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REVIEW OF STATE OF THE ART OF SOLAR COLLECTOR CORROSION PROCESSES

Task 1 of Solar Collector Studies for Solar Heating and Cooling Applications
Final Technical Progress Report

By
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April 11, 1980

Work Performed Under Contract No. AC04-79CS10510

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FINAL
TECHNICAL PROGRESS REPORT

on

REVIEW OF STATE OF THE ART OF SOLAR
COLLECTOR CORROSION PROCESSES

TASK 1 OF SOLAR COLLECTOR STUDIES FOR SOLAR
HEATING AND COOLING APPLICATIONS

Prepared for:

U.S. DEPARTMENT OF ENERGY

April 11, 1980

by

J. E. Clifford

R. B. Diegle

CONTRACT NO. DE-AC04-79CS10510

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ABSTRACT

This report reviews the state of the art of solar collector corrosion processes, and it summarizes Task 1 of a current research program on use of aqueous heat transfer fluids for solar heating and cooling. The review of available published literature has indicated that lack of quantitative information exists relative to collector corrosion at the present time, particularly for the higher temperature applications of solar heating and cooling compared to domestic water heating. Solar collector systems are reviewed from the corrosion/service life viewpoint, with emphasis on various applications, collector design, heat transfer fluids, and freeze protection methods. Available information (mostly qualitative) on collector corrosion technology is reviewed to indicate potential corrosion problem areas and corrosion prevention practices. Sources of limited quantitative data that are reviewed are current solar applications, research programs on collector corrosion, and pertinent experience in related applications of automotive cooling and non-solar heating and cooling. A data bank was developed to catalog corrosion information. Appendix A of this report is a bibliography of the data bank, with abstracts reproduced from presently available literature accessions (about 220) which are also referenced in the body of the report.

This report is presented as a descriptive summary of information that is contained in the data bank. It does not represent an exhaustive digest of such information. The reader is encouraged to turn to the individual references that comprise the bank if detailed subject matter is desired.

REVIEW OF STATE OF THE ART OF SOLAR COLLECTOR CORROSION PROCESSES

INTRODUCTION

Scope of Program

The review of the state-of-the-art of collector corrosion processes is one of three tasks on this contract:

- Task 1. Review of the state-of-the-art of collector corrosion processes
- Task 2. Study of corrosion of multimetallic systems
- Task 3. Determination of interaction between different waters and chemical antifreeze additives.

The effort on Task 1 was initiated first on the contract to provide information and guidance for experimental work on Tasks 2 and Task 3. The effort contemplated for Task 1 was set forth in the statement of work for this contract, which is reviewed below with reference to Task 1.

Overall Program Objective

The work performed under this contract is part of the national program for Research and Development in Solar Heating and Cooling.

The overall objective is to stimulate the advancement of an industrial, commercial, and professional capability for producing and distributing various solar energy systems. It is contemplated that the demand for fossil fuel supplies will be reduced through the widespread use of solar energy:

- in heating and cooling of residential and commercial buildings
- for service and process hot water
- for the thermal needs of agriculture and industrial processes.

Specific Project Objectives

The specific objectives of this project are to:

- (1) research the corrosion properties of aqueous coolants with a variety of additives used in common types of metallic collectors and systems.
- (2) consider the various methods of freeze protection and the question of cost effectiveness.

A principal purpose is to elucidate the corrosion problems and their cures for aqueous coolants with inhibitors and antifreezes in multi-metallic collectors and systems. Also various techniques of freeze protection and their costs are to be enumerated.

Scope of Task

The survey of corrosion in current solar collector systems is intended to provide an updated overview of existing and potential corrosion problems which must be solved in future designs.

Information from the survey will provide direction and emphasis for experimental work underway in Tasks 2 and 3.

Results of Task 1

The state-of-the-art for collector corrosion processes was reviewed and evaluated in Task 1.

A data bank was developed for cataloguing basic corrosion information on the various materials and heat-transfer fluids that are used, or might be used in aqueous liquid-heating collectors. This data bank might be used for:

- developing corrosion modeling techniques
- researching collector corrosion problems
- pinpointing areas of needed research
- utilizing technology in related areas to avoid corrosion
- preparing corrosion design handbooks
- answering field calls on collector corrosion problems

Literature Review

Some pertinent literature references were available at the beginning of the program and had been cited in the proposal. Preliminary computer searches were carried out utilizing the following data sources:

- DOE Recon Energy Data Base
- Copper Data Center
- National Technical Information Service (from 1970)
- Smithsonian Science Information Exchange
- Engineering Index (from 1970)
- Metals Abstracts (from 1970)
- Chemical Abstracts (from 1970)
- Metals and Ceramics Information Center (MCIC)

Initially, the information acquisition was limited to corrosion of solar collectors only. Computer searches covering corrosion of metals and fluids of interest in non-solar applications covers such a broad field that the number of references becomes unwieldy. Therefore, such general computer searches on corrosion were limited to the Copper Data Center and MCIC at Battelle since the original articles were readily available to review for pertinence. A comprehensive computer print-out of relevant literature titles from the Copper Data Center pertaining to corrosion processes totaled 1500 items. Several hundred titles of possible interest were identified but detailed review of the articles was deferred. Bibliographies and references from pertinent available literature accessions began to provide the best leads to new literature.

Organization of Data Bank

During Task 1, approximately 220 literature accessions (e.g., copies of reports and literature articles) were accumulated. Information specialists of the Metals and Ceramics Information Center assisted in organizing this information. Experience has indicated that a simple card file system is the most cost effective in the early stages of developing a data bank for which the number of accessions will be relatively small and cross-referencing will be limited. More sophisticated data management can be included in the future, if warranted, including extensive subject indexing when user needs and the type of information available are better identified. The simple card file was adequate for Task 1 in view of the rather limited quantitative data

on solar collector corrosion available at the present time. This situation is expected to change in the future as the results of recent, current, and future government-funded programs on corrosion become available. Selection of the initial literature accessions was partially directed to the anticipated needs of subsequent tasks on this contract.

Two complete card files were prepared. One card file was maintained with the literature accession file for the use of reasearchers. The second duplicate card file was maintained by the information specialist. The latter card file will be made available to the sponsoring agency at the end of the contract if requested. A copy of each accession (e.g., technical article or report) selected for inclusion in the data bank was assigned a number (beginning with 0001) consecutively as logged in. Each accession was reviewed and categorized into one or more of seven subject categories for an initial subject file. Accessions that contained qualitative information and/or quantitative data on corrosion relating to metals of interest were classified by fluid as "antifreeze" or "water" (e.g., distilled water, tap water, any freezable water or aqueous solution). The accession was further classified by metal into three main groups: aluminum and aluminum alloys (Al); copper and copper alloys including brass and solder (Cu); iron and iron alloys including cast iron, low carbon steel, and stainless steels (Fe). Certain accessions contain information in up to six subject categories. Other accessions of interest were classified by miscellaneous category (e.g., ASTM standards, electrochemical techniques, general information on solar systems for heating and cooling). An accession card was prepared that included the accession number, bibliographic information, subject classifications, and a descriptive abstract to supplement the title. Additional cards were duplicated for four separate card files:

- (1) accession file in numerical order
- (2) title file (alphabetically)
- (3) author file (alphabetically)
- (4) subject file by "metal" ("fluid") or miscellaneous
 - Al (water)
 - Al (antifreeze)
 - Cu (water)
 - Cu (antifreeze)
 - Fe (water)

- Fe (antifreeze)
- Miscellaneous.

Appendix A of this report includes titles and some abstracts of the literature accessions obtained through February, 1979, which were reproduced from the cards in the accession file. The inclusion of an abstract was deemed to have more potential use for readers of this report than a list of references or a bibliography. References cited in this report refer to the accession number in Appendix A. All of the accessions are referenced somewhere in the text to indicate subject and relative importance.

The following sections of the report review the state-of-the-art of collector corrosion processes.

SOLAR COLLECTOR SYSTEMS

Introduction

Background Information

This report reviews the state-of-the-art of collector corrosion processes. To define the variety of potential corrosion problems requires some background in the broad area of solar technology for heating and cooling. Several publications provide general reviews of the subject such as standard references (e.g., ASHRAE 1978 Applications Handbook, Chapter 58, "Solar Energy Utilization for Heating and Cooling") (0217)*. Further technical information on solar thermal processes is contained in books (0210, 0211). Two useful volumes which discuss engineering data, economic factors, and some potential corrosion problems were prepared by the Colorado State University for the Department of Commerce (0212, 0213).

A good assessment of solar heating and cooling technology was prepared by Balcomb and Perry (0097) as of early 1976 covering state-of-the-art, problem areas, and possible R&D objectives.

The assessment was a basis for the National Program Plan for Research and Development in Solar Heating and Cooling (0094). Current R&D programs, including some relating to corrosion, have been identified in project summaries for the U.S. (0206) and other countries (0120).

* References are in Appendix A by accession number.

Several central information sources contacted such as the National Solar Heating and Cooling Information Center(0051) and the Solar Energy Research Institute (SERI), provide general information but are not presently organized to provide specific information relating to corrosion.

Several other accessions in the "miscellaneous" category that are not referenced elsewhere in this report provide limited background information related to demonstration programs (References 0057; 0066; 0067).

Service Life

Solar collector systems are receiving wide attention as an alternate energy source to diminishing fossil fuel supplies. Thus, corrosion resistance is needed for a service life of components that allows recovery of useful solar energy at least equal to the energy used in producing the component. For example, one calculation in the literature indicates 11-1/2 years for energy payback(0052). Other studies are reported(0097) to have shown that energy payback periods for most solar equipment is of the order of 10 to 12 months when compared with other energy alternatives. The energy payback period varies with the assumptions used but components such as solar collectors require a minimum service life apart from economic considerations.

Numerous economic studies have been performed to define the conditions under which solar energy could be an economically viable alternative for service water heating, space heating and cooling. In general, initial installed system costs are high and life cycle costing is required to economically justify solar use to supplement other forms of energy. Inherent in this approach is the need to assume a long useful life for the system. Typically, a life of 20 years is assumed and often without special provision for operating costs for corrosion control.

Quantitative information on the economic aspects of service life of solar collectors is lacking in the available literature. This reflects the lack of quantitative information on solar collector corrosion at the present time, particularly for the higher-temperature operations of solar heating and cooling compared to service water heating (e.g. domestic water heaters). In the final analysis, solar collector corrosion is an economic consideration as are similar corrosion problems in process industries and conventional heating and cooling. At the present state-of-the-art, there is voluminous

literature on design and thermal performance of solar collector systems but little if any published quantitative data on corrosion of solar collectors. There are general statements in the literature on corrosion and service life of solar collectors. Some of these generalizations can be misleading if applied broadly to the wide variety of solar applications and solar system designs. The status of service life of solar collector systems with respect to aqueous corrosion can only be defined accurately with respect to specific applications, component materials, and heat transfer fluids as discussed below.

Applications

Corrosion processes and potential problems depend on the application of solar thermal energy. Thus, it is necessary to differentiate the purpose (service hot water or heating and cooling); since the purpose can influence the corrosivity of the collector fluid and collector temperature. The type of application (residential, commercial, or industrial) can also influence temperature requirements and the size of the installation which in turn affects practical and economic considerations in corrosion monitoring and corrosion prevention.

The three principal purposes for using solar energy of interest for this study are:

- Service or process hot water
- Space heating or process heat
- Space cooling or process cooling

All of the above use liquid heating collectors. (Air heating collectors are not included in this study which relates to aqueous liquid corrosion).

Industrial applications (including agriculture) can cover a wide range of temperature requirements for process water, process heat (0068), and process refrigeration, separately or in combination. Applications in industry can be visualized which might require "once-through" heating of water to very high temperatures (in contrast to domestic water heaters). This and other industrial applications may present special corrosion problems. Usually, industry has experience and access to corrosion expertise to cope with the process heat problems. Thus, the greater emphasis will be on the usual residential and commercial applications of service hot water, space heating and cooling of buildings.

Temperature Requirements

Residential and commercial applications usually involve one of three combinations:

- Service hot water only
- Hot water and space heating
- Hot water, space heating and cooling

The three combinations require progressively higher temperatures. Temperature requirements are usually categorized as follows: (0097)

Low temperature < 120 F

Medium temperature 120 F to 170 F

High temperature 170 F to 230 F

The temperature requirements refer to the maximum temperature of the liquid thermal storage system. The maximum temperature of the collector will be higher under stagnation conditions to be discussed later. Low temperature applications include swimming pool heaters which involve less corrosive conditions than domestic water heaters; for this application non-metallic collectors can be considered. Domestic hot water heaters are a medium temperature application since typically hot water is desired at about 140 F. Space heating is usually a medium temperature requirement with higher temperatures desired to minimize heat storage volume. Cooling systems require the highest temperatures with 170 F usually considered a practical minimum.

Stagnation Temperatures

As the application temperature requirements increase, there is a need for more efficient solar collectors that can collect useful energy up to maximum storage temperature. One method of improvement in solar collectors for high temperature applications relates to minimizing heat losses to ambient. However, such efficient collectors will also achieve very high stagnation temperatures, well above the boiling point of the heat transfer fluid at the usual system design pressures. Under abnormal conditions, safety venting occurs with boil-out of the heat transfer fluid. Possible loss of fluid is an economic factor in selection of heat transfer fluid for corrosion resistance and freeze protection. From the standpoint of defining corrosion conditions, the maximum liquid temperature depends on the boiling point as defined by system pressure. Also, the solution is stagnant or not flowing at the highest temperature,

which could be a very corrosive combination. If boiling occurs, the temperature of the metal collector will be only slightly above the fluid temperature because of the relatively low heat flux in solar applications (in contrast to automotive applications). Nucleate boiling might have some effect on corrosion rates. If boil-out occurs, there is the added possible corrosive condition of liquid/vapor interfaces, vapor-phase corrosion, and ultimately evaporation and concentration of thin liquid films on the inside of the collector surface as the collector, devoid of coolant, increases in temperature until the incident solar heat flux and heat losses are in balance. While boil-out might represent the most serious corrosion condition, it should not exist for a long time relative to the expected service life of collectors. Also, the frequency of boil-out cannot be high in a practical system. Collector systems should be designed to minimize boil-out and also to minimize high temperature stagnation conditions.

High temperature stagnation conditions occur mostly in the spring and fall when required storage temperatures are often reached because of lower heat demand of heating and cooling systems. The problem occurs mainly with simple control systems which stop pump circulation when the designed storage temperature is reached. Alternatives involve dumping heat from secondary fluid loops so that collector flow is maintained and collector temperature does not reach boiling conditions. In this manner, the occurrence of high temperature stagnation is limited to electric power or pump failures under high solar insolation conditions. Even the latter problem can be minimized by automatic drain down in the event of electric power failure.

Stagnation Conditions

When the aforementioned simple control system (often referred to as an "on-off" or "bang-bang" system) is applied to primary loops with antifreeze protection, the pump is turned off when desired storage temperatures are reached and also when the solar heat flux is too low to heat the fluid. Thus, between sun down and sun up stagnation conditions (no liquid flow) exist on a daily basis. For the high temperature requirements (170°F), useful collectors temperatures are only available over a relatively short period of the day (e.g. 8 hours), and stagnation conditions can exist the remainder of the day (e.g. 16 hours). Under

"overnight" stagnation conditions of no pumped fluid flow, the fluid contained in the collector will cool down (from heat losses) and then heat up the next day. Thus, there are high-temperature, medium-temperature, and low-temperature stagnation conditions.

Fluid flow through the collector must be stopped under low solar insolation conditions to avoid loss of previously collected thermal energy. Most discussions of solar collector operation do not mention the obvious fact that stagnation conditions are the most prevalent normal operating mode and that fluid flow conditions are less prevalent on a daily basis. From the standpoint of corrosion processes this might be a significant factor in service life. For example, there may be metal/fluid combinations for which the corrosion at the highest collector temperature with fluid flow may be less than the corrosion under no-flow conditions at lower temperatures for longer periods.

Correlations

There is a need for more information on typical daily cycles of time-temperature-flow (TTF). No such correlated data was noted in the published literature, but they may exist. Many computer programs have been developed to predict solar collector system performance and could be modified to provide TTF cycles. Hopefully, at some time in the future, corrosion data will be available for correlation with TTF cycles to predict service life of solar collectors.

At the present time, laboratory studies of corrosion of solar collector materials usually are conducted at high temperature with static and/or fluid flow conditions to represent the most corrosive conditions. This is often necessary to accelerate testing. However, caution is needed in drawing conclusions from the data. For example, data on metal penetration rate (e.g., mils/yr) for either uniform or non-uniform corrosion obtained at the highest temperature the fluid will experience combined with minimum collector wall thickness are often used to estimate service life in years. Such extreme conditions may represent less than 30 percent of the actual service conditions. Similar considerations apply to data obtained under either flow or no-flow conditions. Also, the use of "corrosive water"

may be justified to represent the extreme of corrosive conditions and/or to accelerate testing. However, direct extrapolation of service life from accelerated corrosion tests may be misleading. The potential problem in interpretation is that metal/fluid combinations that could be economic in practice may be ruled out in preliminary screening.

Several studies of corrosion have used test procedures designed to more closely simulate solar collector operation. One test procedure simulates "drain-down" system operation⁽⁰⁰⁴⁵⁾. Closed-loop operation with antifreeze might use a cycle consisting of fluid flow and static conditions. It is expected that standard corrosion test procedures for solar collectors will be evolved from current technical committee studies which will consider the correlation with actual use.

Solar Collectors

Collector Design

The solar collector is the principal consideration in this study with respect to corrosion because it is exposed to the highest temperature in the system. Fluid channel wall thicknesses are usually small (typically 0.030 inch) which make the collector a corrosion-critical component with respect to leakage.

While liquid flat-plate collectors are more widely used at present, other types of liquid heating collectors are of interest because they are designed to achieve higher temperatures. Advanced collectors are usually categorized as concentrating collectors or non-concentrating collectors. In the latter category are evacuated tube collectors^(0054, 0118, 0162, 0058, 0055). For various reasons, including boil-out and corrosion problems, advanced high temperature collectors will probably use air or non-aqueous heat transfer fluids. Heat pipes, which use water in a sealed metal tube, for high temperatures are a special application covered later in this report.

Most discussion of solar collector corrosion relates to the popular flat-plate type collector.

Methods of measuring the thermal performance of flat-plate solar collectors have a long history⁽⁰¹⁷⁸⁾ and have evolved into standard methods of rating collectors according to ASHRAE 93-77⁽⁰¹⁶⁴⁾. Comprehensive evaluation of solar collector performance (efficiency) has shown the effect of some collector design variables on performance for copper, aluminum, and steel collectors⁽⁰²⁰⁴⁾. Typically, collectors are tested with distilled water at constant flow rates of 10 lb/hr per ft² of collector. Performance ratings based on solar energy collected may be correlated with collector manufacturing cost but do not presently include the effect of optimum combination of metal and fluid and the effect of corrosion on service life.

Collector Materials

The materials most frequently used for flat-plate solar collectors, in decreasing order of cost and thermal conductance, are copper, aluminum, and carbon steel. Stainless steel has low conductance and high cost.

Typical copper alloys of interest are:

CDA 122

CDA 110

Typical aluminum alloys of interest are:

1100

3001

3003

6061

Typical steel alloys of interest are:

1018 mild steel

444 stainless steel

Copper, at least for tubes, appears to be the most durable and dependable material. The principal disadvantage is its substantially higher cost. A plate-type copper collector requires an outlay of about three dollars per square foot in excess of aluminum with a five to six dollar per square foot differential in selling price⁽⁰²¹²⁾. The advantages of copper over other metals are stressed by proponents relative to high thermal conductivity⁽⁰⁰⁹⁵⁾ and good corrosion resistance⁽⁰⁰⁷¹⁾.

Aluminum combines good thermal conductivity and moderate cost but requires more consideration of fluids and operating conditions in multimetal systems. A good review of aluminum alloys for solar collectors was recently presented by Byrne (1977)⁽⁰⁰⁶⁰⁾ of Alcoa. Alloys recommended for service in water are aluminum-manganese, aluminum-magnesium, and aluminum-magnesium-silicon. The aluminum-magnesium series (5xxx) alloys are highly resistant to chloride ion pitting and have been used for heat exchange equipment in sea water. Aluminum should not be used in uninhibited waters containing more than a few parts per billion of "heavy" metals. Other good reviews of corrosion problems with aluminum solar collectors have been presented by Popplewell (1977)^(0075 or 0004) of Olin Brass including some laboratory test data⁽⁰⁰⁴⁵⁾. Another interesting general review of solar heating design and aluminum corrosion problems is based on experience with solar heating at the Beltsville Agricultural Research Center⁽⁰⁰⁰³⁾. Aluminum collector use in Germany^(0193, 0194) and some relative corrosion test data with aluminum have been reported⁽⁰⁰¹³⁾.

Carbon steel represents a potentially low cost material but has a low thermal conductivity (a relative value of 12 compared to aluminum at 50 and copper at 100). However, proponents have shown that with optimum design there is a relatively small difference in solar collector efficiency compared to copper and aluminum⁽⁰⁰⁷²⁾. Steel collectors have been used successfully with commercial antifreeze solutions, with no signs of corrosion during the first year of operation.

Stainless steel has low thermal conductivity (about 1/2 to 1/3 that of mild steel) and high cost with good corrosion resistance depending on the alloy. The advocacy of stainless steel (particularly Type 444) is supported by laboratory corrosion test data comparing Types 304, 316, 430, 439 and 444⁽⁰¹⁷⁷⁾. Type 444 had the best overall resistance to pitting and crevice corrosion using annealed test specimens. However, most "stainless-steel" absorbers are fabricated by welding (usually in a "waffle" pattern) and some stainless steels can be sensitized to corrosion in the weld zone⁽⁰⁰⁶⁹⁾.

Most of the published literature relating to various metals and alloys for solar collectors and discussion of corrosion problems is authored by personnel of organizations having interest in use of particular metals and/or fabrication process. Objective comparisons of all four metals (including stainless steel) supported by practical experience and/or test data are difficult to find. One of the better general reviews of corrosion problems with aluminum, copper, carbon steel and stainless steel was presented by Butt and Popplewell (1977)⁽⁰⁰⁶⁹⁾ of Olin Brass. Most generalizations regarding corrosion are presumably supported by experience but quantitative data are lacking in most reviews.

Some corrosion data are being generated in government programs on collector corrosion and available pertinent experience is reviewed later in this report.

Comparative corrosion data are needed for steel (both carbon steel and stainless steel), aluminum, and copper in typical corrosive environments for solar collectors that can be correlated with thermal performance and cost. Collector fabrication methods must be considered in evaluating corrosion as well as cost and thermal performance.

Collector Configurations

There are over 323 manufacturers of flat-plate solar collectors^(0098, 0099) and there are various designs of flat-plate collectors. The absorber plate may be of different material than the tubes that contain the heat transfer fluid but usually they are the same because of thermal expansion problems. Corrosion of plates and external surfaces of tubes is not a consideration in the present study. Primary interest is in corrosion processes at the interface of the heat transfer fluid and the internal metal surface. Corrosion processes are similar for fluid flow down the surface of an absorber plate (trickle-type collectors).

Most collector designs involve horizontal headers and vertical risers. The fluid passages in the risers can have a variety of cross-sections such as simple circular tubes, square tubes, and triangular tubes.

The tubes may be attached or bonded to the plate or integral with the plate. A popular type of construction is roll-bonding with selective stop-off and subsequent pressurization of stop-off areas to form integral fluid passages. Some collectors are made by selective spot welding and subsequent expansion to form fluid passages. Thus, various types of crevices are created by the fluid passage design except for simple circular tubes as risers. The method of collector plate construction to form passages and the configuration of the passages can be a factor in corrosion depending on the fluid and hydrodynamic conditions.

Heat Transfer Fluids

The use of aqueous heat transfer fluids (often referred to as coolants) can provide economic advantages relating to heat transfer. Improved heat transfer in heat exchangers as well as solar collectors yield reduction in the important first cost of the system in comparison to the alternatives of using air or non-aqueous fluids. However, the disadvantages of aqueous heat transfer fluids relating to freeze protection and corrosion protection have been noted in the literature but have not been quantified in economic terms. Freeze protection, discussed later, considers reliability. Durability covers many aspects and components of the solar collector system of which corrosion of solar collectors caused by the aqueous heat transfer fluid is important. If a heat exchanger is used in the total system to separate two different heat transfer fluids, the corrosion problems in the secondary circuit are similar to those in conventional heating and cooling systems. Principal interest is in the corrosion problems of the primary circuit (i.e., closed circuit except for make-up) or solar collector circuit.

The heat transfer fluid and the solar collector metal must be considered in combination for economic evaluation as well as evaluation of corrosion data. Thus, the data bank was initially organized according to combinations of metals or alloys (aluminum, copper, steel) with heat transfer fluid (water or antifreeze). While there are many different alloy compositions that have been or might be used for solar collectors, there are probably as many or more chemical compositions of heat transfer fluids.

Water (or freezable solutions) includes inhibited water (i.e., additives) and uninhibited water that is often categorized by one or more of the following terms:

- Distilled
- Deionized
- Hard water
- Soft water
- Potable water
- Softened water
- Rain water
- Well water
- Corrosive water
- Aerated water
- Deaerated water

Corrosive water includes significant concentrations of ions known to affect corrosivity such as chloride, sulfate, and bicarbonate ions in varying amounts including standard test solutions usually containing 100 ppm of each ion. Although less than 2% of the water supplies in the U.S. have chloride ion concentrations of 100 ppm or more, very few closed coolant loops are truly closed. Unless venting or pressure relief losses of water vapor are made up with distilled water, ion concentrations will increase over a period of time.

Inhibited water (freezable) covers a large number of combinations and concentrations of chemicals (inorganic and organic) selected for effectiveness for the alloys used in the coolant loop, which in addition to the collector includes piping, solder or braze, valves, pumps, instrument probes, heat storage tank and/or heat exchanger. There are a large number of commercial inhibitors available that are proprietary compositions. No quantitative data has been found in the literature defining service life of a solar collector with a particular commercial inhibitor.

Antifreeze refers to an aqueous solution of glycol or other organic compound added to depress the freezing point of the solution. The water used to dilute the antifreeze could be any of the above described "waters" even though "good quality water" (e.g., distilled water) is always recommended for dilution of commercial antifreeze concentrate for minimum corrosion.

Commercial antifreeze concentrate contains a small amount of water (3%) in which the inhibitors have been dissolved. Most commercial antifreezes are based on "ethylene glycol" (monoethylene glycol)* and may contain small amounts of diethylene glycol and propylene glycol. Ethylene glycol is toxic and other less toxic materials such as propylene glycol are sometimes used. Other antifreezes being evaluated in tests of solar collectors are triethylene glycol and glycerin⁽⁰¹¹²⁾.

Ethylene glycol has been used for 50 years as an automotive coolant in multimetal systems and suitable inhibitors have been developed for this application. A good qualitative review of this information for application to solar collector systems was recently presented by Beynon of Union Carbide⁽⁰⁰⁰¹⁾.

Ethylene glycol can break down to form organic acids under some high-temperature operating conditions as automotive coolant. There are insufficient data in the literature to predict chemical stability under solar collector conditions.

Inorganic salts have been considered as aqueous heat transfer fluids to provide freeze protection to -15°C ⁽⁰¹¹⁶⁾.

Freeze Protection

There are five general categories of "freeze protection" for solar collector systems⁽⁰⁰⁶³⁾:

1. Drain down
2. Use of antifreeze
3. Circulation of warm fluid
4. Use of heating tapes
5. Freeze tolerant design

Of these methods, only "drain down" and "antifreeze" have been developed for broad applicability including northern climates.

* Ethylene glycol is referred to in British publications as ethanediol according to the Geneva convention for naming organic compounds; propylene glycol is propanediol.

Circulation of warm fluid to avoid freezing may be practical in climates where freezing is seldom encountered. Generally, systems that include cooling applications are designed with collectors having low heat loss to ambient. In some southerly climates, the system is designed for the cooling load and during the winter there is an excess of collected heat above the heating needs which allows circulation of fluid for occasional freeze protection.

Use of heating tapes would be economically practical only where freezing is seldom encountered and the feasibility is being explored⁽⁰⁰⁶⁴⁾.

A "freeze tolerant" solar collector panel design has been evaluated at the University of Iowa based on subatmospheric fluid pressure⁽⁰⁰⁶³⁾. However, heating tapes are required on the insulated headers since freezing and unfreezing of headers is a principal problem.

In general, heating tapes and pumped circulation of warm water are susceptible to electric power failure in freezing weather. However, some studies are directed to a residential water heater pumped by differential pressure with circulation dependent on the city water supply system pressure⁽⁰⁰⁶⁵⁾.

In most cases, "freeze protection" involves a choice between "drain down" and use of antifreeze. The principal problem with drain down is the cost of suitable controls and reliability at the present state of the art. Drain down is attractive from a performance and cost standpoint. It reduces daily warmup losses and does not require a heat exchanger between the storage and collector loop. The use of a heat exchanger requires that the collector loop operate at a higher temperature than the maximum storage temperature. The higher collector temperature reduces heat collection efficiency. The increase in temperature required depends on the temperature differential across the heat exchanger for heat transfer which in turn depends on the heat transfer area provided. Thus, there is an optimization required between first cost of the heat exchanger and maximizing efficiency of solar energy collected.

Drain-down systems range from the simple manually-operated valve systems used infrequently for domestic water heaters in the south to automatic, temperature-activated drain-down systems for northern climates. Fail-safe drain-down is usually required in event of power failure. Drain-down systems for hot water heating use potable water (tap water) which

usually restricts the solar collector to copper or stainless steel. Drain-down systems often use air vents which exposes the fluid to oxygen (air) with increase in corrosive conditions. Designs which use nitrogen in the collector loop avoid the corrosion problem of aerated solutions. However, the added cost of the nitrogen system must be compared to the alternative of use of antifreeze or aerated solutions. The added corrosion for aerated, freezable solutions has not been quantified.

For applications involving heating and cooling with heat storage, the potable hot water heating loop is a secondary loop with heat exchange from the hot storage tank. An important consideration is the need for adequate protection of the potable water supply. This requires the use of double-wall heat exchangers or two heat exchangers between potable and non-potable water⁽⁰⁰⁶⁰⁾. Ethylene glycol is considered toxic. It is not clear at present whether the use of propylene glycol or other less toxic antifreezes will allow less than double-wall heat exchangers. Also, use of inhibited water in the primary collector loop or liquid storage may require double-walled heat exchangers depending on the inhibitors used, relative toxicity, and standards yet to be defined.

For heating and cooling systems which require relatively large volumes of liquid storage, it may be possible to use tap water, but usually inhibitors are used which must be low cost. Often these systems are designed for collector drain back to the storage system for freeze protection. Usually, the volume of storage required is too large to consider use of antifreeze. Thus, antifreeze systems usually involve a small-volume, primary loop with heat exchange to the liquid storage.

The choice between drain-down systems and antifreeze systems involves several interrelated cost factors of which corrosion is one factor for which quantitative data are lacking to study the economic tradeoffs for specific applications.

CORROSION TECHNOLOGY

Types of Corrosion

General Corrosion

In solar collector systems, some small degree of corrosion is expected with all aqueous heat transfer fluids and all alloys. Ideally, the corrosion rate should be uniform over the surface and at a very low rate. For example, if the critical (minimum) thickness of the collector is 30 mils, an average corrosion rate of less than about one mpy is required to achieve 20-year life without perforation.

Various terms have been used by different authors to describe general corrosion, such as "general wastage" and "uniform corrosion." General corrosion rates are of interest in screening various combinations of alloys and solutions by measuring weight loss of samples or use of electrochemical methods (e.g., polarization resistance measurements).

Several general review articles on corrosion problems of solar collector systems have implied that in practice general corrosion is not a problem relative to other types of corrosion. For example, Popplewell (1977)⁽⁰⁰⁰⁴⁾ in discussing corrosion prevention in aluminum solar collectors states "General wastage is rarely a consideration in solar collector installations." also "(General wastage) is unlikely to be a problem with aluminum at near-neutral pHs."

When general corrosion is not a limiting factor in service life, the other types of corrosion of concern for solar collectors are listed in Table 1. Some types of corrosion are more often associated with certain metals and alloys. Other types of corrosion are most often related to the environment (fluid composition and flow rate) and result in non-uniform corrosion, which is the more common and serious problem.

TABLE 1. TYPES OF CORROSION OTHER THAN GENERAL
(UNIFORM) CORROSION

Galvanic Coupling Corrosion
Stress Corrosion Cracking
Intergranular Corrosion
Pitting Corrosion
Crevice Corrosion
Erosion Corrosion
Cavitation Corrosion

Galvanic Coupling Corrosion

Galvanic coupling corrosion occurs when two dissimilar metals are joined together in an electrolyte. A common example is an aluminum collector joined (electrically) to copper plumbing. The more noble (less active) metal is copper which will be cathodic and will be protected; the less noble (more active) metal is aluminum which will be anodic and consumed (corroded). The driving force for galvanic coupling corrosion is dependent on the difference in potential between the dissimilar metals, which in the case of copper and aluminum is very high. The anode to cathode ratio is also important, and the rate of anodic corrosion is proportional to this ratio.

Tabular presentations of electrode potentials are contained in several publications:

Common Metals in Sea Water (relative ranking); NBS
Table D-1 (0207)

Common Metals in Sea Water vs SHE; Popplewell (1977)
Table 1 (0004)

Aluminum Alloys vs SCE; Popplewell (1977) Table 1
(0045)

Aluminum Alloys (in 35% ethylene glycol) vs 99.9% Al;
Giner (1977) Table 19 (0002)

As noted by Popplewell (1977)⁽⁰⁰⁴⁵⁾, with aluminum, different alloys have significantly different electrode potentials. Weld filler metals in particular must be carefully selected. An example is shown of accelerated weld filler corrosion in a solar panel tested for six months in potable water. The weld metal contains a high level of silicon which at high temperatures causes the weld to become anodic.

Another form of galvanic corrosion occurs where aluminum alloys are clad, according to Popplewell (1977)⁽⁰⁰⁴⁵⁾. Usually, the cladding is anodic with respect to the core alloy and galvanically protects it. Should pitting occur, only the clad is penetrated preventing perforation of the core. However, at high temperatures, the clad may reverse in polarity with respect to the core. This is particularly true of Al-Zn alloys which gain more noble potentials above approximately 85C. Cladding reversal promotes rapid core penetration. A corrosion example is described of cladding reversal on 7072-clad 1100 after six months testing in uninhibited water.

Stress Corrosion Cracking

The alloy materials presently considered for solar applications are not likely to suffer from stress corrosion cracking, according to Popplewell (1977)⁽⁰⁰⁴⁵⁾.

Giner Inc. (1977)⁽⁰⁰⁰²⁾ found that stress corrosion tests have shown that 1100 and 3003 series aluminum are not susceptible to stress corrosion cracking in solar collector applications.

Intergranular Corrosion

Some alloys are susceptible to intergranular corrosion, which is caused by local galvanic couples on a microscopic scale due to differences in alloy composition between grains and grain boundaries.

Pitting Corrosion

Pitting corrosion has probably produced more failures of solar collectors than any other cause, particularly in uninhibited

aqueous systems, according to Popplewell (1977)⁽⁰⁰⁴⁵⁾. Aluminum is particularly susceptible to pitting corrosion. Pitting of aluminum is aggravated by the presence of chloride ions and heavy metal ions such as copper and iron in multimetal systems. Pitting corrosion was shown to be the predominant failure mode (compared to general corrosion) for aluminum in ethylene glycol solutions containing aggressive ions in the studies by Giner Inc (1977)⁽⁰⁰⁰²⁾.

Johnson (1971)⁽⁰¹³³⁾ provided an excellent review of the state of knowledge of pitting of aluminum. Flaws or defects in the aluminum oxide film that effectively expose bare metal become anodic sites at which pits initiate. Flaws due to impurities are usually cathodic sites.

Pitting proceeds according to the cubic rate law:

$$h = kt^{1/3}$$

where h = pit depth

t = exposure time

The cubic relationship derives from the shape of the pit (assume inverted cone or hemisphere) and the change in volume with corrosion at constant pit current. The validity of the cubic relation has been shown for pitting of aluminum in natural water over a 12-year period by Johnson (1971)⁽⁰¹³³⁾. The relationship was also verified in work by Giner, Inc.⁽⁰⁰⁰²⁾ on pitting of aluminum in glycol solutions.

Pathak and Godard (1968)⁽⁰¹⁸⁷⁾ published an interesting empirical equation, derived from tests on 67 different natural waters for predicting the time to produce a pit 1 mm deep in aluminum (AA 3003) based on the concentration of ions (SO_4^{-2} , Cl^{-1} , Cu^{+2}), pH and solution resistivity.

Other recent sources of information and data on pitting of aluminum include reviews⁽⁰¹⁷³⁾, effect of water composition^(0030, 0029, 0037, 0049), and ethylene glycol solutions⁽⁰⁰³¹⁾. Recent data on pitting of mild steel^(0107, 0005) and electrochemical methods of measurement⁽⁰¹⁰⁶⁾ are of general interest.

Crevice Corrosion

A crevice is any restricted area in which rapid metal loss can occur because a differential aeration cell forms. Oxygen cannot diffuse

readily into the crevice and becomes rapidly depleted, creating an anode. Outside the crevice a ready supply of oxygen is available in the solution, creating a cathode. Rapid corrosion occurs in the small area of the crevice. In solar panels, crevices can be easily created. A few examples cited by Popplewell (1977)⁽⁰⁰⁴⁵⁾ are leaky gaskets, badly fitting metal or plastic couplings, blockages in internal channels, scale deposits, or poor design.

Erosion Corrosion

Erosion corrosion is caused by the joint action of corrosion coupled with mechanical removal of the protective corrosion product film. It is aggravated by abrasive debris. Also, partial constriction of channels by debris can cause local high velocities.

Cavitation Corrosion

Cavitation corrosion is caused when local high solution velocity reduces the static pressure below the vapor pressure of the liquid and a vapor bubble is formed (cavitation). When the vapor bubble subsequently collapses or implodes on the metal surface, the force can disrupt the protective film with an increase in local corrosion rate. Mechanical forces are involved which can change the metallurgical character of the metal under severe cavitation conditions. Cavitation corrosion is most commonly encountered in pumps.

Factors Affecting Corrosion

There are a large number of factors that affect the corrosion rate and the particular type of corrosion. Many of the important factors are summarized in Table 2 and have been mentioned previously. As many as 20 separate factors may require quantitative definition to specify a corrosion situation. Some factors are more important than others for solar collectors. However, many of the listed factors are interrelated

and produce synergistic effects. In view of the apparent complexity, perhaps it is not surprising that there is relatively little quantitative data published on service life of solar collectors.

The organization of factors affecting corrosion presented in Table 2 is similar to the organization of the discussion of solar collector systems earlier in this report. Starting with a particular application, the system should be designed accordingly and presumable with some interaction between collector manufacturer, system designer, and installer. Many of the corrosion problems that have been encountered may have resulted from a lack of communication. One can visualize an aluminum collector used in a system designed with copper piping, installed without nonconducting coupling between dissimilar metals and an oversized pump that yields too high a flow rate. Even the best designed system will be susceptible to corrosion problems unless the heat transfer fluid recommendations are followed for the initial fill which will usually include inhibitors, monitoring, and maintenance.

Temperature is the most important of the application-related factors. Generally, corrosion rates increase with temperature. In the case of systems exposed to oxygen (e.g. "once through" tap water heaters, drain-down systems) the increase in oxygen diffusivity with temperature and decrease in oxygen solubility in water with temperature combine to produce a maxima in oxygen diffusion and corrosion rate at about 70 to 80C. Otherwise, for closed loop (oxygen-free) systems, the maximum corrosion rate will usually occur at the highest temperature (i.e. high temperature stagnation). The relatively low maximum heat flux in solar applications will not produce more than a few degrees increase in metal temperature which is the determinant of corrosion rate⁽⁰¹⁷¹⁾. If fluid boiling occurs at high heat transfer rate, there may be some slight increase in corrosion rate.

The specific metal alloy used is probably the most important of the system design-related factors. The chemical composition of the alloy is usually sufficiently characterized by the type or standardized number designation. Some variation in corrosion resistance is expected among different metal heats and different producers.

TABLE 2. FACTORS AFFECTING CORROSION

Application-Related Factors

- Temperature (storage maximum)

- Stagnation Temperature

- Heat Transfer Rate

System Design-Related Factors

- Specific Metal Alloy

- Chemical Composition

- Heat Treatment (initial or local welding)

- Stress (fabrication and thermal cycling)

- Surface Finish/Treatment

- Fluid Dynamics

- Flow Rate

- Passage Configuration

- Flow Regime (Reynold's Number)

- Galvanic Coupling

- Metallic Couple

- Anode/Cathode Area Ratio

- Metals in Fluid Loop

Heat Transfer Fluid-Related Factors

- Water

- Chemical Composition

- Concentration of Critical Components

- Chloride (or other halides)

- Heavy metal ions (copper, iron)

- Dissolved Oxygen

- Antifreeze

- Chemical Composition

- Concentration

- Chemical Stability

TABLE 2 (Continued)

Corrosion Prevention-Related Factors**Inhibitors**

Chemical Composition

Concentration

Cathodic Protection

Getter Columns/Filters

Oxygen Removal

Corrosion Monitoring/Maintenance**Dependent Variables**

pH

Reserve Alkalinity

Conductivity

Specific Gravity

Polarization Resistance

Test Coupons

Additionally, with some alloys, it is necessary to specify the heat treatment, and if the collector is fabricated by welding there may be heat affected zones that adversely affect corrosion resistance. Metal stress originating during collector fabrication or subsequent thermal cycling is not expected to be a major problem with solar collectors but cannot always be entirely discounted over the long term as a contributing factor of corrosion. The surface finish of the internal collector metal surface in contact with the heat transfer fluid can be a factor in initiating pitting corrosion. Thus, the surface finish and/or method of preparing the surface of corrosion test specimens is usually specified. Possibly metal surface treatments could improve corrosion resistance. In view of the importance of surface oxide films in minimizing corrosion rates, there may be benefit in preconditioning the collector metal surface under controlled condition (fluid, temperature) before placing in service.

Fluid dynamics can be a very important factor in influencing both uniform and non-uniform corrosion rates. Fluid dynamics includes system design-related factors such as liquid flow rate, passage configuration, and their interrelation as they affect the flow regime, especially the degree of turbulence. In the available literature on solar collector corrosion, the subject of fluid dynamics has not been addressed in sufficient detail. The terminology used to describe fluid flow, e.g. "velocity", could lead to misinterpretation in applying information, difficulty in evaluating corrosion data, and some misstatements. Thus some extra attention has been directed to the subject of fluid dynamics.

Solar collector corrosion processes include both static/stagnation conditions and flowing conditions. Static fluid (no net movement along the passage) can still involve fluid motion due to local convection from thermal gradients. In some cases, static conditions can present a more severe corrosive environment, and some fluid flow would be preferable. Fluid flow can be thermally induced (e.g. thermosiphon water heaters) or forced flow (e.g. pumps). In either case, the flow regime can be characterized by the Reynolds Number (N_{Re}) for tubes

(i.e. laminar flow below $N_{Re} < 2000$). For example, in thermosiphon water heaters, the fluid flow under high insolation conditions is usually laminar within the collector but is turbulent most of the day in the pipes leading to the storage tank (riser) and from the storage tank to the collector (downcomer).

With pumped liquid flow to solar collectors as typically designed, the flow in the vertical tubes is laminar and usually low velocity (0.1 to 0.3 ft/sec). Flow in headers may be either laminar or turbulent. Flow in pipe connections to the header are probably turbulent. Piping to the collector and the heat exchanger are usually designed for turbulent flow. Typical hot and cold water plumbing practice is to use the most economic pipe diameter (smallest diameter without excessive pressure drop) which usually results in turbulent flow at the design flow rate. Since copper pipe is widely used, the velocity is limited below values which would cause erosion-corrosion (< 5 ft/sec) and noise. Flow velocity is commonly specified, since for a particular pipe size the Reynolds number increases with velocity and for a particular flow rate (gpm) the Reynolds number (and velocity) increases as pipe diameter is decreased.

Heat exchangers (e.g. shell and tube type) are usually operated under turbulent flow conditions to increase the liquid/metal heat transfer coefficient and thus reduce heat exchanger area and cost. However, solar collectors involve different design optimization factors that usually result in laminar flow in the collector passages.

For solar collector design an increase in flow rate improves the liquid/metal heat transfer coefficient and collector efficiency. However, an increase in flow rate increases pressure drop in the flow direction, pumping power, and electric power costs. Optimization for life time costs usually indicates a specific flow rate of 0.02 to 0.035 gpm/ft² of collector area. For several typical commercial collectors of different passage dimensions, passage spacing, and typical collector length (6 ft), the optimum specific flow range (0.03 gpm/ft²) results in laminar flow ($N_{Re} < 1500$) at the highest temperature. The collector

efficiency (> 95 percent) is very high at these conditions with little improvement to be gained by higher flow rate. However, other collector designs or operating conditions might cause the critical Reynold's Number to be exceeded and create a transition from laminar flow to turbulent flow within the length of the collector passage. Such a transition might cause a more non-uniform corrosion condition than all laminar or all turbulent flow in the passage. Thus, the effect of flow regime on corrosion warrants further study.

A good general review of the effects of fluid flow on corrosion was presented by Copson (1960)⁽⁰¹⁷⁰⁾. In general, an increase in flow rate increases corrosion rate with several exceptions. The corrosion rate response of different metals to fluid flow depends on the corrosion processes occurring and the general effects of mass transport of oxygen, inhibitors, and corrosion products to or from the metal surface.

There is relatively little data available in the literature on the effect of fluid flow on corrosion in solar collectors. One study directed to corrosion of aluminum in solar collectors reported data for "static", "laminar" and "turbulent" flow⁽⁰⁰⁰²⁾. However, the experimental conditions referred to as "turbulent" were actually "laminar" for the rotating-disk type experiments. In research studies, a horizontal rotating disk submerged in the fluid is often used to study the effects of fluid flow on corrosion, electrode processes, and mass transport⁽⁰²¹⁶⁾. However, in correlating the results of a rotating disk with that for confined channels (e.g. tubes), it is important to use the correct dimensionless Reynolds Number to characterize the flow:

$$N_{Re} \text{ (tube)} = \frac{DV}{\gamma} \qquad N_{Re} \text{ critical} = 2 \times 10^3$$

$$N_{Re} \text{ (disk)} = \frac{(r)^2 \omega}{\gamma} \qquad N_{Re} \text{ critical} = 2 \text{ to } 3 \times 10^5$$

where N_{Re} = Reynolds Number

D = diameter of tube, ft

V = velocity, ft/sec

γ = kinematic viscosity, ft²/sec

r = radius of disk, ft

ω = disk angular velocity, 2 π (RPM)

The critical Reynolds Number is the value below which the flow is laminar and above which it may be turbulent.

Rotating disks have been used in corrosion studies and with a large enough disk and speed (e.g. 5 inch diameter, up to 1200 RPM), can show the effects of fluid flow (laminar, transitional, turbulent) on a single disk since the Reynolds Number increases in the radial direction as the square of the radius at constant speed. For example, data for Admiralty brass disks in sea water show an abrupt increase (~5-fold) in corrosion rate at a certain radial dimension or velocity (tangential disk velocity) in a data plot of corrosion rate versus velocity (0170). In much of the corrosion literature correlations are made with velocity (tangential velocity of disks or average linear velocity in tubes). The data has more significance when it is realized that the change in corrosive condition occurred at the critical Reynold's Number of $2 \text{ to } 3 \times 10^5$, corresponding to the transition from laminar to turbulent flow for a disk. One would conclude that the same effect would be observed in a tube for a Reynold's Number of ~ 2000 and a velocity depending on the tube diameter.

Thus, while it appears to be common practice to discuss the effects of velocity on corrosion rate, it would be desirable to also consider the effects of flow regime (i.e. Reynolds Number) on corrosion.

Galvanic coupling refers to an electrically conductive path between dissimilar metals or alloys. Such coupling is a factor in most multimetal systems and may be avoidable (e.g. copper coupled to aluminum), unavoidable in fabrication (e.g. soldered or brazed joints), or intentional for corrosion protection (e.g. cathodic protection, clad alloys). The effect of galvanic coupling on corrosion rate of the anode depends on the anode to cathode area ratio and other factors (e.g. difference in electrode potential, solution conductivity, inhibitors).

The other metals in the fluid loop are a factor since they can corrode and supply heavy metal ions to the solution. A typical example is corrosion of copper piping providing copper ions in solution, which may deposit on aluminum collectors causing local cells and increased local corrosion (pitting) of aluminum. Many authors discuss this occurrence and galvanic coupling together as "galvanic corrosion". In this

report, a distinction is made by the use of the term "galvanic coupling" and treating deleterious heavy metal ions as a fluid contaminant. This allows for the possibility that such ions (e.g. iron, copper) may originate in the water supply rather than from corrosion of metals in the collector fluid loop.

Water quality is an important factor in corrosion of collectors using aqueous heat transfer fluids. It seems preferable to focus attention on the water quality and treat antifreeze (e.g. ethylene glycol) and inhibitors as additives to water. The corrosive tendency of water is dependent on the chemical composition with regard to concentration and types of certain ions that may have a good effect through natural inhibition, or often have an adverse effect (e.g., S^{2-} , HCO_3^-). Some ions found in natural water are beneficial in providing a protective scale. However, an excess of such ions in hard water might cause problems by forming excessive scale at hot collector temperatures, reducing heat transfer and causing higher metal temperature and localized corrosion at breaks in the scale which can be accentuated by stresses from thermal cycling. The total amount of dissolved ions determines the solution conductivity, which for certain types of metals might be monitored as an indicator of corrosive conditions. Compared to distilled water, addition of inorganic salts as inhibitors will increase solution conductivity and can actually increase corrosion rates under some conditions. Certain components of water are usually more critical with regard to corrosion such as chlorides, heavy metals and dissolved oxygen.

Considering antifreeze of a particular composition (e.g. pure ethylene glycol) as an organic additive to water, a principal effect is to increase solution viscosity and decrease mass transfer. This could decrease general corrosion rate but could accentuate crevice corrosion. Another important factor is the chemical stability of ethylene glycol. It appears to be generally accepted that ethylene glycol can oxidize to glycolate resulting in increase in acidity of unbuffered solutions. Presumably, the increase in corrosion rate is due to a lower pH value. The available data in the literature do not specifically show that there would be no change in corrosion rate if the desired pH were maintained

constant by adding buffer or by some other means such as neutralization with sodium hydroxide. Presumably, with automotive coolants, when the reserve alkalinity of the original inhibitor is consumed, the antifreeze solution should be discarded and replaced with fresh solution. The chemical stability of ethylene glycol is a function of temperature, oxidizing conditions in solution, and catalytic effect of metal surfaces. Experience with chemical stability of automotive antifreeze is probably not a good guide to stability under the different solar collector conditions. However, it appears to be the only present source of information and the available information is reviewed later under "Automotive Applications". Chemical stability of ethylene glycol as applied to solar collector systems is a subject of research investigation in the present program. A few references to corrosion of metals in organic solvents and organic acids might be of interest (0044, 0046).

Corrosion Prevention

Inhibitors

The use of inhibitors is one of the most effective ways of minimizing both general corrosion and non-uniform corrosion. There is considerable information in the literature on inhibitors. However, it is difficult to single out a specific inhibitor package (types of chemicals and concentrations) that is best because of the large number of factors affecting corrosion. Also, there can be trade-offs involved between initial cost of inhibitor package and their relative performance in a particular situation. Selection of the best inhibitors for research programs and their evaluation is recognized as a difficult problem.

References to quantitative data on inhibitors is included in a later section of this report under "Pertinent Experience" in sections on "Government Programs on Collector Corrosion" and "Automotive Applications". Good qualitative discussions of inhibitors referenced to solar collectors are included in recent articles by Beynon⁽⁰⁰⁰¹⁾ based on experience with automotive coolants and Popplewell^(0004, 0045, 0075) with reference to aluminum collectors.

Other general sources of information on inhibitors that are not referenced elsewhere in this report are listed below:

General Information: 0073, 0186, 0148

Aluminum: 0110, 0180, 0185

Copper: 0007, 0018, 0103, 0172, 0039

Inhibitors when added to water become part of the total chemical composition of the water. They are intended to supplement any natural inhibition by constituents of water and counteract the effect of any deleterious ions or dissolved oxygen. Inhibitors may or may not be necessary in clean, oxygen-free, solar collector loops using distilled water; inhibitors would be used with tap water in drain-down systems. No corrosion experiments seem to have been conducted comparing inhibited water to the same inhibited water with added ethylene glycol. Such a test might more clearly compare the trade-off between glycol cost plus chemical stability factors versus added system costs for drain down. Inhibitors for multi-metal systems are an important aspect of corrosion prevention.

Cathodic Protection

Cathodic protection has been used historically to protect hot water tanks from corrosion. It is not often mentioned for use in solar collector systems⁽⁰⁰⁰³⁾. Research on cathodic protection of aluminum has been reported⁽⁰⁰⁴³⁾. Generally, the long, small area passages of solar collectors would not be suitable for conventional methods of cathodic protection. However, recent research at Giner, Inc. suggest that use of zinc powder suspended in the ethylene glycol solution can effectively protect aluminum from corrosion⁽⁰²⁰⁹⁾. Galvanized steel pipe and aluminum cladding are versions of cathodic protection based on use of a sacrificial metal for corrosion protection of the base metal. However, at high temperature polarity reversal can occur with detrimental effects.

Getter Columns

A "getter column" can be installed in the fluid feed to a bank of solar collectors⁽⁰⁰⁰³⁾. The column is essentially a chamber galvanically isolated from the collector that contains replaceable pads of an electrochemically active sacrificial material. The active material might be, for example, pads of zinc wool followed by pads of aluminum wool. The purpose is to remove by "plating out" on the getter material such harmful ions as copper and iron that would promote pitting by plating out on aluminum (or carbon steel) collectors. A secondary purpose of the "getter column" can be to act as a filter to remove extraneous solid debris from the fluid loop. There are various designs that can be used for getter columns, from a simple coil to a cartridge containing pellets. The important factor is to provide sufficient surface area. Aluminum alloys (1100, 3003, 7072) will provide efficient gettering⁽⁰⁰⁰⁴⁾. The getter column cannot be considered as a means of completely eliminating pitting in aluminum collectors and should be used in conjunction with inhibitors; the column will provide protection if the inhibition fails for a short period.

Oxygen Removal

Corrosion rates are highly dependent on the concentration of dissolved oxygen in the heat transfer fluid. In a sealed system (closed loop) any oxygen initially present will be consumed and thereafter corrosion rates will decrease. In drain-down systems, displacement of liquid in the collectors with air can renew the oxygen content of the solution and maintain the corrosive effect. Thus, the use of nitrogen (nitrogen blanketing) or other inert gas to minimize oxygen is a corrosion prevention method. Addition of chemicals (e.g. hydrazine) to react with dissolved oxygen is a typical corrosion prevention method but is not usually mentioned for corrosion prevention in solar collector systems. The absence of dissolved oxygen does not guarantee low corrosion rates since in the absence of sufficient oxygen, cathodic areas can polarize to hydrogen evolution potentials. At high temperature many metals and alloys can corrode by reaction with water and evolution of hydrogen. This can be a problem in hermetically sealed heat pipes containing water for which corrosion data are presented later.

Corrosion Monitoring

Dependent Variables

A particular heat transfer fluid has certain characteristics (dependent on specified chemical constituents and concentration) that can be measured, such as pH, reserve alkalinity (buffering capacity), solution conductivity, and specific gravity. These dependent variables can be monitored for change to indicate a change in the chemistry of the original heat transfer fluid. Among the more familiar is the use of a hydrometer to measure specific gravity of automotive coolants. In addition to indicating concentration of ethylene glycol for freeze protection, it can indicate inadvertent dilution of inhibitors with water and less than optimum corrosion protection for commercial anti-freeze. Solution conductivity can be used to monitor high purity water. Measurement of pH can indicate a change to corrosive conditions that has occurred; reserve alkalinity requires a chemical analysis (titration). Corrosion itself is a dependent variable (dependent on factors in Table 1) and is the basis of corrosion monitoring using test coupons and/or electrodes for electrochemical and electrical measurement of change in corrosive environment.

Many corrosion monitoring methods suitable for research and development (demonstration tests) may not be economically practical for wide-scale use. To some extent the degree of sophistication in corrosion monitoring/maintenance depends on the capital investment in solar collectors and other system components to be protected from corrosion. Thus, effective monitoring and maintenance is most likely to be found in large-area solar collector installations (commercial, institutional, industrial) for heating and cooling. Increase in residential heating and cooling solar applications may require the development of simple low-cost corrosion monitoring methods.

There are several methods of corrosion monitoring that are covered in most standard texts on corrosion technology. Assuming that other types of corrosion are not limiting in solar collectors, pitting corrosion is a major consideration relative to general corrosion in monitoring. Test coupons of the materials of interest in the collector fluid loop can be removed and examined at intervals and measurements made to

determine average general corrosion rate from weight loss and pitting penetration rate from microscopic measurements of pit depth and frequency. The use of thin foils of metal would allow greater sensitivity in weight loss measurement and also readily reveal pitting by penetration⁽⁰²⁰⁹⁾. Thinning of metal wires by corrosion and increase in electrical resistance is the basis of one electrical monitoring technique. The use of thin metal foil or films might be adapted to both a visual and electrical corrosion indicator⁽⁰¹⁴⁶⁾. A thin foil or film in the fluid loop that could be visually examined for pitting in a transparent section of the piping, possibly with back lighting, might be the simplest corrosion monitor. No specific references were found on such a development. Linear polarization resistance measurements can be the basis of an electrochemical method of continuous monitoring with advantages over weighing test coupons. However, the application of the technique to pitting corrosion is less well developed at present.

Linear Polarization Resistance Measurement

The linear polarization resistance technique for measuring corrosion rates is based on the concept of polarization resistance developed by Stern and Geary in 1957, and the theoretical basis for the method has been studied over the years^(0176, 0131). The concept of polarization resistance for corrosion monitoring has received wide application since its inception. Reviews of the subject are available in technical articles^(0129, 0130) and textbooks on corrosion⁽⁰²⁰³⁾; other articles deal with specialized aspects of the technique^(0127, 0128, 0132), and measurement of low corrosion rates⁽⁰¹⁷⁴⁾.

A principal advantage of the method is that instantaneous corrosion rates can be determined without disturbing the test specimen. The method has been used in the study of inhibitors for automotive coolants^(0081, 0079, 0168, 0102) in glassware, automotive, and vehicle tests with good correlation with standard weight loss measurements. It has also been used in the laboratory⁽⁰¹⁷⁵⁾ and plant for on-line corrosion control⁽⁰⁰⁷⁷⁾. Commercial instruments are available, and comparisons of the linear polarization method have been made with the weight loss and electrical resistance methods in terms of speed and cost by Feitler⁽⁰⁰⁸⁰⁾.

He also discusses the use of a two-electrode system for obtaining measurements to establish a "pitting index" in contrast to the three-electrode method which gives only average corrosion rate. The linear polarization technique was used in research on aluminum corrosion of solar collectors to obtain average corrosion rates⁽⁰²⁰⁹⁾ but attempts to determine pitting of aluminum by the technique were not successful⁽⁰⁰⁰²⁾. The linear polarization method is being used in the experimental research on this program which includes copper and steels in addition to aluminum.

A recent paper discusses the use of alternating current⁽⁰¹⁰⁸⁾ for speed of measurement relative to direct current techniques.

ASTM Standards For Corrosion Testing

Several ASTM standards pertinent to conducting and evaluating corrosion research tests were included in the data bank:

<u>ASTM Standard</u>		<u>Accession Reference</u>
G 1 - 72	Test specimens	0160
G 3 - 74	Conventions	0141
G 4 - 74	Plant Tests	0142
G 16 - 71	Statistics	0161
G 31 - 72	Immersion Tests	0143
G 46 - 76	Pitting	0144

Good reproducibility among several laboratories was demonstrated for galvanic coupling measurements of current for copper coupled to aluminum (6061) and to 4130 steel using ASTM corrosive water (ASTM Standard D2570-73)⁽⁰⁰⁴⁷⁾.

PERTINENT EXPERIENCE

Solar Applications

Practical Experience

Residential Water Heaters. Domestic hot water is perhaps the most economically justified solar application at present. Solar hot water heaters have been available for over 50 years and are widely used throughout the world. One can surmise that collector corrosion problems were a minor factor in view of their widespread use. Most of the experience relates to relatively simple devices usually operated on a thermosiphon principal with collector temperatures in the medium range of 120 F to 160 F. However, there is relatively little quantitative data available relating to corrosion of solar collectors used for residential water heaters.

An excellent review of the solar water heater industry in South Florida⁽⁰⁰¹⁷⁾ by Scott (1976) covers history, economics, and description of the solar systems and operational problems. A typical collector design originated 50 years ago consisted of 5/8 or 3/4-inch inside diameter soft copper tubing in serpentine fashion soldered to a copper absorber plate. Except for occasional stoppages due to sediment (not corrosion) and a rare leak, they have performed well for 35 years and longer. Modern collector designs use vertical risers to minimize blockage.

Prior to 1940, manufacturers believed their products would operate maintenance free for an indefinite period of time. No one had anticipated that the hot water storage tanks (usually commercially-available galvanized steel tanks) would develop leaks as a consequence of using copper tubing in the collectors and steel in the tank. Quite unexpectedly, many tanks did begin to leak in 12-15 years. An economic analysis presented shows that the life cycle savings were favorable through the 1940's. However, by 1958 the savings for an installed cost of \$550 (1958 dollars or \$1300 in 1974 dollars) for an 82-gallon tank and collector over 15 years just equaled the replacement cost of \$500 for a new tank in 1974. The storage tank location in the attic above the collector made replacement expensive. Water leakage damage was

reduced when drip pans were installed under the tank. Corrosion product buildup in the connection between the collector lead lines and the storage tank reduced the supply of hot water over years of operation.

Collector piping included a manual drain valve for freeze protection which was a rare problem in South Florida (e.g., Miami). However, one freeze in 1958 resulted in many frozen collectors. Collectors which were made of soft copper suffered no damage while nearly all hard copper installations failed. Installations in North Florida included gate valves in the line connecting the absorber and the tank to retain hot water when the collector was drained for freeze protection.

A recent report (1978) on the first year's experience with 100 solar water heaters installed for the New England Electric Company program reviews many of the problems encountered in installation and operation. (0062) No corrosion problems were specifically identified among the 325 items listed under first-year trouble analysis. Freezing problems were encountered with freezable collector design, draindown systems, and on one occasion with antifreeze type (solution too weak).

Solar Heating and Cooling. A survey of materials performance in 25 active solar system installations was conducted by the National Bureau of Standards in 1977. At the time of the field inspection, the period of operation was a few months to 3 years. Leakage resulting from corrosion was observed in several systems utilizing aluminum absorber plates with integral flow passages. It was implied that the cause of corrosion originated elsewhere in the system. Potential problems in piping were considered based on the use of dissimilar metals within the various systems inspected. The use of aluminum, copper, and steel pipes in conjunction with galvanized connections, brass valves, and steel valves, and steel and aluminum storage tanks was noted which might lead to corrosion problems. One pump problem of leakage was traceable to deterioration of the impeller shaft packing material by the high concentration of chromate inhibitor in the system.

As part of the above study, a letter survey was conducted with 136 responses to 459 questionnaires sent out to manufacturers and installers of solar collectors. Eleven manufacturers and/or installation

contractors indicated problems. Ten problems that required repair or replacement of collectors were reported, corrosion was reported in four cases, fluid transport system repairs were required in four cases and only one storage problem was reported.

The summary of questionnaire response relating to liquid transfer medium is interesting:

<u>Type</u>	<u>Total</u>	<u>With Additives</u>
Water	70	7
Ethylene glycol/water	26	14
Propylene glycol/water	10	0
Other	6	4

The interpretation of the column "with additives" could be (1) supplemental additives to commercial antifreeze, or (2) respondents didn't know commercial glycols contain additives, or (3) potential corrosion problems with uninhibited glycols.

The above survey was part of the effort of National Bureau of Standards to develop solar material standards and test methods. NBSIR 77-1305 (September 1977) entitled, "Provisional Flat Plate Solar Collector Testing Procedures" covers many collector tests but not material compatibility involving interaction of collector metals and heat transfer fluids.⁽⁰⁰⁶⁷⁾ Standard tests for solar fluids were not available (1977),⁽⁰⁰⁰¹⁾ but are being developed by task groups of ASTM Committee E21.10 on Solar Heating and Cooling Applications in cooperation with various government agencies.

A brief preliminary review of corrosion technology is included in the recent California Guideline for Certification of Solar Energy Equipment⁽⁰²⁰⁷⁾ as Appendix D (9 pages) entitled, "Corrosion Control Guidelines" (possibly taken from modified NBSIR 77-1305A). Deviations from the recommendations contained in the guidelines of Appendix D are to be specifically identified and justified for certification.

Studies of corrosion related to operational solar collector systems are in progress at Argonne National Laboratory. No reports have been published as yet.

Hardware problems encountered at Marshall Space Flight Center (NASA) over several years experience with development and demonstration of solar heating and cooling have been reviewed by Cash in a report⁽⁰¹¹¹⁾ and related articles.^(0061 or 0165) Few if any significant corrosion problems are cited. From this and similar problem reviews which mention freeze protection, the impression is gained that presently there are more problems of a design and operational nature with automatic drain-down systems than there are corrosion problems with antifreeze systems. This situation could change with experience and operating time.

At the beginning of a research program in 1976 on corrosion and its control in aluminum solar collectors at Giner, Inc.⁽⁰¹⁸⁹⁾, four demonstration projects were examined that used flat plate aluminum collectors. The systems had been in operation for only a relatively short time and no corrosion problems were reported for the three installations using water and drain down to avoid freezing (Atlanta, Ga; Timonium, Md; Warrenton, Va). The installation at the Grover Cleveland School in Boston was designed originally to operate on ethylene glycol/-water and corrosion problems were encountered with the aluminum (1100) panels (integral channel type) after part of two heating seasons. Corrosion occurred at the tubes connecting the aluminum collector panels to the manifold system made of copper pipe. The arrangement produced rapid, severe galvanic attack localized at the aluminum inlet and outlet tubes of the panels sufficient to produce leakage of coolant in some places. The problems were obviated by substitution of silicone oil for ethylene glycol/water with a sacrifice in heat transfer characteristics and favorable cost. The report does not specifically say whether the antifreeze contained inhibitors, the quality of water used, or address the question of using insulating couplings between aluminum and copper.

There may be numerous instances of corrosion problems in the early development of systems for which the causes may appear obvious with hindsight. It seems that the instances should be documented in detail to reinforce the generally accepted "good corrosion control practices" or identify unexpected problems.

Government Programs on Collector Corrosion

Los Alamos Scientific Laboratory. The Los Alamos Scientific Laboratory of the University of California at Los Alamos, New Mexico has a long-standing program of evaluating the potential long-term corrosion effects of leading collector fluids (aqueous and non-aqueous) in resistance-welded, pressure expanded, mild steel collectors such as the collector used on the Study Center at LASL. (8000 sq. ft. collector array on National Security and Resources Study Center for heating and cooling which was placed in operation in 1977) (0096).

As summarized in the progress report (April 1978) (0096), one of the several tests of the mild steel collector under normal service conditions for 30 months used an 85% glycol-15% water solution with NALCO 39L inhibitor. When cut apart, microscopic examination revealed no significant corrosion on plain surfaces or in cracks (crevices).

George C. Marshall Space Flight Center. A long term study of corrosion of solar collectors was begun several years ago at the National Aeronautics and Space Administration, George C. Marshall Space Flight Center (NASA, MSFC) in Huntsville, Alabama. A bibliography (0166) of all solar energy research (in house and contracted) includes references to corrosion research thru 1977 discussed below.

A contracted study of inhibitors at Southern University (0135) investigated corrosion rates of steel and aluminum in a special synthetic corrosive water with 10 different commercial inhibitors, using a bench-scale, flow apparatus, and with daily cycles of temperature to 93 C for 9 hours. The best inhibitor was found to be sodium chromate, which reduced the corrosion rate for steel from 22.7 mpy to 1.77 mpy and for aluminum from 6.3 mpy to 0.12 mpy with no pitting or crevice attack evident in 60 day tests. Inhibitor costs are compared for a 5000 gallon storage system.

Evaluation of various inhibitors for effectiveness in solar heating and cooling was conducted in glassware tests at NASA-MSFC for one year (0016). Small test panels of 1100 aluminum, 1010 steel, 321 stainless steel, and electrolytic tough pitch copper were galvanically coupled and immersed in test solutions with removal to empty covered

flasks each working day for 8 hours to simulate a drain down system of freeze protection. Tests were conducted with solutions at room temperature and elevated temperature of 82 C. Corrosive water was used (100 ppm each of Cl^{-1} , SO_4^{-2} , and HCO_3^{-1} ions).

The inhibitors evaluated are shown in Table 3; the first five listed are compositions typical of those used in automotive coolants. The results of the test program are summarized in Table 4 for steel and aluminum as a relative rating of solutions based on weight loss and visual examination for non-uniform corrosion (detailed in the report). Neither copper nor stainless steel suffered any significant corrosion. The best inhibitors were selected for further testing.

In a continuation of the above program at NASA-MSFC⁽⁰¹⁷⁹⁾, another year of testing was conducted using the same test procedures except duplicate test specimens were used and only at elevated temperature (82 C). The composition of the corrosion inhibitors is shown in Table 5 and rating of corrosion inhibitors for steel and aluminum is shown in Table 6. As before, stainless steel (321) was unaffected and copper was only mildly etched (<0.08 mpy). Inhibitors 1 and 6 were the most effective and were probably used in subsequent collector panel tests under service conditions discussed below.

A major program of evaluation of solar heat transport fluids was begun in 1976 under contract NAS 8-32255 to Houston Chemical Company, Corpus Christi, Texas (subsidiary of PPG). The contractor constructed a test stand at NASA-MSFC⁽⁰¹¹⁵⁾ for evaluating aluminum, copper, and steel solar collectors in a system containing copper plumbing using various heat transfer fluids (water and antifreeze, inhibited and uninhibited). The test stand contains 37 independent closed-loop fluid circuits with either 1 or 2 collectors for a total of 64. The solar collectors (34 inch x 76 inch) being evaluated are about equally divided between Tranter "Econocoil" steel panels, aluminum roll-bond panels and copper roll-bond panels, all with single glazing. The roll-bond construction was selected since it was felt to be more prone to crevice corrosion than the tube sheet type of construction⁽⁰²¹⁷⁾. Details of the test program including data acquisition and planned corrosion evaluation procedures are contained in the first four quarterly reports thru November, 1977⁽⁰²¹⁷⁾. Fluid flow rate is 0.5 gpm per

TABLE 3. CORROSION INHIBITORS (0016)

1.	1.0 NaNO ₃ , 2.0 Na ₃ PO ₄ ·12H ₂ O, 2.5 NaMBT, 3.0 Na ₂ B ₄ O ₇ ,
1.0 Na ₂ SiO ₃ ·9H ₂ O, 1.0 NaOH.
2.	4.0 Na ₃ PO ₄ ·12H ₂ O, 2.0 Na ₂ SiO ₃ ·9H ₂ O, 4.0 NaMBT.
3.	1.5 NaNO ₃ , 2.0 Na ₃ PO ₄ ·12H ₂ O, 2.5 NaMBT, 4.0 Na ₂ B ₄ O ₇ .
4.	1.5 NaNO ₃ , 2.5 Na ₃ PO ₄ ·12H ₂ O, 4.0 NaMBT, 2.0 Na ₂ SiO ₃ ·9H ₂ O.
5.	1.4 Na ₂ HPO ₄ , 2.4 MBT, 6.2 Na ₂ B ₄ O ₇ : Source - 15.0 Cooling System
Inhibitor, Federal Specification 0-I-490A.
6.	50 volume percent "Permanent Type Anti-Freeze"
(ethylene glycol base).
7.	20.0 DuPont "Anti-Rust," an automotive coolant inhibitor.
8.	12.0 NaC ₇ H ₅ O ₂ , 1.0 NaNO ₂
9.	1.0 Na ₂ CrO ₄
10.	Uninhibited test water.
11.	50 volume percent uninhibited ethylene glycol.
12.	Same as No. 1 without the NaOH.

All concentrations in grams per liter except as noted.

NaNO₂ - sodium nitrite

NaNO₃ - sodium nitrate

Na₂B₄O₇ - sodium borate

Na₂SiO₃ - sodium silicate

Na₂HPO₄ - disodium phosphate

MBT - mercaptobenzothiazole

NaMBT - sodium mercaptobenzothiazole (50% solution).

Na₃PO₄ - trisodium phosphate

NaC₇H₅O₂ - sodium benzoate

Na₂CrO₄ - sodium chromate

NaOH - sodium hydroxide

TABLE 4. RATING OF THE CORROSION INHIBITORS^a (0016)

Elevated Temperature			Room Temperature			Combination		
Al	Steel	Both ^c	Al	Steel	Both ^c	Al ^c	Steel ^c	Both ^c
4 ^b	8 ^b	1 [?]	4 ^b	8 ^b	1	4	8	1
3 ^b	1 ^b	3	1 ^b	2 ^b	5	1	1	5
1 ^b	9 ^b	5	3 ^b	5 ^b	12	3	5	
12 ^b	5 ^b		5 ^b	1 ^b		5	7	
5 ^b	3 ^b		12 ^b	12 ^b		12		
9	7 ^b		2	7 ^b				
8	2		9	9				
2	4		8	4				
7	12		7	3				
6 ^d	6 ^d	6 ^d	6 ^d	6 ^d	6 ^d	6 ^d	6 ^d	6 ^d

- NOTES:
- The inhibitors are listed in descending order according to their effectiveness.
 - These are the only inhibitors that were considered acceptable in each category.
 - Only those inhibitors that were considered acceptable in the previous categories are rated.
 - This inhibitor is acceptable in all categories but is listed separately because the solution is glycol-water (see Table 3).

TABLE 5. COMPOSITION OF CORROSION INHIBITORS (grams/liter)⁽⁰¹⁷⁹⁾

1.	1.0 NaNO ₃ , 2.0 Na ₃ PO ₄ ·12H ₂ O, 2.5 NaMBT, 3.0 Na ₂ B ₄ O ₇ , 1.0 Na ₂ SiO ₃ ·9H ₂ O, 1.0 NaOH, formulated by General Motors
2.	Same as No. 1 without the NaOH
3.	1.5 NaNO ₃ , 2.0 Na ₃ PO ₄ ·12H ₂ O, 2.5 NaMBT, 4.0 Na ₂ B ₄ O ₇
4.	1.5 NaNO ₂ , 2.0 Na ₃ PO ₄ ·12H ₂ O, 2.5 NaMBT, 4.0 Na ₂ B ₄ O ₇
5.	1.4 Na ₂ HPO ₄ , 2.4 MBT, 6.2 Na ₂ B ₄ O ₇ : Source-15.0 Cooling System Inhibitor, Federal Specification 0-1-490A
6.	20.0 Mobay Product OC2002 — sodium benzoate base
7.	30.0 Nalco 2755 ^A
8.	1.5 Mogul WS-142
9.	5.0 Mogul WS-142
10.	5.0 Hercules CR408
11.	10.0 Hercules CR408
12.	Uninhibited test water
	NaNO ₂ — sodium nitrite
	Na ₂ SiO ₃ ·9H ₂ O — sodium silicate
	NaNO ₃ — sodium nitrate
	Na ₃ PO ₄ ·12H ₂ O — trisodium phosphate
	Na ₂ B ₄ O ₇ — sodium borate
	Na ₂ HPO ₄ — disodium phosphate
	MBT — mercaptobenzothiazole
	NaOH — sodium hydroxide
	NaMBT — sodium mercaptobenzothiazole, 50 percent solution

TABLE 6. RATING OF THE CORROSION INHIBITORS⁽⁰¹⁷⁹⁾

Al ^a	Steel ^a	Both
1 ^b	6 ^b	1
2 ^b	7 ^b	6
6 ^b	1 ^b	
3	5 ^b	
4	2	
5	4	
7	3	
9	10	
11	11	
8	9	
10	8	
12	12	

- a. The inhibitors are listed in descending order according to their effectiveness.
- b. The only inhibitors that were considered effective.

collector (1 gpm for 2 collectors in parallel). Plans to monitor corrosion by chemical analysis⁽⁰¹³⁶⁾ of the heat transfer fluid were abandoned since some insoluble products remain on the metal. Monthly analysis of fluid samples consists of pH measurement, reserve alkalinity, and color (relative to prepared standards). The test program was initiated in June 1977 and results of sample analysis are tabulated in quarterly reports thru January, 1978⁽⁰¹⁶³⁾ and through May, 1978⁽⁰¹¹²⁾. Subsequent reports on order are not yet available. The contract scheduled for completion in 1978 has been extended to April, 1979. No conclusions can be obtained from the fluid analysis data report except that corrosion is probably occurring in some test loops. No data have been reported on temperatures in the solar collectors. Temperature in each collector loop is maintained by a heat exchanger and a common heat rejection loop for all 37 fluid circuits. No plans for investigating high stagnation temperatures have been mentioned in the reports. Corrosion results will not be available until the test is terminated and solar collectors sectioned for visual examination.

Each type of collector (aluminum, copper, steel) is being evaluated with the following fluids

Deionized water

Hard water

Glycerin (60%)

Ethylene glycol (50%)

- one solution uninhibited
- three inhibited solutions

Propylene Glycol (51%)

- one solution uninhibited
- two inhibited solutions

Triethylene Glycol

- 50% solution inhibited
- 34% solution inhibited (heat rejection coolant)

One Calmac non-metallic plastic collector is being evaluated with inhibited 50% ethylene glycol/deionized water.

Aluminum Corrosion Research

A Department of Energy funded study at Giner, Inc., Waltham, Mass., is entitled "Study of Corrosion and Its Control in Aluminum Solar Collectors". This is one of the few studies on solar collector corrosion for which detailed research results can be found in the available literature. Some of the results of the 2-year study were presented in a recent technical paper in the Electrochemical Society Journal⁽⁰¹⁷⁷⁾. Further details of the work are contained in the various contractor reports listed below:

<u>Report No</u>	<u>Type</u>	<u>End of Period</u>	<u>Reference</u>
1	Quarterly	August 31, 1976	0189
2	Quarterly	November 30, 1976	0191
3	Quarterly	February 28, 1977	0190
4	Annual	May 31, 1977	0002
5	Quarterly	August 31, 1977	0113
6	Semi-Annual	March 31, 1978	0208
7	Annual	July 31, 1978	0209

The results of the program are summarized in the "Abstract" of the most recent report⁽⁰²⁰⁹⁾ reproduced below:

"The use of aluminum solar heat collectors with aqueous glycol solution as the heat transfer medium is potentially attractive but for the critical problem of corrosion. Such a corrosion problem must be resolved to prevent catastrophic plant failure. The goal of this program is then to develop and ascertain the requisite conditions under which such systems will survive a reasonable period of time."

"In Phase I (June 1, 1976 - May 31, 1977) we have developed a non-destructive electrochemical technique (the linear polarization resistance method) to determine the overall aluminum corrosion rate under a wide range of conditions relevant to the operation of existing solar collector systems. Baseline aluminum corrosion data was obtained in 35 vol % aqueous ethylene glycol solutions at temperatures from ~ 25 to $\sim 100^{\circ}\text{C}$. The effects of other parameters such as hydrodynamics, alloy compositions, impurities, dissolved oxygen and ethylene glycol decomposition products were also investigated. We have also collected and analyzed pitting data under laboratory conditions. Probable time to failure of a full size plant due to pitting perforation can be estimated by fitting the laboratory data into a cube root pit growth law and using Gaussian statistics."

"It was concluded that aluminum and its alloys (1100 and 3003 series) possess marginal corrosion resistance in *pure* ethylene glycol solutions. When common contaminants (e.g. Cu^{+2} , Fe^{+3} and Cl^{-} ions) are present, the corrosion of aluminum surges to an *intolerable* level. Other parameters (such as hydrodynamics, dissolved oxygen and ethylene glycol decomposition products) did not seem to affect aluminum corrosion significantly. Aqueous ethylene glycol solutions cannot be used in aluminum solar collectors unless proper corrosion control methods (e.g. inhibitors) are used."

"Phase II (June 1, 1977 - July 31, 1978) has been devoted primarily to the development of corrosion control methods for aluminum solar collectors using ethylene glycol heat transfer fluids. Corrosion inhibitors and impurity scavengers have been tested and evaluated at temperatures up to 160°C under various laboratory conditions. A new

corrosion rate measurement technique based on the use of thin foil samples was developed and adopted in this program to provide accelerated (yet undistorted) results."

"In addition to the development of corrosion control methods, we have also extended the acquisition of baseline corrosion data to the aluminum/*propylene* glycol combination. Propylene glycol was chosen primarily because of its low toxicity. Aluminum corrosion characteristics were determined in 50, 85 and 100% propylene glycol solutions at temperatures between 25 to 160°C."

"Corrosion behavior of aluminum in more concentrated *ethylene* glycol solutions (up to 100%) at higher temperatures (up to 160°C) was also obtained in order to broaden the baseline. The cube root pit growth law was also verified experimentally. All the parameters needed to predict the time to plant failure due to pitting perforation were also determined in the second phase of this program."

"With regard to the aluminum/*propylene* glycol combination, aluminum alloys were found to be about ten times more corrosion resistant in propylene glycol than in ethylene glycol solutions under similar conditions. However, the presence of impurities such as Cu^{+2} , Fe^{+3} and Cl^- still causes rapid and serious corrosion attack unless proper corrosion control methods are implemented. The corrosion resistance of aluminum was also found to increase as the concentration of ethylene (or propylene) glycol solution increases."

"An extensive literature review showed that phosphates, borates, nitrates and silicates and sodium mercaptobenzothiazole are effective corrosion inhibitors which are compatible with glycol solutions. It was determined that most inhibitor formulas, whether proprietary or prepared in-house, can reduce the overall aluminum corrosion rate to below 1 mpy at temperatures below 100°C, even when chloride, cupric and ferric ions are simultaneously present. Pitting corrosion is also completely suppressed. A preferred inhibitor composition (in g/liter) was found to be $(4.5) \text{Na}_3\text{PO}_4 \cdot 12 \text{H}_2\text{O}$, $(2.0) \text{NaNO}_3$, $(10.0) \text{Na}_2\text{B}_4\text{O}_7 \cdot 5\text{H}_2\text{O}$.

(1.5) $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$, and (5.5) $\text{C}_7\text{H}_4\text{NS}_2\text{Ha}$ for ethylene glycol. It was also recommended to add NaOH at 2.0 g/liter for pH adjustment purpose. This is known as Inhibitor Formula II in this program."

"As the operating temperature increases to 130°C , several inhibited commercial solar collector heat transfer fluids began to fail. A surge in overall corrosion rate and the reappearance of pits were observed. Only Inhibitor Formula II and two other commercial automotive coolants remained effective at this temperature. At 160°C , the overall aluminum corrosion rate exceeds the 1 mpy safety limit, even when exposed to 100% glycol (ethylene and propylene)."

"Both aluminum and zinc were selected as heavy metal ion scavengers. Aluminum powder was found to be less effective in the removal of cupric and ferric ions from glycol solutions than zinc. Both 1100 and 3003 series aluminum alloys were found to be free of any type of corrosion damage in uninhibited and contaminated (with Cu and/or Fe) glycol (ethylene and propylene) solutions at temperatures up to 130°C when zinc powder is added. Even at 160°C the aluminum corrosion resistance in such solutions still seems to be acceptable (although marginally so)."

"In addition to being an effective heavy metal ion scavenger, zinc powder was also found to protect aluminum from corrosion attack in ethylene and propylene glycol solutions with NaCl present. This is attributed to a cathodic protection type of mechanism rendered by the floating zinc powder in solution."

"We have determined that zinc powder (2000 ppm) can be safely added to Inhibitor Formula II. The combined use of inhibitors and scavengers was found to provide excellent corrosion protection to aluminum. The corrosion rate was found to be less than 0.2 mpy at 130°C with Cu^{+2} , Fe^{+3} and Cl^- present."

Heat Pipe Corrosion

Heat pipes can be used for solar collection applications related to electric power generation; they operate at temperatures up to 300C. Thus, one of the materials problems being studied is corrosion at high temperature in pure water in sealed tubes under essentially oxygen-free conditions. Corrosion results in hydrogen generation, which is detrimental to heat pipe performance. Corrosion data are summarized in a report⁽⁰¹¹⁴⁾ and two similar articles^(0014,0015). Corrosion rates have been measured at 245C for copper alloys and stainless steels⁽⁰¹¹⁴⁾: Copper (0.05 mpy), CDA 715 (0.048 mpy), Monel 400 (0.03 mpy), Inconel 600, Incoloy 800, and 316SS (0.012 mpy) and 430SS (0.007 mpy). Extended test data were compiled from several literature sources⁽⁰¹¹⁴⁾. The best extended test data with no performance degradation of heat pipes were 9,700 hours for copper at 150C and 7000 hours at 250C. Data are also given to show that nickel (Ni 200) is unacceptable at 30C-90C, and aluminum alloys (1100 and 6061) were not acceptable at 140C. Data for stainless steels (2 years at 149C for 304SS, 2000 hours at 250C for 316SS, and 665 hours at 300C for 347SS) indicate that the protective nature of the oxides formed increased in the order 304SS, 347SS, and 316SS.

Automotive Applications

Introduction

Most of the prior information on corrosion in multimetal systems using inhibited ethylene glycol as a heat transfer fluid is based on over 40 years experience in the related application of cooling internal combustion engines. Most of the information pertains to the large automotive application, although some information relates to cooling diesel engines for locomotives and cooling aircraft engines.

The literature on automotive coolants is a valuable source of information on inhibitors. However, the value of the quantitative data on corrosion is sometimes of limited value because of the proprietary nature of inhibitors used in various commercial coolants. Also, the conditions of use of automotive coolants, which affect life, are sufficiently different as to make direct extrapolation to solar collector applications difficult.

Literature Review Through 1965

A comprehensive review of corrosion of metals by ethylene glycol solutions was prepared by Battelle Columbus Laboratories for the Defense Metals Information Center (DMIC). The review covers the available literature through 1965 and was published as DMIC Report 216⁽⁰⁰⁷⁶⁾. The patent literature was reviewed to identify probably proprietary commercial inhibitor combinations. Available quantitative data on corrosion rates from research reported in the literature were tabulated for copper, brass, steel, cast iron, solder, aluminum and several miscellaneous metals, and conditions such as glycol concentration, temperature, pH, aeration, and inhibitor concentration covering corrosion in ethylene glycol and is organized as follows with reference to Tables in DMIC report:

- Uninhibited solutions (Table 4)
- Borax system (Table 6)
- Sodium Benzoate - Sodium Nitrite system (Table 7)
- Triethanolamine phosphate, sodium mercaptobenzothiazole (Table 8)
- Soluble oil (Table 9)
- Chromate (Table 10)
- Miscellaneous inhibitors (Tables 11 and 12)

The corrosion data were tabulated as mils/year (average) derived mostly from the weight loss data reported with only a few references to non-uniform corrosion and the corrosivity of the water used. Thus, it is necessary to refer to the original literature to evaluate the applicability to solar collector corrosion. Several of the more pertinent literature

references from the DMIC Report (51 references including patents) are included in the data bank and arranged below by year of publication for cross-reference:

<u>Year</u>	<u>DMIC References</u>	<u>Accession Reference</u>
1965	(DMIC Report 216)	0076
1964	10	0027
1963	42	0137*
1962		
1961	32, 33	0023, 0024
1960	4, 16, 44	0021, 0022, 0026
1959	49, 13, 14	0025, 0082, 0083
1958	7, 19	0085, 0086, 0147*
1957	17, 6	0091, 0091
1956	15, 36	0092, 0093
1950-1955	5, 9, 38, 39	0084, 0087, 0088, 0089
1945-1949	1	0078

* Diesel Locomotive

A good qualitative review (no corrosion data) of inhibitors through 1963 is contained in a book by Bregman in Chapter 4⁽⁰¹³⁷⁾ on various cooling systems (automotive, diesel locomotive, and "once-through" systems covering residential, municipal, hot water heaters).

Standards

ASTM Standards. Standard tests and procedures have been developed for evaluating automotive engine coolants, and a knowledge of these standards is essential for proper interpretation of corrosion data obtained by these tests. The following ASTM standards are pertinent:

<u>ASTM Standard Number</u>	<u>Reference No.</u>
D 1121-72 (reserve alkalinity)	0154
D 1176-71 (sampling)	0153
D 1177-65 (freezing point)	0156
D 1287-78 (pH)	0157
D 1384-75 (glassware test)	0140
D 2570-73 (simulation test)	0139
D 2758-78 (dynamometer test)	0158
D 2847-78 (vehicle test)	0159

The ASTM tests are used in the development of inhibitors for automotive antifreeze and involve a standard metal test specimen package, corrosive water (100 ppm each of chloride, sulfate, and bicarbonate ions) and other conditions. Glassware or beaker-scale tests are for 336 hours at $190\text{F} \pm 5\text{F}$ ($88\text{C} \pm 2\text{C}$) with static aerated solution; other tests are with flowing solution for various specified periods (e.g., 700 hours for dynamometer tests). It should be noted that the test temperatures in the ASTM standards have increased since 1965 and the appropriate revision should be consulted. The use of standard test panels (1 inch by 2 inches) provides some indication of corrosion rates, which are usually reported as weight loss. The arrangement of panels in the test fixture is related to automotive use; the copper, solder, and brass panels are galvanically coupled by brass spacers and electrically insulated from the steel, cast iron, and cast aluminum panels, which are galvanically coupled with steel spacers. Some caution is needed in interpreting the precision of corrosion rates in ASTM tests, which can vary by a factor of four or more in repeatability tests by a single laboratory and even more in reproducibility by several laboratories with the same antifreeze. Variations result from differences in specimen composition, grain structure, surface finish, and the random nature of corrosion phenomena (0140, 0158).

British Standards. In 1959 three types of inhibitor for ethylene glycol automotive coolants were covered by British Standards:

BS 3150:1959 Type A

Triethanolamine orthophosphate 2 wt %

Phosphoric acid 9.5 wt %

Sodium mercaptobenzothiazole 0.2 wt %

BS 3151:1959 Type B (0183)

Sodium benzoate 6 wt %

Sodium nitrite 0.5 wt %

BS 3152-1959 Type C

Sodium tetraborate (borax) 2.7 wt %

The above concentrations (in weight percent) are based on concentrated ethylene glycol and are selected on the assumption that the dilution will not be below 20% ethylene glycol solution. (U.S. commercial antifreeze formulations are predicated on dilution to 50% ethylene glycol.) Available corrosion data relating to the three types of British antifreeze were collected in tabular form in the aforementioned DMIC Report⁽⁰⁰⁷⁶⁾.

British test methods for evaluating corrosion inhibition of antifreezes are covered in BS 5117:1974⁽⁰¹⁸⁴⁾ and are generally similar to U.S. methods (ASTM standards).

U.S. Military Standards. According to DMIC Report No. 216⁽⁰⁰⁷⁶⁾, one of the best overall inhibitor systems appeared to be the U.S. Military System of borax, MBT, and phosphate (Specification FS 0-1490a). This inhibitor contains 75 percent borax, 15 percent MBT, and 10 percent disodium phosphate and is added at the rate of 10 oz to 21 quarts of water. This gives a water solution concentration of 1.7 percent borax (sodium tetraborate), 0.1 percent MBT (sodium mercaptobenzothiazole), and 0.06 percent disodium phosphate. In 50% ethylene glycol at the above concentration, excellent protection is given to all cooling systems, including those containing aluminum alloys.

Water Quality

The quality of the water used to dilute commercial automotive antifreeze solutions affects the corrosion rates obtained with and without inhibitors and was examined in a 1959 study⁽⁰¹⁶⁹⁾. Although use of distilled water is recommended, the assumption is that auto owners will use readily available tap water. The same may be true in domestic solar applications unless there is economic justification and a concerted education program to use good quality water.

The chloride content of U. S. water supplies based on U. S. Geologic Survey data for 141 major cities (representing 89,000,000 of the total U. S. population in 1952) as summarized in the above study⁽⁰¹⁶⁹⁾ was:

<u>Chloride ppm</u>	<u>Population percent</u>	<u>Cumulative percent</u>
0-5	23.95	23.95
5-10	29.35	53.30
10-25	24.60	77.90
25-30	11.95	89.85
50-100	8.05	97.90
100-200	1.37	99.27
200-500	0.69	99.60
>500	0.04	100

The ASTM D-1384-55T test method (glassware) was used to compare 14 different commercial antifreezes (composition not given) in distilled water, Detroit Tap Water (8 ppm Cl^- , 19 ppm SO_4^{-2}), and corrosive water (100 ppm Cl^- , 200 ppm SO_4^{-2}) for corrosiveness toward cast iron and cast aluminum. Relative performance was shown for the purpose of selecting the best four antifreezes for further tests of antifreeze concentration (i.e., dilution of inhibitors) and effect of chloride ion concentration, and correlation of ASTM glassware test with a simulated service test and a fleet test using Detroit tap water.

Recent Literature

Service Life of Automotive Coolant. There are several general articles covering practical information on the use of commercial automotive ethylene glycol coolants, such as ASTM publication 120B (1974) (0151) which discusses maintenance, cleaning compounds, artirusts, and stop-leaks. Other general articles by Beynon et al of Union Carbide Corporation emphasize the importance of increase in boiling point with ethylene glycol (0150) and year-round use for corrosion protection of the coolant system (0149). It is interesting to note that antifreeze manufacturers recommend that the coolant be replaced each year (0119) (some auto manufactures recommend 1 to 3 years for initial fill) for adequate corrosion protection based on field surveys in 1965 (0182) and 1975 (0138).

Pump Corrosion. Cavitation-corrosion is a potential problem with cast iron auto coolant pumps, but aluminum is more prone to damage and some antifreeze formulations increase cavitation-erosion damage over that obtained with plain water (0181).

Inhibitors. The types and concentrations of inhibitors used in commercial antifreeze are considered proprietary. Methods of chemical analysis for inhibitors in antifreeze are available in standard texts (0153). However, no published literature has been found that correlates commercial products by brand name and chemical analysis with corrosion data. Thus, corrosion data reported for "antifreeze A", "antifreeze B", etc, have limited value unless the inhibitors are identified.

One recent article (1973) by Walker of General Motors Corporation (0167) does provide some information on composition of inhibitors and corrosion data for typical engine block materials of cast iron and aluminum alloys (390 and 319) with alloy compositions specified. The corrosion rate data are of interest since they relate to high temperatures (150 F - 275 F).

Table 7 shows the chemical analyses of 21 antifreeze formulations that are commercially available. Table 8 indicates the function of the various inhibitors identified in Table 7. The concentrations in Table 7 are grams of salt (calculated as sodium salt) per liter of ethylene glycol. Test solutions were prepared by diluting the ethylene glycol concentrate to 44% by volume with distilled water containing 100 ppm each of chloride, sulfate, and bicarbonate ions (typical corrosive water used in ASTM tests of automotive coolants).

Corrosion rates for cast iron (A-159) increased 2 1/2 times from 180 F to 275 F for antifreeze A and B (Table 7) to 0.5 mpy and 0.7 mpy respectively. Corrosion rates increased faster with temperature for aluminum alloy 390 (17% silicon) and were 3 mpy for antifreeze B (low phosphate) and 40 mpy for antifreeze A (high phosphate) at 275 F metal surface temperature in a simulated service test. It was stated by the authors that corrosion rates increased when nucleate boiling occurred (220 F) while the metal surface temperature was increased to 275 F to simulate the

heat rejecting surface in an automotive engine at high heat flux rate (i.e., high engine power). Data are presented on corrosion rate of aluminum alloy 319 at high metal surface temperature of 270 F for antifreezes A, B, C and D (Table 7) which show low corrosion rate (0.15 mpy) for B and high corrosion rate 19-43 mpy for A, C, and D. Other studies with phosphate show that the corrosion rate of aluminum alloy 319 increases logarithmically with phosphate concentration at high-temperature, heat-rejecting surfaces. The corrosion rate was even higher with additional inhibitors in antifreezes A and C (Table 7).

Studies of coolant performance at high temperatures up, to 300 F⁽⁰²¹⁵⁾, have been reported which show different corrosion rates for three different antifreeze compositions (inhibitors not identified) evaluated by standard ASTM tests (glassware, dynamometer, vehicle). The quantitative data are of limited value except for relative comparisons of the effect of temperature and correlation of ASTM test procedures, since the inhibitors are not specified.

Recent British studies (1977)⁽⁰¹³⁴⁾ to develop new inhibitors provide quantitative corrosion data using sodium sebacate and benzotriazole mixtures compared to the older British formulation of triethanolamine and sodium mercaptobenzothiazole. Earlier studies⁽⁰⁰⁵⁰⁾ provided quantitative corrosion data for cast iron and aluminum in uninhibited solutions of water, ethylene glycol, propylene glycol, glycerin, methanol, and methoxypropanol and data on the stability of the various solutions.

Chemical Stability of Coolants. The above mentioned British study⁽⁰⁰⁵⁰⁾ contains a good review of the state of knowledge regarding chemical stability of ethylene glycol and other potential antifreeze materials. Quantitative data are provided on pH change after 50 days at 70 C for various types of uninhibited coolants with and without the presence of metals (cast iron and aluminum alloys). The results are correlated with corrosion data.

TABLE 7 - Comparative Chemical Analysis
of Antifreeze Formulations(0167)

Antifreeze	Grams of Salt*per liter of Ethylene Glycol					
	Phosphate	Borate	NaMBT	Nitrate	Silicate	Arsenate
A	68.5		7.7			
B	5.0	11.5	3.2	2.5	2.5	
C	19.2	20.2				
D		22.4	1.7			
E	11.8	11.2	3.1	2.8	2.0	
F		29.3	1.1			0.4
G	5.0	12.8	1.8	2.4	3.6	
H	5.0	14.0	1.2			1.6
I	44.5		0.7			
J	11.1	11.6	3.4	2.8	2.3	
K		14.3	2.8			0.9
L		26.7		1.7		
M	12.1	14.7				
N	3.2		1.4	5.3		
O	44.5		3.8			
P	7.6	15.8	2.7			
Q		26.0				0.5
R	16.5	20.8				
S		22.0				0.5
T		16.1	2.0			0.3
U	4.5	12.8	3.0	2.5	3.6	

*The results are reported as the sodium salts described in Table 8. This was done in order to show comparisons even though salts with different cations were used in several antifreezes.

TABLE 8 - Function of Inhibitors Used in Antifreezes⁽⁰¹⁶⁷⁾

Inhibitor	Function
Sodium tetraborate (borax) $\text{Na}_2\text{B}_4\text{O}_7 \cdot 5\text{H}_2\text{O}$	Has strong buffering action and provides some protection for iron and steel.
Sodium mercaptobenzothiazole (NaMBT) 50% aqueous solution of $\text{C}_7\text{H}_4\text{NS}_2\text{Na}$	Protects copper and brass.
Sodium metasilicate $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$	General inhibitor, provides some protection for all cooling system metals and affords protection against cavitation damage.
Sodium orthophosphate $\text{Na}_3\text{PO}_4 \cdot 12\text{H}_2\text{O}$	Protects steel, iron, and aluminum, and affords protection against cavitation damage.
Sodium nitrate NaNO_3	Protects iron to some degree, but is mostly effective for solder and aluminum.
Sodium orthoarsenate $\text{Na}_3\text{AsO}_4 \cdot 12\text{H}_2\text{O}$	General inhibitor, but is mostly effective for aluminum.

In a previously mentioned U.S. evaluation of high temperature coolants⁽⁰²¹⁵⁾, some incidental data on chemical stability was presented. In an ASTM glassware test of uninhibited ethylene glycol for 336 hours, glycol oxidation, as measured by glycolate formation, was 50 ppm at 180 F and 600 ppm at 300 F. For an inhibited ethylene glycol the oxidation was only 12 ppm at 180 F and 92 ppm at 300 F. These increases in glycolate did not significantly affect the pH.

Domestic and Commercial Applications

An excellent review of corrosion problems that can be encountered in water systems in all types of buildings - residential, commercial, institutional, and industrial - was recently presented by Sussman⁽⁰¹⁰⁹⁾. Even after many years of experience with "conventional systems", corrosion-caused operational difficulties and equipment failures occurred which might have been prevented based on available technology and knowledge. Solar water heating systems (not specifically discussed in this paper) should not be expected to be less trouble-free, even when fully developed.

A series of papers was presented at the British Joint Corrosion Group Symposium on "Corrosion and Prevention in Central Heating Systems" in 1970 (References 0122 thru 0126). These closed systems containing mild steel radiators and boilers with copper piping were filled with tap water and inhibitors for operation at 145F to 185F. Hot water heating systems are widely used in England and corrosion related failures, while not prevalent, can occur by radiator corrosion within 3 to 9 years (14% and 61% of failure incidents). In addition to comprehensive discussion of corrosion mechanisms and factors affecting corrosion and research data, the symposium discussion of inhibitors used and their possible toxicity in relation to potable water supplies provides excellent background information for solar liquid heating systems.

Cast aluminum radiators are finding use in Germany for residential heating systems, with a few instances of corrosion failure⁽⁰⁰¹²⁾ and some test results are reported⁽⁰⁰⁴²⁾.

Copper and copper alloys are widely used in the U.S. in hot and cold potable water systems with excellent results, but copper is not immune to corrosion in certain aggressive waters as indicated in a Copper Development Association publication⁽⁰⁰²¹⁾. Corrosion of copper and copper alloys in water under a variety of conditions encountered in heating and cooling applications has been reviewed by the British Non-Ferrous Metals Research Association⁽⁰⁰¹¹⁾, including some information on corrosion of soldered joints⁽⁰⁰¹¹⁾⁽⁰⁰¹⁹⁾.

Corrosion data for various copper alloys, stainless steel (Type 416), and galvanized iron in potable water at room temperature over a 15-year period indicated average corrosion rates in the range of 0.005 to 0.2 mils/year with pitting less than 1 mil/year, except for a few instances of pitting rates to 5 mils/year for relatively mild conditions⁽⁰⁰³²⁾. One example of corrosion of a stainless steel screen (Type 304) in potable water in a water plant was reported⁽⁰⁰³⁴⁾. Corrosion of stainless steel (Type 304 and others) in tap water in domestic heating systems has been studied for gas-fired heat exchangers⁽⁰⁰⁴¹⁾ and brazed joints^(0033, 0035).

Copper-sheathed immersion heater elements for domestic water used in Australia can fail rapidly (three months) in aggressive water or last indefinitely in other water supplies⁽⁰⁰³⁸⁾. The heat flux can produce sheath temperatures up to 130C in water at 98C with unscaled elements; much higher sheath temperatures resulted from scale (CaCO_3 and MgCO_3) in hard water, with crevice corrosion occurring at breaks in the scale (i.e. deposit induced corrosion). Similar problems could be expected with an open-loop solar water heater at high stagnation temperatures with poor water quality.

A rather unusual example of pitting corrosion in a chilled water unit has been reported for copper tubing filled with antifreeze, drained, ends sealed and stored for 12 months outdoors⁽⁰⁰⁷⁴⁾.

Organic and inorganic coatings, and cathodic protection are considerations in corrosion protection for various metals used in hot water tanks (domestic and industrial) when nitrogen blanketing is not used to exclude oxygen⁽⁰⁰⁰⁸⁾.

A French study relates to corrosion of steel in hot water distribution systems⁽⁰²⁰⁵⁾.

Industrial Applications

Introduction

There is extensive literature on corrosion in a variety of industrial applications. Of particular interest is information relating to metals and alloys that might be used in solar collector systems, with emphasis on data for long service life (e.g. 20 years) in specific fluid environments and high temperature use supported by practical experience. Most of the corrosion literature on industrial systems are reviewed in numerous standard reference books on corrosion. Only a few selected literature accessions have been made that contain specific information of interest. For example, long-term (16 years) corrosion rate data for several aluminum, copper, and steel alloys in sea water and fresh water provide baseline data⁽⁰⁰⁴⁸⁾. Fundamental studies of corrosion of aluminum at 25C⁽⁰²⁰²⁾ and 50C⁽⁰⁰⁴⁰⁾ provide data on the effect of pH, dissolved oxygen, chloride ion, and sulfate ion for comparison with extensive data on corrosion in high purity water.

High Purity Water

Aluminum alloys (e.g., 1100, 3003) as tanks, tube and pipe have been used extensively in the chemical industry for distilled water storage and distribution⁽⁰²⁰¹⁾ and at temperatures up to 250F in power plants for handling steam and steam condensate containing carbon dioxide and oxygen where aluminum is favored⁽⁰²⁰¹⁾.

There are extensive data on the corrosion resistance of aluminum (e.g., 1100 and other alloys) in high purity water at high temperatures (to 300C) as related to use in nuclear power reactors. Pertinent research corrosion data is contained in literature from

the late 1950's (0192, 0196, 0197, 0198, 0200). The information through 1971 has been reviewed (0214). More recent information (1970's) on aluminum (0188) and aluminum alloys (0036) as well as information on copper, steel, and stainless steel in high purity water at up to 204 C (0199) is pertinent.

Cooling Towers

A survey of materials and corrosion performance in dry cooling tower applications for central power stations has been made by Battelle's Pacific Northwest Laboratories, including a review of pertinent corrosion technology (0121). Other information on cooling towers used in industry covers aluminum (0195) and steel (0010)(0104). Water treatment is important in cooling towers and there is considerable corrosion control technology available that could be applicable to open-loop solar collection systems for industrial applications.

Heat Exchangers

Heat exchangers are widely used in industry and extensive corrosion data exists covering a wide variety of fluids, metals and alloys, high temperature conditions, service life and economic choices. Copper alloys are widely used in heat exchangers (0006, 0009, 0101). A literature review of corrosion for aluminum, copper, and steel alloys contains references to data pertinent to heat exchangers and fluid flow effects (0121).

APPENDIX A

LITERATURE ACCESSIONS

SURVEY OF STATE OF THE ART
OF SOLAR COLLECTOR CORROSION
PROCESSES AND RELATED TECHNOLOGY
PERTINENT TO SOLAR HEATING AND
COOLING SYSTEMS

0001

Beynon, E.

"Inhibited Ethylene Glycol as the Solar Nexus"

Union Carbide Corporation, Paper presented at the International Corrosion Forum Devoted Exclusively to the Protection and Performance of Materials, March 14-18, 1977, San Francisco, Paper No. 171

Al (Antifreeze); Cu (Antifreeze); Fe (Antifreeze)

The inhibitor technology built into existing well-inhibited ethylene glycol base fluids is quite capable of protecting flat plate solar collector systems from corrosion. Current formulations are designed for multimetal systems, but as solar systems become more standardized, it will be possible to optimize the inhibitor package for a given combination of metals. Regardless of the inhibitor system used, a long trouble-free service life is dependent upon good design features, proper selection of materials of construction, and above all, a consistent monitoring and maintenance program for the heat transfer fluid. The suitability of ethylene glycol is attested to by the many flat plate collector systems operating successfully today with well-inhibited ethylene glycol solutions.

0002

Giner, J., Cocks, F. H., Wong, D.

STUDY OF CORROSION AND ITS CONTROL IN ALUMINUM SOLAR COLLECTORS

Giner, Inc., Waltham, Massachusetts, Annual Progress Report, (June 1, 1976-May 31, 1977) June 1, 1977, Contract EY-76-C-02-2934 (COO/2934-4)

Al (Antifreeze)

The corrosion resistance of aluminum alloys in water/ethylene glycol mixtures has been studied in detail under experimental conditions directly relevant to the operation of existing solar thermal energy collector systems. An aqueous ethylene glycol solution with 35% ethylene glycol by volume was chosen as the typical heat transfer medium throughout the entire program. The scope of this study covers the following range of conditions: (1) four different aluminum alloys (i.e. 99.9%, 1100, 3003 and 3004 series aluminum); (2) 70°-210°F (20°-100°C); (3) stagnant solution, laminar and turbulent flow; (4) under N₂ and air; (5) in the presence of contaminants (e.g. Cl⁻, Cu⁺² and Fe⁺³ ions); (6) effects of ethylene glycol decomposition products.

0003

Thompson, Paul D., Hayden, Michael B.

CORROSION PROBLEMS IN SOLAR ENERGY SYSTEMS

U. S. Department of Agriculture, Paper presented at the International Corrosion Forum Devoted Exclusively to the Protection and Performance of Materials, March 14-18, 1977, San Francisco, California, paper No. 63

Al (Water); Cu (Water); Fe (Water)

Solar heat collection will gain wide acceptance only if the operating life of solar heating systems can be long enough to repay the cost of the initial investment. The key factor that limits operating life is corrosion, particularly the corrosion of aluminum absorbers. The prevention of corrosion requires a combination of correct system design and appropriate water treatment.

0004

Popplewell, James M.

CORROSION PREVENTION IN ALUMINUM SOLAR SYSTEMS

Paper presented at the International Corrosion Forum Devoted Exclusively to the Protection and Performance of Materials, March 14-18, 1977, San Francisco, California, paper No. 170

Al (Water, Antifreeze); Cu (Water, Antifreeze); Fe (Water, Antifreeze)

This paper describes some likely corrosion problems with aluminum flat plate collectors in multi-metal solar systems. Prevention of corrosion using a variety of approaches is discussed. These include "gettering" of heavy metal ions and the use of non-aqueous heat transfer fluids. Topics discussed are: The flat plate collector systems; corrosion of internal surfaces; corrosion prevention in aqueous systems; corrosion prevention in aqueous/antifreeze systems; and non aqueous fluids.

0005

Kononova, M. D., Yudina, V. V., Arutyunyan, R. V.
 DETERMINATION OF THE CRITICAL CONCENTRATION OF CHLORINE IONS FOR INITIATING
 PITTING CORROSION OF CARBON STEELS IN NEUTRAL AQUEOUS SOLUTIONS
 Protection of Metals, 10 (4), July-August 1974, pp 387-388

Iron (Water)

The greatest amount of damage to heat exchange equipment made of carbon steel is caused by pitting corrosion due to the presence in the water of chlorine ions in concentrations exceeding a critical value. The tendency of carbon steel toward pitting corrosion was evaluated from the potential for the formation of pits, determined by the breakdown method, and from current/time curves measured at a constant potential. An analysis of the electrochemical data obtained attests to the fact that, with concentrations of chlorine ions exceeding 10 mg/liter, an effective way to prevent the pitting corrosion of heat exchange equipment from the side of the circulating cooling water is to blow it through with nitrogen.

0006

Akol'zin, P. A., Bogachev, A. F., Grishanina, N. I., Kurnosova, V. M.
 DECREASING CORROSION OF BRASS TUBES IN HEAT EXCHANGERS BY SILICATE TREATMENT
 OF MAKEUP WATER FOR A HEATING NETWORK
 Thermal Eng, 19, (8), August 1972, pp 80-84

Cu (Water)

Results of an investigation into corrosion resistance of materials for heat exchangers with water treatment by sodium silicate are presented. It is concluded that sodium silicate is an inhibitor of corrosion not only for ferrous metals but also nonferrous metals, in particular brass and copper. Satisfactory service of brass tubes in turbine condensers operating at deteriorated vacuum can be ensured when deaeration of makeup water for the heating network is not disturbed and when overall iron concentration in the water is not higher than 400-500 mg/kg.

0007

Korpics, Charles J.

AROMATIC TRIAZOLES INHIBIT CORROSION OF COPPER AND COPPER ALLOYS

Mater Performance, 13 (2), February 1974, pp 36-38

Cu (Water, Antifreeze)

Modes of protection afforded copper and copper alloys by the triazoles may be classified as atmospheric protection, solution protection and vapor phase protection, demonstrating the unique versatility of benzotriazole and tolyltriazole. The protective mechanism is due to the formation of a relatively impermeable polymeric complex on the copper surface. Applications include heat exchangers, desalination and refrigeration systems, and in coolants for automobile engines. 3 refs.

0008

Singleton, Walter T., Jr.

PROTECTING HOT WATER TANKS FROM CORROSION

Mater Prot Performance, 12 (11), November 1973, pp 41-43

Fe (Water)

All dissimilar metal should be insulated from the tank shell regardless of whether there is an interior lining, cathodic protection, etc. Generally, when a proven and properly applied protective coating is used, cathodic protection is not required. When organic linings are used in conjunction with internal heat exchangers of dissimilar metal, the exchanger must be insulated from the steel tank surfaces.

0009

Hager, S. F., Herman, R. S.
PERFORMANCE OF COPPER ALLOY 194 WELDED TUBE IN HEAT EXCHANGERS
Heating, Piping & Air Conditioning, 41 (11), November 1969, pp 98-103

Cu (Water)

High strength, high thermal conductivity, and good corrosion resistance was proved by extensive tests in aggressive environments. Article emphasizes the tube performance in terms of corrosion resistance as related to specific environmental conditions at each test site. Thirty utilities were participating in the tests of welded condenser tube, and the 45 different test sites involved represent a wide range of conditions in terms of cooling water problems, velocities, and compositions.

0010

Donohue, J. M., Nathan, C. C.

UNUSUAL PROBLEMS IN COOLING WATER TREATMENT
Chemical Engineering Progress, 71 (7), July 1975, pp 88-93

Iron (Water)

Proper water treatment is the key to handling some of the more difficult aqueous environments in which steel heat exchangers are proving to be valuable. These environments include high temperature cooling water, sewage treatment plant effluents, ammonia plant cooling systems, low hardness make-up water, and brackish make-up water. This article examines non-chromate corrosion inhibitors, along with other aspects of water quality control, in these rugged environments.

0011

Campbell, Hector S.
CAUSES AND PREVENTION OF CORROSION OF COPPER AND ITS ALLOYS IN HEATING AND
AIR CONDITIONING PLANT
Build Serv Eng, 40, August 1972, pp 109-117

Cu (Water)

The various forms of corrosion that can occur in copper and copper alloys, used as the materials of construction of heat exchangers, and of heating and ventilating equipment, are related to the conditions of service and to indicate how they can be avoided by correct choice of alloy, correct design of components and correct operation of equipment.

0012

Witt, C. A.
RESULTS OF AN ENQUIRY INTO CORROSION DAMAGE WITH ALUMINIUM RADIATORS
Aluminium and Supplement in English, 54 (8), August 1978, pp 528-529 (17-18)

Al(Water)

Very few instances can be cited where the corrosive effect from heating water upon the aluminium is to be regarded as a cause of damage. Apart from mishaps attributable to defects in material, defects consequent upon internal changes in the system, faults in design and inappropriate methods of operation, gassing is cited as the principal fault. As already noted of course, gassing may generally be brought to a halt simply by adding inhibitors to the heating water.

0013

Weidemann, R.

CORROSION BEHAVIOUR OF ALUMINIUM ROLL-BOND ABSORBERS FOR SOLAR COLLECTORS
 Aluminium and Supplement in English, 54 (8), August 1978, pp 501-505

Al(Water, Antifreeze)

For the use of aluminium in solar collectors, the corrosion resistance is of decisive importance. The behaviour of 99.3% purity aluminium and AlMn1.5 towards different heat-transfer agents, namely water with inhibitor additive, inhibited water-glycol mixtures and water-glycol mixtures and water-free media, was tested in the laboratory. Testing was carried out both electro-chemically by potential measurements and by assessment of experiments conducted on absorber circulation systems. Investigations on aluminium roll-bonded absorbers which had been used in practice supplemented laboratory tests and the results of the latter were confirmed. The use of aluminium for solar collectors is in general, justified by these findings. The required corrosion resistance of aluminium towards heat transfer media can be assured by appropriate choice of the latter. The suitability of different systems is discussed.

0014

Gervais, R. L., Taketani, H., Babel, H. W., Pittinato, G. F.

MATERIAL CONSIDERATIONS INVOLVED IN SOLAR ENERGY CONVERSION
 Sampe Quarterly, 6 (2), January 1975, pp 14-22

Al(Water); Cu(Water); Fe(Water)

Recent investigations of the application of solar energy to electrical power generation which have proved encouraging in certain geographic locations in the United States are discussed. These encouraging findings have been due, in part, to the application of aerospace - related technology and systems engineering to critical elements of the solar energy system which have heretofore proven economically unrealistic. Results to date are given on two specific material areas that have benefited from this technology transfer, the heat pipe and the solar mirror (concentrator) subsystems.

0015

Gervais, R. L., Taketani, H., Babel, H. W., Pittinato, G. F.
SOME MATERIAL CONSIDERATIONS INVOLVED IN THE APPLICATION OF SOLAR ENERGY
TO ELECTRIC POWER GENERATION
Sampe Journal, 12 (2), March/April 1976, pp 12-19

Al(Water); Cu(Water); Fe(Water)

Recent investigations of the application of solar energy to electrical power generation which have proved encouraging in certain geographic locations in the United States are discussed. These encouraging findings have been due, in part, to the application of aerospace-related technology and systems engineering to critical elements of the solar energy system which have heretofore proven economically unrealistic. Results to date are given on two specific material areas that have benefited from this technology transfer, the heat pipe and the solar mirror (concentrator) subsystems.

0016

Humphries, T. S., Deramus, G. E., Jr.
CORROSION INHIBITORS FOR SOLAR HEATING AND COOLING SYSTEMS
National Aeronautics and Space Administration, George C. Marshall Space
Flight Center, Huntsville, Ala., Technical Note, NASA TN-D-8409, N77-17198,
February 1977, 20 p.

Al(Water, Antifreeze); Cu(Water, Antifreeze); Fe(Water, Antifreeze)

Problems dealing with corrosion and corrosion protection of solar heating and cooling systems are discussed. A test program was conducted to find suitable and effective corrosion inhibitors for systems employing either water or antifreeze solutions for heat transfer and storage. Aluminum-mild steel-copper-stainless steel assemblies in electrical contact were used to simulate a multimetalllic system which is the type most likely to be employed. Several inhibitors show promise for this application.

0017

Scott, Jerome E.

THE SOLAR WATER HEATER INDUSTRY IN SOUTH FLORIDA: HISTORY AND PROJECTIONS
Solar Energy, 18, 1976, pp 387-393

Fe(Water); Cu(Water)

Solar water heaters were a commercial success because they offered homeowners a system for heating water which was economically superior to either electric or gas units. In 1938 a solar user could recover his initial investment from fuel cost savings in less than 2 yr and anticipate a seemingly endless supply of free hot water. By the early 1950s, however, three primary forces combined to reduce the industry to a few firms whose principal solar activity was the repair or replacement of water storage tanks. (1) The rapid decline in electricity rates along with the increasing first cost of installing a solar unit reversed the economic advantage of the solar approach. (2) The widely held opinion that solar systems would last indefinitely was abruptly altered when the water storage tanks began to develop leaks. Tank failures often caused considerable damage and became increasingly costly to repair. (3) The emergence of the large scale builder-developer largely removed the choice of hot water system from the individual homeowner. Under certain potentially realistic first-cost estimates and projected fuel price increases, a strong economic argument in favor of solar water heaters can be made. Further, homeowner attitudes toward solar units are generally positive and receptive to considering the solar alternatives.

0018

BENZOTRIAZOLE: AN EFFECTIVE CORROSION INHIBITOR FOR COPPER ALLOYS

Copper Development Association, Inc., New York, New York, Application
Data Sheet, 108/9

Cu(Water, Antifreeze); Al(Water, Antifreeze); Fe(Water, Antifreeze)

This data sheet reviews the literature and patents on the use of benzotriazole as a tarnish and corrosion inhibitor for copper and copper alloys. It covers literature on the subject since 1957 in six application areas: Lacquers, Varnishes and Insulation, Storage and Packing, Lubricants and Sealants, Electrolytic Processes, Cleaning Solutions, and Water Systems.

0019

COMPARISON OF COPPER AND STEELS FOR SOLDERED PLUMBING SYSTEMS

Copper Development Association, Inc., New York, New York, Application
Data Sheet, 162/0

Cu(Water); Fe(Water)

A comparative evaluation was made of the three materials available for soldered plumbing systems: copper, type 409 (titanium-chromium) steel, and galvanized steel. The points of comparison were reliability, fabrication time, solder consumption, creep strength, shear strength, and corrosion resistance.

Joints in copper tubing can be made more reliably than joints of the other two metals. Joints in galvanized assemblies require more solder and take longer to make than joints with the other two metals. The superior wetting and flow characteristics of solder on copper lead to the highest percentage of joint filling by the solder. Compared to soldered joints with galvanized steel or copper, those with type 409 steel have considerably lower strength under loads applied for extended periods of time. In short-time shear tests, soldered copper was fifty percent stronger than the other two systems. No serious corrosion was observed on any of the materials after a fifteen week exposure in hot water, although a considerable buildup of scale occurred on the galvanized steel.

0020

Cohen, Arthur

COPPER FOR HOT AND COLD POTABLE WATER SYSTEMS

Heating/Piping/Air Conditioning, May 1978 (Reprint)

Cu(Water); Fe(Water)

To provide dependable potable water systems for commercial, industrial, or residential buildings, the designer must consider a number of variables. A major factor is the quality of the potable water delivered to the site. Equally important are the materials of construction, which should be both corrosion resistant in water service and have suitable properties to meet design, installation, and building code requirements. In addition, the overall economy of the installation, the amortization of the initial cost, and the annual maintenance expense require careful evaluation. Problems may arise if the installation does not follow good design practices. Undersized components can lead to excessive turbulence, resulting in a noisy system that is likely to develop erosion corrosion.

0021

Collins, H. H., Higgins, R. I.
 THE CORROSION OF ROAD VEHICLE ENGINES BY ANTI-FREEZE SOLUTIONS--Part I
 Corrosion Prevention & Control, 2 (2), February 1960, pp 36-48

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze)

A program has been undertaken to examine the various possible reasons why an ethylene glycol solution should become excessively corrosive, and an attempt has been made to relate the findings of this work to the practical conditions of operation of road vehicles. The problem has been examined from three angles. First, the incidence of the corrosion has been considered together with its effect on the metals in the waterways in order to attempt to define the conditions conducive to the corrosion. Secondly, the variation in analysis of anti-freeze solutions throughout their service life has been studied in an attempt to decide what changes in composition have occurred in service. Thirdly, laboratory tests have been carried out in order to determine what effect changes in specific conditions can have on uninhibited ethylene glycol solutions.

0022

Collins, H. H., Higgins, R. I.
 THE CORROSION OF ROAD VEHICLE ENGINES BY ANTI-FREEZE SOLUTIONS--Part 2
 Corrosion Prevention & Control, 3 (3), March 1960, pp 41-48

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze)

It appears that anti-freeze solutions inhibited with triethanolamine phosphate and sodium mercaptobenzothiazole lose most of their phosphate and mercaptobenzothiazole content in the first two months or 4,000 miles of service. The glycol used in anti-freeze solutions is oxidised during its service life to a mixture of acids, of which formic acid is the major constituent. The rate of corrosion of the cast iron and steel in the waterways of a diesel engine using an anti-freeze solution inhibited with triethanolamine phosphate and sodium mercaptobenzothiazole may be much greater than that which occurs when water is used as the coolant: rates of 0.20 to 0.40 in./yr. have been observed on the cast iron and steel components of coolant pumps used with such an anti-freeze solution. The detailed mechanism of this rapid corrosion in an anti-freeze solution is not yet clear, but it appears that oxidation of the glycol to produce appreciable amounts of organic acid is always associated with the phenomenon: there is evidence that the pH value of the solution is, in itself, an inadequate criterion of the corrosivity of the solution and that an index equal to the difference between the total acid and the total base contents of the solution is better.

0023

Collins, H. H., Glover, T. J.

USE OF B.C.I.R.A. TEST RIG FOR EVALUATING CORROSIVITY OF ANTIFREEZE SOLUTIONS
BCIRA Journal, 9, November 1961, pp 812-819

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze)

A test rig built by the Association in the course of investigations into the mechanism of corrosion of cast iron by uninhibited aqueous glycol solutions, has been used to examine the performance of six inhibited antifreeze solutions, three to British Standards and three others. No agreed performance test at present exists and these tests were conducted to estimate the information which the Association's test rig could supply. It is suggested that the test rig might provide a suitable performance test as, from consideration of the results obtained, the test conditions appear to correspond reasonably well with average service conditions in engine waterways. Five specimens were exposed in each test, one aluminium, one bronze and three cast iron.

0024

Collins, H. H., Glover, T. J.

USE OF B.C.I.R.A. TEST RIG FOR EVALUATING THE CORROSIVITY OF INHIBITED
ENGINE COOLING WATERSBCIRA Journal, 10, 1962, pp 679-682

Al(Water); Cu(Water); Fe(Water)

It is generally recommended that engine waterways be drained of antifreeze solutions at the end of the winter. It is also desirable that the "summer coolant" should cause as little corrosion as the antifreeze solution it replaces. Tests carried out in the B.C.I.R.A. test rig have shown that the behaviour of inhibitor systems in water is very similar to that in 20 per cent glycol solutions and thus their use in summer coolants will materially reduce corrosion which could occur during the period when antifreeze solutions are not used. Each test consisted of circulating the appropriate solution at $80^{\circ}\text{C} \pm 2^{\circ}$ for 1,000 hours continuous running.

0025

Demster, N. S.

CORROSION OF ALUMINUM ALLOYS IN GLYCOL-WATER COOLING SYSTEMS

Corrosion, 15 (8), August 1959, pp 395t-398t

Al(Antifreeze); Cu(Antifreeze)

Investigation of galvanic corrosion in an aircraft oil cooler led to tests described in this paper. Corrosion mechanism on aluminum alloy 52S is discussed and results are given of tests designed to find satisfactory inhibitors. Tabular data give inhibitor systems tested. Twenty-two literature references given. Inhibitor tests involved 25 solutions tested. These tests have shown the remarkable sensitivity of an aluminum alloy to corrosion in a 30:70 glycol-water mixture when the latter contains trace amounts (0.3 to 2 ppm) of copper in solution. This applies to redistilled glycol-distilled water mixtures. Marked corrosion accentuation occurred if the distilled water was replaced by fairly pure tap water containing only 10 to 15 ppm chloride. On the basis of laboratory trials conducted on a cyclic temperature basis in ethylene glycol-distilled water mixtures, two inhibitive systems based on (1) sodium tetrasilicate plus sodium tetraborate and (2) sodium tetrasilicate plus sodium tetraborate plus sodium cinnamate can be recommended for service trials.

0026

Rowe, L. C.

SODIUM CHROMATE INHIBITOR IN AN ETHYLENE GLYCOL ENGINE COOLANT

Corrosion, 16 (6), June 1960, p 259t

Cu(Antifreeze); Fe(Antifreeze)

Laboratory tests were made to determine the suitability of sodium chromate inhibitor for ethylene glycol engine coolant. In the presence of light, chromate solutions turned green and dichromate solutions formed greenish precipitates. In the absence of light, little color change was noted. Following completion of laboratory testing, eight-month long tests were made in automobile cooling systems. Methyl alcohol and ethylene glycol antifreezes were tested separately after addition of chromates. Indications were that chromate inhibitors could be used with ethylene glycol in the absence of light in cases where a laboratory evaluation had been made of operational factors.

0027

Cessna, J. C.

PROBLEMS IN THE USE OF CORROSION INHIBITORS IN AUTOMOBILE ENGINE COOLING SYSTEMS

Materials Protection, 3 (5), May 1964, pp 37-41

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze)

Discusses corrosion problems involved in use of inhibitors in automobile engine cooling systems. Topics covered include galvanic corrosion, influence of corrosion products, temperature differences, mineral content of water, influence of dissolved gases, and limitations on inhibitor life. Also discusses selection of corrosion test for study of inhibitors, inhibitor stability, and selection of suitable container to hold the inhibitor.

0028

Mahoney, C. L.

THE INFLUENCE OF ADHESIVE COMPONENTS ON THE CORROSION OF ALUMINUM HONEYCOMB

Dexter Corporation, Pittsburg, California, Paper presented at the Fourth National SAMPE Technical Conference and Exhibition, Palo Alto, Calif., October 17-19, 1972

Al(Water)

With increased reliance on adhesive bonding in structural applications, durability in hostile environments is an increasingly important requirement. As one part of this concern, a brief investigation was made of the influence of various curing agent types in epoxide based adhesive tapes in accelerating the corrosive action of water on bonded aluminum honeycomb structures. With common curing agents, such as dicyandiamide, basic products are evolved during cure, the amount increasing greatly with increasing severity of cure conditions. Under accelerated laboratory conditions, such adhesive tapes do moderately increase the corrosion of aluminum honeycomb over levels caused by water alone. Water by itself causes sufficient corrosion of aluminum honeycomb that protection against its action is needed for strength retention over extended periods. Elimination of corrosion acceleration due to volatile adhesive components and reduction of corrosion to levels well below that caused by water can be obtained through use of honeycomb coated with selected anticorrosion additives. Good protection can also be obtained through use of anodized or corrosion inhibitor primed honeycomb.

0029

Goto, K., Ito, G., Shimizu, Y.

EFFECT OF SOME OXIDIZING AGENTS ON PITTING CORROSION OF ALUMINUM IN NEUTRAL WATER

Journal of the Japan Institute of Light Metals, 20 (2), February 1970, pp 88-94

Al(Water)

→ In the present study, the effects of oxidizing agents (such as dissolved oxygen, H_2O_2 , free chlorine, $K_2Cr_2O_7$, and $KMnO_4$) on occurrence and propagation of pitting corrosion of aluminum were investigated for the specimen placed in neutral water containing sulfate or phosphate ions as inhibitors and chloride ions as activators.

The results obtained were summarized as follows:

(1) In water containing 5 ppm of sulfate ions as Na_2SO_4 and 5 ppm of chloride ions as NaCl, the pitting corrosion was not observed for less than 80 ppm of dissolved oxygen, but it was distinctly observed at that amount of 150 ppm. When the oxygen content was more higher, corrosion occurred over the whole surface to form a boehmite film and no pitting corrosion was observed.

(2) The addition of an oxidizing agent such as H_2O_2 and freechlorine to the water, containing a certain amount of corrosion inhibitors and chloride ions, promoted the occurrence of pitting corrosion of aluminum immersed in the solution. However, the oxidizing agent such as $K_2Cr_2O_7$ acted as a passivator, by which pitting corrosion was not.

(3) Among the corrosion inhibitors, phosphate ion was more active than sulfate ion in provoking and propagating pitting corrosion of aluminum in water containing oxidizing agents. Whereas, fluoride ion had noability for provoking pitting corrosion.

(4) These phenomena were discussed in connection with the results of potentiostatic polarization measurements.

(Received Dec., 4 1969)

0030

Ishida, S., Nakamura, H., Otsuka, T., Iritani, T.

EFFECTS OF SO_4^{2-} AND HCO_3^- UPON THE ARTIFICIAL WATERS CAPABLE OF GENERATING PIT ON ALUMINUMJournal of Japan Institute of Light Metals, 24 (4), April 1974, pp 135-140

Al(Water)

| In this study, coexisting effects of Na_2SiO_3 and Na_3PO_4 upon the artificial water LSW₁ (capable of generating pit on aluminium immersed in waters) found by the authors were investigated. Related to the permanent hard water, effect of SO_4^{2-} ion upon LSW₁ was studied, and very complicated relations were found. Related to the temporary hard water, effect of Ca (HCO_3)₂ upon LSW₁ was studied. Coexisting effect of the permanent (CaSO₄) and the temporary [Ca(HCO_3)₂] waters was studied.

By variations of coexisting ratio of SiO_3^{2-} (or PO_4^{3-}) and Ca (HCO_3)₂, pH of the natural waters becomes either alkali or acid. And in each pH side there existed a unique pitting characteristic. |

0031

Buraya, T. A., Chak, R. O., Adler, Yu. A., Turkovskaya, A. V.
INVESTIGATION OF THE CORROSION OF ALUMINUM AND STEEL Kh18N10T IN SOME
MEDIA, USING MATHEMATICAL PLANNING OF THE EXPERIMENT
Protection of Metals, 11 (3), May-June 1975, pp 309-312

Al(Antifreeze)

In the present work orthogonal and rotatable plans were used to study the pitting and pitting corrosion of aluminum A-99 in aqueous solutions of ethylene glycol and the overall corrosion of steel Kh18N10T in mixtures of H_2SO_4 and HNO_3 containing V_2O_5 . The aim of the work was to obtain mathematical models of corrosion processes for determining their rate with different values of the factors which vary over wide ranges, which is particularly important in operating practice.

0032

Geld, I., McCaul, C.
CORROSION IN POTABLE WATER
Journal of the American Water Works Association, 67 (10), October 1975,
pp 549-552

Cu(Water); Fe(Water)

Various alloys were exposed in quiescent potable water for periods up to fifteen years. Although average corrosion rates were low, a number of interesting instances of significant localized damage were observed. The alloys so affected were aluminum bronze, nickel-copper, manganese bronze, type 416 stainless steel, and galvanized iron.

0033

Jarman, R. A., Linekar, G. A. B., Booker, C. J. L.
INTERFACIAL CORROSION OF BRAZED STAINLESS STEEL JOINTS IN DOMESTIC TAP
WATER--II METALLOGRAPHIC ASPECTS
British Corrosion Journal, 10 (3), 1975, pp 150-154

Cu(Water); Fe(Water)

Previous work has indicated that interfacial corrosion of brazed stainless steel joints in domestic tap water is probably associated with a selective dissolution of one component of a lamellar eutectic structure, which thereby provides easy access to the interface for the aqueous environment. The metallographic features of the phenomenon have now been explored in more detail in order to characterise the structural changes taking place. A tentative mechanism is proposed to explain the changes observed at the interface where copper is found to be deposited.

0034

Randolph, R. C., Lincoln, D. A.
CORROSIVE EFFECTS OF POTABLE WATER
Materials Protection and Performance, 12 (4), April 1973, pp 25-27

Cu(Water); Fe(Water)

The first major installation in the U.S. of Type 304 stainless steel microstrainer screens failed after 8 years of operation due to crevice corrosion initiated by oxygen starvation. Pitting on the galvanized portion of a rapid and filtration system in the same water plant failed within 2 or 3 years of installation. These problems are typical examples of corrosion by potable water.

0035

Jarman, R. A. Myles, J. W., Booker, C. J. L.
 INTERFACIAL CORROSION OF BRAZED STAINLESS STEEL JOINTS IN DOMESTIC TAP WATER
 British Corrosion Journal, 8 (1), January 1973, pp 33-37

Cu(Water); Fe(Water)

The phenomenon of interfacial corrosion of brazed stainless steel joints is described, and previous work reviewed. Experiments are described in which an austenitic (En58E) and a ferritic (En60) steel are examined in combination with certain proprietary braze fillers in the form of 'as brazed' and 'brazed and machined' specimens in contact with stagnant tap water. The results indicate that the observed separation at the joint interface is probably associated with selective dissolution of one component of the lamellar eutectic structure, thus providing access to the interface for the aqueous environment. Residual stress at the interface may play a supplementary role in promoting subsequent failure.

0036

Roženfeld, I. L., Lomakina, S. V., Olkhovnikov, Y. P.
 THE INFLUENCE OF ALLOYING ELEMENTS ON THE PROTECTIVE PROPERTIES OF
 FILMS FORMING ON ALUMINUM ALLOYS DURING CORROSION IN HIGH TEMPERATURE
 WATER
 Protection of Metals, 9 (3), May-June 1973, pp 314-316

Al(Water)

This article presents the results of an investigation of the protective properties of films occurring during the corrosion of some binary aluminum alloys in water. The investigated films were obtained during the corrosion of 99.99% pure aluminum and its binary alloys with Cu, Fe, Cr, Ni, Ti, and Zr in water at 200 deg C. Under these conditions a significant rate of aluminum corrosion is found and the role of individual alloying elements is revealed most clearly. The aluminum-copper system was investigated after hardening from 525-540 deg C and natural aging for 5 days. The remaining alloys were given in homogenization anneal at 350 deg C for 60 min. Without exception all of the alloying elements significantly increase the protective properties of the films formed on aluminum under these conditions. The effect is especially strong in alloying with nickel, an increase of 70 times after 1000 h in water. With titanium and zirconium the criterion of protective properties after an initial period of corrosion of 0.500 h reaches a definite constant value which is especially important for producing alloys for long service in the high temperature water of atomic reactors.

0037

Goto, K., Shimizu, Y., Ito, G.

PITTING CORROSION OF ALUMINUM IN SYNTHETIC SUPPLY WATERS

Transactions of National Research Institute for Metals, 16 (3),

June 1974, pp 105-110

Al(Water)

Pitting corrosion of pure aluminum in synthetic supply water containing calcium, chloride and meta-silicate ions and free chlorine was studied. Experimental results show that free chlorine and meta-silicate ions were harmful constituents of water responsible for pitting of aluminum. Effects of calcium and chloride ions on pitting were not significant when the amount of these constituents was in the range of the composition of supply waters in Japan.

0038

NICKEL ALLOY SOLVES IMMERSION HEATER CORROSION IN AGGRESSIVE WATER

Anti-Corrosion, 24 (2), February 1977, pp 4-5

Cu(Water)

Redring Electric Ltd., has developed a range of long-life domestic immersion heating elements called aqualoy 825. These elements are for use in any locations where the normal copper-sheathed element is unable to cope with aggressive water. The basis of its success is a sheath of Incoloy alloy 825, manufactured by Henry Wiggin & Co., Ltd. Domestic immersion heating elements have long been sheathed in copper, with various superficial coatings and for the majority of applications this provides adequate resistance to corrosion by normal supplies. Incoloy Alloy 825 besides being resistant to corrosive attack will also tolerate much higher temperatures before oxidation commences.

0039

Breske, T. C.

TESTING AND FIELD EXPERIENCE WITH NONHEAVY METAL CORROSION INHIBITORS
Materials Performance, 16 (2), February 1977, pp 17-24

Cu(Water); Fe(Water)

Results of laboratory scale and operating atmospheric cooling tower tests of nonheavy metal corrosion inhibitors are reported. Importance of inhibitor performance in a plant with a circulation of 1 million gallons per minute, average cycles of concentration = 4, 15 M GPM evaporation, and 5 M GPM blowdown are cited. It was estimated cost of nonheavy metal corrosion inhibitors is 1.5 to 2.5 times that of low Zn chromates on an equivalent dosage basis. Limits on some of the chemicals employed for ecological reasons are considered. Among chemicals involved were amino methylene phosphonate, hydroxyethylidene diphosphonate, benzotriazole, chlorinated organic copolymers, diphosphonate, polyamide dispersants, and unidentified amines.

0040

Berzins, A., Evans, J. V., Lowson, R. T.

ALUMINIUM CORROSION STUDIES--II. CORROSION RATES IN WATER

Australian Journal of Chemistry, 30 (4), April 1977, pp 721-731.

Al(Water)

The corrosion rate of aluminum in flowing neutral waters at 50 C has been determined as a function of pH, oxygen concentration and chloride concentration. The corrosion rate, as total aluminum lost between the 4th and 80th day was observed to logarithmic with a minimum rate in the pH range 5-6. Saturating the water with nitrogen or adding up to 15 mg Cl ion/l increased the corrosion rate. It was concluded that this was due to competitive action on the oxide surface, between dissolved oxygen and chloride ions.

0041

Kasahara, K.

UNIQUE MORPHOLOGY OF CORROSION OF AISI 304 AUSTENITIC STAINLESS STEEL
IN HOT TAP WATER

Materials Performance, 16 (12), December 1977, pp 13-17

Fe(Water)

Type 304 steel tested in potable water containing (mg/L) Ca carbonate, 18.5; Si dioxide, 17.5; Fe, 0.4; chloride, 13.8; and sulfate, 15.2 at 7.04pH suffered lamellar attack at a rate of 1.02 mm/yr (40.2 mpy). The water was cycled between 35 and 40 C to simulate domestic heating. X-ray analysis of scales is given. Waterside damage was concentrated above the waterline, where perforations occurred. Tight sulfate scale on upper inside surfaces of the tested heat exchangers and generation of insoluble hydroxides and sulfuric acid is postulated. The acid preferentially attacked along slip bands in the metal.

0042

Isenberg, Ch.

THE CORROSION BEHAVIOUR OF EXTRUDED AlMgSi0.5 RADIATOR SECTIONS IN CLOSED
HOT WATER SYSTEMS

Aluminium and Supplement in English, 54 (4), April 1978, pp 270-273 (12-15)

Al(Water)

The behavior of extruded AlMgSi0.5 radiator elements in respect to corrosion and protective film formation was examined in a test stand with nine heating circuits in which waters with different mineral contents circulated by gravity. Temperature, gas formation, and changes in the circulating water were measured during operation. The aluminum components were examined optically and metallographically after dismantling.

0043

Shigenaga, M., Tanabe, Z-I.

CATHODIC PROTECTION AND THE BLACKENING OF ALUMINUM

Sumitomo Light Metal Technical Reports, 17 (3/4), July 1978, pp 109-115

Al(Water)

In order to obtain the fundamental data for cathodic protection of aluminum, corrosion behavior of 1050 aluminum in tap water and NaCl solution was examined by sacrificial anode method using Zn and impressed current method. The blackening of aluminum under cathodic protection was also investigated in this experiment. It was found that the blackening occurred when the cathodic corrosion rate was less than 100 mdd, and the degree of blackening as represented logarithmic luminosity was proportional to the cathodic corrosion rate less than 10 mdd. For this phenomenon, the influence of Fe, Si etc., was emphasized in the former reports. Our results show, however, that Mg, Ca and Cu are important elements.

0044

Constantinescu, E., Heitz, E.

ON THE INFLUENCE OF THE WATER CONTENT ON CORROSION OF METALS IN MONO-CARBOXYLIC ACIDS

Corrosion Science, 16 (11), 1976, pp 857-867

Al(Antifreeze); Fe(Antifreeze)

Corrosion rates of Fe, Zn, Al and stainless steel AISI 304 in oxygen-free formic, acetic, propionic, and butyric acids with water contents between 0.06m and 4.0m have been obtained by polarisation resistance and mass loss measurements. In addition, the influence of temperature and chloride content on the corrosion of stainless steel has been investigated. The less water-like the organic solvent, the more significant is the influence of water in the sense of stimulating the corrosion reaction. The temperature dependence of corrosion is analogous to that in aqueous solutions.

0045

Popplewell, James M.

CORROSION AND ITS PREVENTION IN FLAT PLATE ABSORBER SOLAR SYSTEMS

Olin Corporation, New Haven, Connecticut, Paper presented at the NACE North Central Region Meeting held at Chicago, Illinois, October 18-20, 1977.

Al(Water, Antifreeze); Cu(Water, Antifreeze)

The purpose of this paper is to discuss some of the internal surface corrosion problems in solar flat plate collectors based on field experience and laboratory testing, and to attempt to provide some information on precautions which should be taken to avoid corrosion problems. Two metals, namely copper and aluminum are discussed. Steel and stainless steel, although candidate absorber plate materials, have not been included in our program to date.

0046

Heitz, E., Kyriazis, C.

REACTIONS DURING CORROSION OF METALS IN ORGANIC SOLVENTS

Industrial and Engineering Chemistry Product Research and Development,
17 (1), March 1978, pp 37-41

Al(Antifreeze); Fe(Antifreeze)

Typical for corrosion of metals in organic solvents is the great variety of systems metal/medium which is a consequence of the huge number of organic compounds. However, the vast field can be made surveyable by application of three simple classification principles. These are based on the physicochemical properties of the aggressive medium. Likewise, these properties determine the type of corrosion reactions involved in the metal dissolution process.

0047

Mansfield, F.

RESULTS OF GALVANIC CORROSION ROUND ROBIN TESTING
Corrosion, 33 (6), June 1977, pp 224-226

Al(Water); Cu(Water); Fe(Water)

The results of Cu/Al 6061 and 4130 steel/Cu have shown that galvanic current measurements can be carried out with good reproducibility in ASTM corrosive water. It should be noted that this result was obtained despite the fact that the choice of the instrumentation for galvanic current measurements was left to the individual investigator. It is interesting to note that most participants used a potentiostat, which is probably due to the convenient arrangement for monitoring the galvanic current and potential. The Al 6061/4130 steel couple in ASTM corrosive water represents a special case which, while very interesting, cannot be used to judge the procedure used in this test.

0048

Southwell, C. R., Bultman, J. D.

CORROSION OF METALS IN TROPICAL ENVIRONMENTS: Part 10 --FINAL REPORT OF
SIXTEEN-YEAR EXPOSURES

Naval Research Laboratory, Washington, D.C., Final Report, NRL-7834,
January 2, 1975, 41p.

Al(Water); Cu(Water); Fe(Water)

A comprehensive long-term investigation of corrosion of 52 metals immersed in seawater and in fresh water, suspended at mean-tide level, and exposed to marine and inland tropical atmospheres has been completed for exposure periods of up to 16 years. A series of reports on specific metal groups has already been published. This is a final report on the project.

[1100 aluminum, 6061, AZ31, Monel 400, 5Ni steel, engineering steel, AISI 410, AISI 302, AISI 321, castings, AISI 316, dissimilar joining, tropical environments, weight change, pitting corrosion, sea water, water, time, corrosion]

0049

Goto, K., Shimizu, Y., Ito, G.

EFFECT OF METALLURGICAL FACTORS ON INITIATION OF PITTING CORROSION ON ALUMINUM IN FRESH WATER

Journal of Japan Institute of Light Metals, 27 (9), September 1977, pp 442-449

Al(Water)

Various metallurgical factors governing initiation of pitting corrosion were examined by electron microscopy, EPMA, and cathodic polarization measurements. Pits nucleate in the adjacent site of precipitates containing iron and/or silicon. Pits are prone to initiate on the cutting edge rather than on rolled surface of aluminium plate. Scratching has the most remarkable effect on initiation of pitting corrosion. The difference in susceptibility to pitting corrosion between the edge and the rolled surface of aluminium plate is attributed to the scratching effect on the edge surface.

0050

Butler, G., Mercer, A. D.

CORROSION OF SOME ALUMINIUM CASTING ALLOYS AND CAST IRON IN UNINHIBITED ALCOHOL/WATER COOLANTS

British Corrosion Journal, 12 (3), 1977, pp 163-170

Al(Antifreeze); Fe(Antifreeze)

Measurements were made of the corrosion behavior of cast iron and five aluminum alloys at 70 C in a range of uninhibited alcohol/water mixtures of practical application as cooling liquids. Corrosion was assessed by weight changes and, with the aluminum alloys where the amount of corrosion was small, by visual observation and comparison. In most solutions appreciable corrosion and graphitisation of cast iron occurred. Absolute values of corrosion rates were much lower for the aluminum alloys with alloy LM8 giving the best performance. Ethanediol/water mixtures were the least aggressive of the coolants tested. Data are provided for the pH stability of the coolants in the test conditions used.

0051

Lifsey, Jeremy A.

THE NATIONAL SOLAR HEATING AND COOLING INFORMATION AND WHAT IT CAN DO FOR YOU

Franklin Institute Research Laboratories, Philadelphia, PA, Paper presented at the Proceedings of the 1978 Annual Meeting of the American Section of the International Solar Energy Society, Inc., August 28-31, 1978, Denver, CO.

Misc.

The Center is an information service funded by the U.S. Department of Housing and Urban Development and the U.S. Department of Energy as part of a program to foster the use of solar energy in domestic hot water systems and the heating and cooling of buildings. The Center answers questions by mail and over toll-free hot lines, operates a mobile exhibit van and several exhibits that appear at conferences and trade shows, and distributes HUD and DOE publications on solar energy. Users can request lists of addresses of solar design and construction professionals, manufacturers, distributors, banks that have given solar mortgage or construction loans and solar films, slides, and video tapes. Users can also obtain information on solar design, equipment testing, standards, climatic data, HUD and DOE construction grants, state and federal tax incentive and solar land use and access legislation, solar courses and seminars, speakers on solar energy, and fact sheets and bibliographies on various aspects of solar energy.

Inquiries are welcome from homeowners and homebuyers, as well as contractors, builders, lenders, community planners, zoning and building code officials, architects, insurance agents, appraisers and manufacturers. The Center's toll-free number is 800-523-2929 in the continental U.S. (800-462-4983 in Pennsylvania only).

0052

Baron, S.

SOLAR ENERGY--WILL IT CONSERVE OUR NON-RENEWABLE RESOURCES?

Burns and Roe, Inc., Oradell, NJ, Paper presented at the Proceedings of the 1978 Annual Meeting of the American Section of the International Solar Energy Society, Inc., August 28-31, 1978, Denver, CO.

Misc.

If solar energy applications are to be economically successful, then the energy consumed for fabricating, constructing, and operating such plants must be less than the energy recovered over their operating life. The total consumption of fossil and nuclear energy resources to produce and operate solar heating systems is a significant portion of the energy that will be recovered by the solar panels over their operating life. Solar thermal electric plants in the Southwest U.S. will pay back their energy requirements in less than five years. However, it is questionable that the payback years would be justified in other U.S. areas. Photovoltaic power plants are highly energy-intensive, and a detailed assessment shows that in operating such a plant for 30 years, the energy payback would be close to 10 years. The U.S. solar energy development program must concentrate on designs and developments that use less energy-intensive materials if they are to be competitive with present energy alternatives.

0053

Bankston, Charles A. and Sargent, Stephen L.

THE NATIONAL PROGRAM FOR SOLAR COLLECTOR RESEARCH, DEVELOPMENT AND
COMMERCIALIZATION

Los Alamos Scientific Laboratory, U.S. Department of Energy, Paper presented at the 1978 Annual Meeting of the American Section of the International Solar Energy Society, Inc., August 28-31, 1978, Denver, CO.

Misc.

The National Program for Research and Development in Solar Heating and Cooling, based on the 1976 program plan published as ERDA 76-144, has now been largely implemented. The collector research, development and commercialization program is the largest element of the R&D Program consisting of approximately 100 projects in the development and commercialization of various types of collectors and relevant studies or research in collector technology and materials. The objectives, scope and structure of the collector program are described. The projects that comprise the program are listed in five categories and the relationships between the projects in each category and the needs and goals of the applications paths of the R&D Program are discussed. The collector development projects are individually described and recent accomplishments are cited.

0054

Ward, John C., Ward, Dan S.

PERFORMANCE OF AN EVACUATED GLASS TUBE SOLAR COLLECTOR INTEGRATED WITH A
SOLAR HEATING SYSTEM

Colorado State University, Paper presented at the Proceedings of the 1978 Annual Meeting of the American Section of the International Solar Energy Society, Inc., August 28-31, 1978, Denver, CO

Misc.

Performance and pertinent operating experience with the Owens-Illinois evacuated glass tube, liquid heating solar collector are reported. This collector was operated with the CSU solar house heating and cooling system. For February, 1978, about 80% of the incident solar radiation was delivered as useful heat, but electrical parasitic power requirements were about 15% of the useful heat delivered. In addition, overnight heat losses from the solar collector were about 33% of the useful heat delivered. The flow rate through the collector was correlated with the outlet liquid temperature.

Because of the numerous operational difficulties experienced with the collector, it cannot be considered practical at the present time for liquid heating applications. However, the excellent performance does show good potential for use as an air-heating solar collector.

0055

Duff, W. S., Conway, T. M., Lof, G.O.G., Meredith, D. B., Pratt, R. B.
 PERFORMANCE OF RESIDENTIAL SOLAR HEATING AND COOLING SYSTEM WITH FLAT-PLATE
 AND EVACUATED TUBULAR COLLECTORS: CSU SOLAR HOUSE I
 Colorado State University, Paper presented at the Proceedings of the 1978
 Annual Meeting of the American Section of the International Solar Energy
 Society, Inc., August 28-31, 1978, Denver, CO.

Misc.

Measurements in Solar House I at Colorado State University have provided comparison data on space heating, water heating, and cooling by systems in which flat-plate collectors and evacuated tube collectors were used. Data were procured on 47 days during operation of the flat-plate collector and on 112 days when the house was heated or cooled by the evacuated tube collector system.

It was concluded that the system comprising an evacuated tubular collector, lithium bromide absorption water chiller, and associated equipment is highly effective in providing solar heating and cooling to a small building, that it can supply up to twice the space heating and several times the cooling obtainable from an equal occupied area of good quality flat-plate collectors, and that a greater fraction of the domestic hot water can be obtained by supplying its heat from main storage. The cost-effectiveness of the system, in comparison with one employing a good flat-plate collector, can be determined when commercial pricing data are made available.

0056

Ward, J. C., Loss, W. M., Lof, G.O.G.
 DIRECT CONTACT LIQUID-LIQUID HEAT EXCHANGER: PILOT PLANT RESULTS
 Colorado State University, Paper presented at the 1978 Annual Meeting of
 the American Section of the International Solar Energy Society, Inc.,
 August 28-31, 1978, Denver, CO

Misc.

Three liquids were tested in a pilot plant scale direct contact liquid-liquid heat exchanger. No temperature stratification was observed in the heat exchanger column. An empirical relationship between the Nusselt and Peclet numbers was observed to be the same for all 3 liquids tested, when the ratio of the viscosities of the continuous and dispersed phase liquids were taken into account.

Analysis showed that the bulk of the resistance to heat transfer lies in the dispersed phase. The minimum continuous phase liquid depth required for complete heat transfer was shown to be a function of the drop size and Prandtl number of the dispersed phase and was less than 1 meter for all 3 liquids tested.

A full scale direct contact liquid-liquid heat exchanger has been constructed and is presently being tested.

0057

Lior, N., Shore, S., Lepore, J. A., Jones, G. F.
 SOLAR HEATING RETROFIT OF AN URBAN ROW HOUSE: CONSTRUCTION AND START UP
 University of Pennsylvania, Paper presented at the 1978 Annual Meeting of
 the American Section of the International Solar Energy Society, Inc.,
 August 28-31, 1978, Denver, CO

Misc.

A row house in Philadelphia was retrofitted to solar comfort and domestic hot water heating, and the system is now in operation. The feasibility of such retrofit, based on a design philosophy of minimal changes to the existing building and heating system, simplicity, high reliability, low maintenance, and the utilization of off-the-shelf components, was successfully demonstrated. The construction procedure and equipment costs are described in detail. The study points to the need for developing labor-efficient solar system construction procedures and equipment, to reduce labor time and cost.

0058

Ward, D. S.
 SOLAR AIR-HEATING AND COOLING SYSTEMS FOR RESIDENTIAL AND LIGHT
 COMMERCIAL APPLICATIONS
 Colorado State University, Paper presented at the 1978 Annual Meeting of
 the American Section of the International Solar Energy Society, Inc.,
 August 28-31, 1978, Denver, CO

Misc.

Solar air-heating collectors integrated with pebble-bed thermal storage units and well-designed air handling equipment have been shown to provide improved seasonal performance over conventional liquid-heating systems. Problems associated with liquid-heating solar collectors (freezing, boiling, corrosion, etc.) and the very substantial difficulty in controlling heat losses from a hot water thermal storage unit, particularly in solar cooling systems, has added additional evidence of the superiority of solar air systems.

Recent developments in solar air-heating evacuated tube solar collectors have now provided the opportunity for solar system designs to achieve high collector outlet temperatures of 100-150°C with good efficiencies (i.e., greater than 40%). In addition, the characteristics of the pebble-bed thermal storage units provide for minimal heat loss to the ambient (even at temperature differentials of 100°C), as well as temperature stratification levels within the pebble-bed capable of providing high temperature air for operating an absorption chiller (or other cooling equipment).

To date, however, solar air collectors have been unable to generate sufficiently high temperatures at acceptable collector efficiencies in order to operate space cooling equipment appropriate for residential and light commercial applications. Operation of absorption cooling machines, for example, would require an air/liquid heat exchanger between the collectors and the cooling unit itself in order to utilize hot water as the heat transfer medium to the generator of the absorption unit. The temperature requirements of the hot water would therefore require the air-heating collectors to achieve outlet temperatures in excess of 100°C.

0059

Holton, J. K.

UPDATING SOLAR PERFORMANCE CRITERIA AND STANDARDS

National Bureau of Standards, Washington, D.C., Paper presented at the 1978 Annual Meeting of the American Section of the International Solar Energy Society, Inc., August 28-31, 1978; Denver, CO.

Misc.

The HUD Solar Minimum Property Standards (S/MPS) and the Solar Interim Performance Criteria (IPC) both residential and commercial were developed by NBS early in the solar demonstration program to be of assistance in promoting the manufacturer and wide spread use of solar energy systems. Considerable experience has been gained during the demonstration program that has revealed the actual problems that can occur in the manufacture, installation and use of solar energy systems and components. In order to keep the S/MPS and IPC reasonable and useful standards they are continually being updated based on current experience. Findings are presented from the residential and commercial demonstration program and from a public commentary process that have led to the updating of numerous sections of the criteria and standards. A comparison is presented of the original criteria, the practical problems and the revised criteria. Topics covered include: system performance covering thermal losses, freeze protection, operating energy, system back-up, thermosyphoning, flow balancing, controls, safety, maintenance and check-out procedures; and component performance covering freeze protection, stratification, stagnation, materials deterioration, heat transfer fluid quality and structural criteria.

0060

Gleman, S.M., Hill, T.S., Hancock, O.G., Jr., Starr, S.O.

USE OF THE HUD MINIMUM PROPERTY STANDARDS IN EVALUATING SOLAR DOMESTIC HOT WATER SYSTEMS FOR THE HUD/FLORIDA SOLAR HOT WATER HEATING INITIATIVE

Florida Solar Energy Center, Cape Canaveral, FL., Paper presented at the 1978 Annual Meeting of the American Section of the International Solar Energy Society, Inc., August 28-31, 1978, Denver, CO.

Misc.

We describe the application of the HUD Minimum Property Standards (MPS 4930.2 or NBSIR 77-1272) for evaluation of solar hot water systems proposed by vendors during the Florida Residential Solar Water Heating Initiative Program. Problems arising in the system evaluations (including materials compatibility, toxicity of heat transfer fluids, system sizing, collector testing, manuals, control systems and freeze protection) will be examined, leading to a discussion of practical strengths and weaknesses in the implementation of the MPS document. Industry attitudes and acceptance of the document will be treated. Suggestions are offered for the future improvement of the MPS and for the use of the MPS by government agencies and private concerns.

0061

Cash, M.

HARDWARE PROBLEMS ENCOUNTERED IN SOLAR HEATING AND COOLING SYSTEMS
 NASA, Marshall Space Flight Center, Ala., Paper presented at the 1978
 Annual Meeting of the American Section of the International Solar Energy
 Society, Inc., August 28-31, 1978, Denver, CO.

Misc.

Marshall Space Flight Center personnel have worked for several years with the development and demonstration of solar heating and cooling systems in support of the Department of Energy. In this work, they have encountered numerous problems in the design, production, installation and operation of the solar energy systems. Many of these problems have been seen in more than one system. This paper describes the hardware problems, which range from simple to obscure and complex, and their resolution when it is not obvious. It is intended to provide personnel in the solar energy field with information that will help prevent the installation of solar heating and cooling systems that will not operate satisfactorily or that will not last for the design lifetime.

0062

Smith, R. O., Meeker, J. F.

ONE HUNDRED SOLAR WATER HEATERS SOME LESSONS LEARNED ABOUT INSTALLATION
 AND PERFORMANCE AT NEW ENGLAND ELECTRIC

Robert O. Smith & Assoc., Newton Highlands, MA., New England Electric,
 Westboro, MA., Paper presented at the 1978 Annual Meeting of the American
 Section of the International Solar Energy Society, Inc., August 28-31, 1978,
 Denver, CO.

Misc.

This paper surveys mechanical troubles found during the first year of operation of solar water heaters installed in 100 single-family homes of customers of New England Electric Subsidiaries during 1975. Costs, savings, and improvements made later are also reported. In 1975 this firm set out to study the electrical load levelling potential and economic viability of solar water heaters. Before such information could be obtained it became necessary for all involved to learn how to get satisfactory operation from the solar water heaters furnished. The project has become a beneficial learning experience and most of the participants appear to be making effective use of the lessons in improving the installations.

0063

Spencer, D.L., Baliga, B. V.

FREEZE TOLERANCE TESTS OF SOLAR COLLECTORS

University of Iowa, Paper presented at the 1978 Annual Meeting of the American Section of the International Solar Energy Society, Inc., August 28-31, 1978, Denver, CO.

Misc.

The heat removal fluid in a liquid type flat plate collector should be drained when the collector is not operating. This is to avoid warm-up losses and prevent freezing. However, a collector should be employed which would be undamaged by freeze-up. This paper examines the nature of the freeze-problems associated with vacuum flow collectors and reports on the results of freeze tests.

0064

Nussbaum, O. J.

EXPERIENCES WITH A LOW COST RESIDENTIAL SOLAR HOT WATER SYSTEM

Halstead Industries, Inc., Scottsboro, Al., Paper presented at the 1978 Annual Meeting of the American Section of the International Solar Energy Society, Inc., August 28-31, 1978, Denver, CO.

Misc.

The installation described in this paper was made to determine the feasibility of a direct hot water system without using special heat transfer fluids and with full utilization of an existing electric hot water storage heater. Another objective was to explore savings in hot water cost under actual usage conditions in a residence occupied by a family of four.

Finally, perhaps the major objective was to develop a reasonably safe and inexpensive method to protect the solar collectors and the water piping from freezing without resorting to draindown or antifreeze solutions.

While this experimental installation has survived one severe winter it cannot be termed a complete success because the electric resistance heating cable used for freeze protection was not properly installed originally and the necessary electric energy to heat the collectors above 0°C was underestimated in the original design. On the other hand, sufficient data have been accumulated to indicate worthwhile savings in the cost of electricity, particularly in areas where power costs are relatively high.

0065

Hoyer, E., Merriam, M.

RESIDENTIAL WATER HEATER PUMPED BY DIFFERENTIAL PRESSURE

University of California, Berkeley, CA., Paper presented at the 1978 Annual Meeting of the American Section of the International Solar Energy Society, Inc., August 28-31, 1978, Denver, CO.

Misc.

A residential solar water heater operating without circulation pump or thermosiphon has been designed and built and is in regular operation. The power to accomplish water circulation is drawn from the city water supply system by means of two pressure regulators set at pressures lower than the city water system pressure. A discharge valve operates at a pressure intermediate between that of the two regulators. Circulation between the collector and storage tank is accompanied by discharge of water from the system. The advantage of the differential pressure system is that the need for a circulation pump and the power to operate it is eliminated, combined with flexibility in collector and storage tank location not available with thermosiphon systems. To the best of our knowledge no solar water heater pumped by differential pressure has been built previously.

0066

Gregory, D., Nash, J. M.

MATERIAL PROPERTY COMPUTATION FOR PROCESSING OF SOLAR ENERGY SYSTEM PERFORMANCE DATA

IBM Corporation, Huntsville, Ala., Paper presented at the 1978 Annual Meeting of the American Section of the International Solar Energy Society, Inc., August 28-31, 1978, Denver, CO.

Misc.

The purpose of this paper is to describe procedures relating to material property computations as they apply to the National Solar Heating and Cooling Demonstration Program. One of the primary tasks associated with this program is the evaluation of system performance and energy savings for selected solar energy systems located throughout the United States. The International Business Machines Corporation (IBM), under the auspices of both the National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE), is participating in this effort by serving as a central point for the collection, analysis, and dissemination of data relating to the performance of instrumented demonstration systems. This participation is provided through the National Solar Data Program [1]. The variety of heat transfer media used in solar energy system designs for this program requires a diverse material property evaluation capability. As a result, IBM has developed a consolidated procedure for using these properties in system performance analysis. This paper discusses the methods presently used for material property computations and the associated data that have been developed from these computations.

0067

Reese, D. R.

AN ASSESSMENT OF RELIABILITY AND DURABILITY TEST METHODS APPLICABLE TO SOLAR COLLECTORS AND ASSOCIATED SYSTEMS

Wyle Laboratories, Huntsville, AL., Paper presented at the 1978 Annual Meeting of the American Section of the International Solar Energy Society, Inc., August 28-31, 1978, Denver, CO.

Misc.

NBSIR 77-1305 entitled, Provisional Flat Plate Solar Collector Testing Procedures was released in September of 1977 and sets forth methods for the performance of various structural, environmental and safety related tests. The applicability and reasonableness of these tests are discussed. Available conventional test methods for collectors and collector materials not called for in NBSIR 77-1305 are addressed. Problems likely to be encountered in system installation when system tests are not conducted are summarized and available durability and reliability test methods for critical components such as pumps, solenoid valves and control systems are discussed.

0068

Casamajor, A. B., Wood, R. L.

POTENTIAL INDUSTRIAL PROCESS HEAT APPLICATIONS FOR SOLAR ENERGY AT TEMPERATURES 170C: FIELD STUDY

University of California, Lawrence Livermore Laboratory, Livermore, CA., Paper presented at the 1978 Annual Meeting of the American Section of the International Solar Energy Society, Inc., August 28-31, 1978, Denver, CO.

Misc.

A field study of potential applications for solar industrial process heat has been conducted. From this study, it has been determined that while many industrial processes appear to be potential candidates for the application of solar energy, there are several, common, site-specific limitations that reduce this potential. These limitations include: insufficient land area, "waste" heat available on site, and the usual economic and institutional factors. A need for additional work is identified.

0069

Butt, S. H., Popplewell, James M.
SOLAR ABSORBER PLATE MATERIALS: QUESTIONS AND ANSWERS
Solar Age, 2 (5), May 1977, pp 9-11

Al(Water, Antifreeze); Cu(Water, Antifreeze); Fe(Water, Antifreeze)

The absorber plate is the warm heart of a solar collector--and discussions of the merits and problems of different absorber materials are absorbing in themselves. Solar Age has therefore asked people knowledgeable about each of the three most-used metals to shed a little light on the matter; first, what are the problems?

0070

Byrne, S. C.
SOLAR ABSORBER PLATE MATERIALS: ALUMINUM
Solar Age, 2 (5), May 1977, pp 19-21, 30-31

Al(Water, Antifreeze)

Because aluminum is highly resistant to atmospheric corrosion, the most important consideration in selecting aluminum for solar systems is its compatibility with the heat transfer liquid. A number of non-water based heat transfer liquids are either available or being developed specifically for solar systems. It is beyond the scope of this article to review all of these fluids except to say that aluminum is usually compatible with these liquids, especially where the manufacturer has either developed the liquid for use with aluminum or where a suitable inhibitor has been added to prevent aluminum corrosion.

0071

Lyman, Stuart W., Anderson, Paul
SOLAR ABSORBER PLATE MATERIALS: COPPER
Solar Age, 2 (5), May 1977, pp 12-15

Cu(Water, Antifreeze)

Copper is the logical material for solar collector systems for buildings: (1) it has the best thermal conductivity of all engineering metals; (2) it is highly resistant to corrosion both by aqueous media and by the atmosphere; (3) it is easy to fabricate and to join by soldering; (4) it is completely familiar in the heating, ventilating, and air conditioning industry and in the building trades, having been used for roofs, plumbing and HVAC systems since metals were first employed in those applications; and (5) it can readily accept selective surface coatings and in fact its own surface oxide is naturally selective. The corrosion resistance of copper in solar collectors is already well documented in practical experience. Copper flat plate solar collectors have been in use in Florida for more than fifty years (National Science Foundation report NSF-RA-N-74-190).

0072

Kruger, Phil
SOLAR ABSORBER PLATE MATERIALS
Solar Age, 2 (5), May 1977, pp 16-18

Fe(Water, Antifreeze)

The thermal performance of a steel absorber may be better, worse, or equal to that of a copper or aluminum absorber--trade-off studies in design are necessary.

0073

Gatos, H. C.

INHIBITION OF METALLIC CORROSION IN AQUEOUS MEDIA

Corrosion, 12 (1), pp 23t-32t, January 1956 [Ref. #18 in DMIC Report 216]

Al(Water, Antifreeze); Cu(Water, Antifreeze); Fe(Water, Antifreeze)

A brief discussion of corrosion processes from the electrochemical standpoint is given along with some of the electrochemical factors affecting corrosion. Organic and inorganic inhibitors are discussed separately and the mechanisms proposed for explaining their action as polarizers of the local corrosion cells are reviewed. Several experimental approaches to the study of corrosion inhibitors are given. In this connection a number of inhibitors are listed and their applications given.

0074

Edwards, J. O., Hamilton, R. I., Gilmour, J. B.

EARLY CORROSION FAILURES IN COPPER HEAT EXCHANGER TUBING

Materials Performance, 16 (9), September 1977, pp 18-20

Cu(Water, Antifreeze)

Early failure of 1.9 cm (0.75 inch) deoxidized copper, Al finned heat exchanger tubes in large commercial building heating and air conditioning systems was investigated. Pinhole leaks in tubing of 3 of 7 units after 2 years exposure to about 4 psi steam were attributed to a lack of proper slope of the tubes, lack of response of a vacuum release valve, and cavitation attack as a result of cycling pressure-vacuum in the tubes. Pimples on exterior tube surfaces coinciding with locations of inside pits supported the cavitation premise, because internal pressures were too low to account for them. Another investigation involved early failure of chilled water tubes in a large building attributed to breakdown or contamination of antifreeze residues left after pressure testing. The tubes were stored outside with end stoppers for 12 months before installation. Attack by oxygen or carbon dioxide from condensation was not ruled out.

0075

Popplewell, James M.

CORROSION PREVENTION IN ALUMINUM SOLAR SYSTEMS

The Construction Specifier, July 1977, pp 52-57

Al(Water, Antifreeze); Cu(Water, Antifreeze); Fe(Water, Antifreeze)

This paper describes some likely corrosion problems with aluminum flat plate collectors in multi-metal solar systems. Prevention of corrosion using a variety of approaches is discussed. These include "gettering" of heavy metal ions and the use of non-aqueous heat transfer fluids.

0076

Jackson, J. D., Miller, P. D., Fink, F. W., and Boyd, W. K.

CORROSION OF MATERIALS BY ETHYLENE GLYCOL-WATER

Battelle Memorial Institute, Defense Metals Information Center, Report

No. DMIC 216, May 10, 1965, Contract AF33(615)-1121

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze)

Galvanic attack can occur in glycol solutions, increasing the attack of the less resistant of two coupled metals. Steel is the least resistant followed by cast iron, aluminum, solder, brass, and copper. Pitting can sometimes occur on aluminum when coupled to other metals. No velocity effects were found for a clad aluminum alloy up to a velocity of 300 ft per minute. Under conditions of heat transfer, the corrosion rate of cast iron increased.

0077

Rowlands, J. C., Bentley, M. N.

DETERMINATION OF CORROSION RATES USING POLARISATION RESISTANCE
MEASUREMENTS AND SOME PRACTICAL APPLICATIONSBritish Corrosion Journal, 7 (1), January, 1972, pp 42-46

Al(Water); Cu(Water); Fe(Water)

A technique for the determination of corrosion rates by measurement of polarisation resistance is described. Instrumentation has been developed so that such measurements can be easily made both in the laboratory and in plant applications for on-line corrosion control. Feasibility studies for a variety of possible applications have been undertaken to evaluate the technique.

[This article was referenced in the proposal.]

0078

[This article was referenced in proposal]

Green, D. H., Kratzer, J. C., Emich, P. I.

REQUIREMENTS OF AN ENGINE ANTIFREEZE AND METHODS OF EVALUATION

ASTM Bulletin, October 1948, pp 57-66

Al(Water, Antifreeze); Cu(Water, Antifreeze); Fe(Water, Antifreeze)

The growing need for industrial standards in engine antifreeze, as indicated by the greater demands on internal combustion engines in all classes of service, has been brought more sharply into focus by the use of stop-gap antifreeze materials when products of known and accepted quality were in short supply. The test methods, data, and conclusions discussed in this paper are based on 20 yr. of experience in research, development, testing, and field service of this organization and are offered for whatever value they may have in the development of suitable antifreeze standards.

The requirements of an engine antifreeze are broadly classified as dependable freezing protection, adequate engine cooling, effective protection against corrosion, and retainability in the cooling system. An integrated test program of laboratory, full-scale engine-dynamometer, and vehicle driving procedures has been adopted for antifreeze development and evaluation. Each phase of this integrated test program serves a special purpose, and none has been found satisfactory as a substitute for any other phase. The value of laboratory type tests usually diminish as service simulation is attempted. Engine dynamometer methods are a closer approximation of field service, but only vehicle driving tests can assure that a newly developed antifreeze will meet all the requirements of a satisfactory winter coolant.

0079

Walker, M. S., France, W. K., Jr.
NEW METHOD DEVELOPED FOR MONITORING AUTOMOTIVE COOLING SYSTEM CORROSION
Materials Protection, 8 (9), September 1969, pp 47-52

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze)

In situ linear polarization measurements were used to determine corrosion rates in an engine cooling system under operating conditions. The performance of cast iron, brass, solder, and aluminum were studied in inhibited and uninhibited ethylene glycol-corrosive water solutions. Standard operating conditions included a temperature of 180 F (82 C), a pressure of 13 psig, and a coolant flow rate (35 gpm) that is equivalent to that in a vehicle at a speed of 60 mph. The modifications in polarization procedures and equipment, including a special cell designed for these tests, are described. Polarization tests provided instantaneous and accurate corrosion rates. Electrochemical measurements correlated well with actual weight loss measurements. The significant advantages of this electrochemical technique over conventional tests are cited, and important applications such as studies of inhibitor dilution effects are discussed.

[This article was referenced in the proposal]

0080

Feitler, H.
INSTANTANEOUS CORROSION RATE MEASUREMENT
Materials Protection and Performance, 9, (1), October 1970, pp 37-41

Misc.

Three methods of measuring corrosion rate are discussed. The coupon method is the lowest in cost and the slowest. The electrical resistance technique is intermediate in terms of speed, and its cost is comparable to that of linear polarization--both methods being higher in cost than coupons. Linear polarization is the newest and least used technique. It is instantaneous and offers much promise for future work.

[This article was referenced in the proposal.]

0081

Legault, R. A., Walker, M. S.

LINEAR POLARIZATION MEASUREMENTS IN THE STUDY OF CORROSION INHIBITION
Corrosion, 19 (6), June 1963, pp 222t-226t

Fe(Water); Misc.

A reliable and accurate method of determining metal dissolution rates in a relatively short time is much needed in studies of corrosion inhibition. Weight-loss determinations on specimens supply only average rate data over the interval of the test. Rate determinations by chemical analysis of the corrosive environment are also subject to this limitation. Both of these methods are subject to errors arising from intermittent removal of the sample from the environment.

Knowledge of corrosion rate changes during the period of exposure is valuable to understanding of the mechanism of the reaction involved. The linear polarization method has been found very rapid and convenient for studying rate changes and evaluating corrosion inhibitors. It has also made possible observations of the synergistic effects that may exist between inhibitor and environment.

[This article was referenced in the proposal.]

0082

Mercer, A. D., Wormwell, F.

CORROSION INHIBITORS FOR CAST IRON AND OTHER METALS IN ETHYLENE GLYCOL
SOLUTIONS AND IN MAINS WATERJournal of Applied Chemistry, 9, November, 1959, pp 577-588

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze)

Ethylene glycol solutions containing 1.5% of sodium benzoate + 0.1% of sodium nitrite will protect cast iron only if the system is initially heated. A mixture of 5.0% sodium benzoate + 0.3% sodium nitrite in 25% ethylene glycol has been shown to be effective in preventing the corrosion of cast iron and other metals both at room temperature and in conditions of intermittent heating. The use of sodium benzoate/sodium nitrite mixtures, sodium nitrite, disodium hydrogen phosphate and potassium chromate as inhibitors for cast iron in mains water has been examined. In the absence of inhibitors the reduced rate of corrosion of many metals in ethylene glycol solutions as compared with mains water has been demonstrated and the significance of this in the maintenance of vehicle cooling systems discussed. Electrode-potential/time curves obtained for various metals in ethylene glycol solutions have consistently reflected the corrosion behaviour of these metals in the solutions studied.

[Reference 13 in DMIC Report 216]

0083

Mercer, A. D., Brasher, D. M.

CORROSION INHIBITORS FOR ETHYLENE GLYCOL SOLUTIONS, WITH PARTICULAR
REFERENCE TO CADMIUM-PLATED AND TERNE-PLATED STEELJournal of Applied Chemistry, 9, November, 1959, pp 589-594

[Reference 14 in DMIC Report 216]

Cu(Antifreeze); Fe(Antifreeze)

In the experimental conditions of these tests:

D.T.D. 344A increases the attack on copper and on terne-plate I (2% tin); the remainder of the metals are protected to some extent, but not as effectively as in D.T.D. 779.

D.T.D. 779 arrests the corrosion of copper and considerably reduces that of all the other metals tested.

Ethylene glycol+sodium benzoate+sodium nitrite mixtures (33:1.5:0.1%) or (30:5.0:0.3%) give good results with cadmium-plated steel (completely plated or with cut edges) and very good results with all other metals or alloys tested.

In conclusion a system containing cadmium-plated steel (with or without exposed steel), terne-plated steel (2% or 20% tin in coating), cast iron, copper, tinned copper and stainless steel should be effectively protected by any one of the following inhibitive solutions: (a) 33% ethylene glycol containing 1.5% of sodium benzoate and 0.1% of sodium nitrite. This is suitable provided the system receives intermittent heating. (b) 30% ethylene glycol containing 5.0% of sodium benzoate and 0.3% of sodium nitrite. This is particularly suitable for solutions maintained at room temperature. (c) D.T.D. 779 at 33% dilution.

0084

Lloyd, W. G., Taylor, F. C., Jr.

CORROSION BY AND DETERIORATION OF GLYCOL AND GLYCOL-AMINE SOLUTIONS

Industrial Engineering Chemistry, 46 (11), November, 1954, pp 2407-2416

[Reference 5 in DMIC Report 216]

Al(Antifreeze); Fe(Antifreeze)

The present work is intended to contribute to the clarification of the chemical factors affecting corrosion by aqueous glycol solutions, and to indicate some means of controlling plant corrosion. The glycol solutions were made up to contain 7.5% by volume of distilled water; these solutions reflux at 146°C. Metal coupons of SAE 1010, Croloy-5, and 3S-H14 aluminum of 2.5 sq. in. size were tested.

0085

Agnew, R. J., Truitt, J. K., Robertson, W. D.
CORROSION OF METALS IN ETHYLENE GLYCOL SOLUTIONS
Industrial and Engineering Chemistry, 50 (4), April 1958, pp 649-656
[Reference 7 in DMIC Report 216]

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze)

This investigation represents part of a systematic study of corrosion by aqueous ethylene glycol solutions of the metals and alloys used in internal combustion engines. The more important chemical variables, including glycol concentration, pH oxygen concentration, chloride ion concentration, and temperature, were studied. Two general procedures were used: constant composition tests in which the solutions were continuously replaced, and static tests in which the solutions were not renewed, corresponding to the closed automotive system. The results will not make it possible to predict complete service behavior but will aid in interpreting service performance.

0086

Levy, M.
CORROSION INHIBITORS IN AUTOMOTIVE COOLANT MEDIA, ACTION ON POLARIZATION CHARACTERISTICS OF STEEL
Industrial and Chemical Engineering, 50 (4), April 1958, pp 657-662
[Reference 19 in DMIC Report 216]

Cu(Antifreeze); Fe(Antifreeze)

This investigation indicates the possible use of the polarization technique with externally applied c.m.f. as a screening test for inhibitors in coolant media, with a substantial saving in time. Polarization tests lasted 48 hours; the corrosion test requires 192 hours. However, the anomalous nature of the results of the triethanolamine and sodium nitrite materials (noncorrelation with test results in the simulated vehicle cooling system) reflects the need for further investigation of the action of the inhibitors on the polarization characteristics of copper, solder, brass, and iron (other metals comprising the automotive cooling system) at both room and elevated temperatures before such an electrochemical test could be adopted as a screening test for inhibitor materials.

0087

Caplan, D., Cohen, M.

ACCELERATING EFFECT OF DECREASING TEMPERATURE ON CORROSION BY GLYCOL SOLUTIONS

Corrosion, 9 (8), August 1953, pp 284-286

[Reference 9 in DMIC Report 216]

Cu(Antifreeze); Fe(Antifreeze)

The corrosion of galvanized steel in solutions of ethylene glycol containing borax is found to increase with decreasing temperature. This is believed to be due to the formation of a soluble complex zinc salt, the stability of which is greater the lower the temperature, which prevents the formation of a barrier film of insoluble corrosion product. Cadmium, magnesium and brass are attacked at low temperature in glycol-borax solution by the same mechanism, as is zinc in solutions of glycol containing sodium acetate or sodium benzoate.

0088

Wormwell, F., Mercer, A. D.

SODIUM BENZOATE AND SODIUM NITRITE AS CORROSION-INHIBITORS IN ETHYLENE GLYCOL ANTI-FREEZE SOLUTIONS. I. LABORATORY INVESTIGATIONS

Journal of Applied Chemistry, 3, January 1953, pp 22-27

[Reference 38 in DMIC Report 216]

Cu(Antifreeze); Fe(Antifreeze)

The addition of 1.5% sodium benzoate and 0.1% sodium nitrite to a 20% ethylene glycol anti-freeze solution effectively prevents corrosion of cast iron and soldered joints in conditions of intermittent heating. In the absence of benzoate, sodium nitrite protects cast iron but increases the attack on soldered joints in glycol solutions, the intensity of attack increasing considerably over the range 0.1 to 1.5% sodium nitrite. A short initial period of heating is necessary to ensure complete protection of cast iron in 20% glycol solution containing 1.5% sodium benzoate + 0.1% sodium nitrite. At room temperature without initial heating, 0.3% sodium nitrite is required to protect machined cast iron in 20% glycol solution containing 1.0 or 1.5% sodium benzoate, with 30% glycol and 1.0 or 1.5% sodium benzoate, 0.1% nitrite is sufficient. With 'as-cast' surfaces higher concentrations of sodium nitrite are required to prevent rusting.

0089

Wormwell, F., Mercer, A. D., Ison, H. C. K.
SODIUM BENZOATE AND SODIUM NITRITE AS CORROSION-INHIBITORS IN ETHYLENE GLYCOL ANTI-FREEZE SOLUTIONS. II. INVESTIGATIONS IN WORKING VEHICLES
Journal of Applied Chemistry, 3, March 1953, pp 133-144
[Reference 39 in DMIC Report 216]

Cu(Antifreeze); Fe(Antifreeze)

Some 60 tests have been carried out in working vehicles to establish the efficiency of the benzoate/nitrite corrosion-inhibitor in service conditions. The testing technique and the method of assessment of results are described. Of special importance is the need to carry out parallel tests in several vehicles, because of the varying rates of corrosion in different vehicles carrying the same coolant. The tests have shown that the addition of 1.5% of sodium benzoate with 0.1% of sodium nitrite to 20% or 33-1/3% solutions of ethylene glycol will effectively prevent corrosion of the cast iron of the cylinder block or head in the usual engine system. Corrosion of the radiator unit will also be prevented. The benzoate/nitrite inhibitor does not always prevent the corrosion of aluminium alloys.

0090

Thompson, P. F., Lorking, K. F.
SOME ASPECTS OF THE CORROSION PROCESSES OF IRON, COPPER, AND ALUMINUM IN ETHYLENE GLYCOL COOLANT FLUIDS
Corrosion, 13 (8), August 1957, pp 531t-535t
[Reference 17 in DMIC Report 216]

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze)

The corrosion potentials of aluminum, iron and copper, the principal metals in coolant systems, were measured in glycol-water solutions. The effect on the corrosion properties of these metals of the addition of triethanolamine phosphate, formerly used as a corrosion inhibitor in glycol coolants, was studied. It was shown that the copper ions produced by corrosion of copper are stabilized by triethanolamine phosphate. The copper went into solution as a blue cuprammine complex, which remained stable until it reached iron or aluminum surfaces where it was deposited, causing localized corrosion.

0091

Rowe, L. C.

AN EVALUATION OF INHIBITORS FOR CORROSION PREVENTION IN AN ENGINE COOLING SYSTEM

Corrosion, 13 (11), November 1957, pp 750t-756t
[Reference 6 in DMIC Report 216]

Al(Water, Antifreeze); Cu(Water, Antifreeze); Fe(Water, Antifreeze)

A rotating specimen type of test is used for the evaluation. The effectiveness of inhibitors, such as sodium borate, sodium nitrite, sodium benzoate, potassium dichromate, soluble oil, and sodium mercaptobenzothiazole, is compared by means of this test. Various test media are used, including ethyleneglycol-water mixtures and tap water with and without additional corrosive constituents. The metals investigated are steel, copper, brass, aluminum, cast iron and solder. The results are based on corrosion rate, microscopic examination, pit depth when applicable, and other general examinations. This work includes the results of one year static room temperature tests on thirteen galvanic couple combinations for each inhibitor.

0092

Twiss, S. D., Guttenplan, J. D.

CORROSION TESTING OF ALUMINUM -- PART I -- HIGH VELOCITY TEST METHOD IN AQUEOUS SOLUTIONS

Corrosion, 12 (6), June 1956, pp 263t-270t
[Reference 15 in DMIC Report 216]

Al(Water, Antifreeze)

A technique of corrosion testing, involving spinning of aluminum disks in aqueous solutions at high velocities, was used to investigate the effect of various natural waters and antifreezes on aluminum corrosion. Type of aluminum used was No. 100 aluminum brazing sheet having zinc-aluminum cladding on one side, and silicon-aluminum cladding on the other. It was established that an increase in velocity of movement up to a maximum peripheral velocity of 4700 feet per minute (12,000 rpm) is accompanied by a systematic increase in corrosion rate reaching very high values in some waters. In permanent antifreeze solutions, Royal Oak tap water--ethylene glycol (1:1), an increase in velocity appeared to reduce an induction period that occurs before rapid corrosive attacks sets in. In Royal Oak tap water--isopropyl alcohol solutions, velocity had no effect, corrosion remaining low at all velocities for the 200 hour test. Ethylene glycol appeared to accelerate corrosion and alcohols to reduce corrosion in all waters tested.

0093

Twiss, S. G., Guttentplan, J. D.

CORROSION TESTING OF ALUMINUM -- PART 2 -- DEVELOPMENT OF A CORROSION INHIBITOR

Corrosion, 12 (7), July 1956, pp 311t-316t

[Reference 36 in DMIC Report 216]

Al(Water, Antifreeze)

An accelerated corrosion test was used to test a number of corrosion inhibitors at different concentrations to determine their effectiveness in preventing corrosion of No. 100 aluminum brazing sheet in Royal Oak tap water. Four inhibitors were found to be effective under conditions of static test, 1000 rpm and 12,000 rpm. These inhibitors were: soluble oil with or without trisodium phosphate, sodium dichromate, sodium silicate, and disodium hydrogen phosphate. Of these, all but the soluble oil are either non-compatible or might lose their effectiveness when used in standard antifreeze solutions. The corrosion inhibition of clad aluminum by soluble oil is less effective in waters of combined high pH and high chloride ion than it is in waters of high chloride alone. Addition of a buffer to the soluble oil to maintain the solution pH near 7.0 improves the effectiveness of this inhibitor in high pH solutions. The combination of soluble oil and buffer satisfactorily inhibits the corrosion of clad aluminum in 1:1 ratio ethylene glycol-water (pH 11) and isopropyl alcohol-water (pH 11) solutions, typical of the worst radiator solutions that might be encountered. The inhibition is somewhat less effective when the clad aluminum is coupled with brass.

0094

NATIONAL PROGRAM PLAN FOR RESEARCH AND DEVELOPMENT IN SOLAR HEATING AND COOLING

Energy Research and Development Administration, Division of Solar Energy, Washington, D.C., Interim Report, ERDA 76-144, November 1976

Misc.

This report presents the ERDA/Division of Solar Energy (DSE) program plan for research and development in the use of solar energy for heating and cooling buildings and for agricultural and industrial process applications.

0095

COPPER FOR SOLAR COLLECTOR SYSTEMS

Copper Development Association, Inc., Application Data Sheet, 419/74

Cu(Water)

Copper is the ideal material for solar collector systems. It has been used for building roofs and plumbing systems of unexcelled reliability for decades--even centuries. Its thermal properties, resistance to aqueous corrosion, and its easy fabricability are unapproached by competing materials; and copper tube and sheet are completely familiar materials to the building trades. The material requirements for solar systems are compatible with the normal pattern of expanding U.S. supply of copper and copper alloy products. Moreover, these requirements can be met from domestic sources, for the U.S. is essentially self-sufficient in copper supply. In comparison, some competing materials come predominantly from foreign lands. Known reserves of copper in the U.S. are reassuringly large. Finally, and uniquely important to considerations of future supply, is copper's aforementioned recyclability.

0096

Bankston, C. A., Neeper, D. A.

SOLAR ENERGY RESEARCH AT LASL

University of California, Los Alamos Scientific Laboratory, Progress

Report LA-7115-PR, April 1978, (July 1, 1976-September 30, 1977), Contract W-7405-ENG-36

Fe(Antifreeze); Misc.

This report documents the work of the Solar Energy Group of the Los Alamos Scientific Laboratory during the period July 1976 through September 1977. The Group provided technical support to ERDA, performed research on solar collectors, and carried out systems studies on both active and passive systems. In addition, significant accomplishments occurred in the group's solar air-conditioning and mobile/modular solar home projects. Two tests of fluids and corrosion are reported. One test ran three fluids for about 30 months in three different collector loops. The fluids were: UCON 280X, silicone oil, and an 80%-glycol, 15%-water solution with NALCO 39L inhibitor. Microscopic examination revealed no significant corrosion either on plain surfaces or in cracks. In another test, two additional collectors have been in service using 85/15 glycol-water for more than three years. In the circulation loop for each collector are pots containing small samples of absorber material that are exposed to the hot circulating fluid. No corrosion has been found.

0097

Balcomb, J. D.; Perry, J. E., Jr.
ASSESSMENT OF SOLAR HEATING AND COOLING TECHNOLOGY
University of California, Los Alamos Scientific Laboratory, Report No.
LA-6379-MS, May 1977, Contract W-7405-ENG-36

Misc.

In order to assess in detail the state of the technology for solar heating and cooling of buildings, five 2-day meetings were held. The meeting subjects were solar collectors, thermal storage, air conditioning and heat pumps, systems and controls, and non-engineering aspects of solar energy. The body of this report is a condensation of these meetings. The existing state of technology for solar heating and cooling presents a mixed picture. Liquid-heating flat-plate solar collectors, for example, are in a rather mature stage, and there is a small, viable industry producing components. Even here, however, there are problems of materials which, if solved, can reduce collector cost, improve performance, or increase lifetime. In other areas such as, for example, desiccant chillers, passive concepts, and many of the systems categories, the technology is at an early stage of evolution, and much research and development remain to be done.

0098

MANUFACTURERS: LIQUID FLAT PLATE COLLECTORS
National Solar Heating and Cooling Information Center, The Franklin Institute
Research Laboratories, Rockville, MD, March 31, 1978

Misc.

323 manufacturers are listed.

0099

MANUFACTURERS OF SOLAR EQUIPMENT IN OHIO

National Solar Heating and Cooling Information Center, The Franklin Institute Research Laboratories, Rockville, MD., January 1, 1978, 5 pp.

Misc.

23 manufacturers are listed.

0100

Skoda, L. F., Masters, L. W.

SOLAR ENERGY SYSTEMS -- SURVEY OF MATERIALS PERFORMANCE

National Bureau of Standards, Washington, D.C., Final Report, NBSIR 77-1314, October 1977

Misc.

A study was performed to obtain data on the performance of materials in operational solar energy systems, to identify and assess available standards for evaluating materials, to provide recommendations for the development of test method standards for materials and to provide guidelines to aid the selection of materials for use in solar energy systems. During the study, field inspections of twenty-five operational solar energy systems were performed and a questionnaire was sent to 459 manufacturers and installation contractors to obtain materials performance data. This report contains the findings of the study. A primary conclusion is that the process of selecting materials for specific applications within solar energy systems is hindered by the lack of an adequate data base of materials performance under the conditions experienced in solar systems and subsystems. Recommendations are made that would help in establishing an improved data base.

0101

COPPER AND COPPER ALLOYS FOR THE PROCESS INDUSTRIES
Copper Development Association, Inc., Application Data Sheet, 143/8

Cu(Water, Antifreeze)

The relative corrosion resistance in many media for 20 copper alloys and two 99.9% pure copper metals is tabulated.

0102

Walker, M. S., Rowe, L. C.

THE USE OF ELECTROCHEMICAL TECHNIQUES FOR CORROSION RESEARCH IN THE
AUTOMOTIVE INDUSTRY

General Motors Research Laboratories, Warren, MI, Paper presented at
the International Corrosion Forum - Corrosion /76, March 22-26, 1976,
Houston, Texas, paper No. 112

Al(Water, Antifreeze); Fe(Water); Misc.

Electrochemical techniques have provided a new dimension to the study of metals corrosion and have led to the use of more corrosion resistant materials and better methods of corrosion prevention. Electrochemical techniques have been used effectively in corrosion research in the automotive industry. Some of the areas of interest have been (1) alloy development, (2) the Study of environmental effects and metallurgical changes on corrosion, (3) the determination of the resistance of metals to specific types of corrosion, (4) the study of the corrosion resistance of thin-film coatings, and (5) the resolution of problems associated with specific component parts.

0103

O'Neal, C., Jr., Borger, R. N.

THE EFFECT OF CHLORINE ON THE PERFORMANCE OF CUPROUS METAL CORROSION INHIBITORS
The Sherwin-Williams Company, Toledo, Ohio, Paper presented at the International Corrosion Forum - Corrosion/77, March 14-18, 1977, San Francisco, CA., Paper No. 68

Al(Water); Cu(Water); Fe(Water)

The present work measured the inhibition performance of benzotriazole (BT), tolyltriazole (TT), and 2-mercaptobenzothiazole (MBT) in the presence of chlorine. In a simulated cooling water (SCW) of pH 8.0 the inhibitors were employed at 3 concentrations at each of three chlorine concentrations. The degree of corrosion was determined by the weight loss method. The results show that the two triazoles (BT & TT) perform quite well when chlorine is present. On the other hand MBT's performance is seriously hampered.

0104

Donohue, J. M., James, E. W.

PASSIVATION AND ITS APPLICATION IN COOLING WATER SYSTEMS

Betz Laboratories, Inc., Trevose, PA., Paper presented at Corrosion/77, The International Corrosion Forum, March 14-18, 1977, San Francisco, CA., Paper No. 71.

Fe(Water)

The present economy requires that more attention be given by operating personnel to preconditioning processes for equipment exposed in cooling water systems. Metal loss and fouling should be minimized. Metal surfaces should properly be maintained in service following pretreatment. Where silt, suspended solids and organic materials are present in cooling water, the most effective dispersants or crystallization inhibitors may need to be applied continuously. Much research work is being done to produce on-stream antifoulants that can overcome the adverse effect of many substances in recirculating cooling water.

0105

Lawson, M. B., Frost, J. G.

SUGGESTED MECHANISM FOR ANODIC DISSOLUTION OF IRON IN AN ACIDIC NON-AQUEOUS SOLVENT

Halliburton Services, Duncan, OK., Paper presented at the Corrosion/77 International Corrosion Forum, March 14-18, San Francisco, CA., Paper No. 77

Fe(Antifreeze)

This paper discusses possible anodic mechanisms for a mild steel working electrode when in contact with a solution of monoethylene glycol which contains phosphoric acid. A mechanism, based on the assumption of low electrode surface coverage, is proposed for the anodic dissolution of iron when in contact with monoethylene glycol which contains phosphoric acid. The mechanism is analogous to that proposed by Bockris, et al for acidic aqueous systems with two exceptions; the anion is different, and the rate determining step is different. The difference in rate determining step can be explained various ways. The relative activation energies for the first two steps in the proposed mechanism can be altered by electron repulsion between electrons in "d" orbitals of iron and the approaching anion.

0106

Tait, W. S.

COMPARISON OF POTENTIODYNAMICALLY DETERMINED PITTING RATES WITH ACTUAL PITTING RATES FOR MILD STEEL AND ADMIRALTY BRASS IN OXYGEN BEARING WATERS

Petrolite Corporation, St. Louis, MO., Paper presented at the Corrosion/78 International Corrosion Forum, March 6-10, 1978, Houston, TX, Paper No. 173.

Misc.

The potentiodynamic method presented measures the actual steady state pitting rate for uninhibited waters and a weighted average pitting rate for inhibited waters. For inhibited waters the potentiodynamic rate is usually within one half of the value of the deepest pit rate. In uninhibited systems the pits on the electrode surface are nucleated at approximately the same time corresponding to the onset of metal exposure. When an inhibitor is present in solution not only can the rate of pit growth be lowered, but the nucleation of pits can occur over a broad range of times. This is most likely dependent upon the type of inhibitor employed. The centroid of a pitting distribution curve, for inhibited systems, approaches the potentiodynamically determined rate.

0107

Tait, W. S.

EFFECT OF PHYSICAL PARAMETERS ON THE PITTING CORROSION OF MILD STEEL IN LOW TOTAL DISSOLVED SOLIDS, OXYGEN-BEARING WATERS

Petrolite Corporation, St. Louis, MO., Paper presented at the Corrosion/78 International Corrosion Forum, March 6-10, 1978, Houston, TX, Paper No. 175

Fe(Water); Misc.

This paper presents the effects of various physical parameters on the pitting corrosion rate of mild steel exposed to low total dissolved solids (TDS), uninhibited oxygen-bearing waters. The metal samples used in this study were at the bulk solution temperature, heat being transferred to the metal from solution. Metal samples were cylindrical in shape, having a 9 cm² geometrical surface area, and were made of AISI 1018 Mild Steel.

0108

Smyrl, W. H., Pohlman, S. L.

DETERMINATION OF CORROSION PARAMETERS BY DIGITAL IMPEDANCE ANALYSIS

Sandia Laboratories, Albuquerque, NM., Paper presented at Corrosion/78 International Corrosion Forum, March 6-10, 1978, Houston, TX, Paper No. 166.

Misc.

This paper presents details of a digital signal analysis system used to measure the impedance of electrochemical cells with corroding electrodes. Multiple frequency voltage stimulation signals produce multiple frequency current signals which may be analyzed by Fast Fourier Transform techniques to obtain the impedance at each frequency. Analysis of the impedance results then provides values of the double layer capacitance and corrosion current density. Application of the system to dummy cells revealed that quite accurate results may be obtained. The corrosion current density of copper in 0.1M nitric acid was determined to be 4.98×10^{-6} amps/cm² with a double layer capacitance of 14.1×10^{-6} farads/cm².

0109

Sussman, S.

WATER SIDE CORROSION

Olin Water Services, Stamford, CT., Paper presented at Corrosion/78 International Corrosion Forum, March 6-10, 1978, Houston, TX, Paper No. 94.

Cu(Water); Fe(Water); Misc.

Corrosion-caused operating difficulties and equipment failures occur all too frequently in each of the many types of water systems in buildings. These difficulties and failures can be virtually eliminated, but this requires informed consideration of potential causes of corrosion and planning for their prevention or elimination starting with the earliest stages of design for components, as well as for the system as a whole, following through during construction, and continuing with close operational control of significant factors, including water treatment, and with good maintenance practices throughout the life of the building.

0110

Matasa, C. G., Setzer, W. C.

CONSIDERATIONS ON ALUMINUM CORROSION INHIBITORS

Paper presented at Corrosion/78 International Corrosion Forum, March 6-10, 1978, Houston, TX, Paper No. 46.

Al(Water, Antifreeze)

To the best of our knowledge, no attempts have ever been made to relate corrosion inhibition efficiency to the complexing properties of substances considering thus inhibitors as ligands. In this paper we will attempt to show that complexing properties are an important consideration in selecting inhibitors, and an understanding of this characteristic should be a valuable tool in the formulation of protection systems especially for those metals which exhibit vacant orbitals (transition elements). The present article considers only the case for aluminum in aqueous solutions under acid and neutral pH conditions.

0111 [See Also 0061]

Cash, M.

HARDWARE PROBLEMS ENCOUNTERED IN SOLAR HEATING AND COOLING SYSTEMS

NASA, George C. Marshall Space Flight Center, Alabama, DOE/NASA Technical Memorandum, TM-78172, May 1978, (N78-25539)

Cu(Water, Antifreeze); Fe(Water, Antifreeze), Misc.

Marchall Space Flight Center personnel have worked for several years with the development and demonstration of solar heating and cooling systems in support of the Department of Energy. In this work, they have encountered numerous problems in the design, production, installation, and operation of the solar energy systems. Many of these problems have been seen in more than one system. This report describes the hardware problems, which range from simple to obscure and complex, and their resolution. It is intended to provide personnel in the solar energy field with information that will help prevent the installation of solar heating and cooling systems that will not operate satisfactorily or that will not last for the design lifetime.

0112

SOLAR HEAT TRANSPORT FLUID

Houston Chemical Company, Corpus Christi, Texas, DOE/NASA Contractor Report CR-150704, June 1978, Contract NAS8-32255, (N78-27535)

Al(Water, Antifreeze); Cu(Water, Antifreeze); Fe(Water, Antifreeze)

This report covers the progress made in the development and delivery of noncorrosive fluid subsystems. These subsystems are to be compatible with closed-loop solar heating or combined heating and hot water systems. They are also to be compatible with both metallic and non-metallic plumbing systems. At least 100 gallons of each type of fluid recommended by the contractor will be delivered under the contract. The performance testing of a number of fluids is described.

0113

Giner, J., Cocks, F. H., Wong, D.
 STUDY OF CORROSION AND ITS CONTROL IN ALUMINUM SOLAR COLLECTORS
 Giner, Incorporated, Waltham, MA., Quarterly Progress Report,
 September 1977 (June 1, 1977-August 31, 1977), Contract
 EY-76-C-02-2934, Report No. COO/2934-5

Al(Antifreeze)

This program is intended to be an in-depth study of corrosion of aluminum in contact with water/glycol coolant, with the specific objectives of developing both corrosion control and monitoring methods applicable to aluminum solar heat collectors. Phase I of this study (now complete) obtained experimentally relevant corrosion information on selected aluminum alloys in a typical aqueous ethylene glycol solution (35% by volume). Phase II is divided into six tasks: (I) laboratory study of the corrosion behavior of aluminum alloy in propylene glycol/water mixtures, (II) development of inhibitors for aluminum in pure and contaminated glycol solutions, (III) further development of techniques to assess corrosion damage, (IV) development of an on-line corrosion monitoring device, (V) development and study of the effect of chemical scavengers for contaminants, and (VI) preparation of a corrosion control manual. Pure propylene glycol solution was found to be even less corrosive than ethylene glycol solution to aluminum alloys; but in the presence of chloride and heavy metal ions, the corrosion rate accelerates again to an intolerable level. Task II completed a literature search for suitable corrosion inhibitors. Task III successfully developed a circulation panel to simulate an actual collector operation.

0114

Pittinato, G. F.
 THE ELIMINATION OR CONTROL OF MATERIAL PROBLEMS IN WATER HEAT PIPES
 McDonnell Douglas Astronautics Company, Huntington Beach, CA, Quarterly
 Progress Report No. 1, NSF-RA-N-74-037, April 1974 (January 1, 1974-
 March 31, 1974), Grant GI-41310, PB 233 936

Cu(Water); Fe(Water)

This report documents the research and development efforts conducted at McDonnell Douglas Astronautics Company on Water heat pipes from January 1, 1974 to March 31, 1974. A definition was made of a water heat pipe associated with a parabolic cylindrical solar collector that will operate in the temperature range of ambient to 300°C. A literature survey was conducted on the problem on noncondensable gas generation in water heat pipes. The design of the heat pipes was completed and all of the materials and component parts have been ordered. Eight different alloys were selected for evaluation as candidate materials for water heat pipes.

0115

PRELIMINARY DESIGN PACKAGE FOR NONCORROSIVE FLUID SUBSYSTEM, SOLAR
HEATING AND COOLING
Houston Chemical Company, Pittsburgh, PA., DOE/NASA Contractor Report
CR 150698, May 1978, Contract NAS8-32255, (N78-25549)

Al(Water, Antifreeze); Cu(Water, Antifreeze); Fe(Water, Antifreeze)

This report contains the information necessary to evaluate the preliminary design for noncorrosive fluids for use in solar heating and cooling systems. Included are drawings for subsystem definition, rationale for special handling, installation and maintenance tools, and an outline for hazard analysis, along with development and testing plans.

0116

Kauffman, K. W.
NON-CORROSIVE, NON-FREEZING, AND NON-TOXIC HEAT TRANSFER FLUIDS FOR SOLAR
HEATING AND COOLING
Franklin Institute Research Labs., Philadelphia, PA., Proceedings of 1977
Annual Meeting American Section International Solar Energy Society, Orlando,
FL, June 6-10, 1977.

Al(Water), Cu(Water); Fe(Water); Misc.

Aqueous heat transfer fluids using inorganic salts have been developed which provide freezing protection to -15°C or better, form protective anticorrosive coatings on aluminum and steel, and which are substantially non-toxic. The performance and reliability of these fluids are compared to that of aqueous glycols and non-aqueous organic heat transfer fluids.

0117

Redmond, J. D., Lizlovs, E. A., Davison, R. M.

THE APPLICATION OF STAINLESS STEEL TO SOLAR COLLECTORS

Climax Molybdenum Company of Michigan, Ann Arbor, MI., Climax Molybdenum Company, Greenwich, CT., Proceedings of the 1977 Annual Meeting American Section International Solar Energy Society, Orlando, FL, June 6-10, 1977

Fe(Water)

The excellent corrosion resistance of some stainless steels suggests they can be used as the absorber plate material for solar collectors. The outstanding corrosion resistance of Type 444 stainless steels indicates it could be used in a once-through system in which potable water or swimming pool water would be the heat transfer fluid. Such a system would be expected to have lower total cost, simpler operation and maintenance requirement, and warrantability of long-term performance.

0118

Nichols, R. L.

OWENS-ILLINOIS LIQUID SOLAR COLLECTOR MATERIALS ASSESSMENT

NASA, George C. Marshall Space Flight Center, Alabama, DOE/NASA Technical Memorandum, TM 78163, March 1978 [N78-21597]

Misc.

From the beginning of this investigation it has been noted that the baseline drawings for the liquid solar collector exhibited a distinct weakness concerning materials specification where elastomers, plastics, and foam insulation materials are utilized. Based on results obtained from boilout and stagnation tests on the solar simulator, it is concluded that proof testing of the collector tubes prior to use helps to predict their performance for limited service life. Fracture mechanics data are desirable for predicting extended service life and establishing a minimum proof pressure level requirement. The temperature capability of this collector system has been increased as the design matured and the coating efficiency improved. This higher temperature demands the use of higher temperature materials at critical locations in the collector. The manifold nonmetallic materials must be upgraded to provide capabilities consistent with those of the improved collector.

0119

Beynon, E., Cooper, N. R., Hannigan, H. J.

COOLING SYSTEM CORROSION IN RELATION TO DESIGN AND MATERIALS

Union Carbide Corporation, Tarrytown, NY, Society of Automotive Engineers, Inc.,
SAE/P-78/78, pp 56-64, (780919)

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze)

Field experience revealing corrosion failures relating to engine cooling system design and material causes as well as coolant deficiencies are reviewed. Basic corrosion mechanisms are described and related to specific component failures. The role of ethylene glycol base inhibited coolants is discussed and the real world of consumer practices and service problems is described. Conclusions are developed which suggest viable approaches to further improvements in cooling system performance and reliability.

0120

SURVEY OF COMPONENT R&D PROJECTS FOR SOLAR HEATING, COOLING AND HOT WATER SUPPLY SYSTEMS--TASK II: COORDINATION OF R&D ON SOLAR HEATING AND COOLING COMPONENTS

U.S. Department of Energy, Research & Development Branch of Heating and Cooling, TID-28721, Contract EG 77-C-01-2522, April 1978

Misc.

One of the purposes of the International Energy Agency, established in 1974, was to promote long-term cooperative efforts in energy R&D. Solar energy was identified as one appropriate energy technology area for international cooperation, and the Program to Develop and Test Solar Heating and Cooling Systems was created with the objective of pooling efforts and experience in order to reduce overall costs of solar energy systems and accelerate the large scale introduction of this technology in the participating countries. One of the five cooperative projects which comprise this multilateral program is "Coordination of R&D on Solar Heating and Cooling Components." An element of this project is the exchange of information on ongoing component R&D projects. Participating countries have submitted descriptive summaries of R&D projects, using a special format. This report is a compilation of 198 project summaries and provides a useful overview of component R&D work underway in eleven countries.

0121

Johnson, A. B., et al

A SURVEY OF MATERIALS AND CORROSION PERFORMANCE IN DRY COOLING APPLICATIONS
Battelle, Pacific Northwest Laboratories, Richland, WA., Report No. BNWL-1958,
UC-12, March 1976, Contract E(45-1)-1830

Al(Water); Cu(Water); Fe(Water)

There is presently only one dry-cooled central power station in the U.S. Battelle contacted a cross section of the U.S. dry cooling equipment industry and made visits to several operating dry-cooled power stations in Europe. This report addresses the construction materials and the scope of the successful performance and operational problems, emphasizing results from the U.S. survey. The results of the survey indicate that U.S. industrial dry-cooled equipment functions with very few operational problems. The types of problems which occur were cataloged, including corrosion, fan blade, fan motor, and gear box failures, freezing, hail damage and hot air recirculation. Corrosion, while not a frequent problem, was the only problem which has resulted in shut downs for major repair. This occurred at one dry-cooled power station (Rugeley) and at a few industrial air-cooled installations having polluted atmospheres. Correct siting and materials selection for large dry-cooled power stations will assure that corrosion is a minimal problem.

0122

vonFraunhofer, J. A.

CORROSION IN HOT WATER CENTRAL HEATING

British Corrosion Journal, 6, January 1971, pp 23-30

Cu(Water); Fe(Water)

The basic principles of corrosion relevant to wet central heating are reviewed. The corrosion phenomena of hydrogen evolution, magnetite formation and radiator perforation are considered in the light of theory and practice. Current and future research work in this field at the Gas Council, Watson House, is outlined.

0123

Gutler, G., Ison, H.C.K., Mercer, A. D.
SOME IMPORTANT ASPECTS OF CORROSION IN CENTRAL HEATING SYSTEMS
British Corrosion, 6, January 1971, pp 31-38

Cu(Water); Fe(Water)

Work at the former National Chemical Laboratory and the National Physical Laboratory is reviewed in the light of corrosion problems that occur in central heating systems. Important factors discussed include variation in composition and aggressivity of the waters used; the morphology of pitting attack; and the influence of flow, temperature and heat transfer on the corrosion process.

0124

Drane, C. W.
SOME ASPECTS OF WATER TREATMENT FOR CENTRAL HEATING SYSTEMS
British Corrosion Journal, 6, January 1971, pp 39-41

Cu(Water); Fe(Water)

Problems considered are hardness and scale formation and the occurrence of noise in central heating systems, and methods of corrosion inhibition. CaCO_3 formation is usually not on a large enough scale to cause trouble, although small amounts may be deposited at specific points and lead to failure. The use of sequestrants as scale controllers may produce unwanted sludge, and suitable threshold treatment reagents are not yet commercially available. Mechanical noise problems are usually solved by venting air from the system, and the use of additives such as Calgon may prevent scale formation and reduce noise. Criteria for corrosion control are listed, and the merits of phosphate, silicate, borate and benzoate inhibitors are compared, and it is concluded that benzoate/nitrite systems are the most suitable.

0125

Cotton, J. B., Jacob, W. R.

PREVENTION OF CORROSION IN DOMESTIC HOT WATER CENTRAL HEATING SYSTEMS

British Corrosion Journal, 6, January 1971, pp 42-44

Cu(Water); Fe(Water)

The corrosion reactions that are likely to occur when bare steel is exposed to water in domestic central heating systems are discussed and the resultant effects are related to corrosion of radiators per se, and to the ancillary occurrence of hydrogen gas-locking in radiators and to blockage of pumps by loose magnetite. The suggested remedial measures include care in installation to prevent air ingress into and water leakage from central heating systems and the use of corrosion inhibitors.

0126

Burns, D., Bonds, J. D., Simms, D. W.

TYPICAL CASES OF CORROSION IN CENTRAL HEATING SYSTEMS IN COUNCIL PROPERTIES--
SUMMARYBritish Corrosion Journal, 6, January 1971, pp 45-48

Cu(Water); Fe(Water)

The authors described measures taken by the Greater London Council to investigate and remedy corrosion problems occurring in council properties, such as schools, houses and flats (including high-rise flats), and outlined some cases of failures. The main problems are blockage, gassing, formation of sludge and perforation. Pitting may occur if oxygen is present, but this is usually more evident in mixed metal systems. Pitting can also be caused by sulfate-reducing bacteria in those parts of a system where sludge may settle. A problem of perforation, occurring at breaks in the mill-scale, was attributed partly to unsuitable design and partly to the high sulfate content of the water, which was itself a result of faulty design. In this system the boiler was at the top of the building, circulation being maintained by a pump. The high sulfate content of the water in the expansion tank was traced to contamination by sulfur dioxide from the flue gases, the siting of the flue discharge being unsuitable and ventilation bad.

0127

Moreland, P. J., Rowlands, J. C.
TECHNIQUE AND INSTRUMENTATION FOR POLARISATION RESISTANCE MEASUREMENTS --
REPORT PREPARED FOR THE EUROPEAN FEDERATION OF CORROSION WORKING PARTY ON
'PHYSICO-CHEMICAL TESTING METHODS OF CORROSION--FUNDAMENTALS AND APPLICATION'
British Corrosion Journal, 12 (2), 1977, pp 72-79

Misc.

Polarization resistance measurements provide a valuable tool for corrosion rate measurements, but limitations and errors that can arise through technique and laboratory and commercial instrumentation are described. Some simple circuits for laboratory measurements are shown, together with a description of some commercial instruments.

0128

Doig, P., Flewitt, P.E.J.
SIMULTANEOUS CORRECTION OF THE iR POTENTIAL DROP DURING POTENTIOSTATIC
POLARISATION MEASUREMENTS
British Corrosion Journal, 11 (2), 1976, pp 78-79

Misc.

Large errors arise in potentiostatic pulse experiments when an iR compensation is not employed. A method for simultaneous iR drop correction during potentiostatic control experiments is described. The method is applied to a Wenking ST72 potentiostat and an example potentiostatic pulse experiment is described.

0129

Callow, L. M., Richardson, J. A., Dawson, J. L.
CORROSION MONITORING USING POLARIZATION RESISTANCE MEASUREMENTS -- I. TECHNIQUES
AND CORRELATIONS
British Corrosion Journal, 11 (3), 1976, pp 123-131

Misc.

Techniques for the measurement of polarization resistance, and the determination of proportionality constants for the conversion of polarization resistance to corrosion rate, are briefly discussed. Studies of the polarization resistance of iron, aluminum, copper and nickel and their alloys, and other miscellaneous metal and alloy systems, in a wide variety of environments, are reviewed. A selection of proportionality constants are quoted. Very few problems have been cited in the literature concerning the correlation of corrosion rates calculated from polarization resistance data for iron and aluminum and their alloys with corrosion rates calculated using Tafel extrapolation and/or weight loss techniques. The situation is less clear for copper and nickel and their alloys, although many workers have claimed that, in these systems too, good correlation can be achieved.

0130

Callow, L. M., Richardson, J. A., Dawson, J. L.
CORROSION MONITORING USING POLARIZATION RESISTANCE MEASUREMENTS -- II. SOURCES
OF ERROR
British Corrosion Journal, 11 (3), 1976, pp 132-139

Misc.

The various fundamental and experimental factors which contribute to inaccuracy in, or even invalidate, the polarization resistance technique of monitoring corrosion rates, are reviewed. The factors include deviations from linearity of polarization data in the vicinity of the corrosion potential, polarization data obtained close to reversible potentials, the presence of appreciable IR drops, failure to achieve steady state during polarization, time-dependent corrosion potentials and Tafel slopes, electrode perturbation, and probe element differences resulting from localized corrosion. An attempt is made to assess the various factors in terms of the possible magnitudes of errors introduced into calculated corrosion rates.

0131

Heitz, E., Schwenk, W.

THEORETICAL BASIS FOR THE DETERMINATION OF CORROSION RATES FROM POLARIZATION RESISTANCE

British Corrosion Journal, 11 (2), 1976, pp 74-77

Misc.

The polarization resistance method is extensively used for corrosion rate measurement. This paper considers the theoretical conditions which must be satisfied in the measurement of polarization resistance and the limitations of the applicability of the method in relation to the properties of the electrolyte, the kinetics of the anodic and cathodic processes, and the surface condition of the corroding metal.

0132

Neufeld, P., Queenan, E. D.

FREQUENCY DEPENDENCE OF POLARIZATION RESISTANCES MEASURED WITH SQUARE-WAVE ALTERNATING POTENTIAL

British Corrosion Journal, 5, March 1970, pp 72-75

Misc.

Polarization resistance measurements have been made on iron and aluminum electrodes in a selection of common inorganic electrolytes. A square-wave alternating potential was applied to the electrodes over the frequency range $0.03-10^4$ Hz. The electrode impedance deviated from a pure resistance to varying extents, the measured value of polarization resistance varying significantly with frequency over the entire frequency range in some cases. Transient effects at high frequencies, which cause distortion of the wave-form, may be minimized by the use of a control circuit of low impedance.

0133

Johnson, W. K.

RECENT DEVELOPMENTS IN PITTING CORROSION OF ALUMINUM

British Corrosion Journal, 6, September 1971, pp 200-204

Al(Water)

This paper draws attention to the practical importance of pitting. The environmental and metallurgical factors controlling pit initiation and propagation are reviewed in the light of recent researches. It is proposed that pits start because of the presence of flaws in the oxide film exposing anodic and cathodic areas and that these pits proceed because the conditions within the pit favour dissolution of the metal. The importance of copper and chloride ions in solution is stressed, as well as the lesser importance of sulfate.

0134

Butler, G., Mercer, A. D.

INHIBITOR FORMULATIONS FOR ENGINE COOLANTS

British Corrosion Journal, 12 (3), 1977, pp 171-174

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze)

The findings of some recent research in the field of corrosion inhibitors for engine coolants is summarized. Some new inhibitor formulations are described and attention drawn to the promising results given by a sodium sebacate + benzotriazole mixture. Test procedures have included studies under conditions of high rates of meta-to-coolant heat transfer and the use of high-chloride waters. In addition benzotriazole reduces scale deposition and pH changes, and has a synergistic effect when combined with benzoate in preventing the corrosion of cast iron.

0135

Tabony, J. H.

INHIBITOR ANALYSIS FOR A SOLAR HEATING AND COOLING SYSTEM

Southern University, Baton Rouge, LA., DOE/NASA Contractor Report,
CR-150513, June 1, 1977, NASA Grant NSG 8025 [N78-17475]

Al(Water); Cu(Water); Fe(Water)

This report is a study of potential corrosion inhibitors for the NASA solar heating and cooling system which uses aluminum solar panels. The work is a continuation of the work performed in Supplement 1 of the NASA Grant 8025. This second phase of the research under this grant consisted of continued testing using the dynamic corrosion system developed in phase one, along with an economic analysis of the corrosion inhibitors tested in phases one and two. Very good progress was made in finding a suitable inhibitor for the system.

0136

THE DETERMINATION OF ALUMINUM, COPPER, IRON AND LEAD IN GLYCOL FORMULATIONS
BY ATOMIC ABSORPTION SPECTROSCOPYHouston Chemical Company, Corpus Christi, TX., DOE/NASA Contractor Report
CR-150520, April 1977, Contract NAS8-32255 [N78-17174]

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze), Misc.

This report describes initial screening tests and the results obtained in developing procedures to determine Al, Cu, Fe, and Pb in glycol formulations. Atomic absorption completion was selected for Cu, Fe and Pb, and after comparison with emission spectroscopy, was selected for Al also. Before completion, carbon, iron, and lead are extracted with diethylene thiocarbamate (DDC) into methyl isobutyl ketone (MIBK). Aluminum was also extracted into MIBK using 3-hydroxyquinoline as a chelating agent. As little as 0.02 mg/L carbon and 0.06 mg/L lead or iron may be determined in glycol formulations. As little as 0.3 mg/L aluminum may be determined.

0137

J. I. Bregman

COOLING WATER--OTHER SYSTEMS - CHAPTER 4

IIT Research Institute, Illinois Institute of Technology, Corrosion Inhibitors,
Published by The MacMillan Company, New York. 1963

Al(Water, Antifreeze); Cu(Water, Antifreeze); Fe(Water, Antifreeze)

The problems associated with the inhibition of corrosion of internal combustion engines are similar in many respects to those described for cooling-tower systems. The main difference between the cooling systems of the internal combustion engines and those of the cooling towers is that the former are essentially "closed" recirculating systems while the latter are "open". The resultant difference in the loss by evaporation and the oxygen content gives a somewhat easier system to protect. The problems associated with cooling systems in internal combustion engines can be further broken down as follows: (1) Diesel engine cooling systems; (2) Automotive cooling systems; (3) Antifreeze in either system. There are other recirculating systems which are treated with corrosion inhibitors and antifreeze, but the diesel and the automotive systems are the major ones. They are treated separately for reasons which become obvious in this chapter.

0138

Payerle, Norman E.

ENGINE COOLANT PERFORMANCE IN LATE MODEL PASSENGER CARS

Union Carbide Corp., Tarrytown Technical Center, Paper No. 760631

Cu(Antifreeze); Fe(Antifreeze); Misc.

A national survey of factory-fill coolants in 1972 to 1974 vehicles has shown that moderate or heavy rusty sediment was present in 23% of these coolants the first year and 36% the third year. Corrosion inhibitor depletion and dilution have additionally contributed to result in a minimum of 35 to 53% of cars requiring cooling system service, increasing over these three years. This survey, showing good agreement with extensive data reported before SAE in 1966, indicates that the cooling system still should be serviced, including flushing and refilling with fresh antifreeze-coolant at minimum 50% concentration, each year for best assurance of continuous, satisfactory cooling system performance in modern engines.

0139

STANDARD METHOD FOR SIMULATED SERVICE CORROSION TESTING OF ENGINE COOLANTS
ASTM Standard, ASTM Designation: D 2570-73, pp 357-367

Misc.

This method evaluates the effect of a circulating engine coolant on metal test specimens and automotive cooling system components under controlled, essentially isothermal laboratory conditions. The method specifies test materials, cooling system components, type of coolant, and coolant flow conditions that are considered typical of current automotive use.

0140

Standard Method for CORROSION TEST FOR ENGINE COOLANTS IN GLASSWARE
ASTM Standard, ANSI/ASTM D 1384 - 70(1975)

Misc.

This method covers a simple beaker-type procedure for evaluating the effects of engine coolants on metal specimens under controlled laboratory conditions. In this method, specimens of metals typical of those present in automotive cooling systems are totally immersed in the test antifreeze solution with aeration for 336 h at 190 F for high-boiling antifreezes and 160 F for low-boiling antifreezes. The corrosion-inhibitive properties of the test solution are evaluated on the basis of the weight changes incurred by the specimens. Each test is run in triplicate, and the average weight change is determined for each metal.

0141

STANDARD RECOMMENDED PRACTICE FOR CONVENTIONS APPLICABLE TO ELECTROCHEMICAL MEASUREMENTS IN CORROSION TESTING
ASTM Standards, ASTM Designation: G3 - 74

Misc.

This recommended practice is intended to provide conventions for reporting and displaying electrochemical measurements in corrosion studies. Sign conventions for potential and current density as well as conventions for graphical presentation of data are included.

0142

STANDARD RECOMMENDED PRACTICE FOR CONDUCTING PLANT CORROSION TESTS
ASTM Standards, ASTM Designation G4 - 68 (Reapproved 1974)

Misc.

This recommended practice outlines procedures for conducting corrosion tests in plant equipment under operating conditions. It is not intended for atmospheric or underground corrosion tests but may possibly apply to other tests under natural conditions where the procedure has proven satisfactory. Corrosion testing by its very nature precludes complete standardization. This recommended practice, rather than a standardized procedure, is presented as a guide so that some of the pitfalls of such testing may be avoided.

0143

STANDARD RECOMMENDED PRACTICE FOR LABORATORY IMMERSION CORROSION TESTING
OF METALS

ASTM Standard, ASTM Designation: G31 - 72

Misc.

This recommended practice also emphasizes the importance of recording all pertinent data and provides a checklist for reporting test data. This recommended practice, rather than a standardized procedure, is presented as a guide so that some of the pitfalls of such testing may be avoided. Experience has shown that all metals and alloys do not respond alike to the many factors that affect corrosion and that "accelerated" corrosion tests give indicative results only, or may even be entirely misleading. It is impractical to propose an inflexible standard laboratory corrosion testing procedure for general use, except for material qualification tests where standardization is obviously required. In designing any corrosion test, consideration must be given to the various factors discussed in this recommended practice, because these factors have been found to affect greatly the results obtained.

0144

STANDARD RECOMMENDED PRACTICE FOR EXAMINATION AND EVALUATION OF PITTING
CORROSION

ASTM Standard, ASTM Designation: G 46 - 76

Misc.

This recommended practice is a guide to assist in the selection of procedures that can be used in the identification and examination of pits and in the evaluation of pitting corrosion to determine the extent of its effect.

0145

STANDARD TEST METHODS FOR PITTING AND CREVICE CORROSION RESISTANCE OF STAINLESS STEELS AND RELATED ALLOYS BY THE USE OF FERRIC CHLORIDE SOLUTION
ASTM Standard, ANSI/ASTM G47 - 76

Misc.

These methods cover procedures for the determination of pitting and crevice corrosion resistance of stainless steels and related alloys when exposed to oxidizing chloride environments. Two procedures are described. Method A is designed to determine the relative pitting resistance of stainless steels and nickel-base, chromium-bearing alloys, whereas Method B can be used for determining both the pitting and crevice corrosion resistance of these alloys. These tests may be used to determine the effects of alloying additives, heat treatment, and surface finishes on pitting and crevice corrosion resistance.

0146

Roller, D.

THIN METAL FILM CORROSION INDICATORS
Corrosion, Vol 14, pages 263t-267t

Al(Water, Antifreeze); Cu(Water, Antifreeze); Fe(Water, Antifreeze)

Tests were made to find a thin metal film which would act as both a visual and electrical corrosion indicator in connection with the packaging of hardware items. Selected for testing purposes were thin, continuous iron films which had been vacuum deposited on borosilicate glass and on Plexiglass 55 in thicknesses ranging from 100 to 2500 Angstroms. Measuring the electrical resistance per inch and computing the resistance per square of the films was a convenient, reasonably accurate method of comparing film thicknesses and determining the progress of corrosion. Early visual detection of corrosion products was not difficult due to change in film characteristics. However, changes in electrical resistance were not great until specimens were moderately corroded. A marked decrease in corrosion occurred when films were too thick or too thin and when Plexiglass 55 was used as a substrate rather than a borosilicate glass. Tests were conducted in atmospheres varying from 0 to 100 percent relative humidity. The effects of different film compositions and characteristics, substrates, specimen preparation, and metal deposition techniques on corrosion rates are not completely understood. When the interrelationships of these factors and their influence on corrosion rate are more completely understood, it should be possible to make useful applications of thin metal films as corrosion indicators.

0148

Miksic, B. A., Levans, W. G.

CORROSION INHIBITING RUBBER SEALS

Northern Instruments Corp., and Garlock, Inc., Paper No. 770174

Misc.

Some elastomeric seal compounds show a tendency to induce corrosion of metals. The corrosion inducing mechanism is not completely understood, but it is believed that certain compounding ingredients are responsible for the corrosive action. The purpose of our investigation was to formulate a corrosion inhibiting system that would inhibit the attack on the metal substrate. To be practically applicable, the inhibiting chemicals would have to be added at the compounding stage with the rest of compounding ingredients and would have to be of zero or low toxicity and pollution.

0147

Bregman, J. I., Boies, D. B.

LABORATORY TESTING OF RAILROAD DIESEL COOLING SYSTEM CORROSION INHIBITORS

Corrosion--National Association of Corrosion Engineers, Vol. 14, pp 33-37

Al(Water, Antifreeze); Cu(Water, Antifreeze); Fe(Water, Antifreeze)

The cooling system of a railroad Diesel locomotive presents a complex corrosion problem, due to the number of different metals used and the wide range of conditions encountered. These factors are discussed in relation to the development of test methods for the laboratory evaluation of corrosion inhibitors. Two types of tests were developed: a flask type test for screening and development work, and a recirculating test, including a heat transfer surface, designed to more nearly duplicate the actual use conditions, and to give a final evaluation to a product. Test results are given for several commercial and experimental inhibitors of the "boron-nitrite", "soluble oil" and other types. Results are also presented for variation of factors such as coupling or insulation of the various metals, inhibitor dosage level, water composition, presence of anti-freeze, etc., as well as effect of the treatment on various nonmetallic parts of the system. The importance of inhibition behavior under these various conditions is discussed in relation to actual use conditions. It is shown that the results of the laboratory tests have correlated well with field use.

0149

Beynon, E., Cooper, N. R., Hannigan, H. J.

AUTOMOTIVE ANTIFREEZE COOLANTS - PART II

Soap & Chemical Specialties, Vol 47, March 1971, pp 52, 54, 56, 109

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze); Misc.

The engine coolant should be recognized as a full time, high performance, functional fluid in the same manner as engine oils and automatic transmission fluids. The modern engine is designed to run with inhibited ethylene glycol coolant year-round. Only a highly inhibited ethylene glycol antifreeze-coolant at the recommended concentration will provide the necessary antifreeze and antifoam properties, as well as the superior corrosion inhibition and full cooling capability demanded by the modern engine.

0150

Beynon, E., Cooper, N. R., Hannigan, H. J.

AUTOMOTIVE ANTIFREEZE COOLANTS - PART I

Soap & Chemical Specialties, Vol. 47, February 1971, pages 44, 46, 48, 108-109

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze); Misc.

Only a highly inhibited ethylene glycol antifreeze-coolant at recommended concentration will provide the necessary antifreeze and antifoam properties and corrosion inhibition required to cool modern car engine.

0151

SELECTION AND USE OF ENGINE COOLANTS AND COOLING SYSTEM CHEMICALS
American Society for Testing and Materials, ASTM STP 120B, January 1974

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze); Misc.

The purpose of this publication is to provide practical information and advice on engine coolants as well as cooling system chemicals, such as cleaning compounds, antirusts, and stop-leaks. The references to cooling system services are confined to the practices directly affecting coolants, since the subject of general cooling system maintenance is already covered in published automotive literature.

0152

Davis, D. D., Johnson, D. L.

PHOTO-ASSISTED CORROSION OF COPPER

Journal Electrochemical Society, Vol. 125, No. 11, November 1978, pp 1889-1891

Cu(Water)

In an anaerobic acidic medium containing chloride ions, corrosion of copper is greatly accelerated by visible light. Such conditions might obtain in solar collectors in which partly saline water is used, particularly if the acidic decomposition products of a heat transfer medium such as glycols are present, and of course if this system is subjected to visible radiation. Although these are fairly stringent limitations, the photoassisted corrosion of copper is a hitherto uninvestigated and novel mode of corrosion and etching which may have importance in diverse applications of copper and its alloys.

0153

Beynon, E.

ANTIFREEZES

Encyclopedia of Industrial Chemical Analysis, Vol. 6, 1968, Interscience Publishers, New York, F. D. Snell and C. L. Hilton, Editors

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze); Misc.

This review article discusses the properties, methods of analysis, additives, inhibitors and performance test methods for a variety of antifreeze.

0154

STANDARD TEST METHOD FOR RESERVE ALKALINITY OF ENGINE ANTIFREEZE, ANTIRUSTS, AND COOLANTS

ASTM Standard, ANSI/ASTM D 1121 - 72, pp 164-168

Misc.

This method covers the determination of the reserve alkalinity of new, unused engine antifreezes and liquid antirusts as received, of used or unused aqueous dilutions of the concentrated materials, and of aqueous dilutions of solid antirusts. A 10-ml sample of concentrated antifreeze-antirust, coolant additive, or an aqueous engine coolant containing these products, is diluted to about 100 ml with water and titrated potentiometrically with 0.100 N hydrochloric acid to a pH of 5.5. The volume of acid used is reported to the nearest 0.1 ml. The concentration of antifreeze or additive in the coolant solution shall be recorded if required, for calculation of depletion of the reserve alkalinity during performance tests.

0155

STANDARD METHOD FOR SAMPLING AND PREPARING AQUEOUS SOLUTIONS OF ENGINE COOLANTS
OR ANTIRUSTS FOR TESTING PURPOSES
ASTM Standard, ANSI/ASTM D1176 - 71

Misc.

This method helps in obtaining reproducible results in laboratory testing by establishing standard methods for: obtaining a representative sample of predominantly liquid commercial coolant or antirust from the original container; separating the water-soluble phase of engine coolant where required; and preparing aqueous solutions of both engine coolants and antirusts.

0156

STANDARD TEST METHOD FOR FREEZING POINT OF AQUEOUS ENGINE COOLANT SOLUTION
ASTM Standard, ANSI/ASTM D 1177 - 65

Misc.

This method covers the determination of the freezing point of an aqueous engine coolant solution in the laboratory. The method involves the determination of the time-temperature curve prior to freezing and the determination of the horizontal or flattened portion of the freezing curve. The freezing point is taken as the intersection of projections of the cooling curve and the freezing curve. If the solution undercools, the freezing point is the maximum temperature reached after undercooling.

0157

STANDARD TEST METHOD FOR pH OF ENGINE ANTIFREEZES, ANTIRUSTS, AND COOLANTS
ASTM Standard, ANSI/ASTM D 1287 - 78

Misc.

This method covers the determination of the pH of unused engine antifreezes, antirusts, and coolants and used or unused aqueous dilutions of the concentrated products. A sample, as received or after dilution with a specified volume of distilled water, is placed in a beaker or sample cup and the pH measured with a pH meter and associated glass-saturated calomel electrode pair.

0158

STANDARD METHOD OF TESTING ENGINE COOLANTS BY ENGINE DYNAMOMETER
ASTM Standard, ANSI/ASTM D 2758 - 78

Misc.

This method covers a full-scale clean engine test designed to evaluate corrosion protection and inhibitor stability of antifreeze coolants under stimulated heavy-duty driving conditions. This technique involves the operation of a standard passenger car engine on a dynamometer stand under constant speed, load, and coolant temperature conditions for a total of 700 h. The performance of the coolant is judged by examination of (1) coolant samples (2) metal corrosion specimens (3) cooling system components, and (4) air entrainment and foaming under conditions of forced aeration.

0159

STANDARD RECOMMENDED PRACTICE FOR TESTING ENGINE COOLANTS IN VEHICLE SERVICE
ASTM Standard, ANSI/ASTM D 2847 - 78

Misc.

This recommended practice covers the procedure for evaluating corrosion protection and performance of an engine coolant in vehicle service. Standard metal corrosion specimens, mounted in special holders, are installed in the coolant flow of the test vehicles. The coolant is tested at approximately the minimum and maximum recommended concentrations in a specified test water. Each test condition requires a minimum of five test vehicles. The test duration in terms of time or mileage should be consistent with the recommended service life of the coolant. The vehicle, corrosion specimens, and coolant are inspected according to a prescribed schedule to provide the basis for coolant evaluation.

0160

STANDARD RECOMMENDED PRACTICE FOR PREPARING, CLEANING, AND EVALUATING
CORROSION TEST SPECIMENS
ASTM Standard, ANSI/ASTM G 1 - 72

Misc.

This recommended practice gives suggested procedures for preparing bare, solid metal specimens for laboratory corrosion tests, for removing corrosion products after the test has been completed, and for evaluating the corrosion damage that has occurred. Emphasis is placed on procedures related to the evaluation of corrosion by mass-loss and pitting measurements.

0161

STANDARD RECOMMENDED PRACTICE FOR APPLYING STATISTICS TO ANALYSIS OF
CORROSION DATA

ASTM Standard, ANSI/ASTM G 16 - 71

Misc.

The purpose of this practice is to provide a set of sample procedures that are in current usage in statistical analysis of corrosion experiments. It is recognized that the procedures selected are but a fraction of methods available and that complete agreement on specific methods selected may not be possible. The examples included are intended to provide a method for planning corrosion experiments, analyzing data obtained, and establishing the degree of confidence that can be placed in the results of specific experimental or field applications data.

0162

Hillner, W. G.

SPECIFICATION OF SOLAR COLLECTORS

Building Systems Design, 75 (5), August/September 1978, pp 46-58

Misc.

This paper deals with flat plate and evacuated tube solar collectors, the two types of collectors most widely used today, because they can produce temperatures in the range of 100-220F with which virtually all buildings can be effectively heated and cooled.

0163

SOLAR HEAT TRANSPORT FLUID -- A Quarterly Report
Houston Chemical Company, DOE/NASA Contractor Report, DOE/NASA CR-150612,
November 1977-January 1978, February 1978, Contract NAS8-32255, N78-21592

Al(Water, Antifreeze); Cu(Water, Antifreeze); Fe(Water, Antifreeze)

This report covers the progress made from November 1977 to January 1978 on the development and delivery of noncorrosive fluid subsystems. These subsystems are to be compatible with closed-loop solar heating or combined heating and hot water systems. They are also to be compatible with both metallic and non-metallic plumbing systems. At least 100 gallons of each type of fluid recommended by the contractor will be delivered under the contract. The performance testing of a number of fluids is described.

0164

Newton, A. B.

GETTING THE MOST OUT OF ASHRAE 93-77 -- THE MEANING AND USE OF CONSENSUS
STANDARDS IN RATING SOLAR COLLECTORS
Solar Age, November 1978, pp 26-29

Misc.

After the usual public review period, the new standard was approved in early 1977 as ASHRAE Standard 93-77, "Methods of Testing to Determine the Thermal Performance of Solar Collectors." ASHRAE 93-97 is designed to produce a wealth of usefull information. Tests made in any location can be used to predict performance in any other location under any conditions and over any desired period of time. This makes system performance predictable.

0165

Cash, M.

LEARNING FROM EXPERIENCE

Solar Age, November 1978, pp 15-19, 32

Misc.

The mistakes found to date in the design, production, installation, and operation of solar heating and cooling systems show there is much to be learned. As knowledge of these problems becomes more widespread, their incidence will decrease. A means of knowing that the system is performing properly is important to ensure maximum benefits, since improper operation of the system is one of the most difficult problems to detect.

0166

Gargus, S.

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NASA, George C. Marshall Space Flight Center, NASA Technical Memorandum
TMX-73398, July 1977, (N78-13554)

Misc.

This document consists of listings of technical briefs, reports, and papers pertaining to research being performed by MSFC personnel and contractor in the field of solar energy. A subject index is included.

0167

Walker, M. S.

THE EFFECT OF INHIBITORS IN ANTIFREEZE ON CORROSION OF HEAT-REJECTING SURFACES
Materials Protection and Performance, 12 (7), July 1973, pp 29-33

Al(Antifreeze); Fe(Antifreeze)

At engine block surfaces, heat is transferred through the metal and rejected to the coolant. Tests have shown that corrosion is more severe at a surface that rejects heat to a coolant than at a surface that accepts heat from a coolant. Aluminum is more susceptible than cast iron to accelerated corrosion at heat-rejecting surfaces. It is particularly sensitive to the concentration of phosphate inhibitor in the coolant and to the temperature of the metal surface. The corrosion rate increases when nucleate boiling of coolant occurs on the metal surface. Alloying constituents and their distribution can affect the nature and severity of corrosive attack on an aluminum heat-rejecting surface.

0168

Walker, M. S.

LINEAR POLARIZATION APPLIED TO CORROSION RATE MEASUREMENT IN AUTOMOTIVE
COOLING SYSTEMS

Materials Performance, July 1974, pp 37-41

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze); Misc.

Linear polarization measurements are rapid and accurate in determining high and low corrosion rates in operating vehicles. The measurements do not disturb the corroding system and give unique information on the effect of time and operating variables on corrosion rate. This report describes how linear polarization measurements were adapted to the study of automotive cooling system corrosion. General Motors studies have shown that car service which leads to prolonged high coolant temperatures causes high corrosion rates.

0169

Boehmer, M. A., Compton, J. W.

THE EFFECTS OF WATER QUALITY ON THE CORROSION OF METALS IN GLYCOL ANTIFREEZE SOLUTIONS

Soap and Chemical Specialties, June, 1959, pp 93,95,97,99; July 1959, pp 85,89, 93,97,102-104

Fe(Antifreeze); Al(Antifreeze)

Fourteen antifreezes, commercially available in the Detroit area, were tested by an accepted laboratory method using Detroit tap water and 100 ppm chloride-200 ppm sulfate test water. Corrosion as a function of dilution was investigated. A chloride-sulfate test water and several other test waters were used in the ASTM test. Based upon the laboratory data, six antifreezes were considered representative of the fourteen. These six were tested further by a simulated service test and duplicate fleet tests in an effort to establish a correlation between the laboratory tests and realistic corrosion evaluations.

0170

Copson, H. R.

EFFECTS OF VELOCITY ON CORROSION

Corrosion, 16, February 1960, pp 86t-92t

Fe(Water); Cu(Water); Misc.

Discusses effects of velocity of fluids on corrosion rate of metals. Explains relation between corrosion rate factors and velocity and velocity effect on corrosion of iron and other metals. Also discusses galvanic effects produced by changes in velocity. Includes discussion of erosion corrosion of iron, copper alloy and other alloys plus explanation of cavitation corrosion.

0171

Fisher, A. O., Whitney, F. L., Jr..

LABORATORY METHODS FOR DETERMINING CORROSION RATES UNDER HEAT FLUX CONDITIONS
Corrosion, 15, May 1959, pp 257t-261t

Fe(Water); Misc.

Laboratory techniques for testing the effect of heat flux and skin temperatures upon corrosion rates of 316 stainless steel, steel and cast iron in various environments are described. Advantages and disadvantages with supporting evidence are given for three practical approaches to this fundamental study in the laboratory. Based on the data obtained, skin temperature rather than heat flux has been found to be the controlling factor in the corrosive environments investigated. Heat removed from the corroding surface through agitation and/or other methods appears to be the most practical means of increasing heat flux input without excessively increasing corrosion rate. Preliminary results indicate the superiority of these techniques over the customary immersion tests for obtaining corrosion data involving heat transfer conditions. Continued research on these methods should eventually lead to the development of limiting skin temperatures for various metals in specific environments. Practical application of the data should form a sound basis for predicting plant corrosion rates in heat transfer equipment.

0172

Korpics, C. J.

AROMATIC TRIAZOLES AS CORROSION INHIBITORS OF COPPER AND COPPER ALLOYS
Anti-Corrosion, 21, March 1974, pp 11-13

Cu(Water, Antifreeze)

Two commercially available aromatic triazoles function as unique corrosion inhibitors particularly of copper and copper alloys. Benzotriazole and tolyltriazole are known by the trade-marked names of Cobrathec 99 and Cobrathec TT-100, respectively. Because these compounds have been studied for at least ten years a wealth of information exists which describes the nature of the protective complex and the wide variety of applications. A general overview of this work is presented.

0173

Godard, H. P., Jepson, W. B., Bothwell, M. R., Kane, R. L.
THE CORROSION OF LIGHT METALS — CHAPTER 5 - PITTING CORROSION
Aluminium Labs., Ltd., Kingston, Ontario, Atomic Energy Research Est., Harwell,
England, The Dow Chemical Company, Midland, Michigan, Titanium Metals Corporation
of America, West Caldwell, New Jersey, Sponsored by the Electrochemical Society,
Inc., New York, published by John Wiley & Sons, Inc.

Al (Water)

Pitting corrosion that occurs on aluminum is the result of local cell action in the presence of an electrolyte. Pitting may develop when the metal is immersed in an aggressive solution, when the surface is covered with a thin film of liquid, or when droplets of electrolyte stand on the surface. It occurs most frequently in nearly neutral media, in which the oxide film is considered stable. The rate of penetration usually diminishes with time, and hence when the metal thickness is adequate, perforation may not occur for a considerable time. Only a small amount of metal is removed, and the mechanical properties are not greatly affected.

0174

Jones, D. A., Greene, N. D.
ELECTROCHEMICAL MEASUREMENT OF LOW CORROSION RATES
Corrosion Research Laboratory, Rensselaer Polytechnic Institute, Troy, New York,
paper presented at the 22nd Conference, National Association of Corrosion
Engineers, Miami Beach, Florida, April 18-22, 1966

Fe (Water); Misc.

Materials with corrosion rates of 0.1 mpy or less are required in many applications. In this investigation, application of linear polarization to measurement of low corrosion rates is examined. Also, two new electrochemical techniques are derived theoretically and verified experimentally. These methods can measure accurately corrosion rates less than 0.0005 mpy and require 20 minutes or less to perform.

0175

Evans, S., Koehler, E. L.

USE OF POLARIZATION METHODS IN THE DETERMINATION OF THE RATE OF CORROSION OF ALUMINUM ALLOYS IN ANAEROBIC MEDIA

Journal of the Electrochemical Society, 108 (6), June 1961, pp 509-514

Al (Water); Misc.

Tafel-type cathodic polarization curves were obtained for aluminum alloys corroding in anaerobic acid and food media. The overvoltage-intercept method was found to give corrosion currents equivalent to the measured rates of hydrogen evolution. Tafel-type anodic polarization curves could not be obtained. Anodic polarization curves calculated from cathodic polarization data in the vicinity of the corrosion potential gave Tafel slopes which were identical to the cathodic Tafel slope, within 20%, in each individual case. On using suitable values for the Tafel slopes in the Stern and Geary equation, the polarization resistance method likewise gave corrosion currents in good agreement with measured rates of hydrogen evolution.

0176

Mansfeld, F., Koldham, K. B.

A MODIFICATION OF THE STERN-GEARY LINEAR POLARIZATION EQUATION

Corrosion Science, 11, 1971, pp 787-796

Misc.

An exact equation for the slope of the current-voltage curve at the corrosion-potential is derived. While the Stern-Geary equation is a valid approximation only if the corrosion-potential lies far from the reversible potentials of the oxidation and reduction processes which determine the corrosion process, two new formulae proposed here are valid approximations under all conditions. For given Tafel-constants these approximations introduce no error greater than 30 per cent, while the error accompanying the Stern-Geary method increases without limit as the corrosion-potential approaches either of the reversible potentials. The proposed formulae include the cases of the corroding Zn electrode in strong alkaline solution and the $\text{Fe}^{2+}/\text{Fe}^{3+}$ -couple on stainless steel. Large discrepancies between corrosion rates determined by electrochemical and weight loss techniques reported recently are analyzed.

0177

Wong, D., Swette, L.

ALUMINUM CORROSION IN UNINHIBITED ETHYLENE GLYCOL-WATER SOLUTIONS

Journal of Electrochemical Society: Electrochemical Science and Technology,
126 (1), January 1979, pp 11-15

Al (Antifreeze)

The corrosion characteristics of some selected types of aluminum in uninhibited ethylene glycol/water solutions have been studied under conditions relevant to the operation of aluminum solar heat collector systems. Measurements of linear polarization resistance and maximum pit depth were used to assess the extent of corrosion activity. Pure aluminum (99.9%) as well as 1100 (Commercially pure aluminum) and 3000 (~1% Mn) series alloys were studied in aqueous solutions of 35 v/o (volume percent) reagent grade ethylene glycol. This investigation covered the temperature range from ~25° to 100°C. The corrosion behavior of these aluminum compositions were determined under various hydrodynamic conditions and in the presence of dissolved oxygen, common water contaminants, and ethylene glycol thermal decomposition products. It was found that the corrosion resistance of all four types of aluminum compositions in pure uninhibited ethylene glycol solutions is marginally acceptable.

0178

Hottel, H. C., Woertz, B. B.

THE PERFORMANCE OF FLAT-PLATE SOLAR-HEAT COLLECTORS

A.S.M.E. Transactions, 64, February 1942, pp 91-104

Cu (Water); Fe (Water)

Four projects are under way: three in the fields of photochemistry, photoelectricity, and thermoelectricity. The fourth follows the conventional attack on the problem, namely, the collection of solar energy in the form of heat in a fluid and the utilization of that heat. The present paper is a first quantitative report on progress in the last field.

0179

Humphries, T. S.

CORROSION INHIBITORS FOR SOLAR HEATING AND COOLING SYSTEMS

NASA-George C. Marshall Space Flight Center, Alabama, DOE/NASA Technical Memorandum, DOE/NASA TM-78180, August 1978

Al(Water); Cu(Water); Fe(Water)

This is a continuation of the test program, that was previously reported (NASA TN D-8409, February 1977), to find suitable and effective inhibitors for solar heating and cooling systems. Inhibitors which appeared promising in the previous tests and additional inhibitors including several proprietary products were selected for evaluation. Evaluation of the inhibitors was based on corrosion protection afforded an aluminum-mild steel-copper-stainless steel assembly in a hot corrosive water. Two inhibitors were found to be effective and show promise for protecting multimetallic solar heating systems.

0180

Boies, D. B., Northan, B. J.

ALUMINUM CORROSION: POSSIBLE MECHANISMS OF INHIBITION

Materials Protection, November 1968, pp 27-30

Al(Antifreeze, Water); Misc.

In this work sponsored by the Manned Spacecraft Center, NASA, the corrosion of aluminum was studied in a closed ethylene glycol/water system that had a high metal surface area to liquid volume ratio. Effects of various chemicals on aluminum corrosion and potentially successful inhibitors are discussed.

0181

Clark, J. B., Jr.

CAVITATION--EROSION DAMAGE CONTROL IN ALUMINUM WATER PUMPS FOR CARS

General Motors Corporation, Paper presented at the Society of Automotive Engineers Mid-Year Meeting, Detroit, Michigan, May 20-24, 1968, Paper No. 680498

Al(Antifreeze); Misc.

Three laboratory tests are described which attempted to predict antifreeze cavitation-erosion performance in aluminum water pumps in cars in the field. Of the three tests, a high speed, high temperature laboratory pump test gave most reliable antifreeze performance prediction. A venturi apparatus gave results that correlated well with actual pump tests and showed promise as a screening tool for antifreeze evaluation, alloy selection, etc. A vibrator test fixture did not correlate well with pump tests. Other means of reducing aluminum pump damage such as use of different aluminum alloys and reducing pump speed are also briefly discussed.

0182

Beynon, E.

FIELD PERFORMANCE OF FACTORY-INSTALLED ANTI-FREEZE COOLANTS IN PASSENGER CAR SERVICE

Union Carbide Corporation, Tarrytown, New York, Paper presented at the Automotive Engineering Congress, Society of Automotive Engineers, January 10-14, 1966, Detroit, Michigan, Paper SAE 660128

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze); Misc.

Four annual surveys have been conducted to determine the condition of factory-installed anti-freeze coolants during typical consumer usage after both one or two years of service. Over 25% of the cars required preventive or corrective cooling system service within the first year, and this increased to 47% or more in the second year. Dilution of the coolant with water in many cars reduced both freezing protection and corrosion protection, often to unsafe levels. The modern anti-freeze coolant is capable of providing satisfactory year-round service in a leak-tight cooling system when accompanied by periodic cooling system inspection and preventive maintenance where required. However, many coolants do not give the anticipated service because of mechanical factors, inhibitor depletion from natural causes, and the practices of service men and car owners.

0183

CORROSION-INHIBITED ETHANEDIOL ANTIFREEZE FOR WATER-COOLED ENGINES--TYPE B.
SODIUM BENZOATE AND SODIUM NITRITE INHIBITED
British Standards Institution, British Standard 3151:1959

Misc.

The type of material covered by this British Standard is suitable for general use in internal combustion engines, other than those used for aircraft. Antifreeze complying with this standard should be accepted, however, as suitable for use in any given engine only if approved for this purpose by the engine manufacturer. While the original formulation recommended 7.5 per cent sodium benzoate and 0.5 per cent sodium nitrite, later work has shown that it is permissible to reduce the sodium benzoate: sodium nitrite ratio to not less than 9:1, and the lower limit of 5 per cent for the sodium benzoate concentration specified in the standard recognizes this.

0184

METHODS OF TEST FOR CORROSION INHIBITION PERFORMANCE OF ANTIFREEZE SOLUTIONS
British Standards Institution, BS 5117:1974

Misc.

This standard specifies four methods for testing the corrosion inhibition properties of antifreeze solutions. Of these methods of test, three are essentially concerned with the estimation of the tendency of metals to corrode under controlled conditions, while the field test describes the outlines of a technique to explore the behaviour of antifreeze under general service conditions in motor vehicles.

0185

Eldredge, G. G., Mears, R. B.

INHIBITORS OF CORROSION OF ALUMINUM

Industrial and Engineering Chemistry, 37 (8), August 1945, pp 736-741

Al(Water)

The use of inhibitors of the corrosion of aluminum is reviewed, and new data are presented. Chromates are effective in phosphoric acid but not in hydrochloric. Nitrogen compounds and pickling inhibitors that are effective for steel are usually more effective for aluminum in hydrochloric than in phosphoric acid. No very effective inhibitors for aluminum in sulfuric acid are known. In waters, chromates, silicates, and soluble oils were most effective. Against galvanic corrosion by contact with copper, the same materials functioned to some extent, especially when the sodium chloride content was as low as 10 p.p.m. In neutral salt solutions, chromates function by increasing the anodic polarization. In sodium carbonate solutions, silicates and fluosilicates are very effective; and in sodium hydroxide, colloids such as glues are stated to be effective. In solutions of sodium hypochlorite, sodium disilicate is effective; it is reported to be effective also in chlorine water. Water may be an inhibitor of attack of aluminum in some nearly anhydrous organic chemicals, such as organic acids, phenols, and alcohols. Borates and phosphates are used as inhibitors in ethylene glycol solutions. Chromates have been quite successfully utilized in alcohol solutions. For some cases, especially in insulation materials, chromates which are slowly soluble have an advantage.

0186

Brooke, M.

CORROSION INHIBITOR CHECKLIST

Chemical Engineering, 69 (3), February 5, 1962, pp 134,136,138,140

Al(Antifreeze); Cu(Water, Antifreeze); Fe(Water, Antifreeze); Misc.

Many inhibitors for many metals in many environments have been developed. This list has been accumulated from 98 references and gives the metal or alloy studied in alphabetical order followed by environment, inhibitor used and reference.

0187

EQUATION FOR PREDICTING THE CORROSIVITY OF NATURAL FRESH WATERS TO ALUMINIUM
Nature, 218, June 1, 1968, pp 893-894

Al(Water)

An equation developed to predict the rate of pitting of aluminum in natural fresh waters from the composition of the water is described. The relationship has practical value. Samples of many fresh waters were brought to the laboratory and pitting rate tests were made using coupons of AA3003 alloy sheet.

0188

Lowson, R. T.

ALUMINIUM CORROSION STUDIES. I--POTENTIAL-pH-TEMPERATURE DIAGRAMS FOR ALUMINIUM
Australian Journal of Chemistry, 27 (1), January 1974, pp 105-127

Al(Water)

The potential-pH-temperature relationships for the aluminium-water system have been calculated by the methods of de Bethune, Khodakovskiy, Criss and Cobble, and Helgeson and a critical comparison made. The Criss and Cobble method produced the most consistent results and was used to construct a corrosion diagram for the range 25-300°C. The effect of the hydrolysed ions $\text{Al}(\text{OH})_2^+$, $\text{Al}(\text{OH})_2^+$ and $\text{Al}(\text{OH})_3^0$ was also calculated. The work has shown up a temperature effect which should be taken into account when designing and operating aluminium circuits in which different parts are operated at different temperatures.

0189

Giner, J.

STUDY OF CORROSION AND ITS CONTROL IN ALUMINUM SOLAR COLLECTORS

Giner, Inc., Waltham, MA., Progress Report (June 1, 1976-August 31, 1976), September 1976, Report No. COO/2934-76-1, Contract E(11-1)-2934

Al(Antifreeze)

This program is intended to be an in depth study of the corrosion of aluminum solar thermal energy collector systems, with the objective of deriving corrosion control methods. It is expected that at the conclusion of the first phase of this investigation (first year), the various possible corrosion mechanisms will have been determined and methods to measure and predict the extent of any corrosion occurring in the aluminum and aluminum alloys in water-ethylene glycol mixtures and other heat transfer fluids will have been developed. No significant test results have been obtained to date.

0190

Giner, J.

STUDY OF CORROSION AND ITS CONTROL IN ALUMINUM SOLAR COLLECTORS

Giner, Inc., Waltham, MA., Progress Report No. COO/2934-3, (December 1, 1976-February 28, 1977), April 1977, Contract EY-76-C-02-2934

Al(Antifreeze)

Task I examined literature regarding various existing solar collector systems with emphasis on those systems using ethylene glycol solutions as the heat transfer fluid. In addition, a site visit was made to the solar energy demonstration project at the Grover Cleveland School in Boston to discuss first-hand corrosion problems with the maintenance staff. Task II, the determination of the corrosion rates and the pitting constants for the baseline system - 1100 series aluminum which is commonly used in making aluminum solar collector panels - has been completed. This study revealed that in a pure aqueous ethylene glycol solution both general wastage and pitting attack will not cause catastrophic plant failure. In Task III the corrosion characteristics of 99.9% and 3003 series aluminum are being investigated in aqueous ethylene glycol solutions under similar conditions selected in Task II. Task IV determined the aluminum alloy galvanic series by means of the Tafel extrapolation method. Task V assesses whether or not discontinuities in continuous recorder linear polarization resistance values can be correlated with the onset of pits.

0191

Giner, J., Swette, L., Wong, D.

STUDY OF CORROSION AND ITS CONTROL IN ALUMINUM SOLAR COLLECTORS

Giner, Inc., Waltham, MA., Progress Report No. COO/2934-2, (September 1-November 30, 1976) December 1976, Contract EY76-C-02-2934

Al(Antifreeze)

In Task II the corrosion characteristics of 1100 series aluminum are being investigated in aqueous ethylene glycol. Task III examines alternate materials such as purer aluminum than 1100 series and manganese-aluminum alloys (3000 series), as well as a different heat transfer fluid such as Therminol. Task IV attempts to generate a galvanic series for common aluminum alloys from each alloy series in ethylene glycol-water.

0192

Draley, J. E., Ruther, W. E.

AQUEOUS CORROSION OF ALUMINUM--PART 1--BEHAVIOR OF 1100 ALLOY

Corrosion, 12, September 1956, pp31-38

Al(Water)

Aluminum alloy 1100 corrodes uniformly in nearly pure water at rates which increase with temperature. The corrosion rate can be reduced by the addition of an acid to the water. The solution pH of minimum corrosive attack on aluminum goes down with increasing temperature. It is of the order of 6.5 at 50 C and 3 at 300C. Corrosion in slightly alkaline solutions (pH 8.5) is more rapid than in neutral water at all temperatures. At 200 C the addition of dichromate ion increased the rate of corrosion. A small concentration of sodium silicate resulted in a higher corrosion rate at pH 9.4, while at pH 3.5 it reduced the rate significantly. Chloride ion (5ppm) caused some pitting and increased the corrosion rate slightly. Electrical coupling to more cathodic materials, such as graphite, zirconium or stainless steel produced no undesirable effects in distilled water at 200 C. At 315 C, the corrosion life of samples was extended by such coupling.

0193

Hufnagel, W.

ALUMINIUM IN THE USE OF SOLAR ENERGY

Aluminium, 52 (2), pp 123-128

Misc.

In the introduction, the types, possibilities and limits of the utilization of solar energy are discussed and the physical principles of the utilization of radiation considered. Aluminum is an advantageous material to use for solar collectors (in conjunction with the roll-bonding process) as well as for other components of solar installations. A number of designs are described as examples. Considerations of economic aspects and trends of the use of solar installations for the utilization of the thermal radiation of the sun round off this summarizing contribution.

0194

Turnheim, G.

EXAMPLES FOR THE UTILISATION OF SOLAR ENERGY USING ALUMINIUM COLLECTORS

Aluminium, 52 (10), 1976, pp 623-625

Al(Water), Misc.

[No Abstract]

0195

Haygood, A. J., Minford, J. Dean
ALUMINUM COOLING TOWERS AND THEIR TREATMENT
Corrosion, 15 (1), January 1959, pp 20t-24t

Al(Water)

Characteristics of aluminum alloys are discussed to show the use of this material in cooling tower construction. Alloy selection, fabricating practice, surface finish and water treatment are covered. Examples of cooling tower installations and data from field research are given.

0196

Dillon, R. L.
OBSERVATIONS ON THE MECHANISMS AND KINETICS OF AQUEOUS ALUMINUM CORROSION--
PART 2--KINETICS OF AQUEOUS ALUMINUM CORROSION
Corrosion, 15 (1), January 1959, pp 13t-19t

Al(Water)

The corrosion of Al in high temperature deionized water in the range 100 to 363 C has been studied as a kinetic process. The observations described in the report coupled with lower temperature data taken from the literature indicate aluminum corrosion successively has a logarithmic, a parabolic and a linear dependence on time as the temperature increases. The temperature dependence for parabolic and linear processes have been determined. Certain similarities between air and water oxidation are pointed out and discussed. The effect of alloying additions has been considered and found to be negligible for the parabolic process, but important in the linear oxidation process.

0197

Troutner, V. H.

OBSERVATIONS ON THE MECHANISMS AND KINETICS OF AQUEOUS ALUMINUM CORROSION
PART 1--ROLE OF THE CORROSION PRODUCT FILM IN THE UNIFORM AQUEOUS CORROSION
OF ALUMINUM

Corrosion, 15 (1), January 1959, pp 9t-12t

Al(Water)

Several experiments are discussed from the standpoint of their implications on the role of the corrosion product film formed on aluminum during uniform aqueous corrosion both as the principal form of corrosion and as a prelude to intergranular penetration. The experiments include barrier film measurements, the effect of an applied potential on corroding aluminum, the effect of various ions and combinations of ions in dilute aqueous solutions on the uniform corrosion, x-ray diffraction studies of corrosion product films, and several comparisons between air oxidation studies and aqueous corrosion studies. Conclusions are given on the composition and structure of aluminum corrosion product film and the role it plays in controlling uniform aqueous corrosion.

0198

Troutner, V. H.

HIGH TEMPERATURE CORROSION PRODUCT FILMS ON ALUMINUM

Corrosion, 15 (1), Jan 1959, pp 7t-8t

Al(Water)

The corrosion product films formed on aluminum in aqueous environments at high temperatures have been examined with the electron microscope. A technique is described for the preparation of electron microscope replicas of the surface of the corrosion product films adjacent to the metal. Electron micrographs are shown of corrosion product films formed during various stages of corrosion in high purity water, and in corrosion inhibited systems. Corrosion inhibition was found to be associated with different crystalline structures of the corrosion product films.

0199

Brush, E. G., Pearl, W. L.

CORROSION AND CORROSION PRODUCT RELEASE IN NEUTRAL FEEDWATER

Corrosion, 28 (4), April 1972, pp 139-136

Cu(Water), Fe(Water)

The corrosion and corrosion products released from materials exposed to typical boiling water reactor (BWR) feedwater chemistries were determined over the temperature range of 38 to 204 C (100 to 400 F). The study included carbon steel, Type 304 stainless steel, and several common copper alloy feedwater heater tubing materials exposed to neutral pH, flowing high purity water of varying dissolved oxygen levels. It was found generally that for acceptable resistance to corrosion in power plant feedwater at neutral pH, copper base alloys can be used only with no oxygen; carbon steel can be used when the dissolved oxygen exceeds 15 ppb; stainless steel can be used regardless of the oxygen content.

0200

Lobsinger, R. J., Atwood, J. M.

CORROSION OF ALUMINUM IN HIGH PURITY WATER

Corrosion, 13 (9), September 1959, pp 582t-584t

Al(Water)

In-reactor corrosion rates of 1245 and M-388 aluminum alloys were determined in demineralized water at temperatures up to 200 C. A correlation between corrosion rates and the effective aluminum surface temperature is presented. The effect of increased hydrogen ion concentration on corrosion rates is also discussed.

0201

Binger, W. W., Marstiller, C. M.
ALUMINUM ALLOYS FOR HANDLING HIGH-PURITY WATER
Corrosion, 13 (9), September 1959, pp 591t-596t

Al(Water)

Aluminum alloys have been used for more than 20 years for storage and distribution systems handling distilled water. Recently, it became possible to investigate experience with some 30 distilled water systems which had been in use for various periods of time up to 24 years. Many of these systems had been made entirely of aluminum. Several were composed entirely of tinned copper or brass and others were made up of a combination of materials including aluminum. Results indicate that aluminum alloy storage tanks, tubing, fittings and valves are highly satisfactory for handling distilled water and do not cause significant contamination of the water being handled.

0202

Godard, H. P., Torrible, E. G.
THE EFFECT OF CHLORIDE AND SULPHATE IONS ON OXIDE FILM GROWTH ON Al IMMERSSED
IN AQUEOUS SOLUTIONS AT 25°C
Corrosion Science, 10, 1970, pp 135-142

Al(Water)

Film growth on Al sheet immersed in solutions containing SO_4^{2-} is markedly influenced by very low concentrations of the ion. Similar concentrations of Cl^- have no obvious effect. The induction period before film growth, and the weight of film per unit area is dependent upon both the sulphate ion concentration and the surface area of metal exposed to the solution. A mechanism of film growth in the presence of SO_4^{2-} is postulated which accounts for most of the experimental observations.

0203

Shreir, L. L. (Editor)

POLARISATION RESISTANCE -- CHAPTER 20

Corrosion, Vol 2, Corrosion Control, 2nd Edition, Newnes-Butterworths, Boston, London, pp 20:35-20:41

Misc.

[No Abstract]

0204

Simon, F.F.

FLAT-PLATE SOLAR-COLLECTOR PERFORMANCE EVALUATION WITH A SOLAR SIMULATOR AS A BASIS FOR COLLECTOR SELECTION AND PERFORMANCE PREDICTION

Solar Energy, 18 (5), 1976, pp 451-466

Misc.

This paper reports the measured thermal efficiency and evaluation of 23 collectors which differ according to absorber material (copper, aluminum, steel), absorber coating (nonselective black paint, selective copper oxide, selective black nickel, selective black chrome), type of glazing material (glass, Tedlar, Lexan, anti-reflection glass), the use of honeycomb material and the use of vacuum to reduce thermal convection losses. The collectors are given performance rankings based on noon-hour solar conditions and all-day solar conditions. The determination with the simulator of an all-day collector performance is made possible by tests at different incident angles. The solar performance rankings are made based on whether the collector is to be used for pool heating, hot water, absorption air conditioning, heating, or for a solar Rankine machine. Another test which aids in selecting collectors is a collector heat capacity test. Results of a cost-effectiveness study is given for conditions corresponding to those required for absorption a/c or heating.

0205

Bond, A.P., Dundas, H.J., Schmidt, W., and Wolf, M.
ETUDE DE LA RESISTANCE A LA CORROSION D'ACIERS INOXYDABLES EN VUE DE LEUR
UTILISATION EN DISTRIBUTION D'EAU CHAUDE
Revue de Metallurgie, 70 (33), 1973, pp 33-42

Fe(Water)

[No Abstract]

0206

SOLAR HEATING AND COOLING

U. S. Department of Energy, Research and Development Project Summaries,
DOE/CS-0010, May 1978

Misc.

This report is one of two volumes that contain summaries of projects that were funded by ERDA/DOE through FY 1977 and conducted under the National Program for Solar Heating and Cooling of Buildings. Volume I summarizes the design and operating characteristics of the demonstration solar heating and cooling systems. It also gives brief descriptions of the buildings where the systems are installed and includes pictures of the buildings and sketches of the systems.

0207

GUIDELINE FOR CERTIFICATION OF SOLAR ENERGY EQUIPMENT

California Energy Resources, Conservation and Development Commission, June 15, 1978

Misc.

This document presents in detail the operation of the California Energy Commission's Testing and Inspection Program for Solar Equipment (TIPSE). To begin the certification process for liquid or air flat-plate glazed solar collectors, in the currently voluntary program, the manufacturer must complete and submit the application package included in Appendix A.

0208

Wong, D., Cocks, F. H., Giner, J.

STUDY OF CORROSION AND ITS CONTROL IN ALUMINUM SOLAR COLLECTORS

Giner, Inc., Waltham, Massachusetts, Progress Report COO-2934-6, (September 1, 1977-March 31, 1978), April 1978, Contract EY-76-C-02-2934

Al(Antifreeze)

Phase I developed a non-destructive electrochemical technique (linear polarization resistance method) to determine the overall corrosion rate under various conditions. Pit depth was determined using a quantitative metallographic analysis. The results indicate that aluminum alloys possess marginal corrosion resistance in pure ethylene glycol solution at temperatures up to 100°C. However, in the presence of common contaminants (e.g. Cu, Fe and NaCl), the corrosion resistance decreases drastically to an intolerable level. It was then concluded that uninhibited ethylene glycol solutions most probably will cause catastrophic plant failure when used as a heat transfer medium in an aluminum solar collector system. Phase II has been geared primarily at the development and evaluation of corrosion inhibitors which will effectively reduce both uniform and localized corrosion.

0209

Wong, D., Cocks, F. H., Giner, J., Majahad, P. S.
STUDY OF CORROSION AND ITS CONTROL IN ALUMINUM SOLAR COLLECTORS
Giner, Inc., Waltham, Massachusetts, Annual Report COO-2934-7, (June 1, 1977-
July 31, 1978) August 1978, Contract EY-76-C-02-2934

Al(Water, Antifreeze)

The acquisition of baseline corrosion data has been extended to the aluminum/propylene glycol combination. Aluminum corrosion characteristics were determined in 50, 85 and 100% propylene glycol solutions at temperatures between 25 to 160°C. Aluminum alloys were found to be about ten times more corrosion resistant in propylene glycol than in ethylene glycol solutions under similar conditions. However, the presence of impurities such as Cu^{+2} , Fe^{+3} and Cl^{-} still causes rapid and serious corrosion attack unless proper corrosion control methods are implemented. The corrosion resistance of aluminum was also found to increase as the concentration of ethylene (or propylene) glycol solution increases. Most inhibitor formulas can reduce the overall aluminum corrosion rate to below 1 mpy at temperatures below 100°C, even when chloride, cupric and ferric ions are simultaneously present. A preferred inhibitor composition was found. As the operating temperature increases to 130°C, several inhibited commercial solar collector heat transfer fluids began to fail. The combined use of inhibitors and scavengers was found to provide excellent corrosion protection to aluminum. The corrosion rate was found to be less than 0.2 mpy at 130°C with Cu^{+2} , Fe^{+3} and Cl^{-} present.

0210

Beckman, W. A., Klein, S. A., Duffie, J. A.
SOLAR HEATING DESIGN BY THE f-CHART METHOD
University of Wisconsin, Madison, Wisconsin, Published by John Wiley & Sons,
New York, 1977

Misc.

0211

Duffie, J. A., Beckman, W. A.

SOLAR ENERGY THERMAL PROCESSES

University of Wisconsin, Madison, Wisconsin, Published by John Wiley & Sons,
New York, 1974

Misc.

0212

SOLAR HEATING AND COOLING OF RESIDENTIAL BUILDINGS--DESIGN OF SYSTEMS

Colorado State University, Solar Energy Applications Laboratory, October 1977.

Misc.

0213

SOLAR HEATING AND COOLING OF RESIDENTIAL BUILDINGS--SIZING, INSTALLATION
AND OPERATION OF SYSTEMS
Colorado State University, Solar Energy Applications Laboratory, October 1977

Misc.

0214

Berry, W. E.

CORROSION IN NUCLEAR APPLICATIONS -- Aluminum Alloys

Battelle Memorial Institute, Columbus, Ohio, Published by John Wiley and Sons,
Inc., 1971

Al(Water)

Aluminum and several of its alloys are used extensively as fuel cladding in water-cooled, water-moderated research reactors where water temperatures do not exceed 100 C. The corrosion behavior of unalloyed commercial aluminum and most commercial aluminum alloys is adequate in high-purity water at temperatures to about 200 C. The effect of impurities on the corrosion behavior is reviewed.

0215

Hannigan, H. J.

COOLANT PERFORMANCE AT HIGHER TEMPERATURES

Union Carbide Corporation, Tarrytown, N.Y., Paper presented at the Society of Automotive Engineers, Inc., Mid-Year Meeting, Detroit Michigan, May 20-24, 1968, Paper No. 680497

Al(Antifreeze); Cu(Antifreeze); Fe(Antifreeze)

The trend of increased coolant temperature and potential benefits for reduced hydrocarbon emissions from further temperature increases has prompted an investigation of the performance of ethylene glycol base coolant at substantially higher operating temperatures. A coordinated program in laboratory glassware and bench apparatus, in engine dynamometer and vehicle tests has been conducted at bulk liquid temperatures as high as 300°F. In this work it has been shown that suitably inhibited glycol-water coolants can operate for reasonable periods of time and mileage without undergoing undesirable degrees of deterioration while maintaining good heat transfer characteristics and adequate corrosion protection. Further findings of the test program to date indicate that conventional brass-solder radiators, coolant hoses, and clamps may need to be modified to be adequate for temperatures and pressures of future cooling system environments.

0216

Riddiford, A. C.

THE ROTATING DISK SYSTEM

University of Southampton, England, Advances in Electrochem. & Electrochem. Eng., published by Interscience, pp 47-116

Misc.

The initial section of this review offers a brief outline of the role which transport processes can play in determining the overall rate of an electrode process. This also serves to introduce certain conventions which are used throughout the subsequent sections, and to state in simple form the basic problem underlying the calculation of the rate at which a given electroactive species can be transported through the electrolyte to the electrode surface. This is followed by sections dealing with the basic theory, with the design of practical electrodes, with their applications, and with certain extensions to the basic theory.

0217

SOLAR HEAT TRANSPORT FLUIDS FOR SOLAR ENERGY COLLECTION SYSTEMS (A Collection of Quarterly Reports)
Houston Chemical Company, Pittsburg, PA, DOE/NASA Contractor Report, DOE/NASA CR-150560, (November 15, 1976-November 15, 1977) January 1978, Contract NAS8-32255

Al(Water, Antifreeze); Fe(Water, Antifreeze)

This document consists of several quarterly reports that cover the progress made by the Houston Chemical Company, who is developing noncorrosive fluid subsystem compatible with closed-loop solar heating and combined heating and hot water systems. The system is also to be compatible with both metallic and non-metallic plumbing systems, and any combination of these. At least 100 gallons of each type of fluid recommended by the contractor will be delivered, and a number of fluids will be performance tested.