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CORROSION PROBLEMS WITH AQUEOUS COOLANTS

Final Report

By
R. B. Diegle
J. A. Beavers
J. E. Clifford

SAC

April 11, 1980

Work Performed Under Contract No. AC04-79CS10510

Battelle
Columbus Laboratories
Columbus, Ohio

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U.S. Department of Energy

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FINAL REPORT

on

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WITH AQUEOUS COOLANTS

to

U.S. DEPARTMENT OF ENERGY

April 11, 1980

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R. B. Diegle, J. A. Beavers, and J. E. Clifford

Contract No. DE-AC04-79CS10510

BATTELLE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

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ABSTRACT

This report summarizes the results of a one year program to characterize corrosion of solar collector alloys in aqueous heat-transfer media. The program involved a literature review and a laboratory investigation of corrosion in uninhibited solutions. It consisted of three separate tasks, as follows:

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

Task 1 involved a comprehensive review of published literature concerning corrosion under solar collector operating conditions. The review also incorporated data from related technologies, specifically, from research performed on automotive cooling systems, cooling towers, and heat exchangers. Task 2 consisted of determining the corrosion behavior of candidate alloys of construction for solar collectors in different types of aqueous coolants containing various concentrations of corrosive ionic species. Task 3 involved measuring the degradation rates of glycol-based heat-transfer media, and also evaluating the effects of degradation on the corrosion behavior of metallic collector materials.

Results of the Task 1 literature review indicated that lack of quantitative information presently exists relative to collector corrosion, 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.

Task 2 consisted of studying corrosion behavior of aluminum alloys 1100, 3003, and 6061, copper alloy 122, Type 444 stainless steel, and 1018 plain carbon steel in uninhibited ethylene glycol and propylene glycol solutions under simulated operating conditions for nonconcentrating collectors. Corrosion morphologies investigated were general attack, pitting, crevice corrosion, and galvanic corrosion. Experimental results indicated that aluminum alloys can experience severe pitting and crevice corrosion at chloride concentrations approaching 50 ppm. The corrosion rate of copper exceeded about 100 $\mu\text{m}/\text{yr}$ in ethylene glycol solutions and about 80 $\mu\text{m}/\text{yr}$ in propylene glycol solutions. Crevice corrosion was not observed for copper, but severe galvanic corrosion occurred when it was coupled to T444 stainless steel. T444 steel corroded at rates of less than 1 $\mu\text{m}/\text{yr}$ under all exposure conditions. During circulation at 100 C in the presence of air, ethylene glycol solutions acidified because of degradation of the glycol. The pH of propylene glycol solutions was initially low, about 4.5. The inherent corrosivity of propylene glycol was somewhat less than that of ethylene glycol, although this difference was usually less than a factor of two in measured corrosion rates. The corrosion rates of aluminum alloys and copper were prohibitively high in uninhibited glycol solutions, and corrosion inhibitors are recommended in operating systems. Use of corrosion inhibitors is less crucial in T444 stainless steel collectors.

Task 3 involved investigating the kinetics and severity of degradation of aqueous ethylene and propylene glycol solutions with and without the presence of various metals in solution. Temperatures of 100 C and 180 C were used. Degradation (acidification) of aqueous ethylene and propylene glycol solutions occurred in the absence of contact with metals, but it was accelerated by their presence. Aeration slightly accelerated the rate of degradation, but increasing the exposure temperature from 100 C to 180 C had substantially no effect. The rate of degradation was

similar for ethylene and propylene glycols, and it was not noticeably influenced by anionic species commonly found in tap waters. The acidic degradation products lowered the pH of the glycol solutions and thereby accelerated pitting of the aluminum alloys. These products probably also contributed to accelerated corrosion of the copper and plain carbon steel specimens. None of the alloys tested exhibited corrosion resistance in degraded glycol solutions adequate for long-term use in solar collectors in the absence of corrosion inhibitors; however, Type 444 stainless steel was not included in this evaluation. Both polarization resistance and corrosion potential qualitatively reflected the corrosion behavior of the various alloy-solution systems that were investigated.

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INTRODUCTION

This research program involved a three-task study of corrosion problems associated with operation of nonconcentrating solar collectors. Investigating the corrosion that occurs in concentrating solar collectors and industrial collectors, which operate at higher temperatures and pressures than nonconcentrating collectors, was outside the scope of the program. The three tasks that were performed under this contract are as follows:

- 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.

Results of these Tasks are reported in individual Technical Progress Reports, References 1-3. The nature of these various Tasks is described below.

Task 1 involved a comprehensive review of the published literature concerning corrosion under solar collector operating conditions.⁽¹⁾ The literature search was not limited solely to information about collector corrosion, because as yet there is not a lot of published data on this subject. Therefore, information was also included from related technologies, specifically, from corrosion research on automotive cooling

systems and from industrial applications. This Task resulted in a data bank that was used for selecting the alloys, coolants, and exposure conditions utilized in the subsequent two experimental tasks. This data bank is now available for other purposes, which might include:

- 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.

Task 2 consisted of characterizing corrosion of different metals and alloys in simulated tap waters of varying ionic strength.⁽²⁾ The metals and alloys were selected based on results of the Task 1 literature survey⁽¹⁾; they consisted of copper, plain carbon steel, a stainless steel, and three aluminum alloys. The waters contained antifreeze additions that were determined most likely to be used in aqueous collector coolants, again based on results of the Task 1 literature review. Exposure conditions simulated the more severe range of those likely to be encountered in residential heating and cooling applications in a nonconcentrating solar collector system. To maximize the amount of useful data that could be gathered during the course of the program, relatively harsh conditions of collector operation were used. These conditions included temperatures near the boiling points of coolants, turbulent flow, access of atmospheric oxygen, presence of harmful ionic species such as chloride, and absence of corrosion inhibitors.

Task 3 involved measuring the degradation of glycol-based aqueous heat-transfer fluids and evaluating the effects of this degradation on the corrosion behavior of collector materials.⁽³⁾ Variables that were studied included types of glycol, catalytic effects of metals on degradation, oxygen concentration, temperature, exposure time, and chemical additives to the fluids. Degradation was monitored by changes in

solution pH and ionic conductivity, and by chemical analysis of the solutions after exposure. Changes in corrosivity were monitored through the use of various metal coupons inserted into the solutions.

This Final Report summarizes the major findings of the three Tasks and makes recommendations for minimizing corrosion-related damage to nonconcentrating solar collector systems. The reader is referred to the individual task reports for more detailed information.

OBJECTIVES

The objectives of this program were to elucidate the corrosion problems likely to be encountered with nonconcentrating solar collectors and aqueous heat transfer fluids, and to recommend procedures for minimizing corrosion damage. Specific objectives were to: (1) review the current state of the art of collector corrosion processes; (2) study corrosion in multi-metallic systems; and (3) characterize the degradation and changes in corrosivity of various chemical antifreeze additives.

TASK ONE -- REVIEW OF STATE OF THE ART OF SOLAR COLLECTOR CORROSION PROCESSES

DATA BANK

Literature Review

Some pertinent literature references were available at the beginning of the program. Comprehensive 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 nonsolar applications covers such a broad field that the number of references became 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 printout 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 provided 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 researchers. The second duplicate card file was maintained by the information specialist. 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; copper and copper alloys including brass and solder; and iron and iron alloys including cast iron, low carbon steel, and stainless steels. 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 Task 1 Report⁽¹⁾ 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. Defining 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) (a). 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)

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

Sufficient corrosion resistance is needed such that the service life of collector components allows recovery of useful solar energy at least equal to the energy used in producing the components. 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 the energy payback period for most solar equipment is about 10 to 12 months.

(a) References from the Task 1 review are in Appendix A by accession number.

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, just as are 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 with respect to specific applications, component materials, and heat transfer fluids as discussed below.

Applications

It is necessary to differentiate the purpose of solar energy use (service hot water, or heating and cooling), since the purpose influences the corrosivity of collector fluids and collector temperatures.

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 heating
- Space cooling or process cooling.

All of the above use liquid heating collectors. (Air heating collectors are not included, because this program relates only to aqueous internal corrosion phenomena).

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 nonmetallic 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

In certain collector system designs the pump used for circulating the heat-transfer fluid is turned off when the desired storage temperature is 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 (> 170F), useful collector 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, stagnation

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.

There is a need for more information on typical daily cycles of time-temperature-flow (TTF). No such correlated data were 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 nonuniform 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 economically viable 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 are considering correlation of test procedures with service-related damage.

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

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, yet it is also a promising material because of its excellent corrosion resistance.

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:

mild steel

444 stainless steel

Copper, at least for tubes, appears to be a durable and dependable material. The principal disadvantage is its relatively high cost.

A plate-type copper collector requires an outlay of about three dollars per square foot more than for aluminum, with a five to six dollar per square foot differential in selling price.⁽⁰²¹²⁾ The advantages of copper over other metals are high thermal conductivity⁽⁰⁰⁹⁵⁾ and good corrosion resistance.⁽⁰⁰⁷¹⁾

Aluminum combines good thermal conductivity and moderate cost, but it 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⁾ 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), 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), high cost, and 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⁾ Annealed type 444 exhibited the best overall resistance to pitting and crevice corrosion. 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)

Tubes may be attached or bonded to a plate or be integral with the plate. A popular type of construction is roll-bonding, involving selective stop-off and subsequent pressurization of stopped-off areas to form integral fluid passages. Some collectors are made by selective spot welding and subsequent expanding to form fluid passages. Thus, various types of crevices are created by the fluid passage designs, except those utilizing 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 yields reduction in the important first cost of the system in comparison to the alternatives of using air or nonaqueous fluids. However, the disadvantages of aqueous heat transfer fluids relating to freeze protection and corrosion protection have been noted in the literature, but they 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., containing chemical additives) and uninhibited water, and it is usually 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; standard test solutions usually contain 100 ppm of each ion. Although less than 2 percent 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 have been found in the literature

defining the 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 those described above, even though good quality water, e.g., distilled water, is always recommended for dilution of commercial antifreeze concentrate to minimize corrosion. Commercial antifreeze concentrates contain a small amount of water (about 3 percent) in which the inhibitors have been dissolved. Most commercial antifreezes are based on "ethylene glycol" (monoethylene glycol)^(a) and may contain small amounts of diethylene glycol and propylene glycol. Ethylene glycol is toxic, and consequently, 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⁾:

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

- (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.

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 of such use 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 thawing 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 required increase in temperature 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 the first cost of the heat exchanger and maximizing efficiency of solar energy collection.

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 expose the fluid to atmospheric oxygen with a resulting 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 using 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 nonpotable 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.

It may be possible to use tap water for heating and cooling systems which require relatively large volumes of liquid storage, 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 liquid storage.

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

CORROSION TECHNOLOGY

Types of Corrosion

General Corrosion

In solar collector systems a small degree of corrosion is expected with all aqueous heat transfer fluids. Ideally, the corrosion rate should be uniform over the surface and should occur 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.

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, one review (1977)⁽⁰⁰⁰⁴⁾ on 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 frequently 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 nonuniform corrosion, which is the more common and serious problem.

Galvanic Coupling Corrosion

Galvanic coupling corrosion occurs when two dissimilar metals are joined together in an electrolyte. A common example is an aluminum

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

collector joined electrically to copper plumbing. The more noble, or less active metal is copper, which would be cathodic and would be protected; the less noble, or more active metal is aluminum, which would be anodic and consumed (corroded). The driving force for galvanic coupling corrosion depends on the difference between corrosion potentials of the dissimilar metals, which in the case of copper and aluminum is very large. The anode to cathode ratio is also important, and the rate of anodic corrosion is inversely proportional to this ratio.

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

Stress Corrosion Cracking

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

Inc. (1977)⁽⁰⁰⁰²⁾ found 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.⁽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 for aluminum in ethylene glycol solutions containing aggressive ions.⁽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:

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

where P = pit depth

t = exposure time.

The cubic relationship derives from the shape of the pit (assumed 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.⁽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; this equation was used to predict 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 influence of 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 geometrically restricted area in which rapid metal loss can occur because an occluded 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. Crevices can be easily created in solar panels. A few examples are leaky gaskets, badly fitting metal or plastic couplings, blockages in internal channels, scale deposits, or poor design.⁽⁰⁰⁴⁵⁾

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. It can be a problem in collector systems that have not been cleaned of debris after assembly.

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, it is not surprising that there is relatively little quantitative data published on the service life of solar collectors.

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 and drain-down systems, the increase in oxygen diffusivity with increasing temperature and decrease in oxygen solubility in water combine to produce a maximum in corrosion rate at about 70 to 80 C. Otherwise, for closed loop (oxygen-free) systems, the maximum corrosion rate usually occurs at the highest temperature (i.e., high temperature stagnation). The relatively low maximum heat flux in solar applications does not produce more than a few degrees increase in metal temperature, which determines the corrosion rate.⁽⁰¹⁷¹⁾ If fluid boiling occurs at a 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. 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 it cannot always be entirely discounted over the long term as a contributing

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 subsequent 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	
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	

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 a benefit in preconditioning the collector metal surface under controlled conditions before placing the collector in service.

Fluid dynamics can be a very important factor in influencing both uniform and nonuniform corrosion rates. 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 it 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 of 0.03 gpm/ft² results in laminar flow ($N_{Re} < 1500$) at the highest temperature. The collector efficiency is very high at these conditions, greater than 95 percent, 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 more nonuniform corrosion 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⁾ An increase in flow rate generally 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 simulating the corrosion of aluminum in solar collectors reported data for "static", "laminar" and "turbulent" flow.⁽⁰⁰⁰²⁾ However, the experimental conditions referred to as "turbulent" appeared to be "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, 2π (RPM)

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

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

The other metals in the fluid loop are a factor in collector corrosion, 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 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 depends on the chemical composition with regard to concentration and types of certain ions that may have either a good effect through natural inhibition, or an adverse effect. 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 caused 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. Addition of inorganic salts as inhibitors will increase solution conductivity, and may actually increase corrosion rates under certain conditions. Certain components of water, such as chlorides, heavy metals and dissolved oxygen are usually more critical with regard to corrosion.

Considering antifreeze of a particular composition, such as 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 an 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. 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 nonuniform corrosion. There is considerable information in the literature on inhibitors. However, it is difficult to identify a specific inhibitor package (types of chemicals and concentrations) that is best because of the large number of factors affecting corrosion. Also, there are 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 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 based on experience with automotive coolants (0001) and aluminum collectors. (0004, 0045, 0075)

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 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 to 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 logically 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. Recent research suggests that use of zinc powder suspended in an 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 depositing 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. An important factor is to provide sufficient surface area. Aluminum alloys (1100, 3003, 7072) will provide efficient gettering. (0004) Gettering cannot be considered as a means of completely eliminating pitting in aluminum collectors, and therefore it should be used in conjunction with inhibitors; the column will provide protection if the inhibition fails for a short period.

Oxygen Removal

Corrosion rates usually depend 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 such as hydrazine to react with dissolved oxygen is a typical corrosion prevention method, but it 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.

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 principle, with collector temperatures in the medium range of 120 F to 160 F. However, there is relatively little quantitative data relative to corrosion of solar collectors used for residential water heaters.

An excellent review of the solar water heater industry in South Florida by Scott (1976)⁽⁰⁰¹⁷⁾ 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.

A recent report 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, drain-down 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 three 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.

This survey was part of the effort of the 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 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.

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) leaked 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 anti-

freeze contained inhibitors, the quality of water used, or address the question of using insulating couplings between aluminum and copper.

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 nonaqueous in resistance-welded, pressure expanded, mild steel collectors such as the collector used on the Study Center at LASL. (800 sq ft collector array on the 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 through 1977, as 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 ten different commercial inhibitors by 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^- , SO_4^{2-} , and HCO_3^- 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 nonuniform corrosion. 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 that duplicate test specimens were used and only at elevated temperature (82 C). The compositions of the corrosion inhibitors are shown in Table 5, and ratings of the corrosion inhibitors for steel and aluminum are 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, a 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 solar collectors (34 x 76 inch) being evaluated are about equally divided among 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

TABLE 3. CORROSION INHIBITORS (0016)

-
-
1.	1.0 NaNO_3 , 2.0 $\text{Na}_3\text{PO}_4 \cdot 12\text{H}_2\text{O}$, 2.5 NaMBT, 3.0 $\text{Na}_2\text{B}_4\text{O}_7$,
1.0 $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$, 1.0 NaOH
2.	4.0 $\text{Na}_3\text{PO}_4 \cdot 12\text{H}_2\text{O}$, 2.0 $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$, 4.0 NaMBT
3.	1.5 NaNO_3 , 2.0 $\text{Na}_3\text{PO}_4 \cdot 12\text{H}_2\text{O}$, 2.5 NaMBT, 4.0 $\text{Na}_2\text{B}_4\text{O}_7$
4.	1.5 NaNO_3 , 2.5 $\text{Na}_3\text{PO}_4 \cdot 12\text{H}_2\text{O}$, 4.0 NaMBT, 2.0 $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$
5.	1.4 Na_2HPO_4 , 2.4 MBT, 6.2 $\text{Na}_2\text{B}_4\text{O}_7$: 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 $\text{NaC}_7\text{H}_5\text{O}_2$, 1.0 NaNO_2
9.	1.0 Na_2CrO_4
10.	Uninhibited test water
11.	50 volume percent uninhibited ethylene glycol
12.	Same as No. 1 without the NaOH
-
-

Note: All concentrations in grams per liter except as noted.

NaNO_2 - sodium nitrite

NaNO_3 - sodium nitrate

$\text{Na}_2\text{B}_4\text{O}_7$ - sodium borate

Na_2SiO_3 - sodium silicate

Na_2HPO_4 - disodium phosphate

MBT - mercaptobenzothiazole

NaMBT - sodium mercaptobenzothiazole (50% solution).

Na_3PO_4 - trisodium phosphate

$\text{NaC}_7\text{H}_5\text{O}_2$ - sodium benzoate

Na_2CrO_4 - 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: (a) The inhibitors are listed in descending order according to their effectiveness.
- (b) These are the only inhibitors that were considered acceptable in each category.
- (c) Only those inhibitors that were considered acceptable in the previous categories are rated.
- (d) 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 $\text{Na}_3\text{PO}_4 \cdot 12\text{H}_2\text{O}$, 2.5 NaMBT, 3.0 $\text{Na}_2\text{B}_4\text{O}_7$, 1.0 $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$, 1.0 NaOH, formulated by General Motors
 2. Same as No. 1 without the NaOH
 3. 1.5 NaNO_3 , 2.0 $\text{Na}_3\text{PO}_4 \cdot 12\text{H}_2\text{O}$, 2.5 NaMBT, 4.0 $\text{Na}_2\text{B}_4\text{O}_7$
 4. 1.5 NaNO_2 , 2.0 $\text{Na}_3\text{PO}_4 \cdot 12\text{H}_2\text{O}$, 2.5 NaMBT, 4.0 $\text{Na}_2\text{B}_4\text{O}_7$
 5. 1.4 Na_2HPO_4 , 2.4 MBT, 6.2 $\text{Na}_2\text{B}_4\text{O}_7$: 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
 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
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-

 NaNO_2 -- sodium nitrite NaNO_3 -- sodium nitrate $\text{Na}_2\text{B}_4\text{O}_7$ -- sodium borate

MBT -- mercaptobenzothiazole

NaMBT -- sodium mercaptobenzothiazole, 50 percent solution

 $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$ -- sodium silicate $\text{Na}_3\text{PO}_4 \cdot 12\text{H}_2\text{O}$ -- trisodium phosphate Na_2HPO_4 -- disodium phosphate

NaOH -- sodium hydroxide

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.

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 through November, 1977.⁽⁰²¹⁷⁾ Fluid flow rate is 0.5 gpm per 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 through 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. The 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 the 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 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.⁽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	Semiannual	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⁾, which is reproduced in part, below:

"In Phase I (June 1, 1976 - May 31, 1977) we have developed a nondestructive 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 ~100 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."

"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."

"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."

Heat Pipe Corrosion

Heat pipes can be used for solar collection applications related to electric power generation; they operate at temperatures up to 300 C. 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 245 C 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 150 C and 7000 hours at 250 C. Data are also given to show that nickel (Ni 200) is unacceptable at 30 C-90 C, and aluminum alloys (1100 and 6061) were not acceptable at 140 C. Data for stainless steels (~2 years at 149 C for 304SS, 2000 hours at 250 C for 316 SS, and 665 hours at 300 C for 347SS) indicate that the protective nature of the oxides formed increased in the order 304SS, 347SS, and 316SS.

Other Applications

The reader is referred to the Task 1 report⁽¹⁾ for reviews of corrosion in related technologies. These technologies are:

- (a) automotive; (b) domestic and commercial applications; and
- (c) industrial applications, including cooling towers and heat exchangers.

TASK TWO -- THE STUDY OF CORROSION IN MULTIMETALLIC SYSTEMS

The following section presents the highlights of Task 2 research. A more detailed presentation can be found in the Task 2 Technical Progress Report⁽²⁾ for this program.

EXPERIMENTAL

Materials

A survey of published literature in the Task One Report⁽¹⁾ and communications with representatives of various metals producers resulted in identification of six metals or alloys for experimental evaluation. These alloys were identified as either already in use in commercial nonconcentrating collectors, or likely candidates for future use. They are: copper alloy CDA 122; aluminum alloys 1100, 3003, and 6061; Type 444 stainless steel; and plain carbon steel. Specimens used in the recirculating system were in the form of tubing, each 17.8 cm (7 in.) long, 0.953 cm (0.375 in.) outside diameter, and 0.755 cm (0.305 in.) inside diameter. Galvanic coupling and crevice corrosion experiments were performed on specimens cut from sheet stock, which was not necessarily from the same heats as the tubular specimens.

The literature review⁽¹⁾ indicated that the most promising aqueous coolants were ethylene glycol/water and propylene glycol/water mixtures. The glycols were of reagent grade purity. The water was either distilled, or else it was a full strength or diluted solution originally containing 148 mg/l of Na_2SO_4 , 165 mg/l of NaCl , and 138 mg/l of NaHCO_3 in distilled water, referred to as "ASTM water". This solution, described in ASTM Specification D2570, contained 100 ppm each of Cl , SO_4 , and HCO_3 ions prior to dilution with glycol. The glycol/water mixtures were made with equal volumes of glycol and water.

Corrosion Under Dynamic Flow

Data obtained under dynamic flow conditions were generated in the recirculating system shown schematically in Figure 1. This system duplicated many aspects of a typical flat plate solar collector. It consisted of four specimen assemblies through which coolant circulated, a 20-liter reservoir, and a pump. During operation, the solution was pumped from the heated reservoir into the inlet header tube, through the four parallel specimen assemblies, into the exit header tube, and back to the reservoir for reheating and recycling. Figure 2 shows a more detailed view of the arrangement of the four specimen assemblies.

The flow rate of 61 cm/sec (2 ft/sec) corresponds to Reynolds numbers, N_{Re} , of 1050 and 6880 for an EG/water mixture (50:50 by volume) at 22 and 100 C, respectively, and N_{Re} of 760 and 5910 for a similar PG/water mixture at these same respective temperatures. Thus, the majority of exposure time during each experiment involved turbulent flow for both types of glycol solutions. Typically, the solutions were equilibrated with air during the exposure except for the last ten to twenty percent of the total time, during which nitrogen was used above the solution to indicate the effects of deaeration on corrosion rate.

The pump head and all transfer tubing were made of polytetrafluoroethylene (Teflon, PTFE). The header tubes were made of Hastelloy C-276 (HC-276), and the valves were constructed from stainless steel. The titanium reservoir was equipped with external electrical resistance heating elements, internal thermocouple well, and ports for aeration, or deaeration by nitrogen. Gas, either air or tank nitrogen, was passed through the reservoir continuously during each experiment. Solution flow rate was adjusted by means of the upper row of valves in the specimen assembly rack. Samples of solution were withdrawn periodically through a drain valve for pH determination. Inlet and outlet solution temperatures were monitored continuously by means of external thermocouples; the outlet temperature was controlled at 99 to 100 C. All parts of the system, including the specimens, were thermally insulated to minimize heat loss from the solution. In two experiments the effect of heat transfer through the specimens to the solution was investigated.

FIGURE 1. RECIRCULATING SYSTEM USED TO OBTAIN CORROSION DATA UNDER DYNAMIC FLOW CONDITIONS

FIGURE 2. SPECIMEN ASSEMBLY RACK AND SPECIMEN ASSEMBLIES

A cross sectional view of a specimen assembly is shown in Figure 3. The bottom specimen in each assembly contained a 0.159 cm (0.0625 in.) Hastelloy C-276 rod that served as a counterelectrode for polarization resistance (PR) measurements. A string bridge penetrated the PTFE connector situated above the bottom tube specimen and connected with a saturated calomel electrode (SCE) at ambient temperature.

Crevice Corrosion

Crevice corrosion susceptibility was evaluated with sandwich-type assemblies that consisted of prepared crevices. The ratio of total metal-metal crevice area to the area of freely exposed metal surface was 1:10. PTFE spacers served not only as electrical insulators, but they also provided polymer-metal crevices for evaluating the effects of this type crevice simultaneously with metal-metal crevices.

The surfaces of the metal coupons were prepared by surface grinding followed by rinsing in acetone. After assembly, the nuts and bolts were tightened to a torque of 0.56 N-m (80 oz-in.). The crevice assemblies were suspended in one liter vessels immersed in oil baths maintained at 100 C. The kettles were nearly filled with a 50:50 mixture of either ethylene glycol/ASTM water or propylene glycol/ASTM water. The solutions were aerated throughout the exposures. Severity of crevice corrosion was determined by optical microscopy of specimens at the end of each test.

Galvanic Corrosion

The effect of galvanic coupling on corrosion was evaluated in experiments involving a wide variety of bimetallic couples. Equal areas of strip specimens, about 7 cm² in exposed area, were etched and inserted through stoppers into polyethylene bottles nearly filled with a 50:50 mixture of either ethylene glycol/ASTM water or propylene glycol/ASTM water. The bottles were immersed in oil baths maintained at 93 C, and the solutions were aerated throughout the exposures. Corrosion potentials, E_{corr} ,

FIGURE 3. SPECIMEN ASSEMBLY

Each assembly consisted of three tubular specimens, PTFE connectors, HC-276 counterelectrode, and reference electrode. Each specimen was surrounded by thermal insulation (not shown).

of the coupled and uncoupled electrodes were measured periodically by means of a string bridge, SCE, and high impedance electrometer. Galvanic current was monitored intermittently with a zero resistance ammeter. The electrode pairs were electrically shorted to each other throughout the exposure periods.

RESULTS

Corrosion Under Dynamic Flow

A summary of experiments performed in the recirculating system is presented in Table 7. A total of eleven experiments was performed, ranging in duration from 259 to 522 hours. Experiments 9 and 10 incorporated the effects of heat transfer through specimens to the solution. Experiment 11 involved the highest level of chloride used, namely, 100 ppm in the aqueous EG solution. Experiments in PG/ASTM water were not performed because trends could be predicted adequately from analogous experiments in EG/ASTM water.

Solution pH, Polarization Resistance, Corrosion Potential

Variations in solution pH, polarization resistance (PR), and corrosion potential (E_{corr}) are given in Table 8 for EG solutions and in Table 9 for PG solutions.

The pH of EG solutions decreased with increasing exposure time in all but the EG/ASTM water solution exposed to aluminum alloys. The pH decreases were caused primarily by oxidation of the EG resulting in acidic by-products; similar degradation was observed in Task 3 of this research project⁽³⁾, and analysis of aqueous glycol solutions after prolonged periods of elevated temperatures confirmed the presence of organic acids, including oxalic acid. The degree of acidification was fairly uniform among the experiments (except number 1), ranging between about 4

TABLE 7. SUMMARY OF EXPERIMENTS PERFORMED IN THE RECIRCULATING SYSTEM^(a)

Experiment Number	Corrodent ^(b)	Alloys	Atmosphere	Duration ^(c) , hr
1	EG/ASTM water	Al 1100, 3003, 6061	air or N ₂	330
2	EG/ASTM water	copper, steel, stainless steel	air or N ₂	522
3	EG/20% ASTM water ^(d)	Al 1100, 3003, 6061	air or N ₂	451
4	EG/20% ASTM water ^(d)	copper, steel, stainless steel	air or N ₂	438
5	PG/20% ASTM water ^(d)	copper, steel, stainless steel	air or N ₂	352
6	PG/20% ASTM water ^(d)	Al 1100, 3003, 6061	air or N ₂	432
7	EG/distilled water	Al 1100, 3003, 6061	air or N ₂	309
8	EG/distilled water	copper, stainless steel	air or N ₂	351
9 ^(e)	PG/distilled water	Al 1100, 3003, 6061	air or N ₂	259
10 ^(e)	PG/distilled water	copper, stainless steel	air or N ₂	334
11	EG/high Cl ⁻ water ^(f)	copper, stainless steel	air or N ₂	309

(a) Temperature and flow rate were maintained at 100 C and 61 cm/sec (2 ft/sec), respectively, during each experiment.

(b) EG = ethylene glycol; PG = propylene glycol; ASTM water contained 100 ppm each of Cl, SO₄ and HCO₃ ions (see text). Equivolume mixtures were used.

(c) Total duration; approximately 10 to 20 percent of the total exposure time accrued at temperatures less than 100 C are included in these times.

(d) This was ASTM water diluted 4:1 with distilled water prior to mixing with EG or PG.

(e) These experiments incorporated the effects of heat flow through the tubular specimens to the solution.

(f) The water used to make this equivolume mixture contained 200 ppm Cl, 100 ppm SO₄, and 100 ppm HCO₃.

TABLE 8. VARIATION IN CORROSION-RELATED PARAMETERS FOR SPECIMENS EXPOSED TO ETHYLENE GLYCOL IN THE RECIRCULATING SYSTEM

Experiment Number	Corrodent	Specimen Material	Elapsed Time, hr	Temperature, °C	Atmosphere	Corrosion Potential, V(SCE)	Polarisation Resistance, $\Omega\text{cm}^2/10^3$	Solution pH
8	EG/distilled water	Copper 122	16	33	air	0.035	2620	5.5
		T444				0.136	4880	
		Copper 122	23	99	air	-0.076	262	5.5
		T444				0.187	394	
		Copper 122	329	99	air	0.194	39	4.7
		T444				0.235	58	
		Copper 122	351	99	N ₂	0.135	24	4.6
		T444				0.220	36	
7	EG/distilled water	Al 1100	21	30	air	-0.235	2430	5.4
		Al 3003				-0.290 to -0.309	2340	
		Al 6061				-0.250	469	
		Al 1100	29	100	air	-0.513	806	5.4
		Al 3003				-0.604	347	
		Al 6061				-0.531	450	
		Al 1100	213	100	air	-0.180	262	4.4
		Al 3003				-0.190	193	
		Al 6061				-0.163	262	
		Al 1100	296	100	N ₂	-0.277	262	4.1
		Al 3003				-0.305	206	
		Al 6061				-0.245	262	
4	EG/20% ASTM water	Copper 122	20	32	air	0.023	628	7.6
		T444				0.038	22,500	
		1018 steel				-0.300	431	
		Copper 122	29	100	air	-0.044	141	7.5
		T444				-0.050	900	
		1018 Steel				-0.559	86	
		Copper 122	358	100	air	-0.144	6.6	
		T444				-0.159	2.6	
		1018 steel				-0.499	3.0	
		Copper 122	429	100	N ₂	-0.269	3.6	4.2
3	EG/20% ASTM water	T444				-0.297	1.7	
		1018 steel				-0.576	1.7	
		Al 1100	3	70	air	-0.526	-	7.6
		Al 3003				-0.850	-	
		Al 6061				-1.050	-	
		Al 1100	23	100	air	-0.856	142	
		Al 3003				-0.916	90	
		Al 6061				-0.925	129	
		Al 1100	358	100	air	-0.130	862	3.8
		Al 3003				-0.145	825	
2	EG/ASTM water	Al 6061	433	100	N ₂	-0.171	1290	
		Al 1100				-0.173	3000	4.1
		Al 3003				-0.188	1730	
		Al 6061				-0.205	2250	
		Copper 122	19	22	air	-0.003	126	7.6
		T444				0.021	37,500	
		1018 steel				-0.405	32	
		Copper 122	25	100	air	-0.014	21	9.7
		T444				-0.014	394	
		1018 steel				-0.621	9.0	
1	EG/ASTM water	Copper 122	186	100	air	-0.040	28	
		T444				0.032	469	
		1018 steel				-0.450	11	
		Copper 122	426	100	air	-0.067	11	4.5
		T444				0.101	14	
		1018 steel				-0.365	9.9	
		Copper 122	522	100	N ₂	-0.147	24	4.5
		T444				-0.045	21	
		1018 steel				-0.603	12.9	
11	EG/ASTM water + 50 ppm Cl	Al 1100	18	34	air	-0.522	122	7.6
		Al 3003				-0.564	225	
		Al 6061				-0.542	187	
		Al 1100	41	101	air	-1.09	34	9.1
		Al 3003				-1.00	24	
		Al 6061				-1.03	319	
		Al 1100	186	101	air	-0.945	47	
		Al 3003				-1.00	49	
		Al 6061				-1.00	41	
		Al 1100	234	101	N ₂	-0.933	52	8.8
		Al 3003				-1.00	49	
		Al 6061				-0.992	34	
		Copper 122	21	33	air	-0.041	161	7.6
		T444				-0.007	262	
		Copper 122	29	100	air	-0.076	49	
		T444				-0.057	206	
		Copper 122	237	100	air	0.104	5.6	4.7
		T444				0.159	4.5	
		Copper	309	100	N ₂	0.075	8.1	4.5
		T444				0.107	4.1	

TABLE 9. VARIATION IN CORROSION-RELATED PARAMETERS FOR SPECIMENS EXPOSED TO PROPYLENE GLYCOL IN THE RECIRCULATING SYSTEM

Experiment Number	Corrodent	Specimen Material	Elapsed Time, hr	Temperature, °C	Atmosphere	Corrosion Potential, V(SCE)	Polarization Resistance, ohm-cm ² ·10 ³	Solution pH
10	PG/distilled water	Copper 122 T444	15	33	air	0.109 0.158	1260 3190	4.1
		Copper 122 T444	23	100	air	0.094 0.183	109 129	
		Copper 122 T444	257	100	air	0.171 0.191	64 92	4.7
		Copper 122 T444	334	100	N ₂	0.158 0.157	41 36	4.5
9	PG/distilled water	Al 1100 Al 3003 Al 6061	19	34	air	-0.277 -0.312 -0.142	1520 1425 3750	4.5
		Al 1100 Al 3003 Al 6061	26	99	air	-0.534 -0.677 -0.777	206 187 225	4.6
		Al 1100 Al 3003 Al 6061	187	99	air	-0.097 -0.082 -0.120	600 544 675	4.3
		Al 1100 Al 3003 Al 6061	259	99	N ₂	-0.111 -0.104 -0.135	619 516 712	4.2
5	PG/20% ASTM water	Copper 122 T444 1018 steel	16	30	air	0.006 0.043 -0.515	144 675 165	4.5
		Copper 122 T444 1018 steel	24	100	air	-0.117 -0.027 -0.630	28 32 16	4.5
		Copper 122 T444 1018 steel	328	100	air	-0.159 -0.131 -0.570	9.7 6.0 6.6	4.2
		Copper 122 T444 1018 steel	352	100	N ₂	-0.297 -0.298 -0.598	5.8 3.4 4.7	4.6
6	PG/20% ASTM water	Al 1100 Al 3003 Al 6061	16	29	air	-0.343 -0.457 -0.417	450 506 600	4.1
		Al 1100 Al 3003 Al 6061	23	100	air	-0.751 -0.679 -0.762	67 90 101	4.1
		Al 1100 Al 3003 Al 6061	352	100	air	-0.203 -0.205 -0.196	127 184 206	4.4
		Al 1100 Al 3003 Al 6061	424	100	N ₂	-0.510 -0.463 -0.482	165 216 244	4.4

and 5 units after 230 to 520 hours of circulation. Similar pH shifts were not observed in the PG solutions, probably because of the relatively low initial pH of these solutions.

Concerning E_{corr} , that of copper 122 shifted in the noble direction with increasing exposure time in EG/distilled water and in EG/ASTM water plus 50 ppm Cl. It moved in the active direction in EG/20% ASTM water and EG/ASTM water. Qualitatively similar behavior was observed in PG/distilled water and PG/20% ASTM water. E_{corr} of T444 stainless steel moved in the noble direction in EG/distilled water, PG/distilled water, EG/20% ASTM water and EG/ASTM water in equilibrium with air; deaeration usually caused a large active shift. In PG/20% ASTM water the shift was in the active direction regardless of the atmosphere in equilibrium with the solution. E_{corr} of the 1018 steel was relatively active for all exposure conditions, as expected, and it was not largely influenced by changes in solution chemistry. E_{corr} of the aluminum alloys displayed the greatest relative movements. For example, the respective final potentials of 1100, 3003, and 6061 alloys were -0.277, -0.305, and -0.245 V(SCE) in EG/distilled water, but they were -0.933, -1.00, and -0.992 V(SCE), respectively, in EG/ASTM water. Similar changes in the active direction were observed for these three alloys in PG/20% ASTM water, relative to those in PG/distilled water. Potential behavior during a given experiment was less definable. Thus, in EG/distilled water E_{corr} of the three aluminum alloys exhibited maxima (i.e., were most noble) part way through the exposure, whereas in EG/ASTM water the values essentially shifted monotonically in the active direction. It will be shown in a subsequent section that corrosion potential correlates qualitatively with pitting behavior for the aluminum-base alloys.

Polarization resistance measurements were made periodically to ascertain, in a semi-quantitative manner, real-time corrosion behavior of specimens in the recirculating system. The PR data could not be transformed into actual instantaneous corrosion rates for two reasons. First, the Tafel slopes necessary to reduce the PR data could not be measured with sufficient accuracy because of IR drop effects in the solution.

Second, it appears that redox reactions were occurring in the glycol solutions simultaneously with corrosion, and such reactions possibly would have introduced errors into the calculated corrosion rates. Therefore, relative changes in PR were used to ascertain the influence of experimental variables on corrosion rate.

Examination of the PR-time behavior given in Tables 8 and 9 shows that a large reduction of PR occurred during initial heating of the electrolyte, whereas subsequent behavior depended on the corrosivity of the particular electrolyte.

It should not be assumed that corrosion represents the only oxidation reaction giving rise to the PR behavior in Tables 8 and 9. Corrosion data from T444 will be presented that indicates that other redox reactions apparently occurred in conjunction with corrosion, because although the low PR values observed on T444 stainless steel suggest a rapid corrosion rate, no measurable corrosion was detected on this alloy under any exposure conditions.

Corrosion Rates

Corrosion rate data based on weight loss are presented in Table 10. No pitting occurred on copper 122, and on T444 and 1018 steels. Because pitting was the predominant form of attack on all three aluminum alloys, corrosion data are presented as a rate of pitting rather than a rate of overall weight loss in Table 11. The corrosion rates of copper in EG solutions were least in EG/20% ASTM water (101 $\mu\text{m}/\text{yr}$) and greatest in EG/ASTM water plus 50 ppm chloride (239 $\mu\text{m}/\text{yr}$). Intermediate rates occurred in EG/distilled water (171 $\mu\text{m}/\text{yr}$) and EG/ASTM water (180 $\mu\text{m}/\text{yr}$). These rates are approximate because they are extrapolated to an annual basis, a period about 25 times longer than the exposure time. Furthermore, there may have been some protection afforded by a growing corrosion product film, although such films were not well developed on the copper tube specimens after exposure. These corrosion rates provide an estimate of the upper bound of the rate of attack, and they are adequate for assessing the suitability of an

TABLE 10. AVERAGE CORROSION RATES FOR COPPER, STAINLESS STEEL, AND PLAIN CARBON STEEL OBTAINED IN THE RECIRCULATING SYSTEM

Experiment Number	Corrodent	Alloy	Average Corrosion rate ^(a)	
			mg/cm ² /yr	μm/yr
8	EG/distilled water	Copper 122	152	171
		T444 SS	<1	<1
4	EG/20% ASTM water	Copper 122	90	101
		T444 SS	<1	<1
		1018 steel	3930	5040
2	EG/ASTM water	Copper 122	160	180
		T444 SS	<1	<1
		1018 steel	890	1140
11	EG/ASTM water + 50 ppm Cl	Copper 122	212	239
		T444 SS	<1	<1
10	PG/distilled water	Copper 122	71	80
		T444 SS	<1	<1
5	PG/20% ASTM water	Copper 122	70	79
		T444 SS	<1	<1
		1018 steel	2930	3760

(a) Rates are averages from triplicate tube specimens. They were extrapolated to annual rates in a linear manner.

TABLE 11. MAXIMUM PIT DEPTHS AND APPROXIMATE PIT DENSITIES FOR ALUMINUM ALLOYS EXPOSED IN THE RECIRCULATING SYSTEM

Experiment Number	Corrodent	Alloy	Exposure Time, (a) hr	Maximum Pit Depth, (b) μm	Maximum Pit Density, cm^{-2}
7	EG/distilled water	1100	260	5	$>1.8 \cdot 10^5$
		3003		5	$< 9 \cdot 10^3$
		6061		19	$>1.8 \cdot 10^5$
3	EG/20% ASTM water	1100	440	6	$>1.8 \cdot 10^5$
		3003		8	$>1.8 \cdot 10^5$
		6061		20	$>1.8 \cdot 10^5$
1	EG/ASTM water	1100	285	72	$>1.8 \cdot 10^5$
		3003		127	$>1.8 \cdot 10^5$
		6061		150	$>1.8 \cdot 10^5$
9	PG/distilled water	1100	234	3	$< 9 \cdot 10^3$
		3003		4	$< 9 \cdot 10^3$
		6061		13	$>1.8 \cdot 10^5$
6	PG/20% ASTM water	1100	404	3	$>1.8 \cdot 10^5$
		3003		5	$< 9 \cdot 10^3$
		6061		14	$>1.8 \cdot 10^5$

(a) Time at operating temperature, 100 C.

(b) Determined by means of a microscope with a calibrated focus adjustment. Pit depths and pit densities were obtained by examining about 125 cm^2 of each type of specimen.

alloy/solution combination over a 10 to 20 year design lifetime. Since the wall thickness was 889 μm (0.035 in.), a corrosion rate of 89 $\mu\text{m}/\text{yr}$ would penetrate a tube in 10 years.

The corrosion rate of T444 stainless steel was less than 1 $\mu\text{m}/\text{yr}$ under every exposure condition studied. The high concentrations of chromium and molybdenum resulted in an extremely protective passive film that was almost totally inert in the various test solutions. The corrosion rates of 1018 steel specimens were relatively large, as expected, and ranged between about 1100 to 5000 $\mu\text{m}/\text{yr}$.

In PG solutions the corrosion rate of copper was less than in EG solutions, provided the make-up water was either distilled or 20% ASTM water. The corrosion of 1018 steel likewise was less in PG solutions, whereas T444 stainless steel again was unattacked. The difference in corrosivity of PG versus EG solutions was about a factor of two or less.

Pit depths and pit densities are listed in Table 11 for the three aluminum alloys that were investigated. (Because pits in aluminum usually grow at a nonlinear rate, some manipulation was required to convert the pit depths into rates of attack; see Table 12). The least susceptible alloy to pitting was 1100 and the most susceptible was 6061. This relationship prevailed in both EG and PG solutions. Except in EG/ASTM water, pitting behavior of the 3003 alloy more closely approximated that of 1100 aluminum than that of 6061 alloy. Pit depths were somewhat less in PG solutions than in EG solutions. With few exceptions, notably on 3003 alloy, the number of pits per unit area of exposed specimen surface ("pit density") was extremely high, exceeding $1.8 \times 10^5 \text{ cm}^{-2}$. It is apparent that the mode of attack was one of formation of a great many pits, but relatively shallow in depth.

Pitting rates were calculated based on a cube root law of pit growth for aluminum alloys⁽⁴⁾. Note, from Table 12, that penetration would be fastest in EG/ASTM water, in which penetration would occur in as little time as 1.3 years. In all other environments calculated penetration would occur only after long exposure times, ranging from about 82 to 1.2×10^6 years. Differences in chloride ion concentration are primarily responsible for this variability.

TABLE 12. PITTING CONSTANT AND EXTRAPOLATED PIT DEPTHS FOR ALUMINUM ALLOYS EXPOSED IN THE RECIRCULATING SYSTEM^(a)

Experiment Number	Corrodent	Alloy	Pitting Constant, k ($\mu\text{m/hr}^{1/3}$)	Time Required for Pit Depths of 889 μm and 508 μm , yr ^(a)	
				889 μm	508 μm
7	EG/distilled water	1100	0.784	$1.7 \cdot 10^5$	$3.1 \cdot 10^4$
		3003	0.784	$1.7 \cdot 10^5$	$3.1 \cdot 10^4$
		6061	2.98	$3.0 \cdot 10^3$	$5.7 \cdot 10^2$
3	EG/20% ASTM water	1100	0.789	$1.6 \cdot 10^5$	$3.1 \cdot 10^4$
		3003	1.05	$6.9 \cdot 10^4$	$1.3 \cdot 10^4$
		6061	2.63	$4.4 \cdot 10^3$	$8.2 \cdot 10^2$
1	EG/ASTM water	1100	10.9	$6.2 \cdot 10^1$	$1.2 \cdot 10^1$
		3003	19.3	$1.1 \cdot 10^1$	$2.1 \cdot 10^0$
		6061	22.8	$6.8 \cdot 10^0$	$1.3 \cdot 10^0$
9	PG/distilled water	1100	0.487	$6.9 \cdot 10^5$	$1.3 \cdot 10^5$
		3003	0.648	$2.9 \cdot 10^4$	$5.5 \cdot 10^4$
		6061	2.11	$8.5 \cdot 10^3$	$1.6 \cdot 10^3$
6	PG/20% ASTM water	1100	0.406	$1.2 \cdot 10^6$	$2.2 \cdot 10^5$
		3003	0.676	$2.6 \cdot 10^5$	$4.8 \cdot 10^4$
		6061	1.89	$1.2 \cdot 10^4$	$2.2 \cdot 10^3$

(a) Calculations were based on a cube root growth law of pits in these alloys.

(b) 889 μm and 508 μm correspond to thicknesses of 0.035 and 0.020 in., respectively.

Effect of Heat Transfer

The influence of heat transfer through the copper and aluminum alloy tube specimens into the circulating solutions is summarized in Table 13. The purpose of these experiments was to determine whether effects of heat transfer on corrosion could be neglected without incurring serious error in measurement of corrosion rates. These tables show that neither pitting nor weight loss was influenced substantially by the presence of heat transfer rates up to 4730 W/m^2 .

Crevice Corrosion

Results of the crevice corrosion experiments are presented in Table 14. No attack was noted on Cu 122 or T444 stainless steel in either EG or PG solution. Some discoloration did occur in the crevices in T444 and evidence of severe general corrosion was found on the freely exposed surfaces of copper 122. Crevice attack on the aluminum alloys, when it occurred, tended to be worse at PTFE-metal interfaces than at metal-metal interfaces, although more experiments need to be performed to confirm this observation. Crevice corrosion was somewhat less severe in PG/ASTM water, although more experiments are also needed to verify this finding.

Galvanic Coupling

Table 15 summarizes results of galvanic coupling measurements of various electrode pairs. Couples yielding the largest currents, which were proportional to corrosion rates, were those between T444 stainless steel and aluminum alloys, and between T444 and 1018 steel; fairly large currents also flowed between T444 and copper 122. Currents were least among the aluminum-to-aluminum couples. The influence of type of glycol on the nature of galvanic corrosion was, in some cases, quite pronounced. For example, PG caused a reversal in polarity of couples involving 1100/3003, 3003/6061, and 1018/6061. It also caused much lower currents for couples of 3003/1100, 1018/1100, 1018/3003, 1018/6061, and 444/1018.

TABLE 13. INFLUENCE OF HEAT TRANSFER ON CORROSION BEHAVIOR OF ALLOY SPECIMENS EXPOSED TO A 50:50 MIXTURE OF PROPYLENE GLYCOL AND DISTILLED WATER AT 100 C^(a)

Experiment Number	Specimen Material	Heat Flux, W/m ²	Maximum Pit Depth, μ m	Weight Loss, mg/cm ²
10	Copper 122	0	No pits	2.98 ^(b)
	Copper 122	946	No pits	2.96 ^(c)
	Copper 122	4730	No pits	3.00 ^(d)
9	Al 3003	0	4	0.11 ^(b)
	Al 3003	946	4	0.11 ^(c)
	Al 3003	4730	3	0.09 ^(d)

(a) Experiments performed in recirculating system at a flow rate of 61 cm/sec ($N_{Re} = 5910$).

(b), (c), (d) Averages from 6, 2, and 1 specimen, respectively.

TABLE 14. SUMMARY OF RESULTS OF CREVICE CORROSION EXPERIMENTS (a)

Solution	Alloy	Severity of Crevice Attack (b)	
		Metal-metal interface	Metal-PTFE interface
EG/ASTM water	1100	Moderate	Minor
	3003	minor	none
	6061	minor	severe
	Cu 122	none	none
	T444	none	none
PG/ASTM water	1100	None	Moderate
	3003	none	minor
	6061	minor	severe
	Cu 122	none	none
	T444	none	none

(a) Duplicate specimens were exposed in non-flowing aerated solutions at 100 C for 50 days. Chloride concentration was 50 ppm.

(b) Terms are relative.

TABLE 15. RESULTS OF GALVANIC CURRENT EXPERIMENTS IN
AERATED EG/ASTM WATER AND PG/ASTM WATER AT
93 C(a)

Solution	Anode/Cathode	Potential, V(SCE) Anode/Cathode	Galvanic Current, $\mu\text{A}/\text{cm}^2$
EG/ASTM water	6061/1100	-0.322/-0.670	0.3
EG/ASTM water	3003/1100	-0.265/-0.650	0.6
EG/ASTM water	3003/6061	-0.350/-0.550	<0.1
EG/ASTM water	444/1100	-0.040/-0.690	12.9
EG/ASTM water	444/3003	0.035/-0.680	16.5
EG/ASTM water	444/6061	0.055/-0.675	14.5
EG/ASTM water	1018/1100	-0.725/-0.843	1.0
EG/ASTM water	1018/3003	-0.715/-0.885	1.4
EG/ASTM water	1018/6061	-0.715/-0.855	1.2
EG/ASTM water	122/1018	-0.490/-0.695	2.2
EG/ASTM water	444/1018	-0.615/-0.700	19.9
EG/ASTM water	444/122	0.110/ 0.028	6.1
PG/ASTM water	6061/1100	-0.500/-0.660	0.1
PG/ASTM water	1100/3003	-0.570/-0.833	<0.1
PG/ASTM water	6061/3003	-0.500/-0.810	<0.1
PG/ASTM water	444/1100	0.015/-0.690	15.7
PG/ASTM water	444/3003	0.040/-0.700	22.3
PG/ASTM water	444/6061	-0.150/-0.679	6.4
PG/ASTM water	1018/1100	-0.701/-0.718	<0.1
PG/ASTM water	1018/3003	-0.715/-0.800	<0.1
PG/ASTM water	6061/1018	-0.590/-0.718	0.3
PG/ASTM water	122/1018	-0.195/-0.700	2.9
PG/ASTM water	444/1018	-0.672/-0.690	2.9
PG/ASTM water	444/122	0.170/-0.020	5.7

(a) Readings taken after about 500 hours of exposure. Potentials measured after electrically uncoupling the electrodes, which were of equal areas.

DISCUSSION

Corrosion Under Dynamic Flow

The data in Tables 10 through 12 are particularly revealing because they indicate relative anticipated corrosion rates in solar collectors under near-worst case conditions. If a tolerable corrosion rate is taken as $89 \mu\text{m/yr}$ (0.0035 in./yr), which will yield about a 10 year lifetime for tubing with $889 \mu\text{m}$ (0.035 in.) thick walls, then it is apparent that T444 stainless steel would be satisfactory under all conditions that were studied (Table 10). The high chromium and molybdenum contents of this alloy rendered it virtually inert in all solutions. Conversely, copper 122 corroded at prohibitively high rates in EG solutions, presumably because of the ready availability of dissolved oxygen. Because of the noble corrosion potential of copper, its corrosion rate probably would have been less in deaerated solutions, although this statement is not supported by apparent PR behavior. However, the influence of glycolic degradation products on removal of the protective corrosion film on copper is not established, and this phenomenon could conceivably sustain corrosion in the absence of air.

A protective film possibly would have developed on the inner copper tube surfaces during longer exposures in the presence of dissolved oxygen and thereby reduced the corrosion rates substantially. It was not practicable to determine this possibility because of the very long exposure times that would have been required. On the other hand, examination of the freely exposed surfaces of copper crevice coupons indicated the presence of a thick, porous, nonprotective film after 500 hours exposure. It is suspected that the combined influence of acidification and chloride ion prevented formation of protective Cu_2O . The rather large weight losses of about 8 mg/cm^2 measured during descaling copper tube specimens also suggest the presence of thick and nonprotective films.

The large corrosion rates of 1018 steel indicate the need for proper inhibition of solar collector systems containing ferrous, non-stainless components. The smaller corrosion rate in Experiment 2 may

have resulted from the increased pH and buffering capacity of the full strength ASTM water, which would have delayed acidification.

The corrosivity of PG/water solutions toward copper and steel was marginally less than that of EG/water solutions for the anion concentrations that were investigated. This factor, and its lesser toxicity, constitute some advantage over EG for use in certain types of solar collector systems.

The pitting propensities of 1100 and 3003 were similar and considerably less than that of the more highly alloyed 6061 in the dilute solutions, although in EG/ASTM water 1100 was noticeably superior to 3003. More quantitative comparisons are possible with the computed pitting constant, k , in Table 12. Larger k values denote a stronger dependence of pit depth on the cube root of exposure time, and thus greater susceptibility to pitting. The values of k for 6061 alloy were consistently higher than those for the other two alloys, and they varied substantially with solution composition. These values clearly show the detrimental effects of chloride ion on pitting corrosion. (The other anions present, namely, sulfate and bicarbonate, do not stimulate pitting of aluminum alloys as strongly as chloride). Specifically, k values increased sharply as the dissolved chloride level reached 50 ppm in EG/ASTM water. A concentration of 50 ppm chloride in the glycol solution corresponds to 100 ppm in the water itself. This is less than the chloride concentration present in many tap waters in the United States. The effect on k of increasing chloride from 0 to 10 ppm, EG/distilled water versus EG/20% ASTM water, was much smaller. Comparison of k values in EG and PG solutions provides a clear indication of the greater corrosivity of EG, and shows that the difference is not large. The last column shows that even alloy 6061, the most susceptible to pitting, would allow a design lifetime exceeding 20 years in every solution except EG/ASTM water, and presumably PG/ASTM water. A small change in the exponent of time, t , in Equation 1 would not change the preceding statement because of the very large safety factor present in the calculated penetration times. For example, for 6061 alloy to fail in 20 years in EG/distilled water by

penetration through a wall thickness of 508 μm , the exponent in Equation 1 would have to be increased from 0.33 to about 0.50.

It is significant that Task 3 research results⁽³⁾ showed much deeper pits in aluminum alloys than those reported in Table 11. For example, after 1750 hours in aerated EG/distilled water at 100 C, the maximum pit depths in 1100, 3003, and 6061 alloys were 530, 450, and 240 μm , respectively. At least two possible explanations exist for the more severe pitting in this companion study. First, the exposure of 1750 hours resulted in lower final pH values, generally in the range of 3.3 to 3.8, and these lower pH's may be responsible for the greater attack. Second, the stagnant exposure conditions may have promoted the growth of fewer pits and to deeper depths than the dynamic flow used in the present investigation.

It is conceivable that aluminum alloys could be used successfully in uninhibited flowing EG and PG solutions, provided the only corrosive species is chloride ion and its concentration is kept well below 50 ppm. However, the possibilities of enhanced pitting during periods of stagnant flow, from possible contamination by additional chloride, or from accumulations of Cu^{++} or Fe^{+++} ions strongly dictate the need for adequate chemical inhibition of corrosion in commercial aluminum collector systems.

The acidification of the glycol solutions of pH values below 5 after only 300 to 400 hours of exposure at 100 C is the result of relatively rapid degradation of these solutions. Acidification may also have been assisted by hydrolysis of corrosion products; however, results of Task 3 research showed that acidification also occurs in the absence of metals although at slower rates. Task 3 also demonstrated that acidification continued for many hundreds of hours and, therefore, the pH values of 4+ listed in Tables 8 and 9 should not be considered the minimum attainable by these solutions. The relatively rapid rates of acidification of EG solutions, the initially low pH of the PG solutions, and the known deleterious effects of acidic solutions on the corrosion of aluminum and copper alloys underscore the advisability of buffering glycol solutions adequately to a near-neutral or mildly alkaline pH.

Corrosion potential qualitatively reflected the pitting behavior of the aluminum alloys. Specifically, those instances in which k exceeded $10 \mu\text{m/hr}^{1/3}$ also resulted in active values of E_{corr} , usually between -0.90 and -1.00 V(SCE). Values of k of $3 \mu\text{m/hr}^{1/3}$ or less correlate with E_{corr} 's more positive than about -0.20 V(SCE). Thus, E_{corr} may be useful as an indicator of loss of passivity and rapid pitting in aluminum collectors; a measurement device based on this principle is being evaluated elsewhere for possible use in aluminum collectors.(5)

The lack of effect of heat transfer on corrosion rate is significant, because the maximum flux of 4730 W/m^2 is about that anticipated in tube-and-fin solar collectors. However, certain types of corrosion inhibitors are influenced by heat transfer; thus, heat transfer should be included in any laboratory study of corrosion inhibitors, unless there is evidence showing that it exerts no significant influence.

Crevice Corrosion

Results of Table 14 show that crevice corrosion could be a severe problem with aluminum alloys in uninhibited glycol solutions, especially those containing 50 ppm or more of chloride ion. Crevices in commercial collectors can arise as a result of fabrication technique, such as at welded seams, and through assembly, such as at attachment points for hoses and tubing. Because of the known tendency of aluminum for crevice corrosion, the use of corrosion inhibitors is advisable. A preferable deterrent, however, is avoidance of crevices in the collector system.

It should not be assumed that the absence of crevice attack in Table 14 implies absolute immunity. It is conceivable that a different surface treatment, or greater number of replicate specimens, would have resulted in some attack. Nevertheless, the data in Table 14 show relative susceptibilities. Note that in the case of 6061 alloy, PTFE-metal crevices corroded more severely than metal-metal crevices.

Galvanic Coupling

The accelerating influence on corrosion of galvanic coupling can be calculated, as follows. Shifts in E_{corr} of the anodic member of a galvanic couple by more than about 25 mV results in the measured galvanic current being nearly equal to the corrosion rate of the anode. Such large shifts were measured for couples between aluminum alloys and other metals, 3003 and 6061 aluminum alloys, and in certain other couples. Faraday's law can be used to show that for aluminum, a corrosion current of $1 \mu\text{A}/\text{cm}^2$ corresponds to a metal recession rate of $10.9 \mu\text{m}/\text{yr}$, based on the overall reaction:

and not considering the influence of alloying elements in the 3003 and 6061 alloys. Also ignored are other possible oxidation reactions that may occur in degraded glycol solutions, as referred to earlier. If a $51 \mu\text{m}/\text{yr}$ ($0.002 \text{ in.}/\text{yr}$) corrosion rate is taken as the allowable limit, then a galvanic current of $4.6 \mu\text{A}/\text{cm}^2$ is the maximum permissible. However, the common form of corrosion of aluminum alloys is pitting, and the current densities within pits are much higher than the nominal value calculated over the entire specimen area. Therefore, galvanic corrosion of almost any magnitude should be avoided with aluminum alloys.

Galvanic couples between aluminum alloys and copper were not investigated during this research. Such couples are to be avoided at all costs, since prior experience in many applications has shown that severe pitting of the aluminum member occurs, primarily as a result of the high concentration of cupric ion and noble E_{corr} of copper.

For copper, the calculated maximum permissible corrosion current is $4.4 \mu\text{A}/\text{cm}^2$; therefore, coupling to T444 stainless steel would not be advisable.

The influence of type of glycol on the mixture of galvanic corrosion was, in some cases, quite pronounced. For example, changing from EG to PG caused a reversal in polarity of couples involving 1100/3003, 3003/6061, and 1018/6061, and it caused lower galvanic currents

to flow in others. Although uninhibited PG solutions appear to offer some advantage over EG solutions with respect to crevice corrosion, the presence of corrosion inhibitors probably would reduce the difference between their relative corrosivities.

CONCLUSIONS -- TASK 2

Task 2 research has provided information about corrosion in solar collector systems under simulated harsh operating conditions. The following points are especially significant:

- (1) Type 444 stainless steel corroded at negligibly small rates (less than 1 $\mu\text{m}/\text{yr}$) under all exposure conditions that were evaluated. It is a promising alloy for use in uninhibited collector systems, or in those that operate under harsh conditions or with poor anticipated maintenance.
- (2) Aluminum alloys 1100, 3003, and 6061 pitted in EG and PG solutions, but at very acceptable rates provided the chloride concentration is kept well below 50 ppm. However, because of possible contamination of solutions in commercial solar collector systems, and because pitting of aluminum alloys is more rapid under stagnant exposure, the use of adequate corrosion inhibition is strongly recommended for satisfactory performance.
- (3) Copper corroded at prohibitively high rates in EG solutions and at near-prohibitive rates in PG solutions. Exclusion of dissolved oxygen might have reduced the corrosion rates. The impossibility of insuring oxygen-free solutions in commercial collector systems, and the accelerating effects of glycol acidification on corrosion rates, mandate the use of corrosion inhibitors.

- (4) Crevice corrosion can be a severe problem with aluminum alloys in glycol solutions. It does not appear to threaten the integrity of copper and T444 stainless steel.
- (5) Galvanic coupling in glycol solutions can seriously accelerate the corrosion rates of aluminum alloys, especially if the other member of the couple is much more noble. Couples between copper and stainless steel also should be avoided.
- (6) Aqueous glycol solutions, both EG and PG, underwent acidification during several hundred hours of exposure to air at 100 C. The resulting pH values, in the range of 4 to 5, can accelerate corrosion rates. Therefore, glycol solutions should be buffered and inhibited when used in aluminum or copper collectors.
- (7) PG appeared to produce somewhat smaller rates of pitting and general corrosion on aluminum alloys and copper. These differences may become insignificant if the glycols are properly inhibited and buffered to minimize corrosion.
- (8) Polarization resistance measurements did not accurately indicate the corrosion behavior of T444 in glycol solutions. Its suitability for corrosion monitoring of aluminum alloys and copper needs additional investigation.
- (9) Heat transfer rates as large as 4730 W/m^2 did not substantially influence corrosion of aluminum alloys or copper in uninhibited glycol solutions.

In principle, and under unrealistically ideal conditions, it might be possible to achieve a 10- to 20-year lifetime of aluminum and copper collectors with uninhibited EG and PG solutions, provided contamination by chloride, metal ions, and oxygen is prevented, and crevice corrosion and galvanic coupling are minimized. However, the

near-impossibility of maintaining these conditions throughout the life of the collector system underscores the advisability of using adequate corrosion inhibitors and buffering capacity. The need for such inhibition is much less critical in a T444 stainless steel system.

TASK THREE -- DETERMINATION OF INTERACTIONS
BETWEEN DIFFERENT WATERS AND
CHEMICAL ANTIFREEZE ADDITIVES

EXPERIMENTAL

Materials and Preparation

Five metals or alloys, identified during Task 1 research⁽¹⁾ as the most commonly used solar collector materials, were selected for use in Task 3 of this research program, and are the same as those used in Task 2 research. Three specimen geometries were used in these studies. Polarization resistance (PR) measurements were performed on specimens 3.2 mm in diameter by 100 mm in length (Type 1 specimens). Weight-loss and pit-depth measurements were performed on specimens 19 mm by 19 mm by 0.81 mm (Type 2 specimens). Included in each exposure cell were cylindrically shaped specimens 31.75 mm in diameter by 76 mm in length by 0.81 mm wall (Type 3 specimens) used to increase the metal surface-to-solution volume ratio, thereby accelerating any degradation reaction that might be catalyzed on metallic surfaces.

Aqueous solutions of 50 volume percent ethylene glycol and 50 volume percent propylene glycol were used throughout this program, based on the results of the Task 1 review. Accordingly, other candidates such as methanol/water were excluded. The glycols were of reagent grade purity. The water used was either distilled/deionized or a mildly aggressive simulated tap water that was prepared according to specifications in ASTM D2570. The pH values of solutions that were prepared with ASTM water were adjusted to 4, 7.5, and 11 by adding either HCl or NaOH. In some tests the glycol-based media were prepared with distilled water and buffered to a pH of 7.5 with $\text{Na}_2\text{B}_4\text{O}_7$.

Exposure Tests at 100 C

The majority of the data generated during this task was obtained at 100 C. This is a reasonably high temperature for a non-concentrating solar collector under normal operating conditions. The exposure tests were conducted in 1 & Teflon^(R) vessels that were immersed in a constant temperature oil bath. Condensers were mounted to each vessel to prevent water loss. The solutions were sparged with humidified N₂ at rates of 50 ml/min by means of Teflon^(R) bubblers. In test vessels sparged with N₂, bubblers containing distilled water were also connected to the open end of the condensers to supply a slight back-pressure to the system and prevent air entry. Aliquots of the solutions were taken periodically and analyzed for pH and conductivity. Selected aliquots were also analyzed for total acid, volatile acid, and oxalic acid.

In studies on catalysis of glycol degradation by metals, each exposure cell contained two Type 1 specimens, four Type 2 specimens, and two Type 3 specimens. The Type 1 specimens passed through the Teflon^(R) cap of each test vessel to enable electrical measurements to be made. The PR of Type 1 specimens was periodically monitored to determine the time dependence of corrosion. A potential of 10 mV was applied between the two Type 1 specimens and the ensuing current flow at steady state was measured across a precision resistor. The polarity of the electrodes was reversed every 100 seconds during the measurement to prevent permanent polarization of the electrodes. When PR measurements were not being taken, the specimens were electrically shorted by means of an external wire. The PR, which is inversely proportional to the corrosion rate, was determined by the ratio of applied polarization to resulting current flow ($\Delta E/\Delta I$).

The corrosion potential of the Type 1 specimen was periodically measured with respect to a standard calomel electrode (SCE) by means of a high impedance Keithley^(R) electrometer. The calomel electrode was connected to the test cell by means of a string bridge and was isolated to prevent chloride contamination of the test solutions.

Duplicate Type 2 specimens were periodically removed from the solutions, descaled, weighed, and optically examined for pitting with a low-power optical microscope. The depths of pits were measured optically with a microscope having a calibrated focus adjustment.

Exposure Tests at 180 C

A limited number of exposure tests were conducted at 180 C to evaluate degradation of the glycol-base heat transfer media under simulated stagnation conditions. The tests were performed in Teflon^(R)-lined autoclaves fabricated from Type 304 stainless steel. Solutions were aerated or deaerated by pressurizing the vessels with air or nitrogen to 0.93 MPa (120 psig) total pressure, which was approximately 0.07 MPa (9 psi) greater than the vapor pressures of the solutions at 180 C. Aliquots of the solutions were taken periodically and analyzed for pH and conductivity. Selected aliquots were also analyzed for total acid, volatile acid, and oxalic acid.

Each autoclave contained two Type 1 specimens and two Type 3 specimens of CDA 122 copper. Copper was used in this study because it is reported in the literature to catalyze the degradation of glycol-based heat transfer media. The Type 1 specimen passed through electrically insulated Conax^(R) fittings to the exterior of the autoclaves to provide for measurement of PR. The techniques used for PR measurement and for evaluation of the PR data are described in the previous section. Weight-loss and pit measurements were also performed on Type 3 specimens following testing.

RESULTS

Exposure Tests at 100 C

Decomposition Studies

pH Measurements. The pH of ethylene glycol and propylene glycol solutions was periodically measured over exposures of 1750 hours under deaerated and aerated conditions. Testing was done on solutions in the presence of CDA 122 copper, 1100 aluminum, 3003 aluminum, 6061 aluminum, and 1018 steel, as well as in the absence of metals. Data show that the pH of all solutions decreased rapidly for the first 400 hours and gradually thereafter, during the first 1000 hours from 5.3 to values between 3.2 and 3.8. Over the remaining 750 hours of exposure the pH of the control solution (no metal present) increased, whereas the pH of the other solutions was approximately constant. There was no apparent reason for the pH increase. Over most of the testing time the solution containing copper had the lowest pH and the solution containing 1018 steel had the highest. The pH's of the control solution and the solutions containing the aluminum alloys generally fell between these two extremes. Aeration and deaeration affected the initial pH of the solutions slightly, but there was no significant difference between aerated and deaerated solutions after 100 hours of exposure. Similar behavior was observed for propylene glycol solutions.

Aerated ethylene glycol and propylene glycol solutions were buffered to pH 7.5 and pH was monitored as a function of exposure time in the presence of CDA 122 copper, 1100 aluminum, and in the absence of any metal. The pH of the propylene glycol solutions did not change significantly from the initial value of 7.5 over 2000 hours (see Figure 4), but the pH of ethylene glycol solutions decreased in the presence of CDA 122 copper to about 5.8.

Ethylene and propylene glycol solutions that were prepared with ASTM water were adjusted to pH values of 4, 7.5 and 11 with HCl or NaOH. The pH of these solutions was monitored as a function of

FIGURE 4. THE pH AS A FUNCTION OF EXPOSURE TIME AT 100 C FOR AERATED PROPYLENE GLYCOL SOLUTIONS THAT WERE INITIALLY BUFFERED TO pH 7.5, IN THE PRESENCE OF VARIOUS METALS AND WITH NO METAL PRESENT (CONTROL)

exposure time in the absence of any metal. Results showed that the pH generally decreased with exposure times for the solutions having the higher initial pH values. The effect was most pronounced in ethylene glycol, and the pH eventually reached 4.7 from an initial value of 11. The pH of solutions having the lower initial values increased during the first 200 hours and decreased thereafter. The pH increase may have resulted from decomposition of HCO_3 .

Conductivity Measurements. The conductivity of the aerated and deaerated ethylene glycol and propylene glycol solutions was periodically measured during the exposure tests. Typical results are given in Figure 5. The data show that the conductivity generally increased with exposure time. No discernible difference in behavior was found between the two heat transfer media. Slightly higher conductivities were observed under aerated conditions. Under all testing conditions, the heat transfer media containing CDA 122 copper and 1018 steel exhibited the highest conductivities. The conductivities of the control solutions (no metal present) were similar to those of the solutions containing the aluminum alloys, and they were considerably lower at a given exposure time than those of the previously mentioned solutions.

The conductivities of the solutions that were buffered to pH 7.5 were also measured as a function of exposure time. Results given in Figures 6 and 7 show that conductivities of buffered solutions were considerably higher than those of unbuffered solutions and did not vary substantially with exposure time. Again, there was no discernible difference between the behavior of ethylene glycol and propylene glycol solutions. The solutions containing 1100 aluminum consistently had the highest conductivity.

The conductivity of heat transfer media prepared with ASTM water was also measured as a function of exposure time with no metal present. The solution conductivities decreased slightly with exposure time, and the effect was most pronounced for the pH 7.5 solutions. Slightly higher values were observed in ethylene glycol solutions and in pH 11 solutions. The conductivity in both ethylene glycol and

FIGURE 5. CONDUCTIVITY AS A FUNCTION OF EXPOSURE TIME AT 100 C FOR AERATED ETHYLENE GLYCOL SOLUTIONS IN THE PRESENCE OF VARIOUS METALS AND WITH NO METAL PRESENT (CONTROL)

FIGURE 6. CONDUCTIVITY AS A FUNCTION OF EXPOSURE TIME AT 100 C FOR AERATED ETHYLENE GLYCOL SOLUTIONS THAT WERE INITIALLY BUFFERED TO pH 7.5, IN THE PRESENCE OF VARIOUS METALS AND WITH NO METAL PRESENT (CONTROL)

FIGURE 7. CONDUCTIVITY AS A FUNCTION OF EXPOSURE TIME AT 100 C FOR AERATED PROPYLENE GLYCOL SOLUTIONS THAT WERE INITIALLY BUFFERED TO pH 7.5, IN THE PRESENCE OF VARIOUS METALS AND WITH NO METAL PRESENT (CONTROL)

propylene glycol solutions was approximately one order of magnitude greater than that measured in solutions prepared with distilled water.

Solution Analysis. Selected solutions from the exposure tests in distilled water-glycol solutions were analyzed for total acid and volatile acid contents. Results, displayed in Table 16, show that all of the metals enhanced the degradation, i.e., acidification, of both heat transfer media and that the overall degree of acidification was approximately similar for the two media. The 1018 steel caused the greatest amount of acidification of ethylene glycol, as evidenced by high levels of total acid and volatile acid. Degradation was more severe under aerated conditions.

In general, volatile acid was present where significant quantities of total acid were found. The oxalic acid content of ethylene glycol solutions was also determined and similar trends were found. Selected samples from exposure tests with buffered solutions and with those prepared with ASTM water were also analyzed for volatile acid. Analyses of total acid were not performed because pH adjustment and buffering would have complicated data analysis. Results for buffered solutions displayed in Table 17 show that buffering decreased the concentration of volatile acid, suggesting that degradation was reduced.

Less than 1 m equivalent/l of volatile acid was detected in ethylene glycol and propylene glycol solutions that were prepared with ASTM water, pH adjusted and exposed at 100 C under aerated conditions in the absence of metals. Thus, the presence of the ions found in the glycol-ASTM water solutions did not affect degradation, within experimental error, over the pH range of 4 to 11.

Corrosion Studies

Polarization Resistance Measurements. The polarization resistance (PR) of Type 1 specimens was monitored periodically during

TABLE 16. TOTAL ACID AND VOLATILE ACID CONTENTS OF SELECTED GLYCOL SOLUTIONS FOLLOWING EXPOSURE AT 100 C

Solution	Metal Present	Aeration	m equivalents/l	
			Total Acid	Volatile Acid
Ethylene glycol ^(a)	-	-	1.5	(b)
Ethylene glycol	-	Deaerated	< 1.0	(b)
Ethylene glycol	CDA 122 Cu	Deaerated	15	< 1.0
Ethylene glycol	None	Aerated	< 1.0	(b)
Ethylene glycol	CDA 122 Cu	Aerated	36.5	2.8
Ethylene glycol	1100 Al	Aerated	9.8	9.8
Ethylene glycol	1018 Steel	Aerated	33.0	18.6
Propylene glycol ^(a)	-	-	1.5	(b)
Propylene glycol	-	Deaerated	4.0	(b)
Propylene glycol	CDA 122 Cu	Deaerated	12	< 1.0
Propylene glycol	None	Aerated	1.0	(b)
Propylene glycol	CDA 122 Cu	Aerated	20	3.10

(a) 50 percent aqueous solutions of as-received heat transfer media (control solution).

(b) Not determined because of low value of total acid.

TABLE 17. VOLATILE ACID CONTENTS OF SELECTED GLYCOL SOLUTIONS THAT WERE BUFFERED TO pH 7.5 AND EXPOSED AT 100 C UNDER AERATED CONDITIONS

Solution	Metal Present	m equivalents/l
Ethylene Glycol	None (control)	0.2
Ethylene Glycol	CDA 122 Cu	0.2
Propylene Glycol	None	0.5
Propylene Glycol	CDA 122 Cu	0.2

the course of the exposure tests at 100 C^(a). Data show that there was no significant difference in PR behavior between propylene glycol and ethylene glycol solutions. Aerated conditions were generally more severe for all of the alloys tested. PR values for CDA 122 copper and 1018 steel were lower under aerated conditions than under deaerated conditions, whereas greater fluctuations in PR for aluminum alloys were observed under aerated conditions. PR of the aluminum alloys increased with time over the first 500 hours, indicating a decreasing corrosion rate, and fluctuated between 1000 and 10,000 K Ω -cm² over the succeeding 1000 hours. The PR of many of the aluminum specimens decreased during the remainder of the test (during period of low pH). PR of CDA 122 copper and 1018 steel decreased with time for the first 1000 hours, indicating an increasing corrosion rate. Under deaerated conditions the PR of the alloys stabilized to values between 2 and 6 K Ω -cm² over the remainder of the tests; conversely, PR values continued to decrease under aerated conditions.

The polarization resistance of Type 1 specimens was also monitored periodically during the exposure tests at 100 C in aerated buffered solutions. Typical results are given in Figure 8. Comparison of these data with similar data for unbuffered solutions indicates that the corrosion rate of CDA 122 copper was decreased and that of 1100 aluminum was slightly increased by buffering. However, smaller fluctuations in PR of 1100 aluminum were observed in the buffered solutions than in unbuffered solutions.

Corrosion Potential Measurements. The free corrosion potential of Type 1 specimens was periodically monitored during the course of exposure tests at 100 C. Typical behavior is given in Figure 9. The potential of 1018 steel was approximately constant at 0 V (SCE) throughout the studies in both ethylene glycol and propylene glycol, and it was not affected by aeration. The potential of CDA 122 copper

(a) PR is inversely proportional to the oxidation rate occurring at the electrode surface.

FIGURE 8. POLARIZATION RESISTANCE OF VARIOUS ALLOYS AS A FUNCTION OF EXPOSURE TIME AT 100 C IN AERATED ETHYLENE GLYCOL SOLUTIONS INITIALLY BUFFERED TO pH 7.5

FIGURE 9. FREE CORROSION POTENTIAL OF VARIOUS ALLOYS AS A FUNCTION OF EXPOSURE TIME AT 100 C IN AERATED ETHYLENE GLYCOL SOLUTIONS

was not influenced by aeration, and it decreased slightly with exposure in both ethylene glycol and propylene glycol solutions. At termination, potentials of 0.11 to 0.12 V (SCE) were measured in ethylene glycol solutions, whereas slightly more noble potentials (0.135 to 0.145 V (SCE)) were measured in propylene glycol solutions. The potentials of aluminum alloys fluctuated between approximately +0.1 V (SCE) and -0.3 V (SCE) in aerated ethylene glycol and propylene glycol solutions. Less fluctuation was observed in deaerated ethylene glycol solutions, and the potentials in deaerated propylene glycol were nearly constant at 0 V (SCE) over the exposure period.

The free corrosion potential of Type 1 specimens was measured periodically during exposure tests at 100 C in aerated buffered solutions. Results showed that buffering slightly decreased the potential of CDA 122 copper, and that the potential of 1100 aluminum was much more stable than under unbuffered conditions and remained at a value of about 0 V (SCE) throughout the testing.

Weight-Loss and Pitting Measurements. Weight-loss and pit-depth measurements were performed on Type 2 specimens exposed to aerated and deaerated ethylene glycol and propylene glycol solutions at 100 C. The deepest pit on each specimen was measured with a calibrated microscope. Corrosion rates were calculated from average weight losses for duplicate specimens. Results are given in Table 18 and 19. These data show that corrosion behavior in both ethylene glycol and propylene glycol was similar for 1018 steel and CDA 122 copper. 1018 steel did not undergo pitting attack, and CDA 122 copper pitted in only two instances. Corrosion rates of CDA 122 copper and 1018 steel were greater under aerated conditions. The corrosion rate of 1018 steel was unacceptably large under all test conditions, and the CDA 122 copper exhibited marginal corrosion resistance. No definite trends in general corrosion behavior with time were apparent.

Pitting corrosion resistance is more critical to the performance of aluminum alloys than is general corrosion. Pitting of these alloys occurred under many test conditions. It was generally more severe

TABLE 18. AVERAGE CORROSION RATES CALCULATED FROM DESCALED WEIGHT-
LOSS AND MAXIMUM PIT DEPTHS(a) FOR TYPE 2 SPECIMENS
EXPOSED TO ETHYLENE GLYCOL SOLUTIONS AT 100 C

Alloy	Aeration	Pit Depth, μm		Corrosion Rate ^(e) $\mu\text{m}/\text{y}$	
		750 Hours Exposure	1750 Hours Exposure	750 Hours Exposure	1750 Hours Exposure
1100 Al	Aerated	135 ^(b)	530	18	28
3003 Al	Aerated	240	450 ^(c)	5.0	17
6061 Al	Aerated	None	240	1.5	4.0
CDA 122 Cu	Aerated	None	100 ^(d)	33	22
1018 Steel	Aerated	None	None	210	280
1100 Al	Deaerated	None	325	0.2	0.6
3003 Al	Deaerated	None	280	2.0	1.6
6061 Al	Deaerated	70	195	2.3	0.2
CDA 122 Cu	Deaerated	None	200 ^(d)	14	9.4
1018 Steel	Deaerated	None	None	98	110

(a) Averaged for duplicate specimens

(b) Measured near edges of holes used for suspending the specimens in solution

(c) Measured at specimen edges

(d) Only one pit found

(e) Combined weight loss due to pitting and general corrosion

TABLE 19. AVERAGE CORROSION RATES CALCULATED FROM DESCALED WEIGHT-LOSS AND MAXIMUM PIT DEPTHS^(a) FOR DUPLICATE TYPE 2 SPECIMENS EXPOSED TO PROPYLENE GLYCOL SOLUTIONS AT 100 C

Alloy	Aeration	Pit Depth, μm		Corrosion Rate ^(b) $\mu\text{m/y}$	
		750 Hours	1750 Hours	750 Hours	1750 Hours
1100 Al	Aerated	235	440	4.0	11.5
3003 Al	Aerated	None	None	2.2	0.2
6061 Al	Aerated	None	470	-	3.0
CDA 122 Cu	Aerated	None	None	33	41
1018 Steel	Aerated	None	None	365	280
1100 Al	Deaerated	None	None	0.70	0.75
3003 Al	Deaerated	None	None	1.5	0.9
6061 Al	Deaerated	None	None	2.7	1.5
CDA 122 Cu	Deaerated	None	None	11.5	15
1018 Steel	Deaerated	None	None	115	140

(a) Averaged for duplicate specimens

(b) Combined weight loss due to pitting and general corrosion

in ethylene glycol in aerated solutions and at long exposure times (after pH dropped). Pitting of 1100 aluminum was somewhat more severe than that of 3003 aluminum and 6061 aluminum. The total corrosion of the aluminum alloys, calculated from weight-loss, was slightly more severe in ethylene glycol solutions, but it was acceptable except where pitting occurred to a significant degree. Total corrosion rates in aerated solutions generally increased with exposure time, but no such trend was apparent in de-aerated solutions.

Weight-loss and pit-depth measurements were performed on Type 2 specimens that were exposed to aerated buffered ethylene glycol and propylene glycol solution at 100 C. Results, presented in Table 20, show that corrosion rates in propylene glycol solutions were somewhat higher than those in ethylene glycol solutions. Comparison of Table 20 with Tables 18 and 19 shows that buffering the solutions slightly accelerated the corrosion rate of 1100 aluminum, and that the corrosion rate of CDA 122 copper increased significantly. However, corrosion data for CDA 122 copper in buffered solution may be in error due to difficulties encountered in descaling. Comparison of pitting data for unbuffered and buffered solutions shows that pitting of 1100 aluminum was much less severe in the latter solution.

Exposure Tests at 180 C

Decomposition Studies

pH Measurements. The pH of ethylene glycol and propylene glycol solutions was measured periodically over exposure periods of up to 825 hours at 180 C under deaerated and aerated conditions. Testing was performed in the presence of CDA 122 copper. Results given in Figure 10 show that the pH of the solutions dropped rapidly within the initial 50 hours, increased slightly over the next 150 hours, and stabilized over the remainder of the testing periods. Behavior of ethylene glycol and propylene glycol and of aerated and deaerated solutions was essentially the same. Comparison of these data with data

TABLE 20. AVERAGE CORROSION RATES CALCULATED FROM DESCALED WEIGHT-LOSS AND MAXIMUM PIT DEPTHS^(a) FOR TYPE 2 SPECIMENS EXPOSED TO BUFFERED AERATED ETHYLENE GLYCOL AND PROPYLENE GLYCOL SOLUTIONS

Alloy	Solution	Pit Depth μm		Corrosion Rate ^(a) $\mu\text{m/y}$	
		1000 h Exposure	2000 h Exposure	1000 h Exposure	2000 h Exposure
1100 Al	Ethylene Glycol	None	None	12.5	7.5
CDA 122 Cu	Ethylene Glycol	None	365	200	180
1100 Al	Propylene Glycol	None	None	34	80
CDA 122 Cu	Propylene Glycol	None	None	870	820

(a) Combines general corrosion and pitting, if present.

FIGURE 10. pH AS A FUNCTION OF EXPOSURE TIME AT 180 C FOR DEAERATED AND AERATED GLYCOL SOLUTIONS IN THE PRESENCE OF CDA 122 COPPER

obtained at 100 C indicates that the higher temperature caused a more rapid decrease of pH, but it did not influence the final plateau values significantly.

Conductivity Measurements. The conductivity of the ethylene glycol and propylene glycol solutions in the presence of CDA 122 copper was measured periodically over exposure periods of up to 825 hours at 180 C under deaerated and aerated conditions. The results in Figure 11 show that conductivity generally increased over the first 50 hours and then stabilized over the remainder of the test periods. Behavior of ethylene glycol and propylene glycol was essentially the same. The conductivity behavior at 180 C was considerably different from that at 100 C, in that conductivity gradually increased with time over the entire testing period (1750 hours) at 100 C to values approaching those observed at 180 C within 50 hours.

Solution Analyses. Solutions from the exposure tests at 180 C were analyzed for total acid and volatile acid contents following termination of the tests. Results showed that there was not a significant difference in acidification between ethylene glycol and propylene glycol. Under deaerated conditions acidification was more pronounced in ethylene glycol, whereas the reverse was true under aerated conditions. Comparison of these data with similar data obtained during 100 C exposures indicates, somewhat unexpectedly, that acidification was not accelerated at the elevated temperature.

Corrosion Studies

Polarization Resistance Measurements. The polarization resistance of Type 1 specimens of CDA 122 copper was monitored periodically during the course of exposure tests at 180 C. The PR values generally increased, but they fluctuated considerably during the initial 250 hours. PR generally decreased slightly with time after 250 hours for the propylene glycol solutions, suggesting an increasing corrosion

FIGURE 11. CONDUCTIVITY AS A FUNCTION OF EXPOSURE TIME AT 180 C FOR AERATED AND DEAERATED GLYCOL SOLUTIONS IN THE PRESENCE OF CDA 122 COPPER

rate, whereas the opposite was true for ethylene glycol solutions. PR values were lower under aerated conditions than under deaerated conditions for propylene glycol, whereas no effect of aeration was observed for ethylene glycol solutions.

Comparison of these data with PR data obtained at 100 C indicates that corrosion was less severe at the elevated temperature. At 100 C there was no discernible difference between the behavior of ethylene glycol and propylene glycol, whereas PR values were slightly lower in propylene glycol at 180 C.

Weight Loss and Pitting Measurements. Weight loss and pitting measurements were performed on Type 3 specimens that were exposed to aerated and deaerated ethylene glycol and propylene glycol solutions at 180 C. The testing procedure was similar to that used at 100 C. Results, given in Table 21, show that corrosion rates were much lower under all test conditions than those observed at 100 C. Weight losses in the tests at 180 C approached the detection limit of the measuring equipment.

DISCUSSION

The major goals of Task 3 were to determine the degree to which degradation^(a) of the glycol-base media occurs under normal operating conditions and under upset conditions for nonconcentrating solar collector systems, and to evaluate the influence of such degradation on the corrosion behavior of the most common metallic materials found in these systems. Accordingly, the experimental program was designed such that both corrosion and degradation were monitored simultaneously. The use of a variety of techniques to characterize the corrosion and degradation also enabled identification of promising techniques for monitoring these phenomena in operating systems.

(a) "Degradation" is used synonymously with "acidification", which is produced by elevated temperature exposure and results in increased corrosivity of glycol solutions.

TABLE 21. AVERAGE CORROSION RATES CALCULATED FROM DESCALED WEIGHT-LOSS FOR TYPE 3 SPECIMENS OF CDA 122 Cu THAT WERE EXPOSED TO AERATED AND DEAERATED ETHYLENE GLYCOL AND PROPYLENE GLYCOL SOLUTIONS AT 180 C

Solution	Aeration	Exposure Time Hours	Corrosion Rate (a) $\mu\text{m/y}$
Ethylene Glycol	aerated	840	4.8
Propylene Glycol	"	840	<1
Ethylene Glycol	deaerated	675	<1
Propylene Glycol	"	675	<1

(a) Average from duplicate specimens.

Degradation Studies

Results of the chemical analyses of solutions from tests at 100 C indicate that degradation of the glycol-based heat transfer media was catalyzed by metals commonly found in nonconcentrating solar collectors. Mild steel most severely catalyzed acidification; whereas, within experimental error, the effects of CDA 122 copper and 1100 aluminum on catalysis were approximately equal at 100 C. Buffering the solutions did not affect the degradation significantly, Table 17. Furthermore, the chemical species present in ASTM water did not accelerate degradation of the glycol-based heat transfer media.

Results of the chemical analyses of solutions from the elevated temperature tests indicate that degradation was not accelerated significantly by the increased temperature. These tests included the effect of oxygen, but not that of heat transfer. The data from these experiments suggest that stagnation may not contribute substantially to degradation in an operating system. However, it is recommended that future research pursue this question with the effects of heat transfer included, and in the presence of typical corrosion inhibitors.

The pH behavior as a function of exposure time indicated that degradation of the glycol solutions occurred in the absence of metals, although the concentration of the acidic degradation products was below the detection limit for chemical analysis. Trends in pH showed that the pH of the control solutions decreased with time at rates similar to those of solutions that contained various metals. The pH values of the solutions that contained metals may have been significantly influenced by the presence of corrosion products. This contention is supported by the fact that the pH of solutions that contained 1018 steel, which contained the highest concentration of degradation products, decreased the least with exposure time. In addition, the pH of the solutions exposed in the presence of the aluminum alloys was approximately the same at a given exposure time as the control solutions that contained significantly lower concentrations of acidic degradation products. The corrosion products may have buffered the solutions and reduced the apparent degree of acidification.

The pH of glycol solutions prepared with ASTM waters also decreased with exposure time, indicating that degradation was occurring. The greatest decrease was observed in the ethylene glycol solution initially adjusted to pH 11. The pH of the buffered solutions was generally controlled by the action of the buffer. However, in the ethylene glycol solution that contained CDA 122 copper, a decrease from 7.5 to ~6 occurred within 2000 hours, indicating that degradation indeed had occurred.

The ionic conductivity changes of the solutions typified in Figure 5 correlate reasonably well with the results of the solution analyses. The conductivity of the solutions that contained the largest concentrations of degradation products increased the most with exposure time. However, the corrosion products present in the solution probably also contributed to increases in conductivity.

The increased conductivity caused by buffering the solutions or by adding species found in a typical corrosive tap water generally masked the subsequent influence of degradation on conductivity. In an operating system such masking effects would be more pronounced, because the corrosion inhibitors that are commonly used would further increase the conductivity in the absence of degradation products. Thus, conductivity measurement may not be a practical means for assessing degradation in an operating system.

One of the most significant findings of the study was that propylene glycol did not degrade at a greater rate than ethylene glycol. The pH and conductivity behavior of solutions prepared with the two heat transfer media were indistinguishable. Furthermore, results of the chemical analyses did not indicate significant differences in the concentrations of degradation products in solutions containing ethylene glycol and propylene glycol.

Corrosion Studies

The major reason that degradation of glycol-base heat transfer media is of technological interest is because the acidic degradation

products can accelerate corrosion of solar collector materials. Accordingly, the corrosion behavior of several common metallic solar collector materials of construction was measured in conjunction with degradation, to provide information on the effects of degradation on corrosion.

None of the alloys tested exhibited adequate corrosion resistance in the degraded glycol solutions. As anticipated, 1018 steel underwent rapid general corrosion, and the corrosion resistance of CDA 122 copper was marginal. Corrosion rates of 27.5 $\mu\text{m}/\text{y}$ and 250 $\mu\text{m}/\text{y}$ were found for CDA 122 copper and 1018 steel in aerated uninhibited ethylene glycol, giving life expectancies of 18.5 years and 2.0 years, respectively, for piping with a 510 μm wall thickness. The general corrosion rates of the aluminum alloys were quite low, but pitting to depths exceeding 500 μm was observed within 1750 hours of exposure to the glycol solutions. Thus, a 20 year life could not be guaranteed for a nonconcentrating solar collector system that was constructed of these materials and utilized uninhibited glycol-based heat transfer media.

Results of the polarization studies indicate that corrosion behavior was similar in ethylene glycol and propylene glycol solutions. This conclusion was corroborated by the weight-loss and pitting data in Tables 18 and 19. Furthermore, these tables show that pitting attack in propylene glycol was somewhat less severe than in ethylene glycol solutions. These results are different from those of similar studies⁽⁶⁾ on ethylene glycol and propylene glycol, which showed that the latter heat transfer medium was more corrosive toward aluminum alloys. PR qualitatively correlated with weight loss for all of the alloys studied. Fluctuations in PR of the aluminum alloys was associated with pitting, indicating that pits were formed and then arrested throughout most of the testing period. Thus, PR may be useful for corrosion monitoring in operating systems. However, monitoring general corrosion of mild steel and of copper alloys by PR is probably more accurate than detecting pitting in aluminum alloys, because the small surface area of the active pits necessitates relatively high corrosion rates in order to contribute to the overall corrosion current.

Electrochemical potential measurement was also a useful means to monitor corrosion behavior of the various alloys. Reasonably good correlation was found between PR and corrosion potential measurements. A gradual decrease in PR corresponded to a gradual decrease in the corrosion potential for CDA 122 copper and 1018 steel under most of the test conditions. Fluctuations in PR for the aluminum alloys also correlated with fluctuations in the corrosion potential and the occurrence of pitting. Variation in these parameters was greatest in the aerated ethylene glycol solution, Figure 9. In contrast, PR and potentials in deaerated propylene glycol, in which pitting was not observed, were constant throughout most of the tests. Furthermore, considerably less variation in PR and potential of 1100 aluminum occurred in buffered solutions in which no pitting was observed (Table 20).

It is well established that the corrosion stability of aluminum alloys is reduced in aqueous environments below pH 4.⁽⁷⁾ Thus, it appears that the acidification of the glycol solutions contributed to the pitting of the aluminum alloys. This conclusion is supported by results obtained in the buffered solutions. The PR, weight loss and pitting data indicate that general corrosion rates of 1100 aluminum were slightly accelerated by buffering, but that pitting was prevented; the former effect probably resulted from the increased ionic conductivity of the solutions.

The issue of whether the unacceptable general corrosion rates of CDA 122 and 1018 steel were influenced by degradation products is difficult to evaluate conclusively. Both alloys generally showed a decrease in PR with exposure time, which indicates that corrosion rates increased with time. From these data one is tempted to conclude that degradation of the glycols produced an increase in corrosion rate. However, the increasing concentration of corrosion products (rather than organic oxidation products) in the solutions with increasing exposure time could increase the corrosion rate in two ways. First, the corrosion products would increase solution conductivity, which could accelerate the reduction reaction rate. Second, both cuprous and ferrous ion can be oxidized in the acidic bulk solution to the higher valence states, and then be reduced at the metal surface. Therefore, the

increasing corrosion rates with exposure time may have been affected by the presence of corrosion products as well as organic oxidation products.

Results of the PR and weight-loss tests conducted at 180 C, Table 21, indicate that stagnation conditions actually decreased the corrosion rate of CDA 122 copper. Corrosion testing was not performed with the other alloys at 180 C, but results of the degradation tests indicate that there was not a significant increase in acidification at the elevated temperature over that which occurred at 100 C, and thus any effect that stagnation conditions have on corrosion presumably may relate to parameters other than the generation of these products.

In summary, the results of these experiments indicate that degradation of ethylene glycol and propylene glycol solutions occurred under simulated operating conditions for solar collectors in the absence of metals, but it was catalyzed by their presence. This degradation accelerated the corrosion of the alloys used in these systems. Therefore, corrosion inhibitors and buffering agents are necessary to attain a reasonable design life for nonconcentrating solar collector systems. Under most testing conditions the corrosion and degradation behavior of propylene glycol solutions was indistinguishable from that of ethylene glycol. Thus, use of the less toxic propylene glycol in systems that interface with potable water should not exacerbate corrosion in the system.

CONCLUSIONS -- TASK 3

The following conclusions are based on the results of this Task 3 study:

- (1) Degradation of aqueous ethylene glycol and propylene glycol solutions occurred in the absence of metals but was significantly accelerated by their presence. Degradation was manifested as the appearance of organic acids and acidification of the glycol solutions.
- (2) Aeration slightly accelerated the rate of degradation.
- (3) The rate of degradation was not significantly accelerated by simulated elevated temperature

stagnation conditions.

- (4) The rate of degradation was similar in ethylene glycol and propylene glycol solutions.
- (5) The chemical species found in simulated tap water, which contained sodium, chloride, bicarbonate, and sulfate ions, did not substantially accelerate degradation in the absence of metals.
- (6) Degradation of the glycols caused a decrease in pH in solutions prepared with distilled water, as well as with simulated tap water and a buffering agent.
- (7) Degradation of the glycols caused an increase in the ionic conductivity only in solutions prepared with distilled water; the high conductivity of the solutions prepared with simulated tap water and solutions containing a buffering agent masked conductivity changes caused by degradation.
- (8) None of the alloys tested had adequate corrosion resistance in degraded glycol solutions for long-term use in solar collectors in the absence of corrosion inhibitors.
- (9) The acidic degradation products lowered the pH of the glycol solutions, which in turn accelerated pitting of aluminum alloys.
- (10) The acidic degradation products probably contributed to an acceleration in corrosion of CDA 122 copper and 1018 steel.
- (11) The PR and potential measurements generally reflected the corrosion behavior of the various alloy-solution systems studied. A gradual decrease in either parameter indicated a gradual increase in general corrosion, whereas rapid fluctuation indicated pitting.

REFERENCES

- (1) Clifford, J. E., and Diegle, R. B., Technical Progress Report, "Task 1 of Solar Collector Studies for Solar Heating and Cooling Applications", United States Department of Energy, Contract No. DE-AC04-79CS10510, April, 1979.
- (2) Diegle, R. B., Technical Progress Report, "Task 2 of Solar Collector Studies for Solar Heating and Cooling Applications", United States Department of Energy, Contract No. DE-AC04-79CS10510, October, 1979.
- (3) Beavers, J. A., and Diegle, R. B., Technical Progress Report, "Task 3 of Solar Collector Studies for Solar Heating and Cooling Applications", United States Department of Energy, Contract No. DE-AC04-79CS10510, September, 1979.
- (4) Goddard, H. P., Jepson, W. B., Bothwell, M. R., and Kane, R. L., The Corrosion of Light Metals, John Wiley and Sons, Inc., New York (1967), p 60.
- (5) Cheng, C., Personal communication.
- (6) Butler, G., and Mercer, A. D., British Corrosion Journal, Volume 12, Number 3, 1977, p 163.
- (7) Pourbaix, M., Atlas of Electrochemical Equilibria in Aqueous Solutions, National Association of Corrosion Engineers, Houston, 1974, p 168.

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 multimetallic 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 1

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 WATERS
BCIRA 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 Khl8Nl0T 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 Khl8Nl0T 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

Rozenfeld, 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
WATERProtection 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 WATERMaterials 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 SYSTEMSAluminium 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

Mansfeld, 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. (200-462-4933 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 20 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 liquid heating and cooling system. For February, 1978, about 50% 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 3 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 1976. Costs, savings, and improvements made later are also reported. In 1975 this firm set out to study the electrical load leveling 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 3°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.

MSIR 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 MSIR 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., Guttenplan, 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 SPECTROSCOPY

Houston 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 21-25

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.

SOLAR ENERGY BIBLIOGRAPHY

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.

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 37-43

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

Mansfield, 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 ALUMINUMCorrosion, 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.