 effect on
 intergranular corrosion, 226-227
 stress corrosion, 189, 198-199

- Service failures, stress corrosion, correlation with test failures, 211, 212
- Shipments of components, *see* Storage and Shipment
- Significance of corrosion rate, 76-80, 101
- Silastic, static corrosion classification, 100
- Silica abrasive papers, *see* Abrasives, 266
- Silica base grinding wheels, *see* Abrasives, 266
- Silica, fused, 100
- Silicon bronze (Everdur 1012),
static corrosion classification, 98
use in bearings,
vs. AISI 304, 129
vs. Armco 17-4 PH, 129
vs. chromium plate, honed, 129, 130, 131
vs. Stellite No. 3, 129
vs. Stellite No. 21, 129
- Silver, static corrosion classification, 99
- Silver bearing alloy, static corrosion classification, 99
- Silver braze, static corrosion classification, 99
- Silver cadmium, static corrosion classification, 99
- Silver-copper alloy, static corrosion classification, 99
- Simulated component tests, 245-251
thrust bearings in, 161-162
typical problems arising in, 245-246
- Sintered stainless steel filters,
operating characteristics of, 236-237
- S-Monel, use in bearings,
vs. AISI 304, 119, 122, 129
vs. Armco 17-4 PH, 124, 129
vs. chromium (as plated), 132
vs. chromium plate (honed), 125, 130, 131
vs. USS 18-8 W, 125, 129
- Sodium sulfite, prevention of stress corrosion, 210
- Solaramic (glass enamel), static corrosion classification, 100
- Special alloy (Pd 15, Cd 30, Ag 55), corrosion data, 120
- Special alloy (Pd 20, Cd 30, Ag 50), dynamic corrosion data, 120
- Spectrographic analysis, of stainless steel crud, 230
- Split piston-cylinder wear test apparatus, 65
- Spring applications,
hardenable stainless steels, 195
helical, for tests, 89
importance of crevice corrosion, 165-166
other materials investigated, 195
- Stagnant area corrosion, 149
- Stainless steel
austenitic, *see* Stainless steel types
cleaning of, 267
ferritic,
 see stainless steel types
 susceptibility to crevice corrosion, 152-155
 susceptibility to stress corrosion, 190
hardenable, industrial failures of, 220
intergranular corrosion,
 effect of carbon content, 226-227
 effect of chromium and nickel, 227
- Stainless steel—Continued
intergranular corrosion—Continued
 engineering importance of, 225-226
 heat treatment after welding, 227
 heat treatment, effect on, 226
 heat treatment investigated, 227
 mechanism of attack, 226-227
 nitrogen, effect on, 226
 role of corrosive environments, 227-228
 role of ferrite in, 226
 role of grain size in, 226
 sensitization, role in, 226-228
 stabilized steels, need for, 225
 unstabilized steels, 227-228
 unstabilized steels, disadvantages of, 225
 weldments, thickness effects in, 227
- martensitic
 see also stainless steel types
 effects of stress corrosion on, 221
 wear applications in, 256
static corrosion classification of, 97
- types,
 AISI 301, static corrosion classification, 97
 AISI 302, dynamic corrosion data, 102
 AISI 302, static corrosion classification, 97
 AISI 302, Scottsonized, static corrosion classification, 98
 AISI 303, dynamic corrosion data, 102
 AISI 303, static corrosion classification, 97
 AISI 304, dynamic corrosion data, 102, 103
 AISI 304, static corrosion classification, 97
 AISI 304 (2.5 percent Silicon), static corrosion classification, 97
 AISI 304 ELC, dynamic corrosion data, 103
 AISI 304 ELC, static corrosion classification, 97
 AISI 304 modified, static corrosion classification, 97
 AISI 304 nitrided, static corrosion classification, 98
 AISI 304, use in bearings
 vs. AISI 304, 122
 vs. brazing alloy (BT AG), 122
 vs. brazing alloy (RT SN), 122
 vs. chromium, as plated, 122
 vs. chromium plate, honed, 130
 vs. Haynes No. 21, 122
 vs. Haynes 25 (CW), 122, 128
 vs. lead, 119, 122, 126, 127, 132, 133
 vs. silicon bronze (Everdur 1012), 129
 vs. S-Monel, 122, 129
 vs. Stellite No. 3, 125
 vs. Stellite No. 6, 122
 vs. USS 18-8 W, 122, 125
 AISI 305, static corrosion classification, 97
 AISI 308, static corrosion classification, 97
 AISI 309, static corrosion classification, 97
 AISI 310, static corrosion classification, 97
 AISI 316, dynamic corrosion data, 103
 AISI 316, static corrosion classification, 97

AISI 316, (2.5 per cent Silicon), static corrosion classification, 97
 AISI 317, static corrosion classification, 97
 AISI 318, static corrosion classification, 97
 AISI 321, dynamic corrosion data, 104
 static corrosion classification, 97
 AISI 329, nitrided, static corrosion classification, 98
 AISI 329, static corrosion classification, 97
 AISI 347, Armco chromate treatment, static corrosion classification, 98
 AISI 347, dynamic corrosion data, 104
 AISI 347, MoS treatment, static corrosion classification, 98
 AISI 347, nitrided,
 static corrosion classification, 98
 use in bearings,
 vs. AISI 347, nitrided, 132
 AISI 347, Scottsonized, static corrosion classification, 98
 AISI 347, static corrosion classification, 97
 AISI 348, static corrosion classification, 97
 AISI 410, chromium enriched surface, static corrosion classification, 98
 AISI 410,
 dynamic corrosion data, 105
 static corrosion classification, 97
 use in bearings,
 vs. AISI 410, 122
 vs. chromium, as plated, 121, 122
 vs. Stellite No. 3, 122
 vs. Stellite No. 6, 122
 wet hydrogen oxidized, static corrosion classification, 99
 AISI 414, static corrosion classification, 97
 AISI 416,
 static corrosion classification, 97
 use in bearings,
 vs. AISI 416, 123
 vs. chromium plate, as plated, 121, 122
 AISI 420,
 dynamic corrosion data, 105
 static corrosion classification, 97
 use in bearings,
 vs. AISI 420, 123
 vs. chromium (as plated), 131
 AISI, 431,
 static corrosion classification, 97
 AISI 440 A, Armco chromate treatment, static corrosion classification, 99
 AISI 440 BM, static corrosion classification, 97
 AISI 440 C,
 chrome enriched surface, static corrosion classification, 99
 dynamic corrosion data, 105
 nitrided, static corrosion classification, 99
 static corrosion classification, 97

Stainless steel—Continued

types—Continued

 use in bearings,
 vs. AISI 440C, 123
 vs. chromium, as plated, 131
 vs. chromium plate, honed, 123
 vs. Wall Colmonoy No. 6, 129
 vs. USS 18-8 W, 124
 wet hydrogen oxidized, static corrosion classification, 99
 AISI 440 F, static corrosion classification, 97
 AISI 442, static corrosion classification, 97
 AISI 443, static corrosion classification, 97
 AISI 446, static corrosion classification, 97
 AISI 450 BM, static corrosion classification, 97
 Armco 17-4 PH,
 dynamic corrosion data, 108
 static corrosion classification, 97
 use in bearings,
 vs. AISI 304, 122-124
 vs. Armco 17-4 PH, 123-124
 vs. chromium, as plated, 123-131
 vs. chromium carbide (in nickel matrix), 119, 123
 vs. chromium, nitrided, 124
 vs. chromium plate, honed, 123, 124, 125, 130, 131
 vs. Haynes 25, 124
 vs. Silicon bronze (Everdur 1012), 129
 vs. S-Monel, 124
 vs. Stellite No. 3, 123, 124, 125, 126, 129
 vs. Stellite No. 6, 124, 126
 vs. Stellite No. 21, 124
 vs. titanium, nitrided, 124
 vs. Wall Colmonoy No. 6, 124, 129
 Armco 17-4 PH, nitrided,
 dynamic corrosion data, 106, 107
 static corrosion classification, 98
 use in bearings,
 vs. Armco 17-4 PH, nitrided, 132
 vs. chromium, as plated, 131
 vs. chromium plate, honed, 124, 125, 126, 131, 132
 vs. Graphitar 14, 126, 132
 vs. Metamic LT-1, 127, 133
 vs. S-Monel, 132
 vs. Stellite No. 3, 125
 vs. titanium, nitrided, 132
 Armco 17-7 PH,
 dynamic corrosion data, 107
 static corrosion classification, 98
 Armco 17-7 PH, nitrided, static corrosion classification, 98
 Carpenter 10, static corrosion classification, 97
 Carpenter 20, dynamic corrosion data, 107
 static corrosion classification, 97
 Octolloy (experimental alloy), static corrosion classification, 97

Stainless steel—Continued

types—Continued

USS 18-8 W,

- dynamic corrosion data, 106
- nitrided, static corrosion classification, 99
- static corrosion classification, 97
- use in bearings,
 - vs. AISI 304, 122, 125
 - vs. AISI 440 C, 124
 - vs. chromium, as plated, 124, 131
 - vs. Hastelloy D, 125
 - vs. Haynes 25, 125
 - vs. S-Monel, 125, 129
 - vs. Stellite No. 3, 124, 125, 126
 - vs. Stellite No. 6, 126
 - vs. Stellite No. 21, 127
 - vs. titanium, nitrided, 125
 - vs. USS 18-8 W, 125
 - vs. Wall Colmonoy No. 6, 124, 125

Standard electrode potential, iron-ferrous ion couple, 16

Static autoclave tests, *see* Corrosion tests, static

Steam flashing, in stress corrosion, 188

Steam generation system, chlorides, occurrence in, 188-190

Stellite No. 1, static corrosion classification, 97

Stellite No. 3,

- dynamic corrosion data, 108
- static corrosion classification, 97
- use in bearings,
 - vs. chromium, as plated, 131
 - vs. chromium plate, honed, 120, 124, 125, 126, 130, 131
 - vs. Hastelloy D, 120, 125, 126
 - vs. Haynes 25, 125, 127, 128
 - vs. KR Monel, 122, 128
 - vs. Metamic LT-1, 127, 133
 - vs. silicon bronze (Everdur 1012), 129
 - vs. stainless steel,
 - AISI 304, 125
 - AISI 410, 122
 - Armco 17-4 PH, 123, 124, 125, 126
 - Armco 17-4 PH, nitrided, 125
 - USS 18-8 W, 124, 125, 126
 - vs. Stellite No. 3, 120, 125, 126
 - vs. Stellite No. 6, 125, 126
 - vs. Stellite No. 12, 127
 - vs. Stellite No. 21, 120, 127
 - vs. Wall Colmonoy No. 6, 120, 125, 126, 132

Stellite No. 6,

- dynamic corrosion data, 108
- static corrosion classification, 97
- use in bearings,
 - vs. chromium, as plated, 126, 132
 - vs. chromium plate, 126
 - vs. chromium plate, honed, 126
 - vs. Haynes 25, 128
 - vs. KR Monel, 128

Stellite No. 6—Continued

use in bearings—Continued

- vs. stainless steel
 - AISI 304, 122
 - AISI 410, 122
 - Armco 17-4 PH, 124, 126
 - USS 18-8 W, 126
- vs. Stellite No. 3, 125, 126
- vs. Stellite No. 6, 126
- vs. Stellite No. 21, 126-127
- vs. Wall Colmonoy No. 6, 126, 129

Stellite No. 12,

- static corrosion classification, 97
- use in bearings,
 - vs. chromium plate, honed, 127
 - vs. Stellite No. 3, 127

Stellite No. 19,

- dynamic corrosion data, 108
- static corrosion classification, 97

Stellite No. 21,

- dynamic corrosion data, 108
- static corrosion classification, 97
- use in bearings,
 - vs. chromium, as plated, 127, 131
 - vs. chromium plate, honed, 127, 130
 - vs. Haynes 25, 127
 - vs. KR Monel, 128
 - vs. Metamic LT-1, 127
 - vs. Silicon bronze (Everdur 1012), 127
 - vs. stainless steel
 - Armco 17-4 PH, 124
 - USS 18-8 W, 127
 - vs. Stellite No. 3, 127
 - vs. Stellite No. 6, 127
 - vs. Stellite No. 21, 127
 - vs. Wall Colmonoy No. 6, 129

Stellite No. 23, static corrosion classification, 97

Stellite No. 26, static corrosion classification, 97

Stellite No. 31, static corrosion classification, 97

Stellite No. 33, static corrosion classification, 97

Stellite No. 42, static corrosion classification, 97

Stellite Star J Metal, static corrosion classification, 97

Storage and shipment, 14, 270-271

Stress corrosion,

- alkaline-phosphate treatment, 197-202
- alloy structure, effect on, 187-191
- austenite stabilization, 220
- austenitic stainless steels, as affected by, 188-190
- alkaline-phosphate treatment in, 199-205
- beam specimen test results, 194
- chloride bearing waters, in, 199, 205, 208
- chloride concentration, effect of, 220, 221, 222
- chloride content, role of, 221
- conclusions on, 222
- control by vapor phase inhibitors, 190, 196, 204
- cracking, characteristic, 188-190
- cracking, occurrence of in sensitized alloys, 189, 190
- crevices, as points of origin, 221

Stress corrosion—Continued

- design, role of, 190
 - elimination of, 190
 - failures in industry, 219–222
 - galvanic couples, protection afforded, 190, 209
 - low stresses occurrence with, 187, 194–195
 - materials of construction, 188–191
 - oxygen, role in, 188, 195–205
 - residual stresses in, 188, 208, 209
 - spring temper, 195
 - steam phase, sensitivity to, 190
 - stress relieving, 188, 195
 - structural components, in, 188–191, 211–217, 220–222
 - sulfite treatment, 202–205
 - temperature effects in, 188–191
 - thickness, effects in, 188–191
 - time of occurrence, 188–191
 - wetting cycles, role of, 196–205
- auxiliary boiler experiences, 211–219
 - conclusions from 211–219
 - in chloride free water, 214
 - in oxygen free water, 214
 - in tube joint design, 214–219
 - chloride-bearing waters, tests in, 196–205
 - cold working,
 - effects of, 188–189, 208–209
 - corrosion fatigue as a special case of, 211
 - cracking,
 - relation to, 205
 - reported in alkaline-phosphate treated water, 197–199
 - types of, 210–211
 - crevices,
 - control in, 211–219
 - location of, 211–219
- definition of, 187
- design characteristics, relation to, 187–191, 211–219
- ferritic stainless steel, 190
 - immunity at low hardness levels, 190
- firetube boilers, 211–219
- general observations on test results, 191–211
- general problem of, 187–191
- hardenable stainless steels, conclusions on, 191
- hydrazine, as oxygen scavenger, 210
- industrial experiences, conclusions from, 219–221
- industrial failures in, 219–221
 - hardenable stainless steels, 219–220
- inhibitors,
 - effectiveness of, 209–210
 - octadecylamine, 210
- intergranular, 188–189
 - failures, 188–189
- joint designs, effect of, 211–219
- laboratory tests,
 - apparatus and procedures described, 191
 - conclusions from, 191–211
 - artensitic stainless steels, 194–195
 - metals, susceptibility to, 188–191
 - model heat exchangers,
 - conclusions from, 214–219
 - nickel-base alloys,
 - conclusions on, 191, 220
 - oxygen,
 - concentration in, 191–211
 - role of, 191–211
 - phosphate additives to boiler water, 191–211
 - problems in,
 - secondary steam-water system, 187–191
 - protection by nickel plating, 209
 - protective films, role of, 187
 - secondary steam-water systems, tests in 191–211
 - sodium sulfite, utilization for deoxidation, 209, 210
 - special tube joint crevice tests, 206
 - spring cracking, problem of, 188
 - springs,
 - exposed to primary water, 188, 195
 - under static and dynamic loads, 195
 - stresses,
 - tensile compared to torsional, 87–89
 - test methods in, 86–92
 - tests,
 - samples for 86–92
 - tilt tests,
 - oxygen content in, 199–207
 - wear, effect on, 258
- Surface contamination, definition of, 263–264
- Surface fatigue, 29
 - in wear, 28
- Surface finish (*see* Surface Roughness)
 - of corrosion test specimens, 76, 101
- Surface layers,
 - destruction and maintenance of, 25
 - nature of in friction determination, 25
- Surface phenomena, physical, associated with friction, 257–258
- Surface roughness,
 - effect on corrosion resistance of materials, 248
 - wear applications, special considerations for, 252
 - wear test specimens, 121
- Surfaces,
 - machining of, 266
 - roughness of, 266
- Systems,
 - effect on corrosion, 139–141
- Tanin, as inhibitor, 210
- Tantalum,
 - effect on intergranular corrosion,
- Tap water, for cleaning, 271
- Teflon,
 - impregnated with asbestos,
 - static corrosion classification, 100
 - impregnated with copper,
 - static corrosion classification, 100

- Teflon—Continued
 - static corrosion classification, 100
 - thermal stability, 256
- Temperature, *see* Corrosion and Wear
- Tensile stress versus torsional stress, stress corrosion, 87-89
- Test duration,
 - dynamic corrosion data, 79-80
 - static autoclave test, 76-79
- Test loop *see* (Corrosion Tests, Dynamic)
- Test methods,
 - crevice corrosion, 80-83
 - galvanic corrosion, 83-86
 - general corrosion, 75-80
 - stress corrosion, 86-92
- Test specimens,
 - corrosion tests, observations and evaluation of, 56
 - corrosion tests, preparation of, 56
 - crevice corrosion,
 - journal-sleeve, 80-83
 - plate-type, 80-82
 - degreasing of, 56
 - dynamic corrosion, surface finish, 56
 - general corrosion tests, 75-80
- Test systems,
 - dynamic, 46-51
 - semi-static, 44-46
 - static, 41-43
- Test, wear,
 - description of journal-sleeve specimens, 67
 - description of piston-cylinder specimen, 65
- Testing techniques (*see* Test Methods)
- Thermal difference loops, 47
- Thermal history, effect on stress corrosion, 187-188
- Threaded joints, lubrication of, 266
- Thrust bearings, effect of crevice corrosion, 161-162
- Tilt tests (*see* Stress Corrosion)
- Time, effect on corrosion rate, 137-138
- Tin, static corrosion classification, 99
- Titania (fused), static corrosion classification, 100
- Titanium,
 - dynamic corrosion data, 119
 - static corrosion classification, 99
- Titanium boride, static corrosion classification, 100
- Titanium carbide (nickel binder), static corrosion classification, 100
- Titanium carbide (platinum binder), static corrosion classification, 100
- Titanium (nitrided),
 - static corrosion classification, 99
 - use in bearings,
 - vs. Armco 17-4 pH, 124
 - vs. Armco 17-4 PH (nitrided), 132
 - vs. chromium (as plated), 131
 - vs. chromium carbide in nickel matrix, 133
 - vs. titanium (nitrided), 132
 - vs. USS 18-8 W, 125
- Tools, cutting, carbide, 266
- Torque sensing element, 246
 - frictional, ball bearings measurement of, 246
 - tube, 246
- Toxicity of acid fumes in pickling, 269
- Transported corrosion products, 231-236, 237
- Trichlorethylene, inhibited, for vapor degreasing (*see* Degreasing), 268
- Tube joint,
 - crevice tests for stress corrosion, 206
 - designs, effect of stress corrosion on, 211-218
- Tube rolling,
 - as a source of stress corrosion attack, 206
 - tube-to-tube sheet joints, stress corrosion in, 214-219
- Tubing,
 - small diameter pickling of, 268-269
- Tungsten carbide (cobalt binder), static corrosion classification, 100
- Tungsten carbide (platinum binder), static corrosion classification, 100
- Two-bed deionization system,
- U-bend specimens, stress corrosion of, 191
- Ultrasonic cleaning, 237
- Universal cyclops 17-A, static corrosion classification, 97
- Unstabilized steels (*see* Intergranular Corrosion)
- Uranium fuel element, consequences of rupture, 269
- Vacuum drying, 271
- Validity factors, in dynamic corrosion tests, 101
- Valves, fouling of,
 - safety, in corrosion test loops, 46
 - throttling, fouling of, 232
- Vanadium, static corrosion classification, 99
- Van de Graaff irradiation experiments,
 - stainless steel, 233-235
- Vapor blasting, 266
- Vapor degreasing, 270
- Vasclloy Ramet, static corrosion classification, 97
- Velocity (*see* Corrosion)
- Wall Colmonoy No. 6,
 - static corrosion classification, 131
 - use in bearings,
 - vs. AISI 440 C, 129
 - vs. Armco 17-4 PH, 129
 - vs. chromium (as plated), 131
 - vs. chromium plate (honed), 129, 130, 131
 - vs. Stellite No. 3, 125, 126
 - vs. USS 18-8 W, 124, 125
 - vs. Wall Colmonoy No. 6, 126
- Water,
 - analysis, 96-97, 121
 - chemistry
 - conventional boiler comparison, 31
 - affected by
 - corrosion, 32
 - nuclear reaction, 33
 - purification by ion exchange, 33

Water—Continued

- affected by—Continued
 - radiation synthesis, 32
 - water dissociation, 32
- choice of as coolant, 3
- composition, during stress corrosion tests, 192–206
- conditions,
 - practical, 34–36
- demineralized, quality for cleaning, 270–271
- dissociation, 32
- distilled, quality for cleaning, 270–271
- electrical resistivity of, effect on corrosion resistance, 141, 142
- employed for cleaning, 269
- phase tests, for stress corrosion, 196
- purification system, test loops, 54
- purity,
 - effect on corrosion, 16–19
 - importance of, 31, 35, 36
- quality of, for cleaning, 269
- tap, for initial cleaning, 270
- technology—*see* water chemistry
- treatment, role in stress corrosion, 188, 189–190, 196–208
- vapor exposure, effect on stress corrosion, 196–208
- velocity, effect on corrosion resistance, 138

Wear,

- abrasive, 28, 29
- adhesive, 27, 28
- related to load, 29
- areas of future research, 258
- effect on wear of,
 - accumulated particles, 258
 - composition, 239–240
 - crevice corrosion, 257
 - distance traveled, 29
 - general corrosion, 257–258
 - pitting corrosion, 257
 - stress corrosion, 258
- evaluation of,
 - by wear factor, 241–242, 121
 - by weight change, 241–242
- factor, as a method of ranking materials, 241–242
- factors influencing wear, 242–243
- guides for evaluation of, 28–29
- hydrogenated environment in, 120
- oxygenated environment in, 121
- reciprocating motion, how produced, 121, 65–67
- rotational motion, how produced, 121, 67
- specimens, metallurgical condition of, 121
 - surface roughness of, 121
- test apparatus,
 - journal-sleeve, tests (rotating), 67
 - specimens for, 67
 - piston-cylinder tests (reciprocating), 65
 - specimens for, 65–66
 - pendulum slide test, 40, 68–70

Wear—Continued

- Simulated component test, 40
 - test conditions, 121
 - test data, background of, 121
 - tests,
 - ball bearing, 246–250
 - autoclave test station, 246
 - break-in period, 250,
 - chemical additions, 247–248
 - cladding and hard facing, 250–251
 - frictional torque measurements, 246
 - load effects, 248–249
 - lubricants studied, 250
 - service life, effect of, 250
 - temperature effect, 248
 - test rigs, 246
 - basic,
 - effects on wear of,
 - corrosion, 244
 - environment, 244
 - hardness, 242–243
 - temperature, 244
 - test duration, exposure to corrodent, 242
 - factors influencing wear, 242–244
 - journal-sleeve, operating conditions for, 64
 - material relationships, 239–240, 121–133
 - partial summary of data, 243
 - piston-cylinder, operating conditions for, 64
 - representative data from, 241–242
 - results of high pH tests, 244
 - screening phase, 239–244
- Weighing methods, 56–57
- Weight change, used to evaluate wear, 241–242
- Weight gains, in dynamic corrosion data, 101
- Weight losses, in dynamic corrosion data, 101
- Weight of specimens, procedure for determining, 56–57
- Welded areas, stress corrosion in, 211
- Welding of asperities, 23
- Westphal R. C. and Gatter, J.
 - basic wear tests, 239–244
- Wetting cycle test, for stress corrosion, 196–205
- Wheels, grinding
 - resin or rubber bonded, 266
 - silica base, 265
- Worthite,
 - static corrosion classification, 97
- Zinc, static corrosion classification, 99
- Zircalloy 1,
 - static corrosion classification, 99
- Zircalloy 2,
 - dynamic corrosion data, 119
- Zirconium, static corrosion classification, 99
- Zirconium boride, static corrosion classification, 100
- Zirconium crystal bar, dynamic data, 120